# Cave and Karst Science

*The Transactions of the British Cave Research Association*

BCRA

Volume 28 Number 1 April 2001

# Cave and Karst Science

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

### 1. Papers

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.

### 2. Reports

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

### 3. Forum

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.

### 4. Abstracts

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

Manuscripts may be sent to either of the Editors: Dr D J Lowe, c/o British Geological Survey, Keyworth, Nottingham, NG12 5GG, UK, and Professor J. Gunn, Limestone Research Group, University of Huddersfield, Queensgate, Huddersfield, HDI 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: djlo@bgs.ac.uk or j.gunn@hud.ac.uk.

# Notes for Contributors

These notes are intended to help authors prepare their material in the most advantageous way, so as to expedite publication and reduce both their own and editorial labour. Time and effort are saved if the rules below are followed.

**Text:** All material should be presented in a format as close as possible to that adopted by *Cave and Karst Science* since 1994. Text should be typed double-spaced on one side of the paper only. Subheadings within an article should follow the system used in *Cave and Karst Science*; a system of primary, secondary and, if necessary, tertiary subheadings should be indicated clearly. Initial manuscripts may be supplied as hard copy, as a suitably formatted text file on computer disk, or as an E-mail attachment (addresses above) in appropriate format. Where possible the final revised text should be submitted on computer disk or as an E-mail attachment, although paper copy remains acceptable. It is recommended that, where text includes unusual characters or equations, a hard copy highlighting non-standard features be provided as a guide for the Editors. Most modern PC-based word processing packages can be translated but, if in doubt, please consult one of the Editors. Apple Mac disks are accepted, but cannot be dealt with routinely and may cause delays.

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

**References** to previously published work should be given in the standard format used in *Cave and Karst Science*. In the text the statement referred to should be followed by the relevant author's name and date (and page number if appropriate) in brackets. Thus: (Smith, 1969, p.42). All such references cited in the text should he given in full, in alphabetical order, at the end of the manuscript. Thus: Smith, D E, 1969. The speleogenesis of the Cavern Hole. *Bulletin of the Yorkshire Caving Association*, Vo1.7, 1-63. Books should be cited by their author, date, title, where published and publisher. As there is no readily available listing of abbreviated titles, and as references to publications in languages other than English are becoming more common, periodical titles should be written in full. Failure to provide full and unambiguous Reference information may lead to a delay in publication.

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

**Figures**: Illustrations in a number of digital graphics file formats are acceptable for eventual publication. However, as changes to figures may be requested by referees, recommended practice is to provide hard copies with the initial submission and reference hard copies and digital files with the final draft. Authors should contact the Editors to check both the desirability of this approach and suitable file formats before submitting the manuscript. Traditional hard copy line diagrams and drawings must be in black ink on either clean white paper or card, or on tracing paper or such materials as Kodatrace. Anaemic grey ink and pencil will not reproduce! Illustrations should be designed to make maximum use of page space. Maps must have bar scales only. If photo-reduction is contemplated, all letters and lines must be large and thick enough to allow for their reduction. Letters must be done by stencil, Letraset or similar methods, not hand-written. Diagrams should be numbered in sequences as figures, and referred to in the text, where necessary, by inserting (Fig.l), etc, in brackets. A full list of figure captions should be submitted on a separate sheet or on a new page following a hard page break in digital files.

**Photographic plates** are welcome. Photographs in various digital formats can be handled but, as only a selection of illustrations provided with a manuscript may be included in the final publication, recommended practice is to provide hard copies with the initial submission and reference hard copies and digital files with the final draft. Authors should contact the Editors to check both the desirability of this approach and suitable file formats before submitting the manuscript. Traditional hard copy photographs are equally acceptable and may be good clear black and white prints, colour prints or colour transparencies with sharp focus and not too much contrast. Prints about 15 x 10cm (6 x 4 inches) are best; if in doubt, a selection may be submitted. They should be numbered in sequence but not referred to in the text, except where essential, and then only after discussion with one of the Editors. A full list of plate captions, with photographer credits where relevant, should be submitted on a separate sheet or on a new page following a hard page break in digital files.

**Tables**: These should not be included in the text but should be typed, or clearly hand-written, on separate sheets or on a new page following a hard page break in digital files. All tables, especially those provided in digital form, should use a simple format to allow ready translation into an appropriate publication style. They should be numbered in sequence, and a list of captions, if necessary, should be submitted on a separate sheet or on a new page following a hard page break in digital files. Authors may mark approximate locations for tables, plates and figures, in pencil in the manuscript margins, as a guide to formatting for publication.

**Copyright:** It is the author's responsibility to obtain written permission where necessary to reproduce all material submitted for publication. Copyright on articles published in *Cave and Karst Science* rests with the British Cave Research Association.

**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

Volume 28, Number 1 April 2001

# Contents



## Cover photo:

**Fallen stalactite, Casa de Pedra, Brazil.**

The speleothem to the right of the figure is a large stalactite block that has detached from the cave roof and rotated through 90 degrees before landing on the floor. The point from which it fell is marked by an area of 'fresher' rock on the ceiling, but the original top of the stalactite is buried beneath sediment. The area around the cave is thought to be tectonically inactive, raising the interesting question of what processes led to the block becoming detached and why it should have rotated before hitting the ground. Perhaps a topic for a future *Cave and Karst Science* paper?
Photo by John Gunn.

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

*Cave and Karst Science* is published three times a year by the BCRA and is issued free to all paid up members of the Association. The 2001 subscription rates to *Cave and Karst Science* are £16.00 (UK) and £18.00 (overseas) per annum (postage paid). Details of Association membership and annual subscriptions can be obtained from the BCRA Membership Secretary, Lynne Bailey, British Cave Reserach Association, Hafod Swn-Y-Dwr, The Dardy, Crickhowell, Powys, NP8 1PU, UK (E-mail address: membership@bcra.org.uk). The Association's Registered Office address is: BCRA, The Old Methodist Chapel, Great Hucklow, BUXTON, Derbyshire, SK17 8RG, UK. (E-mail address: enquiries@bcra.org.uk). Individual copies and back issues of *Cave and Karst Science* can be obtained from BCRA Publication Sales, at the address shown at the foot of the inner back cover.


ISSN 1356-191X

*Printed by The Sherwood Press, Nottingham, UK: September 2001*

# EDITORIAL

John Gunn and David Lowe

Once again we have to apologise to readers that many events and a variety of technical issues, each one seemingly trivial in itself, have conspired to impose serious delays on production of this issue. However, we hope that this is to some extent compensated by the contents, which include a wide geographical range - from Mendip and Yorkshire to China and Australia - and aspects of both surface and underground studies. We are also pleased to report that issue 28(2) is also now more or less full and awaiting the attentions of our new Desk Top Publishing assistant, Becky Talbot. The present issue is the first to be produced by Becky, taking over from Jean Reeve, who did sterling work, starting with the first issue that we edited back in 1994 and continuing right through to Volume 27(3). We thank Jean once again for her long-lasting good will and ever-optimistic approach to the task and its constantly moving goalposts. Equally we wish Becky luck as she begins to ascend a very steep learning curve and as the full complexity and frustration of the task she has agreed to take on gradually begin to unfold.

In an effort not to delay the despatch of copy to the printers any longer, we are keeping this Editorial brief, so would reiterate just one request. Some while ago we suggested that individuals might wish to contribute a cover photograph not related to any specific article but illustrating a particular topic, or raising a question. The present issue has just such a cover photograph, and we repeat our request. All we require is a good quality colour slide or print of a cave or karst feature, together with a few words for the caption. Should contributors wish to provide more detail, or a longer discussion, this would be very welcome, and would be published in the Forum.

We hope you have had a good summer's caving, despite the restrictions imposed in parts of the UK, and we look forward to receiving details of at least some of the results for possible publication!

CAVE KARST SCIENCE Vol. 28, No.1 April 2001
Transactions of the British Cave Research Association


ISSN 1336-191X

# Halls and Narrows: Network caves in dipping limestone, examples from eastern Australia.

**R Armstrong OSBORNE**
School of Development and Learning, A35, University of Sydney, N.S.W. 2006, Australia

**Abstract:** Structurally guided network caves formed in limestones dipping at greater than approximately thirty degrees differ in plan and section from maze caves developed in horizontal to gently-dipping limestone. These caves are characterised by the development of large elongate cavities called halls, oriented along strike, and smaller, short cavities called narrows, oriented perpendicular to strike. Halls typically terminate blindly along strike. A range of hall and narrows development is recognised, resulting from increases in dip and differing disposition of joints. Entrances to hall and narrows caves appear to have little genetic relationship to the caves. Hall and narrows caves are common in the steeply dipping Palaeozoic limestones of eastern Australia. Whereas the origin of these caves has yet to be completely explained, many of their features suggest that hydrothermal or artesian water had a role in their development.

*(Received 02 April 2001; Accepted 05 June 2001)*

## INTRODUCTION

A previous paper (Osborne, 1999a) described how the cross-sectional shape of cave passages developed in Palaeozoic limestones of the Tasman Fold Belt in eastern Australia (Fig.1) differs from those illustrated in conventional texts. While the texts described cave development in horizontal to gently-dipping limestone, much of the limestone in eastern Australia is steeply-dipping. As a consequence, the cross-sectional shapes of cave passages were found to be different, and genetic interpretations based on conventional text-book descriptions of passage morphology were found to be misleading. This paper extends the previous work by examining the gross morphology, as reflected in maps and cross-sections, of structurally-guided network caves developed in dense, steeply-dipping limestones.

Maze caves, consisting of structurally-guided passages developed in horizontal to gently-dipping limestone, have long been recognised and described (Palmer, 1975, Ryder, 1975). Bakalowicz *et al* (1987) considered that some types of maze caves were formed by descending *(per descensum)* meteoric waters, whereas others formed by ascending *(per ascensum)* hydrothermal or artesian waters. Klimchouk (1996) described the development of large complex maze caves by artesian processes in the gypsum karst of the Ukraine.

This paper considers the range of structurally-guided network caves that can develop in limestones under different structural settings. Maze caves are but one example of this type of cave structure. The emphasis is on a particular style of cave development, hall and narrows, which is characteristic of structurally-guided caves developed in limestones dipping at more than 30 degrees.

The examples upon which this paper is based, and the author's field areas, are located in the Tasman Fold Belt, which underlies the highlands of eastern Australia. The Early Palaeozoic limestones of the Tasman Fold Belt were deposited as carbonate ramp and platform deposits in the shallow seas of an active volcanic island arc. As a consequence lateral facies changes are widespread. Some of the limestone bodies are allochthonous blocks that slid into deep water soon after deposition. Major regional orogenic phases, from the Late Ordovician to the Early Carboniferous have folded the limestones, with many undergoing multiple phases of deformation. This is a quite different geological environment from that in which the Inception Horizon Hypothesis (Lowe and Gunn, 1997; Lowe, 2000) was developed, and some of the observations reported in this paper are likely to be specific to cave development in multiply folded Palaeozoic terrains.

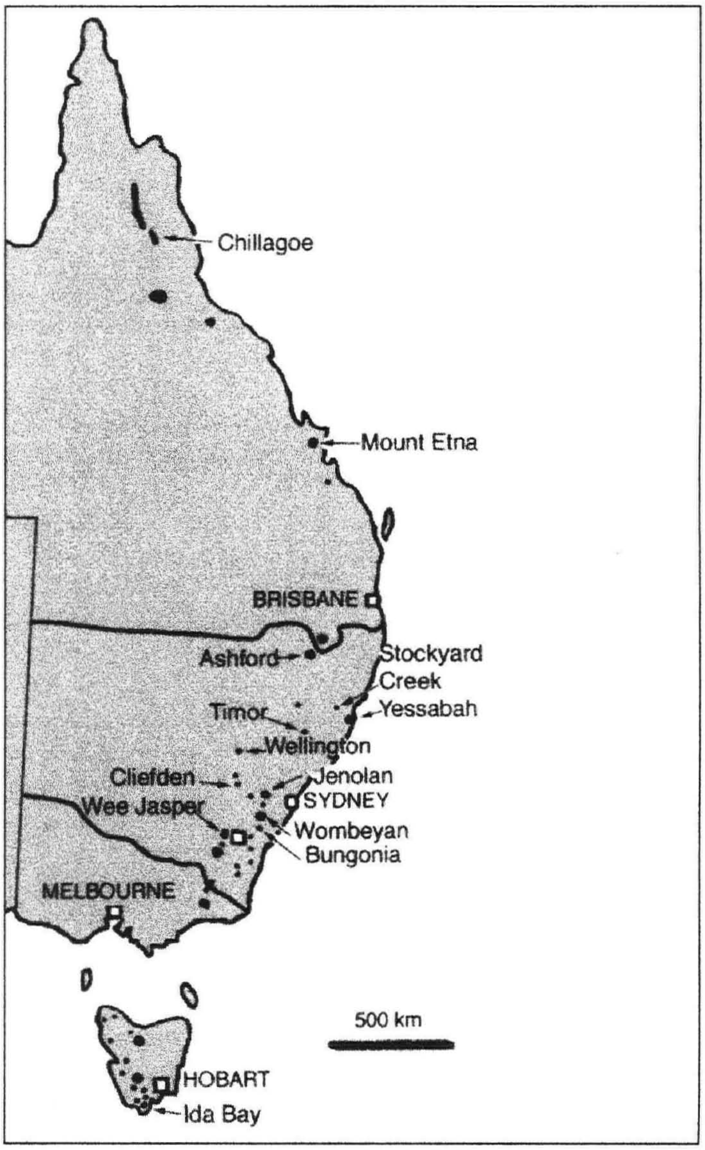



*Figure 1. Eastern Australia showing major karsts developed in Palaeozoic limestones of the Tasman Fold Belt.*

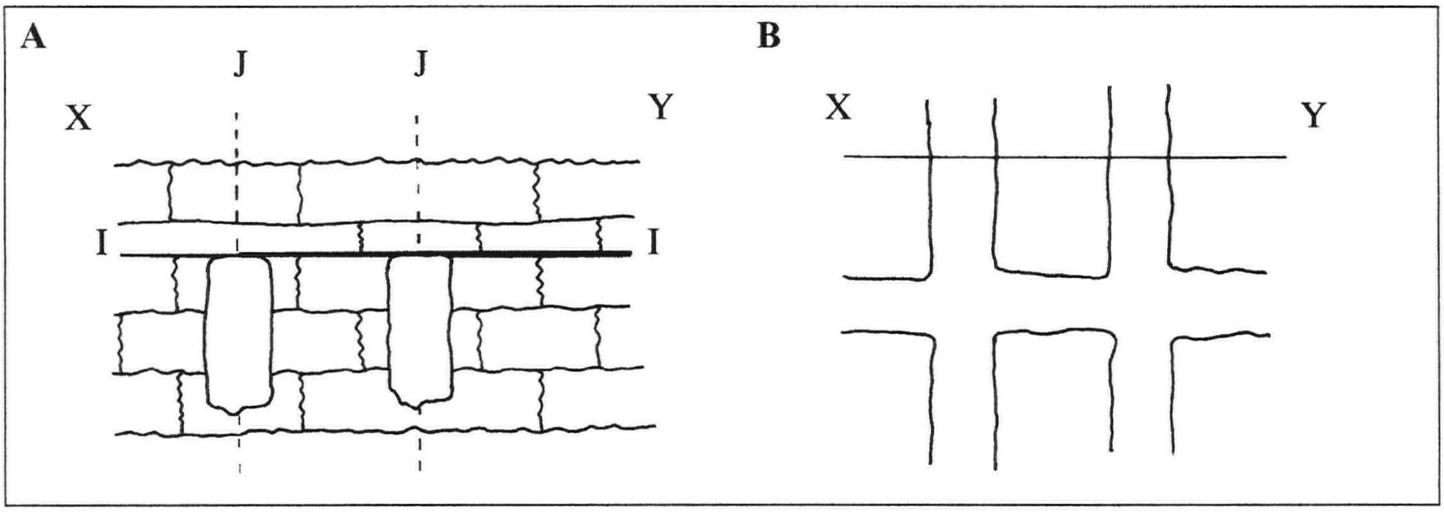



*Figure 2. Cross-section (A) and plan (B) of a horizontally bedded limestone body, in which two sets of vertical joints are developed. "I" = inception horizon; "J" = joints. A maze cave is developed, with passages forming at the intersection of joints with inception horizons.*

## HALL AND NARROWS MORPHOLOGY

Hall and narrows caves consist principally of two types of cavity — *halls and narrows* — joined in a geometric pattern. Halls are elongate structurally-guided cavities. They are generally higher than they are wide and commonly end blindly along strike. Shannon (1970) described cavities of this type perceptively, as having *"cross-sections of door-way proportions"*. Typically, halls are guided by bedding-related features, rather than by joints or fractures.

Narrows are cavities of small cross-section and relatively short length that join halls together. Typically, narrows are guided by structures oriented perpendicular to strike, such as cross-joints. Frequently, parallel halls are joined by a single narrow. Some halls are not blind, but joined to similar cavities developed along strike by narrows. This is the case with Caesars Hall in Wyanbene Cave (Figs 1 and 16), from which halls are named.

## DEVELOPMENT OF NETWORK CAVES IN DIFFERENT STRUCTURAL SETTINGS

Just as the cross-sectional shape of cave passages can differ with the dip of the limestone (Osborne, 1999a), the gross geometry of network caves, reflected in their plans and cross-sections, is influenced by the angle of dip of the limestone. In the discussion that follows it is assumed that caves begin to form along, and are guided in their later development by:

- particular lithostratigraphical horizons, described as inception horizons by Lowe and Gunn (1997) and
- joints and fractures acting as inception links (Lowe, 2000).

It is also assumed that the bedrock is massive and recrystallised, with no remaining primary porosity and that inception horizons are widely spaced. The examples that follow form a sequence between two extreme end members:

- a rectilinear maze in horizontally-bedded limestone, guided in plan by two sets of vertical joints, and
- a rectilinear maze in vertically-bedded limestone, guided in plan by bedding and one set of vertical joints and in section by a prominent set of horizontal joints.

Hall and narrows development occurs between these two extremes. It is a common form of cave morphology in the Tasman Fold Belt of eastern Australia (Fig.1), where impounded karsts are developed in elongate narrow outcrops of steeply dipping limestone. As well as occurring as separate entities, hall and narrows morphology is found in sections of many of the more complex caves and cave systems in eastern Australia, such as those at Bungonia and Jenolan in New South Wales (Fig.1).

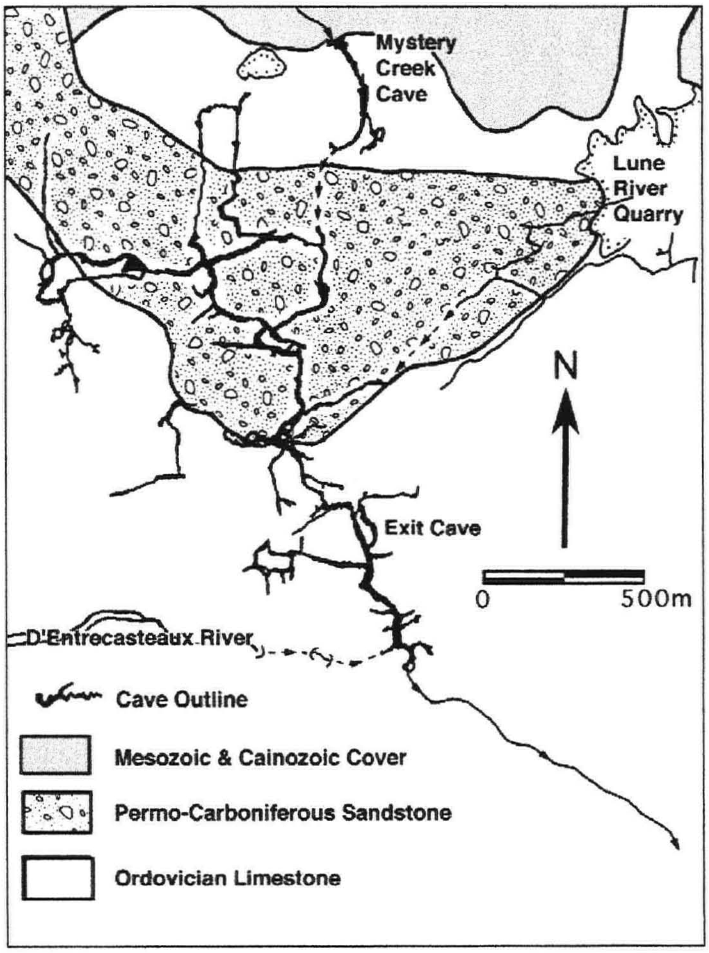



*Figure 3. Exit Cave, Ida Bay, Tasmania. Streams in the cave flow to the south. Note how passage size does not increase systematically to the south.*

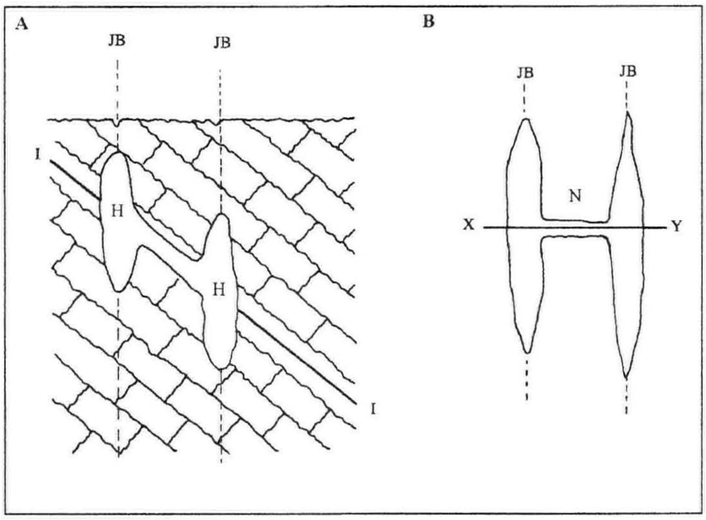



*Figure 4. Cross section (A) and plan (B) of a moderately dipping limestone body in which one set of vertical joints is developed parallel to strike and another set of vertical joints is developed perpendicular to the strike direction. "I" = inception horizon; "J" = joints. Halls (H) are guided by joints parallel to bedding. They are joined by Narrows (N), which are guided by the intersection of the inception horizon with joints perpendicular to bedding.*

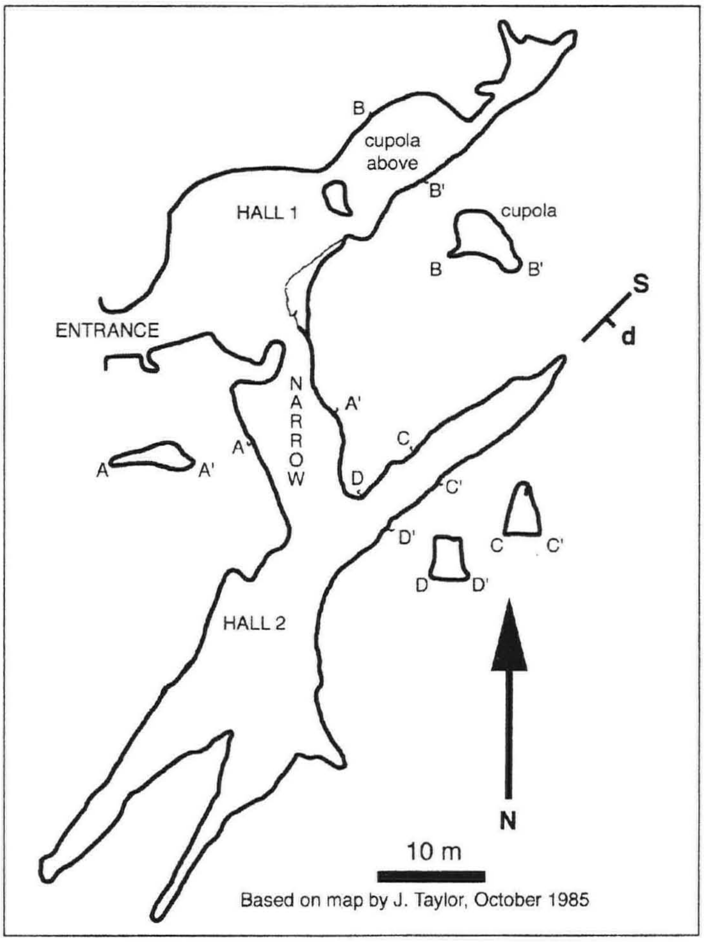



*Figure 5. Yessabah Bat Cave, New South Wales. Cave consists of two principal halls developed along strike, joined by a narrow developed down dip. Note passage cross-sections at "C" and "D". S = strike of limestone, d = dip direction.*

For each case discussed, figures are provided that give a simplified diagrammatic example, followed by the map and section of a real cave illustrating each particular permutation.

**Gentle dip and vertical joints**

Where the limestone is horizontal or gently dipping (up to 30°), joints guide the development of caves in plan (Fig.2). The result is the classic maze cave pattern described by Palmer (1975). True maze caves are not common in eastern Australia, as lower Palaeozoic limestones usually dip at 40° or more. Good examples of maze caves do occur in less-deformed Ordovician limestones at Ida Bay in Tasmania (Fig.1,) and Cliefden in New South Wales (Fig.1).

Exit Cave (Fig.3) at Ida Bay in southern Tasmania is considered to be the largest maze cave in eastern Australia, with plan length exceeding 40km. The cave is developed in horizontally bedded limestones of the Ordovician Gordon Group. The limestone mass containing the cave is capped by clastic rocks of the Late Carboniferous Parmeener Supergroup. The clastic rocks rest on, and infill, an irregular, karstic, unconformity surface on the limestone. Palaeokarst deposits of two distinct ages are exposed both in the Lune River Quarry, which drains into the cave (Osborne, 1995, Osborne and Cooper, 2001), and in the cave.

Though surveys of the cave remain incomplete, available maps suggest that vertical joint sets striking NNW-SSE and NE-SW (Fig.3) guided cave development. Major passages in Exit Cave are rectangular in cross-section, commonly 10m wide by 30m high. Trunk passages do not increase in size downstream of junctions and in places they actually decrease in size downstream. Osborne and Cooper (2001), following Bakalowicz et al. (1987), took the lack of systematic downstream increase in passage size as one of the characteristics suggesting that the cave had a hydrothermal origin.

**Moderate dip and vertical joints**

As bedrock dip increases above 30°, a hall and narrows pattern, rather than a maze pattern, develops. Joints parallel to bedding guide the halls, whereas joints perpendicular to bedding guide the narrows.

Figure 4 illustrates this style of cave. The limestone has a moderate dip (40°) and there are two sets of vertical joints, one parallel to strike and the other normal to strike. Halls follow strike-joints. They originate at the intersection of strike joints with inception horizons. Narrows develop down the bedding planes, following joints normal to the bedding. In many instances the narrows are low, wide, bedding plane "flatteners".

Caves with this structure are common in the Permian limestones of the New England Fold Belt of New South Wales (a sub-division of the Tasman Fold Belt). Yessabah Bat Cave (Figs 1 and 5) shows many of the characteristics of this type of cave. It consists essentially of two NE-SW trending halls, joined by a low sloping narrow. Both halls have blind terminations (apart from the entrance). A cupola is developed at section B-B' in the western hall.

**Steeper dip and vertical joints**

When dips become steeper (approximately 60°), halls are guided principally by the bedding, whereas narrows follow vertical joints, oriented perpendicular to bedding (Fig.6).

Transmission Cave at Cliefden Caves (Fig.7) consists of a series of halls guided by both bedding and steeply dipping joints with strikes close to that of the bedding. The halls are joined together by short narrows guided by two sets of vertical joints, striking roughly perpendicular to bedding. The larger halls generally have a triangular cross-section, but show no sign of being produced by structurally-guided breakdown. Rather the cross-sectional shape appears to result from the interplay of variable rock solubility and the intersection of structural planes. Some of the smaller halls are narrow sloping-sided rifts developed along bedding. Speleogens in the cave include bell holes, blades, roof pendants, rock bridges and complex spongework. The entrance has formed where cliff retreat has exposed a narrow.

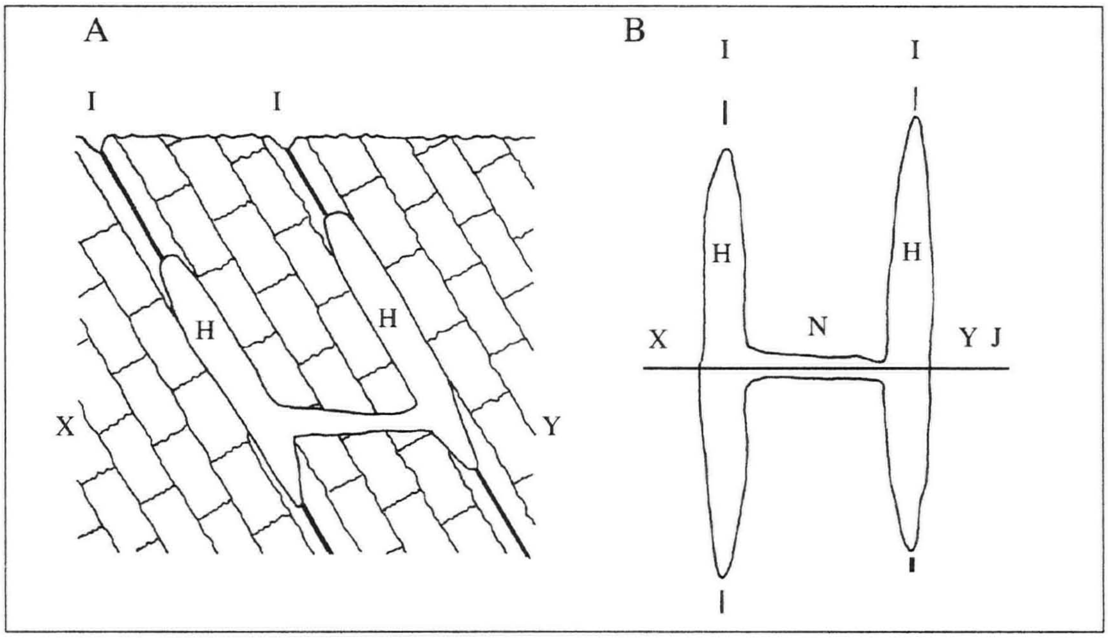



*Figure 6. Cross section (A) and plan (B) of a steeper-dipping limestone body in which one set of vertical joints is developed parallel to strike and another set of vertical joints is developed perpen - dicular to the strike direction. "I" = inception horizon; "J" = joints. Halls (H) are guided by the inception horizons. These are joined by Narrows (N), which are guided by joints perpendicular to bedding.*

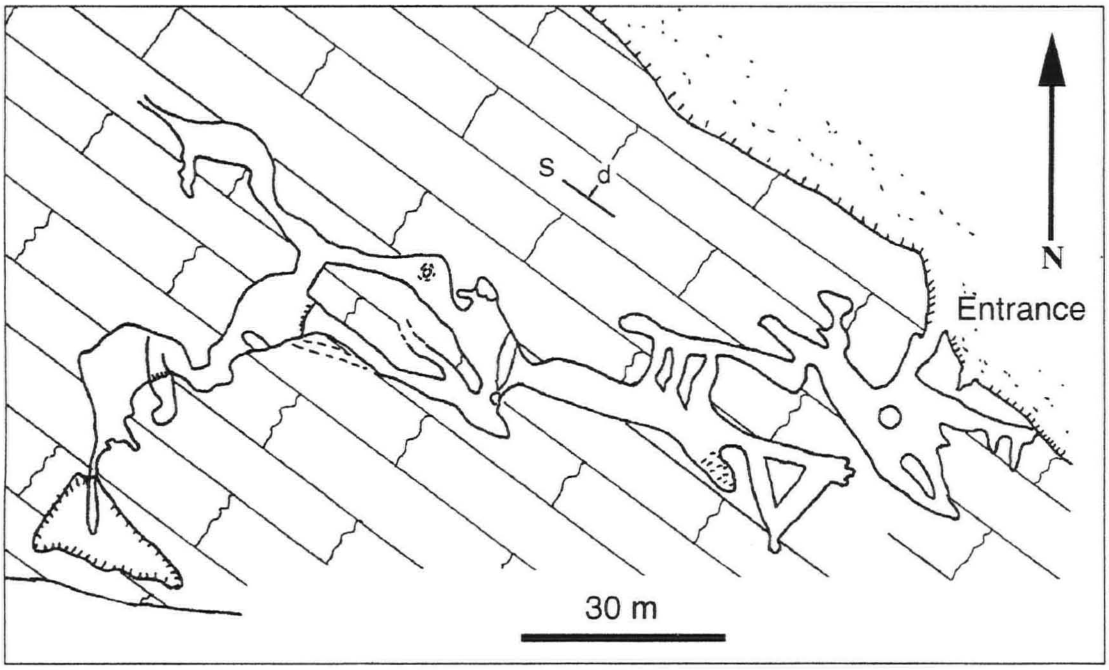



*Figure 7. Transmission Cave, Cliefden Caves, New South Wales. Map after Osborne (1978). Eastern part of cave consists of halls developed along strike, joined by narrows following joints. S = strike of limestone, d = dip direction.*

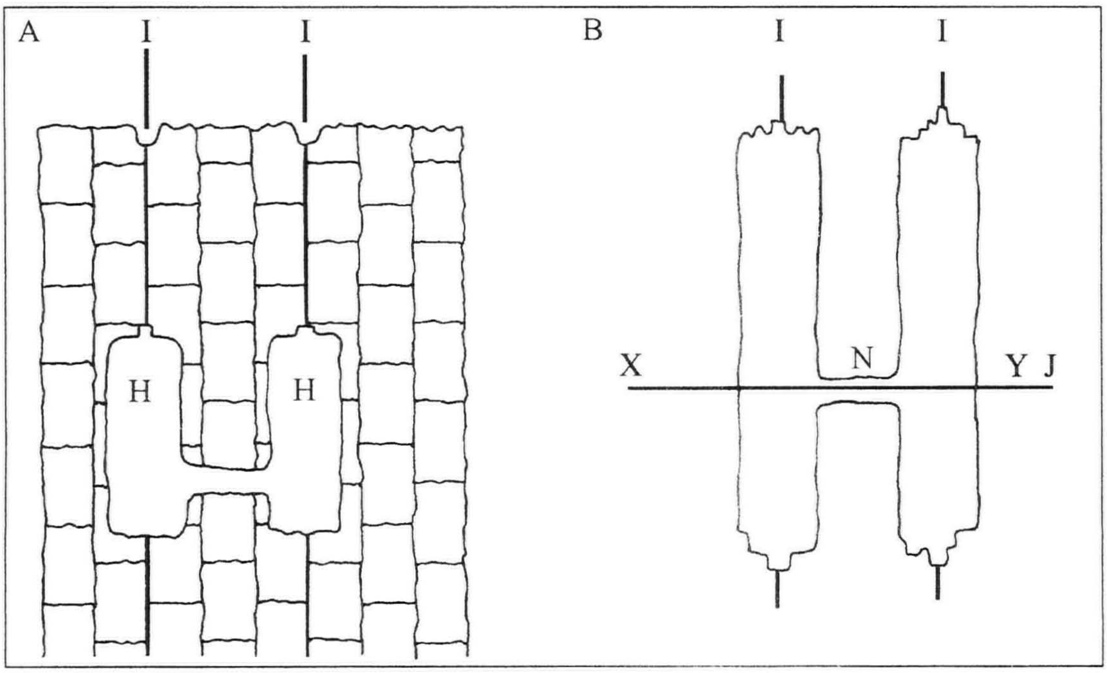



*Figure 8. Cross section (A) and plan (B) of very steeply dipping to vertically bedded limestone body. One set of vertical joints is developed parallel to strike and another set of vertical joints is developed perpendicular to the strike direction. "I" = inception horizon; "J" = joints. Halls (H) are guided by the inception horizons. These are joined by Narrows (N), which are guided by joints perpendicular to bedding.*

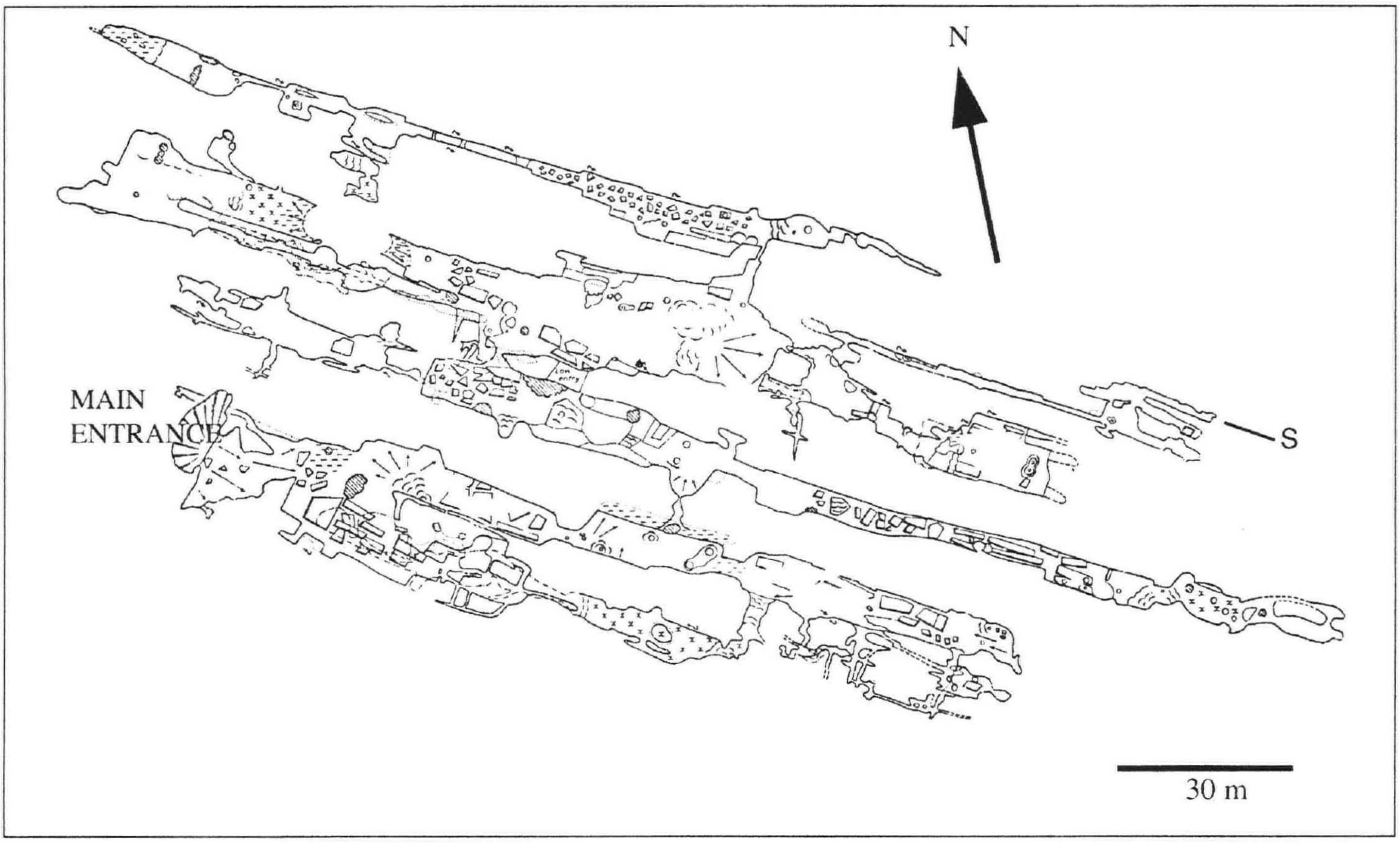



*Figure 9: Dip Cave, Wee Jasper New South Wales after Jennings (1963). Cave consists principally of a series of halls guided by bedding, which strikes NW-SE and dips vertically. The narrows in this cave are small passages that join the halls at ceiling level. S= strike of vertical bedding.*

This type of cave is common in eastern Australia. Examples are found at Mt Etna, Queensland (the "rainwater inflow" and "ramifying caves" of Shannon, 1970), Stockyard Creek, New South Wales (Holberton, 1984) and Timor, New South Wales (James *et al*, 1976; Osborne, 1986) (Fig.1).

**Very steep to vertical dip and vertical joints**
Where bedding is very steep to vertical, cave development is guided along strike by inception horizons and normal to strike by vertical joints (Fig.8). This produces halls with almost vertical walls in more readily soluble beds, joined by constricted narrows guided by joints through more resistant beds. Horizontal joints, if present, can determine the disposition of narrows in the vertical plane.

Dip Cave at Wee Jasper, New South Wales (Figs 1 and 9) is an outstanding example of this type of cave. It consists of five major parallel halls developed along strike, joined together by a few (commonly only one) tiny narrows running perpendicular to strike. The halls are rectangular in cross-section. Parting along vertical beds has resulted in breakdown, modifying the sides of the halls.

The walls and ceilings of Dip Cave have pitted etched surfaces. Remnant deposits of sediment, situated at various levels in the cave, remain from large quantities of poorly-sorted sediment and flowstone that once partly filled the cave and have since been removed. Phreatic speleogens have formed on both bedrock and flowstone. Remnants of stalagmite occur on the ground surface adjacent to two of the cave's vertical entrances.

Examples from Chillagoe Caves in Queensland (Fig.1) described by Ford (1978) illustrate a situation somewhat the reverse of that at Dip Cave. In the Queenslander-Cathedral Cave System (Fig.10) major halls are guided by joints perpendicular to the strike of bedding and joined by narrows (on occasions widened into chambers) trending parallel to bedding.

**Steep dip and horizontal joints**
The combination of steeply dipping beds, prominent sub-horizontal joints and vertical joints perpendicular to bedding can produce a cave that mimics in plan true mazes developed in horizontal limestone (Fig.11). In this case the sub-horizontal joints, rather than the bedding, guide cave development in the vertical plane, whereas inception horizons and joints perpendicular to bedding guide the horizontal (plan) development of the cave.

Ashford Cave in northern New South Wales (Figs 1 and 12) is a network cave developed in steeply-dipping limestone in which sub-horizontal joints are developed. Prominent halls have developed along strike, joined by short, low narrows with relatively flat ceilings. In some parts of the cave, the halls also have flat ceilings.

Gillieson (1981) interpreted the flat ceilings as products of epiphreatic dissolution. Many, however, appear to follow the irregular sub horizontal joints, rather than truncating them. This suggests that the ceilings may have formed by structurally guided dissolution, rather than by epiphreatic or paragenetic planation. Small bell holes and large cupolas have formed in some parts of the hall ceilings. Other speleogens developed in the cave include roof pendants and small symmetrical pits (approximately 5mm in diameter) that occur on both the walls and the ceilings.

**Steep dip and dipping joints**
When a limestone body has steeply-dipping beds and more gently-dipping joints parallel to strike, a system of stepped halls can develop, joined by short, steep narrows that have been guided by vertical joints perpendicular to strike (Fig.13).

This type of development occurs in Flying Fortress Cave at Bungonia (Fig.14). The cave consists of two, north-south-trending, principal halls, an upper, western, hall that includes the entrance, and a lower, eastern, hall, known as Magnathera Chamber. These are joined by a westward-

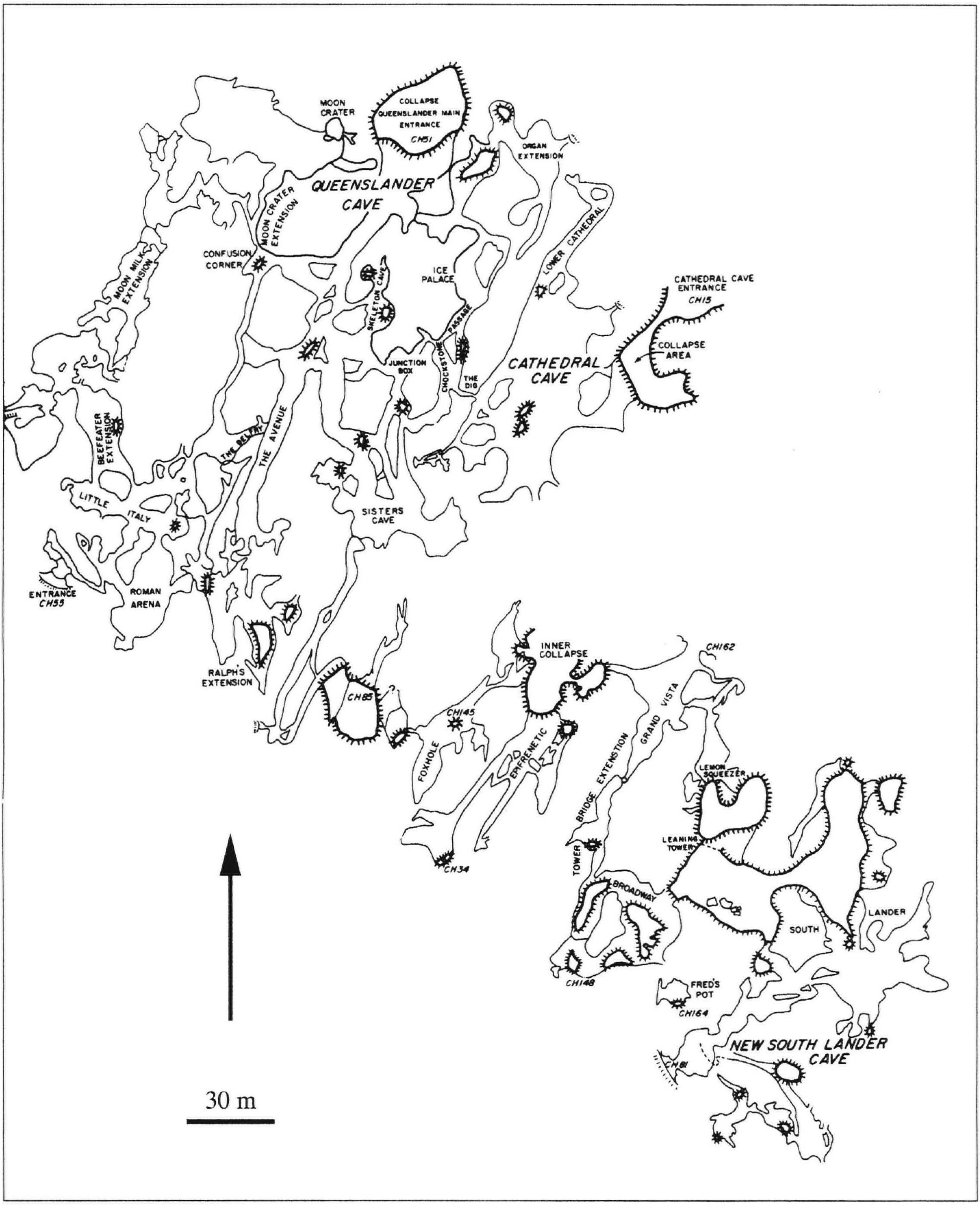



*Figure 10 . The Queenslander-Cathedral Cave System, Chillagoe, Queensland after Ford (1978). Halls, trending NE-SW, follow vertical joints that strike perpen - dicular to bedding (J). Narrows, and a few chambers, are oriented parallel to bedding (B), which is almost vertical.*

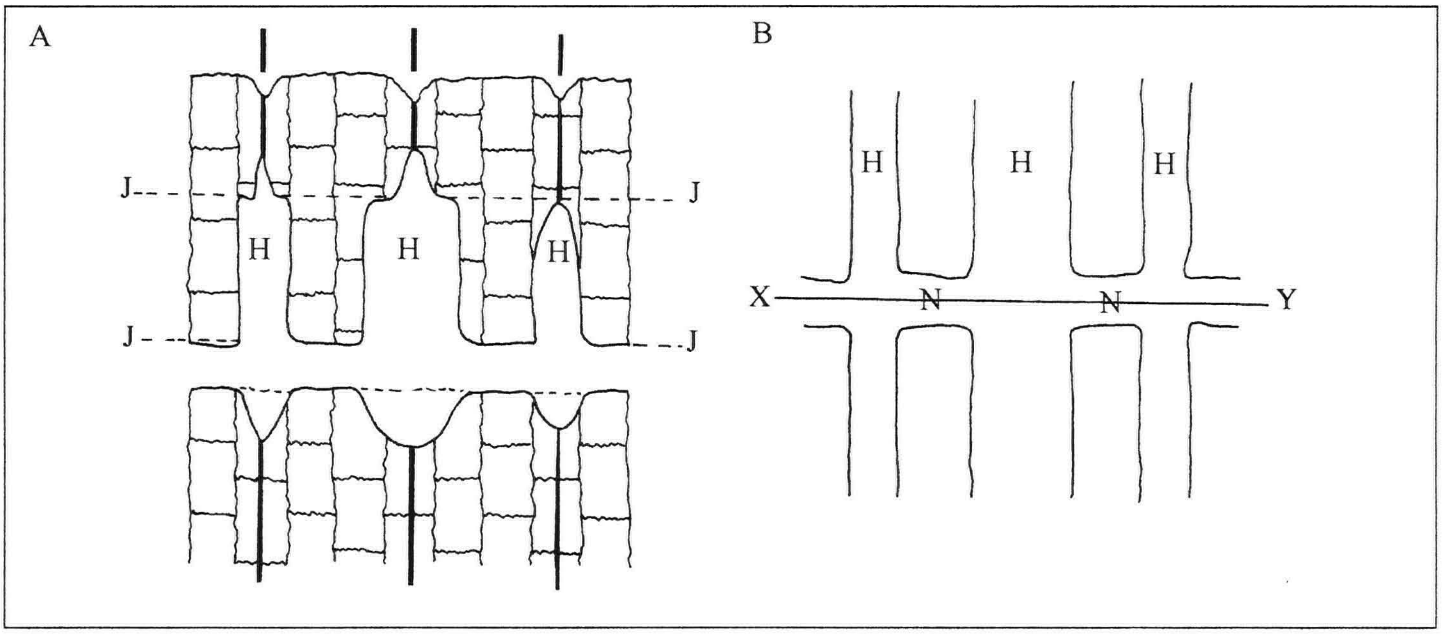



*Figure 11. Cross section (A) and plan (B) of a very steeply to vertically dipping limestone body. A set of vertical joints is developed perpendicular to the strike direction. A prominent set of horizontal joints is also developed. "I" = inception horizon; "J" = joints. Halls (H) are guided by the inception horizons. These are joined by Narrows (N) (Flats), which are guided by joints perpendicular to bedding and guided (constricted) in a vertical plane by horizontal joints.*

sloping passage, which is essentially a set of at least four close-spaced halls linked by a slightly enlarged northwest to southeast trending narrow. Magnathera Chamber consists of two halls that have coalesced at the southern end, where they terminate at a dyke. A hole in the floor on the eastern side of the chamber drops 12m to another hall below.

**Development along a principal vertical structure**
The halls first described by Osborne (1996) were not blind cavities joined at right angles by narrows, as in the examples above, but rather elongate semi-blind cavities in a series, developed along strike in the same structure. These halls are separated by constrictions (narrows) as shown in Figure 15. Narrows occur where materials of low solubility, such as dykes, ore bodies and palaeokarst deposits filling cross-joints, intersect the limestone perpendicular to strike.

Wyanbene Cave (Fig.16) is a system of halls and narrows through which a stream flows. A few closely spaced vertical joints running parallel to strike have guided the halls. These joints are filled with sulphide-bearing palaeokarst deposits that are weathering under vadose conditions (Osborne, 1996). The weathered palaeokarst deposits have fallen away from the bedrock and then been removed by the stream, exhuming the halls in the process. This process continues today. Similar systems of halls and narrows through which streams now flow are also found at Jenolan Caves (Osborne, 1999b).

## GENERAL CHARACTERISTICS OF HALL AND NARROWS CAVES IN EASTERN AUSTRALIA

**Hydrological isolation**
Most hall and narrows caves seem to have little, if any, relationship with the hydrology of the landscapes in which they are situated. It is rare for permanent springs to rise from these caves, and ever rarer for permanent streams to sink into them. Most do not contain permanent bodies of water.

Some hall and narrows caves occur high in hills and ridges, hundreds of metres above the floors of adjacent valleys. Others occur directly adjacent to, and within ten metres vertically of, the beds of major streams, but do not appear to be related to them genetically.

**Blind termination along strike**
One of the most significant features of hall and narrows caves is the blind termination of halls along strike. Though this is a feature of many, perhaps hundreds, of small caves and sections of large caves in eastern Australia, the significance of these cavities and the implications of their blind terminations seem to have escaped comment in the literature.

Many workers, including the author (Osborne, 1993), have discussed elongate cavities, now recognised as halls, as though they were abandoned stream passages or phreatic conduits along which water formerly flowed. In the case of Bungonia Caves there was frequent discussion about the location and elevation of palaeosprings from which water "flowing" in these "passages" might have risen in the past (see James *et al*, 1978).

Blind terminations along strike can take a number of forms. Some halls become narrow along strike, forming a conical or v-shaped termination in the guiding bed or joint. In others the termination is more rounded. Flat terminations occur where the hall ends at a structural plane. Some halls, for example Magnathera Chamber, and other smaller halls in Flying Fortress Cave at Bungonia (Fig.12), terminate abruptly at dykes.

**Modification of halls**
Many halls are more complex in shape than the simple *"...door-way...with all the corners rounded off..."* described by Shannon (1970). Cupolas are common in the ceilings of halls, in some cases at, or close to, their terminations. In some cases a number of halls coalesce along a single narrow to form a large room, as in the Queenslander-Cathedral Cave System (Fig.10).

**Speleogens**
Various speleogens, generally interpreted as being indicative of slow phreatic dissolution, occur in hall and narrows caves. These include bell holes, spongework, rock bridges, roof pendants, wall pockets, blades, symmetrical pits and juts. Most caves contain few, if any, speleogens indicative of rapid flow or vadose incision, such as scallops or floor canyons.

**Entrances**
The entrances of hall and narrows caves appear to have little genetic relationship with the rest of the cave, and generally appear to have

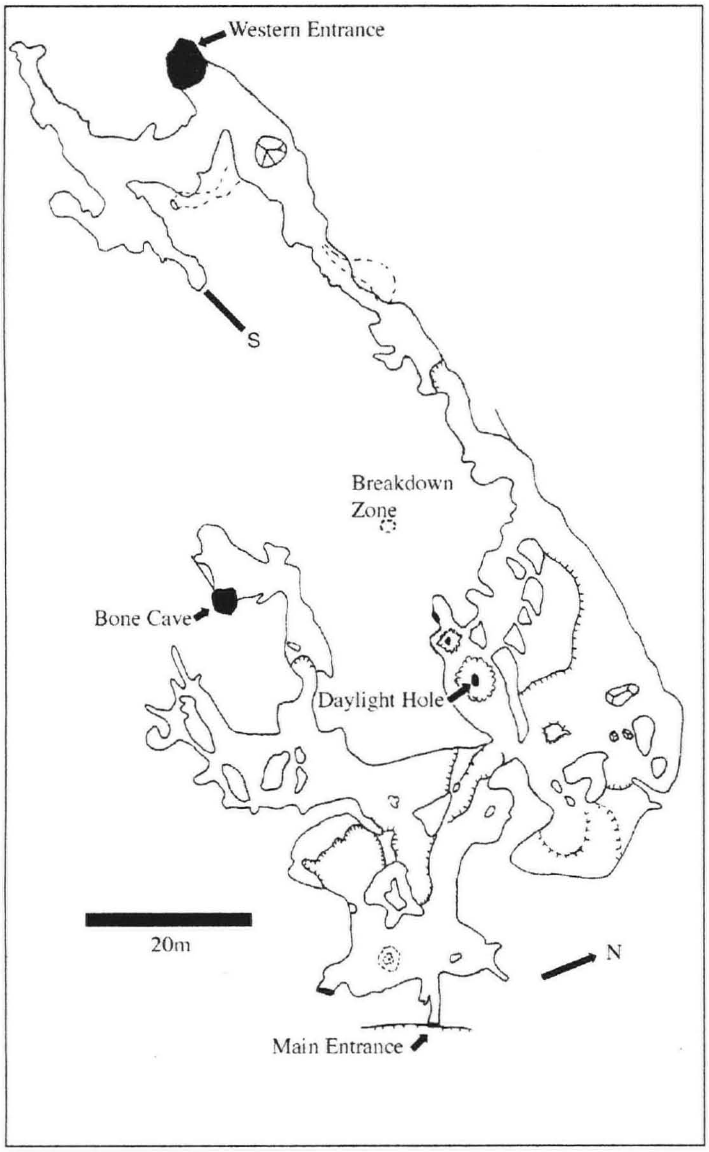



*Figure 12. Ashford Cave, New South Wales. Halls are guided by vertical bedding, which strikes west-east. These are joined by broad "narrows", which are guided laterally by vertical cross-joints and guided vertically by horizontal joints. S = strike of vertical bedding.*

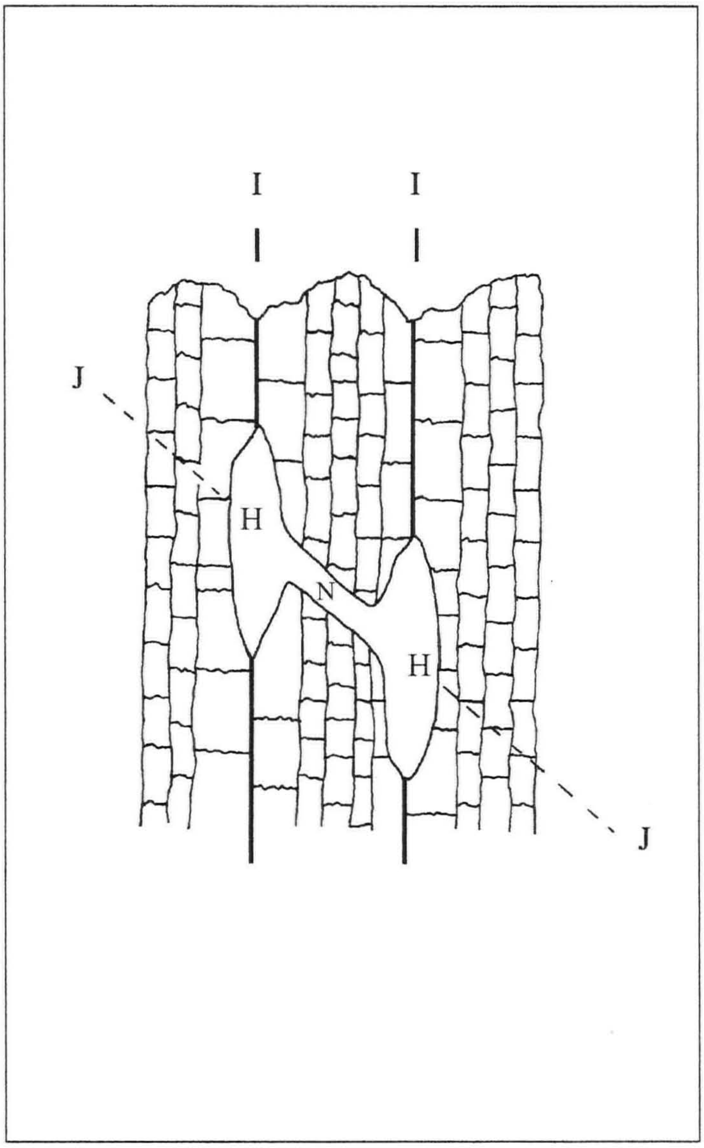



*Figure 13. Cross section of a very steeply dipping to vertically-bedded limestone body. A set of vertical joints is developed perpendicular to the strike direction. A prominent set of dipping joints is also developed. "I" = inception horizon, "J" = joints. Halls (H) are guided by the inception horizons. These are joined by Narrows (N), which are guided by joints perpendicular to bedding and guided (constricted) by the dipping joints. This has resulted in a system of stacked halls joined by short, steep narrows.*

formed after most, or all, of the cave was excavated. Few entrances appear to have acted as inflow points to the caves in the past. Where intermittent streams now sink into the entrances there is clear evidence of the cave having been modified, but not formed, by the action of these streams. Three main types of entrances are recognised: breakdown entrances, surface lowering entrances and cliff retreat/incision entrances.

Breakdown entrances are common in hall and narrows caves. Many, such as the entrance to Yessabah Bat Cave (Fig.3) and the main entrance to Dip Cave (Fig.8) are developed in the cave ceiling close to, or at, the blind ends of halls. Jennings (1963) recognised that the main entrance of Dip Cave resulted from an advanced (i.e. late in the history of the cave) stage of breakdown.

Surface lowering entrances occur where lowering of the ground surface penetrates an underlying cave. Some of these entrances are simple holes in the roof, commonly at the apex of a cupola. Others, as at Ashford Cave, are more complex, consisting of a segment of unroofed cave that remains connected to the cave below it.

Cliff retreat/incision entrances occur where a retreating cliff or an incising stream intersects a hall or narrow. These are the most common types of horizontal entrances into hall and narrows caves. Some caves have multiple entrances of this type, where the ends of a series of halls are intersected by a cliff-line, whereas in other cases (e.g. Transmission Cave, Fig.7), the cliff face has intersected a single narrow.

At all three types of entrances, cave structures are truncated, indicating that the entrances formed after, rather than during, the excavation of the caves.

**Sediments**

Many hall and narrows caves intersect palaeokarst deposits, are partly filled with clays, and contain remnants of vadose deposits such as flowstone.

Although remnants of gravel deposits occur in some caves, many hall and narrows caves located directly adjacent to major streams do not contain any stream deposits. (e.g. Transmission Cave at Cliefden (Fig.7) and Ashford Cave (Fig.11)).

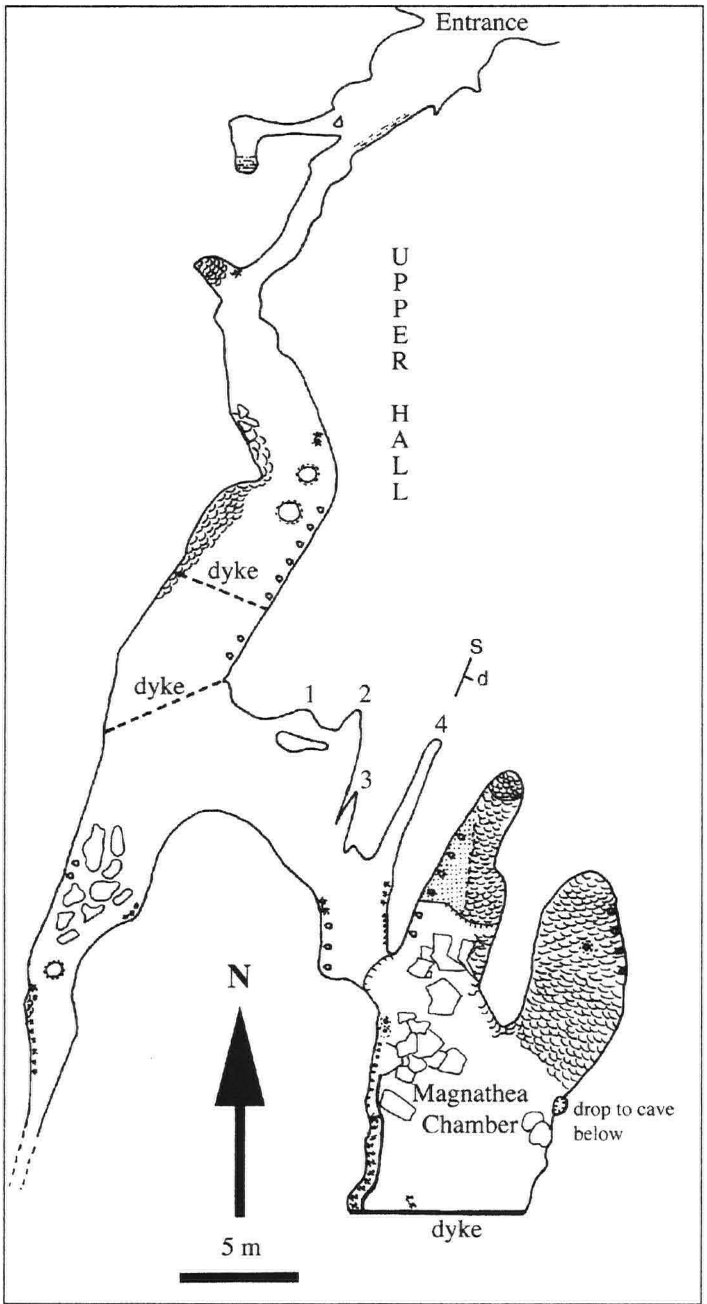



*Figure 14: Flying Fortress Cave, Bungonia Caves. New South Wales. Cave consists of two principal halls, following strike, joined by an eastwardly-sloping narrow. The narrow penetrates a series of steeply dipping beds with variable solubility, resulting in the development of a series of minor halls (1, 2, 3 and 4) along the more soluble beds. Map after Bauer and Bauer (1998). S = strike of limestone, d = dip direction. The joint that guides the narrow has the same strike and dip direction as the bedding, but a much gentler angle of dip.*

Thick deposits of clays or, more commonly, the remnants of clay deposits are widespread in these caves. Many of the clays are finely laminated and similar in appearance to the "cap muds" described by Bull (1977). It has usually been assumed that either the clays were derived from the surface, or that they consist of insoluble residues derived from dissolution of the limestone. However, since there has been little study of their mineralogy, comment on the origin of these clays is based largely upon speculation. Work in progress suggests that at least some of the clays are probably autochthonous. It appears that the bulk of the clay deposits were removed relatively recently in the history of the caves (Osborne, 1978), but it remains unclear exactly how and when this occurred.

The palaeokarst deposits and significant amounts of flowstone appear to have been removed by phreatic dissolution. Phreatic speleogens are developed on flowstone at Timor Caves (Osborne, 1986), Moparabah Cave, Dip Cave and Ashford Cave. When and how this phreatic dissolution, particularly the re-solution of the flowstone, took place has yet to be explained adequately, and is currently being investigated.

**Alteration**

Exposed bedrock in many hall and narrows caves shows signs of chemical alteration. As some large halls, particularly those with cupolas, have been used as bat roosts, some phosphatic alteration is the result of interaction between the bedrock and guano. Commonly, however, the alteration is not phosphatic.

Boxwork, silicification of fossils, and emplacement of dolomite and pyrite occur widely in hall and narrows caves. The walls of some halls are not smooth, but deeply etched, and silicified fossils protrude. Outstanding examples of this type of alteration occur in Flying Fortress Cave (Fig.13) (Bauer, 1998) and Grill Cave (Osborne, 1993) at Bungonia.

The walls of narrows, which develop where joints penetrate relatively less soluble beds, do not show this etching, but the bedrock exposed in them may be pervasively altered. Bauer (1998) noted that the limestone walls of "the Flattener", a squeeze (narrow) joining two halls in Argyle Hole Cave at Bungonia, are extensively dolomitised. Resistant spiculite beds, located farther inside the cave, are also altered, with secondary emplacement of dolomite and pyrite.

Dykes at the end of halls are significantly altered. Gypsum and calcite have replaced feldspars in dykes at Bungonia, and quartz and gypsum have replaced feldspars in dykes at Spider Cave, Jenolan.

Two explanations of this alteration seem possible. One is to propose, by analogy with the changes that occur to limestone in contact with phosphatic sediments, that alteration results from chemical interaction between clay and the bedrock. Osborne (1993) proposed that silicification of bedrock and fossils at Bungonia Caves resulted from such an interaction, considered to relate to a Mid-Tertiary episode of deep weathering.

An alternative explanation, outlined by Osborne (1999b), proposed that the cavities themselves, and at least some of the clays found in them, were produced by rising hydrothermal waters. This would explain not only the alteration of the bedrock and the dykes, but also many elements of the morphology of these caves.

## DISCUSSION

Hall and narrows caves are common in eastern Australia; consequently, many are described in the scientific and speleological literature. Their characteristic morphology has not, however, been discussed previously. Most commentators have proposed a phreatic origin for these caves, and related their development to periods in the past when water tables were higher, usually before a particular phase of stream incision.

Those who went further than just noting the evidence for phreatic dissolution encountered significant difficulties. Jennings (1963) commented on Dip Cave at Wee Jasper that: *"...the clarity with which the morphology of the cave reflects the geological structure, is almost counterbalanced by the obscurity which hinders any effort to interpret the origin and evolution of the cave".*

The major, although unrecognised, problem was that phreatic water could not possibly have flowed along strike through blind halls, so the halls could not have acted as "stream passages" or "phreatic conduits". Nevertheless, Jennings (1963) discussed the direction in which the blind halls in Dip Cave "drained", and how the evolution of the surface geomorphology caused the cave to come *"under the influence of stronger water currents".*

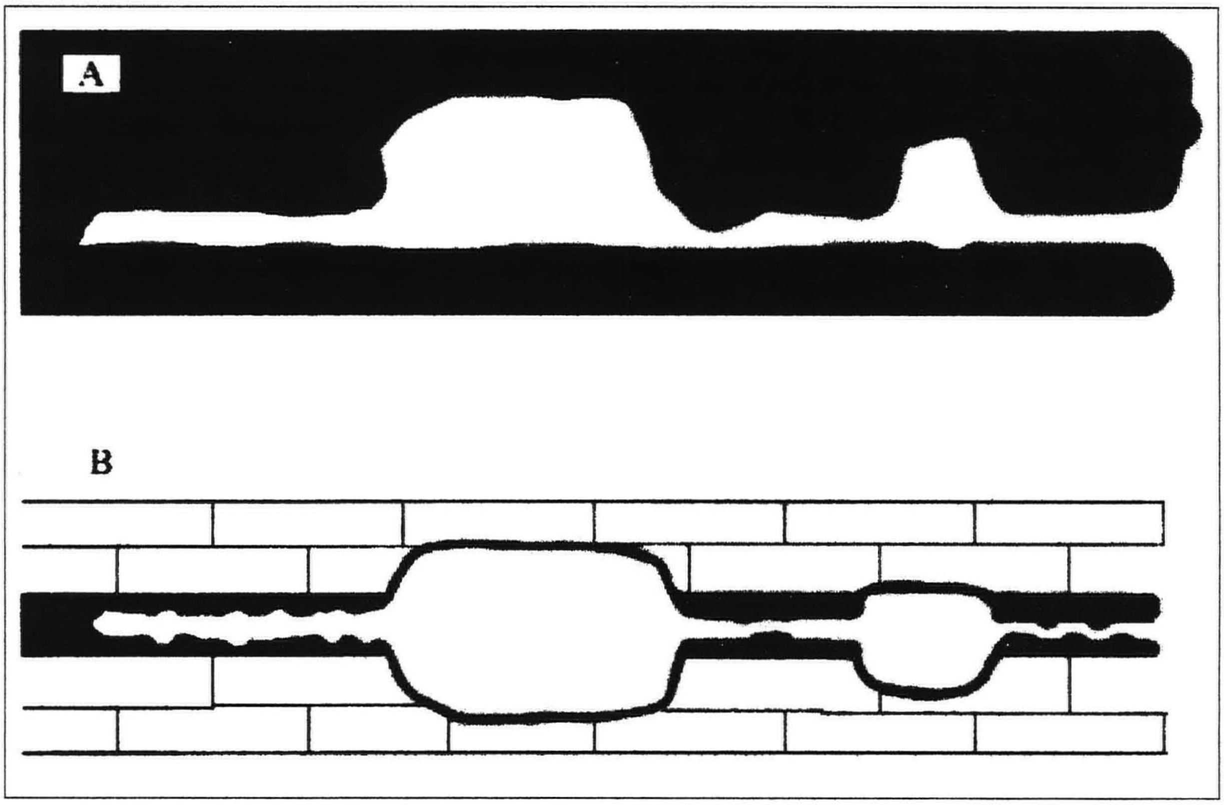



*Figure 15. Cross-section (A) and plan (B) of a hall and narrows cave developed along an ore vein or dyke that follows strike in vertically-bedded limestone. Halls result from expansion of the initial cavity into the limestone host rock.*

Many caves with hall and narrows morphology in eastern Australia were attributed to dissolution under conditions characterised by Jennings (1977) as nothephreatic. Nothephreatic dissolution, as described by Jennings, was thought to take place by the action of slowly flowing or convecting water in a water-filled cave. Jennings (1980) cited Ochtinská Aragonite Cave in Slovakia and Cathedral Cave at Wellington Caves, New South Wales (Fig.1) as examples of nothephreatic caves. Frank (1971) had attributed the development of Cathedral Cave at Wellington Caves to dissolution by *"eddy currents in the phreatic zone"*.

Jennings definition of nothephreatic, and the later use of the term in the eastern Australian context, assumed very slow and diffuse flow of "a few metres a day" (Jennings, 1985). This differs considerably from the definition of Lowe and Waltham (1995), who defined nothephreatic as *"conduit flow, which is always laminar"*.

Following Jennings, the author (Osborne, 1978) considered that the caves at Cliefden, including Transmission Cave (Fig.7), formed by *"sluggish solution of the nothephreatic type"*. Similarly, Osborne and Branagan (1988) commented that the larger caves in the Western Slopes region of New South Wales were *"structurally controlled nothephreatic networks"*.

Nothephreatic (sensu Jennings) has proved a useful term for grouping caves exhibiting a series of characteristics indicative of dissolution under slow-moving, water-filled conditions. The term, however, does not imply any mechanism for generating diffuse flow or convection currents, nor does it propose any mechanism by which water in the phreas remains aggressive.

Shannon (1970) proposed that hall and narrows caves at Mt Etna in Queensland resulted principally from vadose dissolution. His idea was that dissolution resulted from organic-rich runoff (rainwater inflow) entering the limestone through karren fields. He envisaged that the caves were continuing to form by dissolution at the terminal sediment plug, as the inflowing water soaked away through the sediment to a postulated lower-level conduit. The *"ramifying horizontal caves"* (hall and narrow caves), to which many of the more vertical *"rainwater inflow caves"* connect were interpreted as *"former water dispersion and discharge caves"*. Shannon's mechanism, like the phreatic mechanisms discussed above, involved movement of water, in his case dispersal, through the blind (dead) ends of halls.

Since hall and narrows caves and maze caves are structurally guided networks, mechanisms proposed for the origin of maze caves may help explain the origin of hall and narrows caves. Three, quite different, explanations have been given for the origin of maze caves.

Palmer (1975) proposed two mechanisms by which descending meteoric water could produce maze caves. The first involved dissolution from surface waters seeping down into joints in the limestone through a porous cap rock, usually an overlying sandstone bed. The second involved flooding during the evolution of a stream cave. Alternatively, Bakalowicz et al. (1987) proposed that rising thermal waters excavated large maze caves in the Black Hills of South Dakota. Similarly, Klimchouk (1996) proposed that recharge from a basal, non-karst; aquifer (ie. artesian processes) excavated large gypsum maze caves in the Ukraine.

Except in a few cases, where sandstones and laterites overly limestone unconformably, network caves in eastern Australia do not occur in limestones that are either stratigraphically or topographically overlain by porous cap rocks. At Wyanbene and Bungonia, sandstone and laterite cap rocks appear to have inhibited, rather than promoted, cave development (Osborne, 1996). Thus, Palmer's seeping dissolution mechanism does not apply.

Few true mazes, or hall and narrows caves, in eastern Australia appear to have formed by flooding during the evolution of a stream cave. Most maze caves in eastern Australia do not contain passages that have formed as streamways. The large elongate passages in these caves

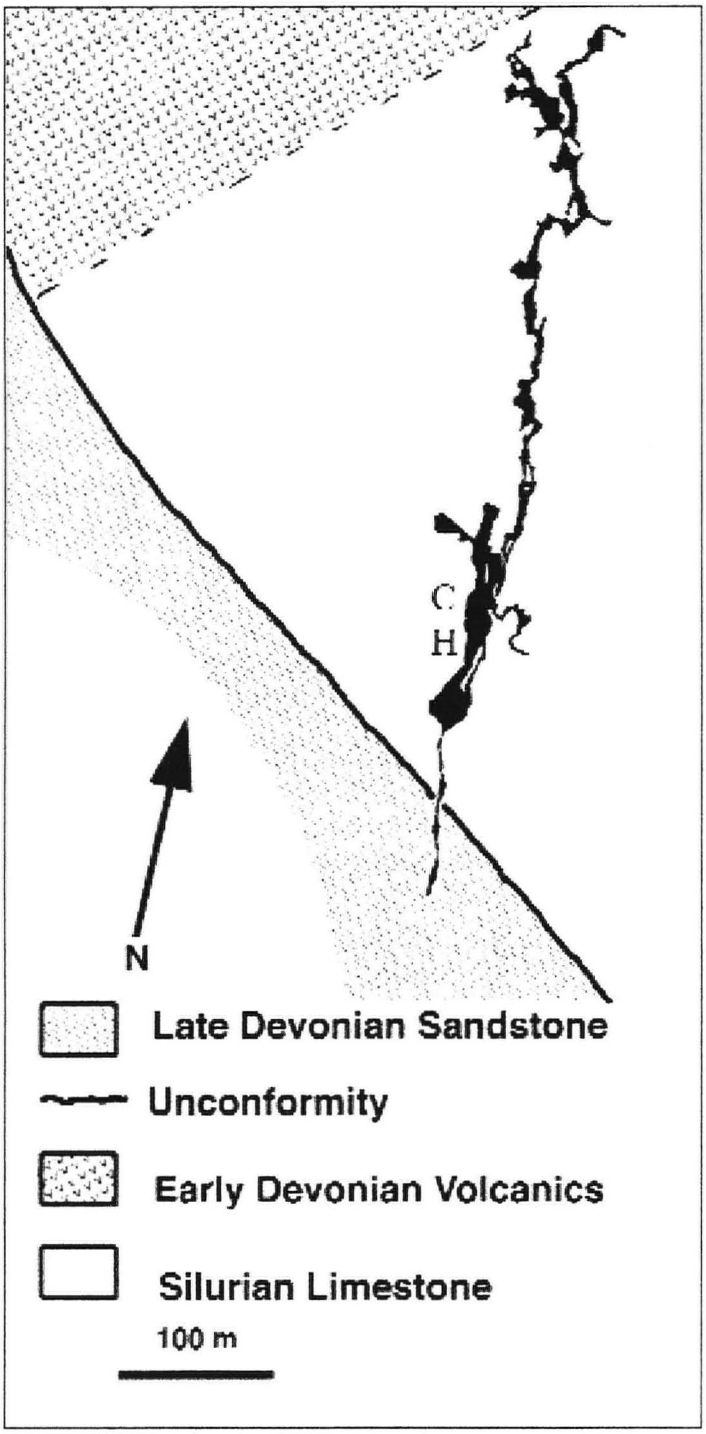



*Figure 16: Wyanbene Cave, New South Wales. The cave consists of a series of halls and narrows, of which Caesars Hall (CH on map) is the largest. Map modified after Webb and Brush (1978).*

are halls, with blind terminations along their principal axis and speleogens indicating dissolution by slowly convecting phreatic water. Though significant streams flow through Exit Cave (Fig.3), Osborne and Cooper (2001) noted that passage size does not increase systematically downstream of junctions, in fact in some cases it actually decreases. This type of passage behaviour was seen by Bakalowicz *et al* (1987) as being characteristic of maze caves formed by rising hydrothermal water.

Fundamental questions concerning the origin of hall and narrows caves include:

- how were halls excavated if water did not flow along, or out of, them?
- how were convection currents generated in the nothephreas?
- how did water become, or remain, aggressive?
- why is there an association with silicification, dolomitisation and pyrite?
- why do these caves commonly intersect palaeokarst?

These might be explained if the caves were dissolved (at least in part) by rising artesian or hydrothermal waters. Hall and narrows caves have many characteristics similar to those cited by Dublyansky (1980) and Bakalowicz (1987) as indicating a hydrothermal or artesian origin, in that they:

- have a poor relationship with surface topography;
- have poor connections with surface hydrology;
- expose and intersect palaeokarst;
- have cave walls that show signs of chemical alteration;
- have crystal linings and contain unusual minerals;
- were dissolved by slowly-moving water;
- exhibit a high degree of structural guidance;
- have cupolas developed in their highest parts.

The author (Osborne, 1999b) used this type of evidence to propose that Jenolan Caves underwent at least one phase of hydrothermal development during their complex history.

Some hall and narrows caves may have developed under conditions similar (but with tilted bedding) to the *"upward recharge from a basal aquifer"* process described in gypsum maze caves by Klimchouk (1996). Hall and narrows caves, such as Yessabah Bat Cave, are developed in the Permian Yessabah Limestone west of Kempsey in northern New South Wales. The upper beds of the Yessabah Limestone are strongly silicified (possible aquiclude), whereas the lower beds are composed of purer, more massive limestone. Cave development is largely restricted to the lower beds. Stratigraphically and physically underlying the limestone are clastic sediments, including shales, sandstones and conglomerates, that may have acted as a granular aquifer, feeding artesian water up into the massive limestone.

Research is continuing into the origin of these caves, with evidence for the role of warm, rising water being evaluated. Emphasis is being given to mineralogy, stable isotope studies and the detailed morphology of halls, narrows and cupolas.

## ACKNOWLEDGEMENTS

The ideas presented in this paper began to come together in October 1998 after a period of fieldwork at Jenolan Caves, and came to fruition following a reconnaissance trip to Ashford Caves in October 1999. Steve Reilly and staff assisted with fieldwork at Jenolan Caves and Penney Osborne assisted with fieldwork at Ashford. Thanks to Art Palmer for his constructive review of the originally submitted manuscript.

Julie and Peter Bauer, the British Cave Research Association, and the Australian Speleological Federation gave permission to reproduce maps published in *Under Bungonia*, *Cave and Karst Science* and *Helictite*.

## REFERENCES

Bakalowicz, M J, Ford, D C, Miller, T E, Palmer, A N and Palmer, M V, 1987. Thermalgenesis of dissolution caves in the Black Hills, South Dakota. *Bulletin of the Geological Society of America*. Vol.99, 729-738.

Bauer, J, 1998. Lithological controls on cave development: a preliminary investigation. 61
66 in Bauer J and Bauer P, eds., *Under Bungonia*. [Oak Flats: J B Books.]

Bauer, J and Bauer, P, 1998. *Under Bungonia*. [Oak Flats: J B Books.]

Bull, P A, 1977. Laminations or varves? Processes and mechanisms of fine grain sediment deposition in caves. *Proceedings, 7th International Speleological Congress*, Sheffield, 86-89.

Ford, D C, 1996. Paleokarst as a target for modern karstification. *Carbonates and Evaporites*, Vol.10(2), 138-147.
Dublyansky, V N, 1980. Hydrothermal karst in the alpine folded belt of the southern parts of USSR. *Kras i Speleologia*, Vol.3, 18-36.
Ford, T D, 1978. Chillagoe-A tower karst in decay. *Transactions of the British Cave Research Association*. Vol.5(2), 61-84.
Frank, R M, 1971. The clastic sediments of Wellington Caves, New South Wales. *Helictite*. Vol.9(1), 3-26.
Gillieson, D S, 1981. Scanning electron microscope studies of cave sediments. *Helictite*. Vol.19(1), 22-27
Holberton, P, 1984. Brief history of the Kempsey Speleological Society. Trog. Vol.19(10), 1-40.
Jennings, J N, 1963. Geomorphology of Dip Cave, Wee Jasper, New South Wales. *Helictite*. Vol.1, 43-58.
Jennings, J N, 1977. Caves around Canberra. *Proceedings of the Eleventh Biennial Conference of the Australian Speleological Federation*, Canberra 1978, 79-95.
Jennings, J N, 1980. The problem of cave formation. *Australian Speleological Federation Newsletter*. 89 (1980), 2-19.
Jennings, J N, 1985. *Karst Geomorphology*. 293pp. [Oxford: Basil Blackwell.]
Klimchouk, A, 1996. Speleogenesis in gypsum. *International Journal of Speleology*. Vol.25(3-4), 61-82.
Lowe, D J, 2000. The Speleo-inception Concept. 65-76 in Klimchouk, A B, Ford, D C, Palmer, A N and Dreybrodt, W (editors) Speleogenesis: Evolution of karst Aquifers. 527pp. [Huntsville Alabama: NSS Inc.]
Lowe, D J and Gunn J, 1997. Carbonate Speleogenesis: an inception horizon hypothesis. *Acta Carsologica*, Vol.26(2), 457-488.
Lowe, D J and Waltham, A C, 1995. A *Dictionary of Karst and Caves: A Brief Guide to the Terminology and Concepts of Cave and Karst Science*. Cave Studies Series Number 6. British Cave Research Association, London. 41pp.
Osborne, R A L, 1978. Structure, sediments and speleogenesis at Cliefden Caves, New South Wales. *Helictite*, 16(1), 3-32.
Osborne, R A L, 1986. Cave and landscape chronology at Timor Caves, New South Wales, Journal and Proceedings of the Royal Society of New South Wales, Vol.119, 55-75.
Osborne, R A L, 1993, A new history of cave development at Bungonia, N.S.W. Australian Geographer, Vol.24(1), 62-74.
Osborne, R A L, 1996. Vadose weathering of sulfides and limestone cave development-evidence from eastern Australia. Helictite, Vol.34(1), 5-15.
Osborne, R A L, 1999a. The inception horizon hypothesis in vertical to steeply-dipping limestone: applications in New South Wales, Australia. *Cave and Karst Science*. Vol.26(1), 5-12.
Osborne, R.A.L., 1999b. The origin of Jenolan Caves: Elements of a new synthesis and framework chronology. *Proceedings of the Linnean Society of New South Wales*. Vol.121, 1-27.
Osborne, R A L and Cooper, I B, 2001. Sulfide-bearing palaeokarst deposits at Lune River Quarry, Ida Bay, Tasmania. *Australian Journal of Earth Sciences*. Vol 48(3):409-416.
Osborne, R A L and Branagan, D F, 1988. Karst landscapes of New South Wales, Australia. *Earth-Science Reviews*, Vol.25, 467-480.
Palmer, A N, 1975. The origin of maze caves. *National Speleological Society Bulletin*, Vol.37, 56-76.
Ryder, P F, 1975. Phreatic network caves in Swaledale, Yorkshire. *Transactions of the British Cave Research Association*. Vol.2(4), 177-192.
Shannon, C H C, 1970. Geology of the Mt Etna area. 11-21 in Sprent, J K (ed.), *Mount Etna Caves:* A collection of papers *covering several aspects of the Mt Etna and Limestone Ridge area of Central Queensland*. [St Lucia: University of Queensland Speleological Society.]
Webb, J A and Brush, J B, 1978. Quill anthodites in Wyanbene Cave, upper Shoalhaven district, New South Wales. *Helictite*. Vol.16(1), 33-39.

CAVE KARST SCIENCE Vol. 28, No.1 April 2001
Transactions of the British Cave Research Association

ISSN 1336-191X

# A review of Chinese travertines

**Allan PENTECOST [1] and ZHANG Zhaohui [2]**

[1] Division of Life Sciences, King's College London, 150 Stamford Street, London SE19 NN, UK
(e-mail: allan.pentecost @kcl.ac.uk)
[2] Department of Biology and Biotechnology, Guizhou Normal University, Guiyang 550001, Guizhou, China.

**Abstract:** This review provides a summary of the published information on Quaternary Chinese travertines. A coded list of 88 sites (74 active, 14 inactive) accompanies a distribution map of the epigean deposits. Most travertines occur in the provinces of Guangxi, Guizhou, Sichuan, Yunnan and Xizhang. Meteogene travertines (N=74), which develop in karst where there are no deep-seated $CO_2$ sources, are most strongly developed in the warm, humid southern part of China, and are rare in cold and dry regions. A map showing the travertine-forming potential of Chinese karst is provided. Thermogene deposits (N=14), associated with tectonic activity and/or vulcanism, are confined to geothermal regions, particularly the Tibetan plateau. At several sites deposition occurs on a huge scale, providing spectacular examples of travertine-dammed lakes and cascades. They have spawned a large tourist industry with its attendant environmental problems.
Several sites have been investigated in detail, improving our understanding of the travertine deposition process. The flora of some sites has been shown to be rich and diverse, containing several rare plants. Rapid advances in cave travertine (speleothem) isotope geochemistry have been made, permitting a better understanding of Quaternary climate in parts of China, particularly in relation to air temperature and monsoon events. Subject areas currently lacking information are: modern fauna, travertine palaeobiology, petrology and mineralogy. Knowledge of these would increase understanding of travertine formation, its biodiversity, and past environments in China.
Key words: travertine, tufa, speleothem, cave, China, distribution, climate, biology, chemistry.

*(Received 03 January 2001; Accepted 04 June 2001)*

## INTRODUCTION

Travertines are freshwater carbonates deposited below karst springs. They are formed mainly through the loss of $CO_2$ from water containing an excess of that gas over the atmosphere. Losses occur mainly via diffusion into the overlying air (Julia, 1983; Pedley, 1990; Pentecost and Viles, 1994). Cave speleothem, another form of travertine, results from $CO_2$ loss in a comparable manner. The deposits are also referred to as *calcareous tufa, tufa* and *sinter*. We use the term travertine in its broadest sense. The *lapis tiburtinus (travertino)* was well defined in ancient times and is less likely to be confused with the modern Italian term for volcanic ash *(tufo)*, which is still in use.

In this review we survey the current state of Quaternary travertine research in the People's Republic of China, a country containing some the world's largest karst areas. During recent years much interest has been expressed in these deposits, resulting in the publication of some important papers, especially in the fields of palaeoenvironments, geochemistry and ecology. The aim of our review is to provide an up to date summary of travertine research in China, with the assistance of climatic maps illustrating the travertine-depositing potential of the Chinese karst. We also provide descriptions of the known epigean (surface) travertines of China. Finally, we provide a section on cave travertines, focusing on sites where recent geochemical and palaeoenvironmental work has been undertaken, and point toward knowledge gaps, future research and exploration in this fascinating country.

## DISTRIBUTION, GEOMORPHOLOGY AND FABRIC

A Chinese classification of travertine has been proposed by Yang Hankui *et al.*, (1986, 1991), based on gross fabric and morphology. However, we have used here a genetic classification (Pentecost and Viles, 1994) that accounts for $CO_2$ source and travertine morphology. We do not propose it as an ideal classification, indeed none probably exists since at many sites a 'travertine complex' occurs, embodying a range of distinct but intergrading morphologies. Nevertheless the scheme has found use in an earlier review of European travertines (Pentecost, 1995) and it permits direct comparisons between China and Europe. A simplified version of the scheme is presented in Table 1.

The travertines are divided into two major geochemical groups. The meteogenes are deposited from shallow groundwaters containing $CO_2$ originating from the epigean and soil atmospheres. The dissolved inorganic carbon (DIC) concentration is constrained largely by soil microbial activity and resultant bedrock dissolution, and rarely exceeds 10mM/l (usually 2-5mM/l). The thermogenes are essentially hydrothermal deposits, where $CaCO_3$ is precipitated from high-$CO_2$ groundwaters. Most of this $CO_2$ comes from deep within the crust as a result of magmatic degassing or limestone decarbonation, with DIC values typically >>10mM/l. They are usually found in tectonically- and/or volcanically active regions. Inevitably such waters contain a meteogene component, but this is usually swamped by hydrothermal $CO_2$. Most thermogene springwaters are warm or hot, but retarded circulation may result in high-$CO_2$ cold springs. Travertines belonging to a rarer group of are found in regions of recent serpentinisation, resulting from the direct combination of atmospheric $CO_2$ with hydroxyl (Clark and Fontes, 1990). So far these *invasive meteogenes* have not been reported from China.

The resulting travertines, whatever their $CO_2$ source, may be found *in situ* (autochthonous) or transported and redeposited (allochthonous). Most travertines so far noted from China appear to be autochthonous. Morphology can be used to complete the description of a travertine deposit. Spring-deposited travertines are those that develop around a spring orifice. On flat ground they produce ridges or mounds around

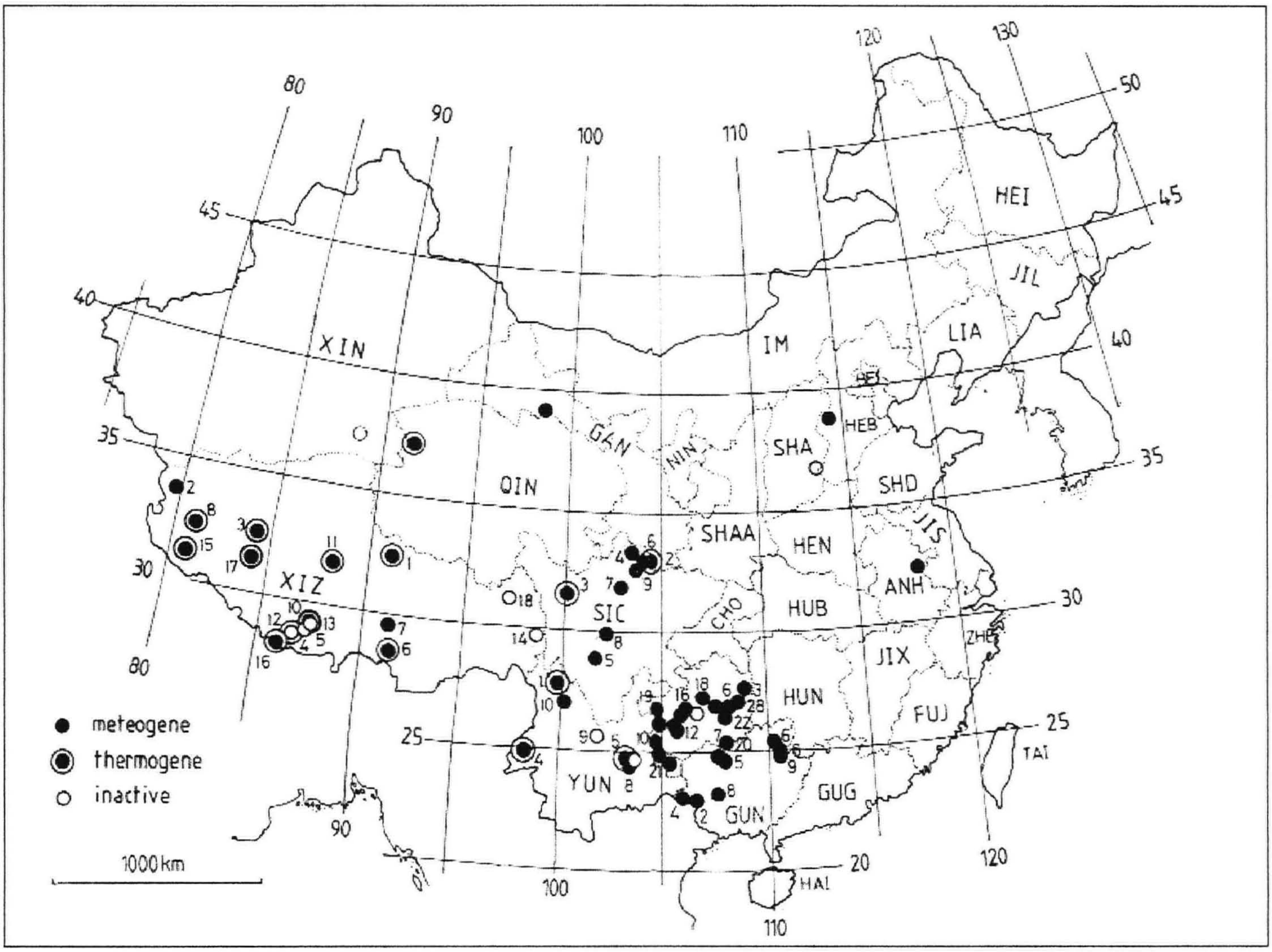



*Figure 1a. Distribution of epigean Chinese travertines referred to in the text.*

point sources. On vertical surfaces they produce stalactite-like pendants. In stream channels, deposits are common on waterfalls, where $CO_2$ loss is increased through turbulence. Self-built travertine dams form on local obstructions or steep gradients, commonly impounding lakes behind them. Crust-like accumulations occur in stream channels of shallower gradient. Such stream-deposited travertine is widespread in China. Deposits also form in the littoral and profundal region of lakes and also in marshes. Equivalent morphologies occur in caves, but the fabrics are usually unmodified by plants.

The known distribution of Chinese travertines is shown in Fig.1a,b, with meteogenes occurring mainly in the central provinces and the thermogenes virtually confined to the mountainous west. Meteogenes develop where there is a limestone aquifer, sufficient precipitation to feed springs and a degree of soil cover. These conditions prevail through most of central and eastern, but not western, China, so the observed pattern is to be expected. The paucity of sites in some eastern provinces is partly the result of low topography, which means that spectacular, and therefore well recorded sites may not occur, but must also indicate a lack of recording.

It has been argued that the 'travertine-forming potential' of a karst region increases with increasing air temperature and precipitation. In Europe, statistical evidence supports this view (Pentecost, 1995). In Fig.2 the major limestone regions of China have been classified into six zones dependant upon the mean annual air temperature and mean annual precipitation (taken from Liu Min-Gang, 1998). This figure is based on a similar European map of Pentecost (1995) and shows that meteogene travertine formation should be least in the cold and arid north and greatest in the warm and humid south. Almost 80% of the recorded meteogene travertines of China belong to the warm and more humid zones 4 to 7. In Europe such travertines occur mainly in zones 2 and 4, as zone 6 is hardly represented. However, the world's largest known meteogene travertine, at Antalya, Turkey, belongs to zone 6. In Europe, travertine, including speleothem, is rare in regions where the mean air temperature is below 5°C (zone 1) and this also seems to be the case in China. Of the six Chinese meteogenes belonging to zone 1, four occur on the Tibetan Plateau, where there may be a geothermal influence. Tibet is an interesting area for karst hydrology. In addition to the low temperature, the high elevation of the plateau has a significant effect on the atmospheric partial $CO_2$ pressure and groundwater chemistry, well demonstrated by Waltham (1996) and Zhang Dian (1997a). Little is known of these remote sites and most of the travertines may be thermogenes developing independently of air temperature. One of China's largest sites at Juizhaigou (Fig.3a) also occurs in zone 1. Like its neighbour Huanglong it may be a cool thermogene, but further work is required to confirm this.

Thermogene travertines are concentrated in Xizhang, Sichuan and Yunnan provinces. There is no active vulcanism in China but there are three large geothermal fields, one associated with the Tengchong Pliocene volcanic area, where some travertines occur. The hot springs of Tibet (Qinghai + Xhizang) are believed to result from groundwater circulating above deep magma chambers below the thick crust (Yokoyama *et al.*, 1999). Southern and central Xizang and western Yunnan where most of the thermogene travertines occur are also

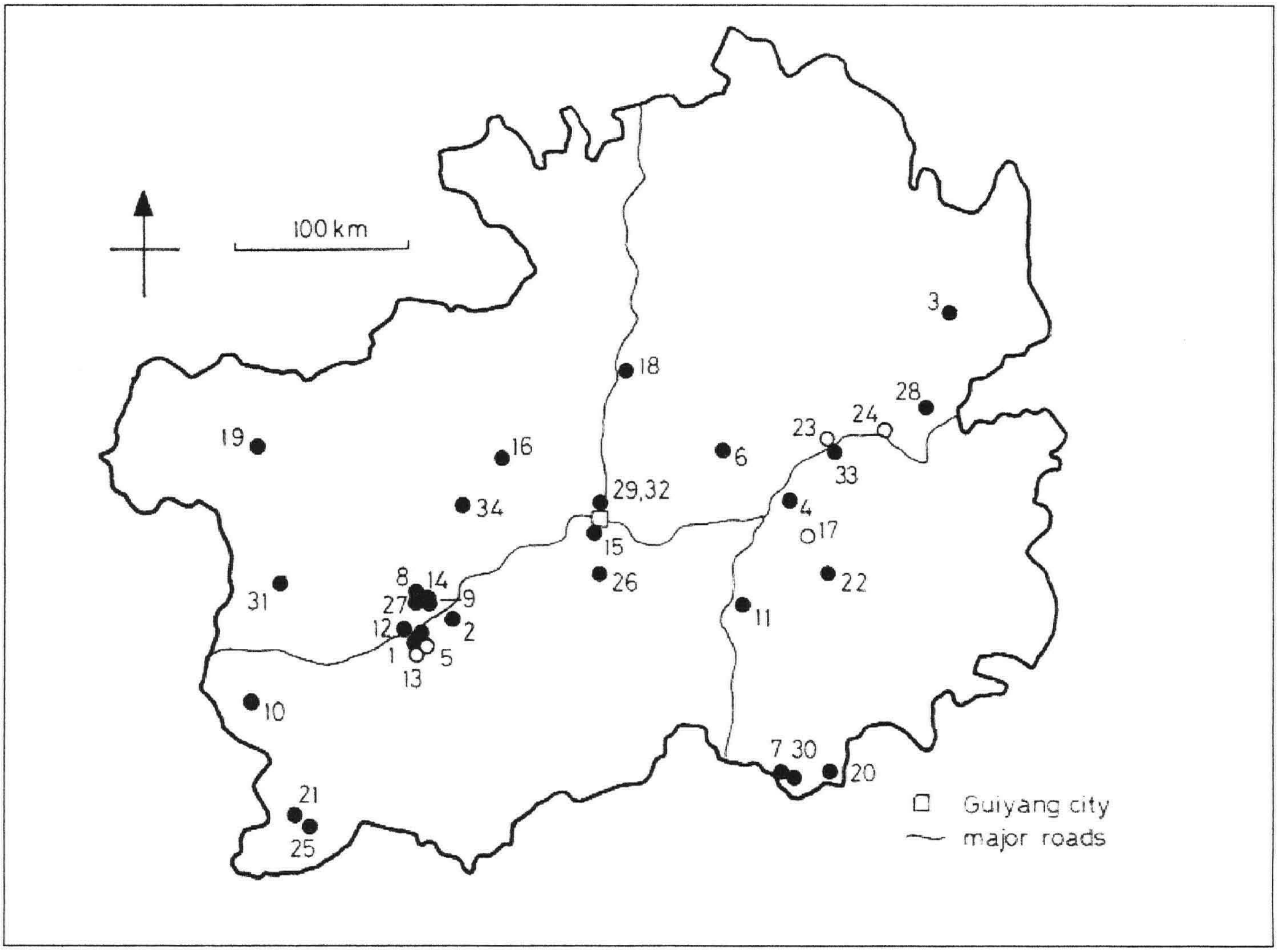



*Figure 1b. Map showing location of the travertines of Guizhou province.*

seismically active (Liu Zaihua, 1998; Yuan, 1997). More than 2,000 thermal springs are known in China (Keary and Wei, 1993), and it is likely that many deposit travertine.

The altitudinal range of the Chinese deposits is 0-4,850m, and the world's highest known site at Erdizheng, Xizhang. The world's highest limestone cave (alt. 5,600m) occurs in the same region (Zhang Dian, 1995). Eight other travertine sites occur at more than 4,000m in Xizhang (numbers 5, 6, 7, 12, 13, 16, 17, 18 in the travertine coded list below).

From a morphological perspective the Chinese travertines fall into two major groups, cascades and dams. Along large rivers, these travertines are commonly of spectacular size and among cascades, Huangguoshu takes pride of place as one of China's greatest waterfalls (Fig.3a). It is the largest of a series of cascades and dams on the Beishuihei River. Huangguoshu at 74m is difficult to study because of high summer discharge and the deep pound pool below. However, it possesses a part natural, part excavated travertine cave, which traverses the 10m-thick deposits, allowing access to some old and recently deposited travertine. Above Huangguoshu is Doupe Pool cascade. Although lower, at 21m, it is 105m in length and one of the widest cascade travertines in China. Other noteworthy cascades in Guizhou are Dragon Palace (4) and Gaotang (12), the latter 130m high. Cascades of similar size occur in Yunnan (2, 8).

Travertine dams provide spectacular scenery by impounding lakes above them. In Europe the best examples are those at Plitvice, Croatia, with which several Chinese sites are comparable, notably Dalugou, Huanglong and Jiuzhaigou in Sichuan (Fig.3b), Beishutai in Yunnan and Reigongtan in Guizhou. The largest lakes are those at Juizhaigou; Shuzeng and Five Flower Lakes, being 2 to 4km long and 1 to 2km wide. The highest dam is Panda Lake Fall (70m). This area is a major Chinese tourist attraction.

There are many reports on Chinese spring-deposited travertines, particularly those of seepages at cave thresholds. They include mounds deposited around hot springs in Xizang (6, 8) and a deposit partly exposed below a glacier in Gansu (1). Chonganjing in Guizhou provides a rare example of a travertine deposited below a periodic spring.

Of other travertine morphologies little seems to be known. Cemented rudites, common in the UK are reported only from Xizhang (10) and stream crusts occur in Anhui, Guizhou and Xizhang. Oncoids, a significant component of spring crusts in Europe and North America, receive no mention in the Chinese literature available to us, but are known from the Beishuihei River, Guizhou (*authors, unpublished*). In addition there is little work on allochthonous travertines, which in other regions are worked commercially for lime (e.g. Sweet and Hubbard, 1990). Natural karstic lakes are rare in eastern China but lake travertines are known from Inner Mongolia (1), Xizhang (17) and Yunnan (9).

There have been few studies of travertine fabric or petrology in China, in stark contrast to the west (e.g. Irion and Mueller, 1968; Braithwaite, 1979). Yang Hankui *et al.*, (1986) and Tian and He (1997) discuss fabric types without reference to deposit petrology. Tan et al., (1998b) describe briefly the radial-fibrous calcite of some laminated speleothems and Qiu (1984) describes stages of calcite and aragonite

*Table 1. Simplified travertine classification scheme for China.*

| Factor | | | | | | |
|---|---|---|---|---|---|---|
| Geochemical | THERMOGENE | | | METEOGENE | | |
| Emplacement | AUTOCHTON | | | | | ALLOCHTON |
| | SPRING | STREAM | LAKE | MARSH | CAVE | |
| Morphological forms | fissure-ridge, mound, pendent | cascade, crust, dam | crust, mound | crust, mound | flowstone, dripstone, dam | clastic lake and valley fills, bars and cones (commonly cemented) |

deposition in Xiniu Cave, Guizhou. We provide two examples of common fabrics from Jiuzhaigou illustrating the association of algae and bryophytes with travertine (Fig.3 c,d). Similar biofabrics occur in other parts of the world (Irion and Müller, 1968).

Some cascade and dam travertines show signs of intense erosion in China. In the vicinity of Huangguoshu, on the Beishiuhei River, much of the travertine possesses a scoured surface pitted with pot-holes or deep scallops. At Stone Village, a large dam has been pierced by caves, through which a river flows in the rainy season. A large series of dams at Xiangxekong, Guizhou show similar signs of erosion and little evidence of accretion. Both sites occur in areas of high rural population where land use has increased over the past few centuries. In contrast the dams at Jiuzhaigou, where the population density is low, show no sign of erosion. Although climate change could be partly responsible for the erosion, we suspect that direct or indirect human activity is affecting travertine formation in these areas, as evidenced in parts of Europe (Goudie *et al.*, 1993). The travertines of China are also utilised in some places. Large excavated masses can be seen in several city centres, where they are used for traditional Chinese gardens and ornaments. At Huangguoshu, licensed traders are permitted to collect smaller pieces for the same purpose. There is also an illicit trade in some areas. Several sites are visited by millions of tourists every year. While efforts are being made to reduce the impact of visitors themselves, the wider implications such as expansion of the local economy also need monitoring.

## HYDROCHEMISTRY AND TRAVERTINE DEPOSITION

A need to understand the geochemical processes that lead to calcite precipitation in streamwater has stimulated several studies in China, particularly at Huanglong in Sichuan, which has been used as a 'natural geochemical laboratory' by several researchers. Huanglong, at 3,650m altitude, is one of the most spectacular travertine sites in the world, commanding magnificent views of high mountains above the large dams. Rimstone pools and stream channel deposits extend 3.63km below the main spring. The springwater is meteoric in origin (Lu *et al.*, 2000) and its temperature (6°C) is above the mean air temperature (c.1°C), defining it as a thermal source (Edmunds *et al.*, 1968). The spring discharges much $CO_2$ gas and the DIC is high (>12 mM/l). This suggests, along with isotopic data, that the $CO_2$ has a geothermal, or mixed geothermal/soil origin. The spring breaks out near a deep fault in a tectonically active area (Liu Zaihua *et al.*, 1995) in common with many European thermogene travertine source waters. Several authors report downflow changes in the Ca-$CO_2$ system at Huanglong (Zhu *et al.*, 1989; Zhu and Zhou 1990; Liu Zaihua *et al.*, 1993, 1995; Lu, 1994; Lu *et al.*, 2000). All found significant falls in DIC and Ca and rises in pH and the calcite saturation quotient was consistent with $CO_2$ loss from water and travertine precipitation. These changes have been used, with direct measurements of the travertine deposition rate using marble and glass substrates, to test some calcite precipitation models. Under turbulent flow in the channels, calcite deposition rates have been estimated using the Plummer-Wigley-Parkhurst equation incorporating a correction for the travertine-water boundary layer thickness (Liu Zaihua *et al.*, 1995). Estimated rates of deposition were close to measured rates providing flow was moderate to high, and the calcite supersaturation exceeded 15. A further investigation on rimstone pools where flow was sluggish, was undertaken by Lu *et al.*, (2000) using a $CO_2$ mass-balance equation. It was found that the deposition rate at flow rates of 2m/sec was about 11 times as high compared with areas where the rate approached 0 m/sec in the larger pools. It was suggested that the smaller pools where deposition was rapid, evolved into larger pools where it was reduced. Despite the existence of both diel and seasonal variation in the DIC and dissolved Ca, both Lu *et al.*, (2000) and Liu Zaihua *et al.*, (1995) believed that biological processes at Huanglong were unimportant sinks for $CO_2$. Huanglong translates into 'Yellow Dragon', referring to growth of diatoms on the travertine surface. Lu *et al.*, (2000) found that diatoms inhibited travertine deposition on artificial substrates, an observation at variance with some other studies (e.g. Winsborough and Golubic, 1987; Pentecost 1998). Reliable measurements on biological activity at Huanglong are wanting and desirable in the light of these findings.

Further downflow studies have been made in the Jiuzhaigou Valley, close to Huanglong (Chou, 1987; Zhang Jie, 1993; Zhu *et al.*, 1989). The Jiuzhaigou site is much larger than Huanglong with over 20km of large travertine-dammed lakes recalling those of Plitvice. On the basis of the available chemical evidence, the source waters appear to be meteogene, but data are insufficient at present to apply deposition models to this system. Experimental studies of thin films generated by bubbles have produced interesting results and demonstrated the importance of bubbles in gas exchange on the larger cascades (Zhang Yingjun et al., 1994; Zhu An 1994a). Recently, Zhang Dian (2001) further demonstrated the importance of aeration on cascades, and obtained downstream chemical gradients at the Huangguoshu Waterfall, Guizhou.

Hydrochemical data are also available for some travertine-depositing waters in Guizhou Province. Several analyses have been made on and around Huangguoshu Falls (Yang Hankui *et al.*, 1985; Chou, 1987) and Maolan (Tian and He, 1997). The data indicate meteogene source waters, but there have been no detailed downflow investigations testing models (e.g. Dreybrodt *et al.*, 1992).

Some representative water chemistries from China are listed in Table 2. The DIC and Ca values range from 2.88-4.86 mM/l and 0.77-1.54 mM/L respectively. These are in the same range as those from other subtropical and cool-temperate sites (e.g. Herman and Lorah, 1987; Pentecost 1992; Troester and White, 1986).

The calcite saturation index $\Omega$ is a measure of the calcite precipitation potential of a water at a given temperature and pressure. ($\Omega$ = calculated

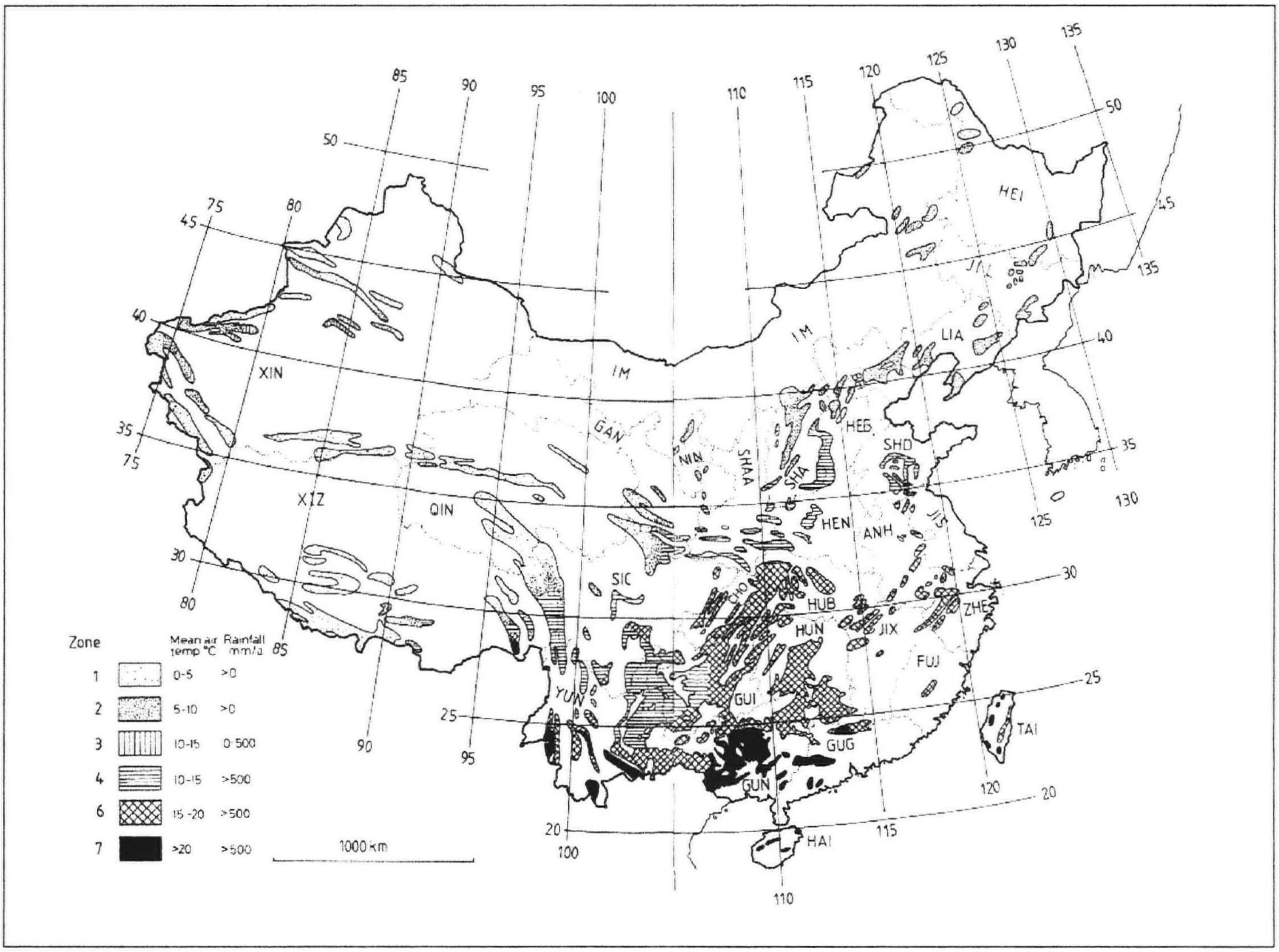



*Figure 2.*
*Map of China showing limestone areas classified into zones of travertine-depositing potential dependant upon mean air temperature and mean annual precipitation (see Pentecost, 1995). Zone 5 (temperature 15-20°C, precipitation 0 to 500mm) is hardly represented in China and omitted from the map. Limestone outcrop data were obtained from Anon (1990) and Liu Ming-Gan (1998).*

sample solubility product of $CaCO_3$/tabulated calcite solubility product, $K_{sp}$). Values exceeding unity demonstrate thermodynamically favourable calcite precipitation. Although Ω is easy to determine from the chemical composition of a water, its value is pH sensitive and its accuracy largely dependent on the precision of the pH determination. Calcite saturation values are reported for several Chinese travertine-depositing waters, usually as the SIC (log Ω). At Huanglong, Ω values ranging from 0.79-20 were found by Liu Zaihua *et al*., (1993; 1995) with the source waters rising close to calcite saturation (Zhu *et al*., 1989). At Huanglong it was observed that travertine deposition was only significant where Ω >10 (Liu Zaihua *et al*., 1995) but this is not always so. For example, values ranging from 4.07 to 6.31 were found along the Juizhaigou Valley (Zhang Jie, 1993) and from 0.4 to 2.2 at Munigou (Zhu Xuewen and Zhou, 1990) in the travertine-depositing sections. In the latter it is evident that periods of calcite undersaturation occur, which could result in travertine dissolution. Significant deposition has also been observed in the UK at Ω values much less than 10 (Spiro and Pentecost, 1991). Values below unity, indicating undersaturation (calcite dissolution favourable) are also known to occur in some UK streams with variable chemistry (*authors unpublished*). A seasonal study at Huanglong by Lu (1994) found that Ω was positively correlated with temperature. This is to be expected since higher temperatures result in more rapid $CO_2$ evasion, increasing pH, which in turn raises $CO_3^{2-}$ and Ω.

## BIOLOGY

Most active epigean travertines are rich in cryptogamic plants, and those in China are no exception. In common with European deposits, algae and bryophytes predominate in the harsh high-energy conditions prevailing on dams and cascades. Of the 88 sites listed below, algae are recorded from 13 and bryophytes from 22. Among algae, cyanobacteria and diatoms are most frequently found. Tian and He (1997) found a wide range of travertine fabrics associated with particular cyanobacterial communities including *Scytonema (Petalonema) alatum* and *Synechocystis pevalekii*. Similar communities have been described from Europe (Golubic, 1967). One of the more interesting effects of algae on travertine occurs at cave thresholds, where seepages produce pendents resembling stalactites. These have been named *aussenstalactit* or *remora* (Pentecost and Viles, 1994) and are a common feature of the Chinese tower karst. Algae, consisting mainly of cyanobacteria cause the formations to diverge from the vertical in the direction of highest irradiance, often in dramatic fashion (Wang Fuxing et al., 1993; Rong Kunfang *et al*., 1996). Algal photosynthesis, probably aided by increased evaporation on the illuminated side appears responsible.

Travertine algae have been studied in some detail at Juizhaigou and Munigou, Sichuan (Pentecost and Zhang Zhaohui, 2000). At both sites cyanobacteria and diatoms dominated the algal flora. Important genera were *Achnanthes, Calothrix, Cymbella* and *Dichothrix*.

*Table 2. Hydrochemistry of some Chinese travertine-depositing waters*

*Mean values reported, all in mM/l unless otherwise stated.*

| Site | Huangguoshu Bridge, Guizhou. | Huanglong, Tangra Stream, Sichuan | Jiuzhaigou, Zutse Hotel, Sichuan | Jumping Cat River, Guizhou | Xiangzhigou, Godi-ching Waterfall, Guizhou |
|---|---|---|---|---|---|
| Date sampled | May-Sept 1981 | - | 12-Jul-86 | - | - |
| Altitude (m) | 1050 | 3500 | 2600 | - | 1100 |
| Water temp. °C | - | 3.6 | 6.5 | - | 10 |
| pH | 7.34 | 8.36 | 7.66 | 7.66 | 7.69 |
| DIC[1] | 4.86 | 5.32 | 2.88 | 3.21 | 4.23 |
| $PCO^2$ % | 0.98 | 0.1 | 0.08 | 0.33 | 0.4 |
| Ω[2] | 0.74 | 11.7 | 2.73 | 0.91 | 0.8 |
| Ca | 1.54 | 2.56 | 1.18 | 1.29 | 0.77 |
| Mg | 0.71 | 0.51 | 0.41 | 0.78 | 1.46 |
| $SO_4$ | 0.53 | - | 0.20 | 0.6 | 0.13 |
| Number of measurements | 4 | 1 | 1 | 3 | 2 |
| Reference | Yang Hankui *et al.*, (1985) | Liu *et al.*, (1993) | Chou (1987) | Yang Hankui *et al.*, (1985) | Tian and He (1997) |

[1] *Dissolved inorganic carbon*
[2] *The calcite saturation quotient (see text for explanation)*

About 60 species of bryophytes are recorded from Chineses travertines, the most common being *Cratoneuron filicinum, Fissidens grandifrons, Hydrogonium ehrenbergii* and *Gymnostomum aurantiacum*. Some appear to be confined to travertine-depositing sites (Zhang Zhaohui 1993, 1998; Zhang Zhaohui and Pentecost, 2000). Bryophytes are often conspicuous on Chinese travertines, where they are instrumental in the trapping and binding of calcium carbonate (Zhang Jie, 1993; Zhang Zhaohui *unpublished*). Among mosses, the genera *Bryum* and *Fissidens* were considered important in the formation and stabilisation of travertine on dams and cascades. Scanning electron microscopy of the leaves of three moss genera showed that travertine deposition was confined to semi-enclosed regions of the leaves and stem (Fig.3d), reminiscent of intercellular calcification in marine algae (Pentecost and Zhang Zhaohui, 2000). In general, however, calcite precipitation around bryophytes appears largely a function of their capillarity, aided by evaporation. The Chinese travertine bryophyte flora shares 16 species with the UK, which is significantly lower than the algal flora as currently known, and probably reflects the greater endemicity of bryophytes. The Chinese travertine-bryophyte flora is currently one of the best studied in the world.

Ferns, trees and shrubs have been seen colonising active travertine dams and cascades in Sichuan, the most celebrated being the Water Forest at Munigou. The maidenhair fern, (*Adiantum capillus-veneris*) is common on the Huangguoshu Cascade, in sheltered, non-depositing areas and known widely from other Eurasian travertines (*authors, unpublished*). What controls the dynamics of these ecosystems, or the extent to which trees stabilise the travertine surface, is unknown. Much work remains to be done.

Fossil leaves and pollen have been discovered in a Late Pliocene/Early Pleistocene travertine of the Kunlun Mountains, Xinjiang (Zhang Qing-Song *et al.*, 1990; Guo Shuang-xing and Gu, 1993). The flora includes *Salix* and *Pterocarya*, indicative of a humid-temperate climate, unlike that of today. However, there are no detailed investigations of travertine biostratigraphy known to us from China. In the West such studies have thrown much light on past ecosystems and climates (e.g. Kerney *et al.*, 1980; Preece and Day, 1994), and are eagerly awaited.

## CAVE TRAVERTINE

Although one of the richest caving regions known, serious exploration and research of Chinese cave travertines has begun only recently. During the past decade significant advances have been made in speleothem geochemistry and chronostratigraphy, and the results have thrown light on the Quaternary climate of the region. The major speleothem research sites are shown in Fig.4. Most are in the warmer, humid parts of China and were not glaciated during the Pleistocene. Chinese caves contain some of the largest speleothems known, such as the 39m column of Nine Dragon Cave, Guizhou (Waltham, 1984).

Fine stalagmite laminations have been reported from several provinces, and at Shihua Cave, Beijing, a series of 2246 layers was counted (Tan *et al.*, 1999a). Fluorescence microscopy, bright field microscopy and ionization mass spectroscopy have shown that the layers are caused by differences in organic matter content, probably soil-derived but augmented by surface bacterial growth resulting in a range of lamina types (Qin *et al.*, 1998; Tan *et al.*, 1999a,b). Correlation with direct $^{14}C$ dating and modern rainfall data demonstrate that laminae are normally annual (Tan et al., 1998a,b). Although the layers have been compared with tree rings, their chrononology cannot be determined with as much precision, since hiatuses and sporadic biannual rings occur (Li *et al.*, 1998). This leads to problems when attempts are made to cross-correlate stalagmites from the same cave. Wang Xunyi (1986) showed that stable isotope values vary according to position within a cave, but in areas where the physical environment is stable, similar isotopic signatures are obtainable from different stalagmites. With reliable dates, it has been possible to explore centennial trends and correlate these with isotopic data. This has been done at Panlong Cave, Guilin (Li *et al.*, 1998) where a warm and humid period (c.7 to 4.5ka) preceded a cooler drier period (2.5 to 4ka). Similar conclusions were obtained from Chinese ice core data (Wei and Lin, 1994).

A number of carbon dates are available for cave and surface travertines and are shown in Fig.5. Little can be concluded at present but several dates indicate deposition of travertine during the last

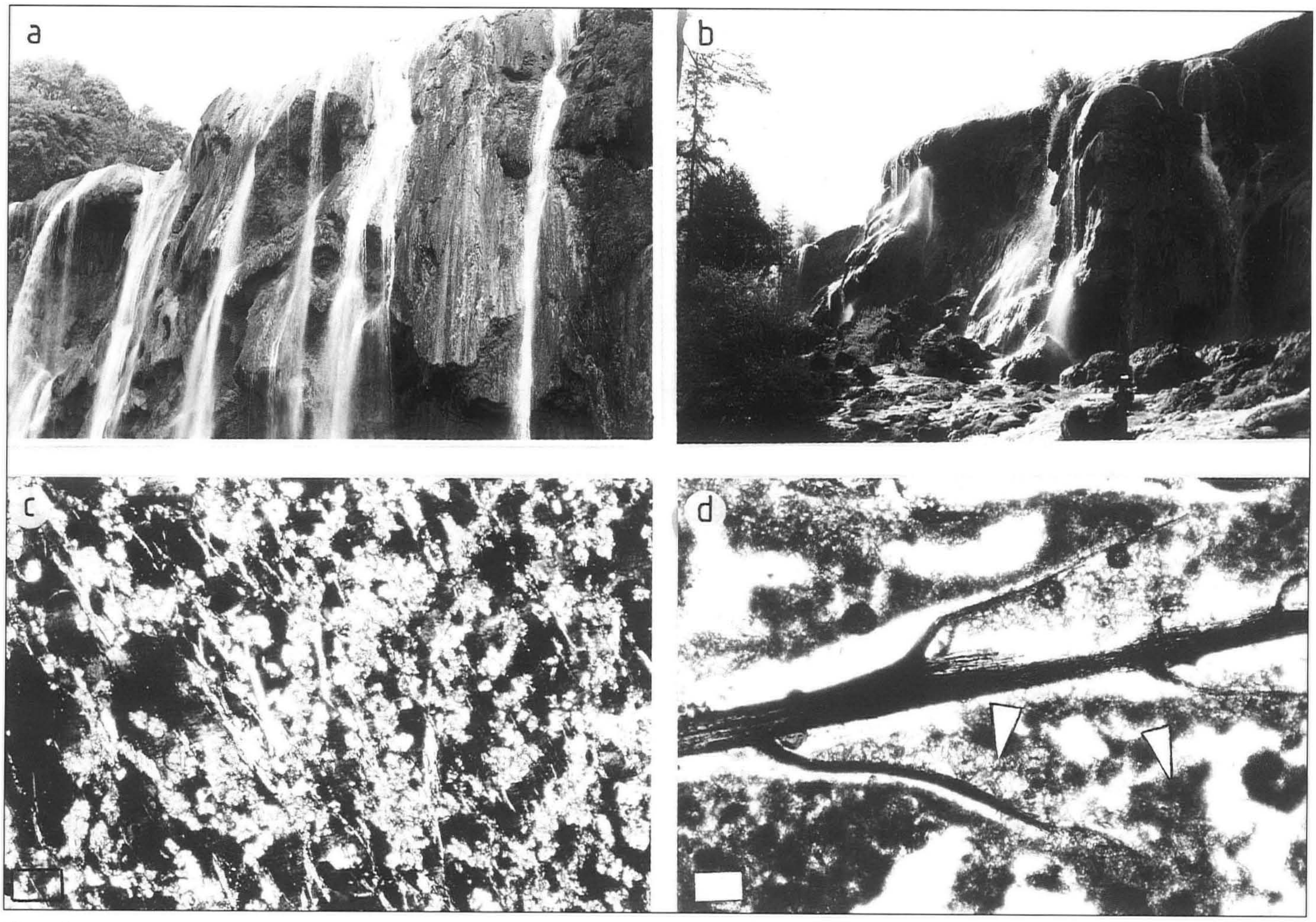



*Figure 3.*
*a: Huangguoshu Falls, Guizhou, showing the upper part of this large travertine cascade. A travertine cave runs the length of the waterfall at the level at which the photograph was taken.*
*b: Pearl Waterfall, Jiuzhaigou, Sichuan. This waterfall, about 20m high, forms the front of a large lake-dam complex in Jiuzhaigou valley. Above is Pearl Shore, a broad expanse of active travertine colonised by rare plants.*
*c: Vertical section through a colony of the cyanobacterium Dichothrix baueriana from the travertine cascade at Nourilang Falls, Juizhaigou, Sichuan. Irregular crystals of microspar measuring 20-50mm in diameter are intimately associated with this alga. The sheaths of the Dichothrix are strongly birefringent. Crossed polarized light. Bar 100mm.*
*d: Vertical section through a cushion of the moss Gymnostomum subrigidulum from the travertine of Shuzeng Falls, Jiuzhaigou, Sichuan. Two forms of calcite are associated with the moss. A microspar with crystals in the range 15-30mm is appressed to the inner surfaces of the leaves (centre arrow) whereas the entire moss stem is surrounded by a darker micrite with crystals 1-5mm (right arrow). The sparite may have been deposited as a result of 'intercellular space calcification' as described by Pentecost and Zhang Zhaohui (2000). Plane polarised light. Bar = 100mm.*

glaciation (>15ka BP). This is likely in subtropical southeast China where the dates were obtained. Thermogene travertines will be less affected by air temperature, which could explain the existence of two early dates from the glaciated regions in western China. However, groundwater circulation is bound to be influenced by sub-zero air temperatures and it is not clear from the literature if the 'hardwater effect' was taken into account when these dates were calculated. If they were not then some dates are probably overestimates. Several U series dates are also reported, but most of are limited in accuracy. Dates ranging from 112 to 385ka were found for a speleothem in Maomaotou Cave, Guilin, a non-glaciated region (Wang Xunyi, 1986) with interruptions of growth at 130 and 21ka. Uranium dates in the range 100 to 1,000ka have been found for several Tibetan travertines (Sweeting *et al.*, 1991) recording previous interglacials. Large speleothems dating to earlier interglacials have also been noted from this region by Yuan (1997) and also from Shaangxi and Guangxi provinces. Careful selection and analysis of speleothems could provide detailed information on the recent uplift of the Tibetan plateau.

Several investigations of the stable isotopic C and O composition of travertine have been reported. Data are available for a number of speleothems from the Guilin caves, where evidence for deposition at isotopic equilibrium was found, and the potential for palaeoenvironmental work recognised (Wang Xunyi, 1985; 1986). The most detailed studies to date are those from Panglong Cave, Guilin and Shihua Cave, Beijing. In the former the $\delta^{18}O$ record of a speleothem of Late-glacial to Holocene age was investigated (Yuan, 1997; Li Bin, 1998). The $\delta^{18}O$ values can be interpreted as a palaeothermometer, given certain assumptions about past water composition. Unfortunately the situation in China is complicated by monsoon-type precipitation, which has been found to cause large variations in the water $\delta^{18}O$. When the monsoons are weak, precipitation is low and the water $^{18}O$ content substantially depleted. The $\delta^{18}O$ data from speleothems has therefore been interpreted in terms of changing monsoon patterns rather than water temperature alone, whose signature becomes overprinted by variations in rainfall. At Panglong Cave, evidence was found for increased monsoon activity during the warm (Atlantic) period about 7ka. Modern calcite values for $\delta^{13}C$ and $\delta^{18}O$ were –5.89 per and –8.59‰ PDB respectively. At Shihua Cave a laminated Holocene stalagmite was studied and the $\delta^{18}O$ record compared with the thickness of dated annual growth layers. Although statistical methods were not applied, it was evident that the $\delta^{18}O$ was correlated positively with lamina thickness (Tan *et al.*, 1998a,b). This would be expected if water was depleted in $^{18}O$ during periods of reduced precipitation. Some $\delta^{13}C$ data were also analysed but found more difficult to interpret. This is often the case due to the large number of variables affecting $^{13}C$ values. The

*Table 3. Representative epigean travertine compositions from China.*

| Location | $CaCO_3$ % dry weight | Acid insoluble minerals % | Organic matter % | Mg ppm | Fe ppm | Mn ppm | Zn ppm | Pb ppm |
|---|---|---|---|---|---|---|---|---|
| Doupe Pool, Guizhou | 87.0 | 5.8 | 7.2 | 2910 | 1080 | 330 | 16 | <2 |
| Huangguoshu Falls, Guizhou | 79.7 | 15.3 | 5.0 | 3260 | 1090 | 200 | 22 | <2 |
| Xiangzhigou Guizhou | 87.1 | 9.9 | 3.0 | 565 | 480 | 153 | 11 | <2 |
| Huanglong, Sichuan[1] | 98.4 | 0.99 | - | 840 | 2800 | 13 | - | - |
| Jiuzhaigou, Sichuan[2] | 97.9 | 0.7 | 0.1 | 382 | 2430 | 107 | 32 | 2 |
| Mean | 90.0 | 6.53 | 3.83 | 1590 | 1576 | 134 | 20 | - |

[1] *Mn from Lu (1994), remainder calculated from Zhu Xuewen and Zhou (1990).*
[2] *From Pentecost and Zhang Zhaohui (2000). Remainder: Pentecost and Zhang (previously unpublished)*

mean $\delta^{13}C$ and $\delta^{18}O$ for the caves were −9.2 and −9.3‰ PDB respectively. There are few reports of stable isotopes from surface travertines. Some data are available for Huanglong where a $\delta^{13}C$ value of +4.1‰ PDB was found (Liu Zaihua *et al.*, 1995), typical of most thermogene travertines. At Huanglong water isotope data have been obtained but insufficient to add much to our understanding of the depositional processes (Chen *et al.*, 1988; Liu Zaihua *et al.*, 1993).

Trace element compositions of travertines have been determined at Panlong Cave, Guangxi and there is evidence to indicate that concentrations of heavy elements such as Fe and Co are higher in cold stages, possibly reflecting lower growth rates (Li *et al.*, 1997; Yuan, 1997). There are also a few analyses of surface travertines, which demonstrate that the active deposits are geochemically similar to those of Europe (Lu, 1994; Zhu Xuewen and Zhou, 1990; Pentecost and Zhang, 2000). Some representative compositions are given in Table 3. At present we do not know whether trace element compositions act as proxies for climatic variables in the surface travertines.

## CONCLUSIONS

Travertines have been shown to be widely distributed in China and beginning to receive attention from a wide range of scientists. It is clear that great regions of the country remain unexplored, but all of the major sites are probably known, as they are usually associated with spectacular scenery and are tourist attractions. In common with those in Europe, the meteogenes are most abundant in the warmer, more humid regions, but there are a few large sites at high altitude that appear anomalous and need further investigation (e.g. Jiuzhaigou, Sichuan). Some major sites, such as Huangguoshu, are visited by millions of sightseers each year and, although steps have been taken to protect the fragile ecosystems, catchments need to be carefully monitored for direct and indirect human impact.

Hydrochemical and geochemical investigations on the deposits and associated waters have advanced our understanding of calcite precipitation. These studies could be extended to investigate more subtle variations caused by plant metabolism and the effects of trace elements such as phosphorus, which may inhibit calcite nucleation.

Biological studies have revealed diverse and specialised plant communities on some Chinese deposits. At present only a small number of sites have been investigated, but this is likely to be extended in the near future. Although floristic studies are developing, there appears to be no work on the fauna. The invertebrate faunas of Western travertines have been found to be diverse and highly specialised (e.g. Durrenfeldt, 1978) and those of China are likely to be the same, enhancing their conservation value. There is also a lack of information on the fossils of travertine. The European fossil flora/fauna is remarkably rich and has provided numerous insights into Quaternary environments (examples cited in Pentecost, 1995). The same should be the case in China, and biostratigraphical studies should be encouraged to complement recent advances in speleothem isotope geochemistry.

Finally, it was interesting to find how few Chinese studies were reported in the Western literature, and few Western studies are cited in the Chinese literature. Less biased citing was evident in Chinese-Western collaborations and the number of collaborative studies has increased significantly over the past decade.

## CODED LIST OF CHINESE TRAVERTINES

After each province name the area of exposed carbonate rock in km$^2$ x $10^{-4}$ is given, followed by the % limestone cover in parenthesis. Most of the data are from Li Datong and Luo (1983). Abbreviations in parentheses, e.g. (ANH) correlate with province names shown on Fig.2. For each province a brief summary of the exposed limestones (abbreviated L) is provided. Each site within a province is numbered to facilitate location, and the latitude and longitude are given. Sites shown in bold are believed to be active, and for these sites the climatic zone value (Z) is given (see Fig.1). Only epigean (surface) travertines are listed here. For the distribution of cave travertines refer to Fig.4.

**Abbreviations in list**

*a* = archaeology; *ch* = water chemistry; *cl* = classification; *do* = carbon 14 dating; *dp* = deposition processes; *du* = U-series dating; *fa* = fabric analysis and petrology; *fm* = fossil Mollusca; *fp* = fossil plants; *ge* = geomorphology; *hyd* = groundwater hydrology; *in* = industrial; *la* = live algae; *lb* = live bryophytes; *penv* = palaeoenvironments; *s* = general site description; *si* = stable isotopes.

ANHUI (ANH) 2.4 (9)

A few limestones, one forming a NE-SW belt across province, mostly Precambrian, in the hills bordering the Tongling Nanchang. Also on E side of the Yangtze River and in scattered low-lying areas SE of Tongling.

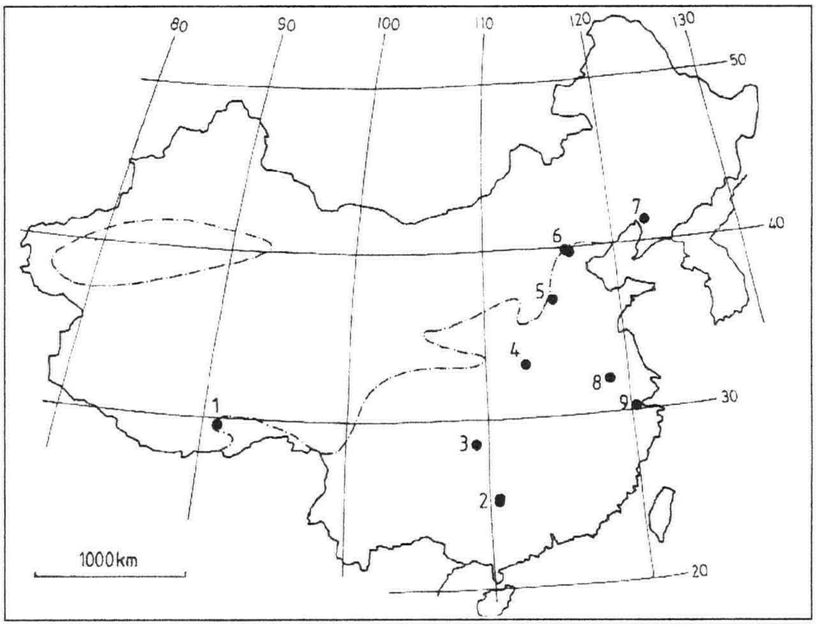



*Figure 4.*
*Locations of some important cave travertine research sites mentioned in the text. 1) Big Buddha Cave, Lhasa, Xizhang; 2) Maomaotou and Panlong Caves, Guangxi; 3) Nine Dragon Cave, Guizhou; 4) Jiguan Cave, Henan; 5) Bayun Cave, Hebei; 6) Shihua and Yinhu Caves, Beijing; 7) Water Cave, Liaoning; 8) Hulu Cave, Nanjing, Jiangsu; 9) Yaolin Cave, Zhejian. Broken line shows the estimated Pleistocene 0°C air temperature line (after Liu Min-Gan, 1998).*

1. **Zeiong Temple, Tuzhou City**. 32.10N, 118.19E. Stream deposit with mosses. Z4. Li Xinjiang (1996) *lb*.

BEIJING (BEI) 0.21 (12.5)
To the SW is fissured L containing Zhoukoutien Cave, where Peking Man was discovered. In NE is part of a large area of Cambrian L and dolomite bordering Hebei. Archaean marbles and magnesites occur W of Beijing City.

CHONGJIANG (CHO) 2.0 (24.0)
*L* in the SE bordering Guizhou karst plateau. In the NW outcrops of dolomite and *L* trending SW-NE, N of Chonqing.

FUJIAN (FUJ) 0.2 (0.3)
Small areas of L in the centre of the province in the mountains surrounding Sanming, W of Fuzhou.

GANSU (GAN) 6.8 (7)
Some *L* in the high mountains S of Lanzhou and in the Minshan Mountains extending into N Sichuan.

1. **Baishui Valley, Wine Spring City.** 39.15N, 98.31E. Large spring deposit 425 x 30 x 5.2m thick under glacier on Mt. Chiniang at 3,500m. alt. Z1. Zen *et al.*, (1983) *s*.

GUANGDONG (GUG) 2.1 (12.0)
Some Devonian *L* in the N and in scattered localities elsewhere. Areas include part of the Hunan *L* massif in the N and parts of the Huan Shan Range S of Shaoguan. Large cave at Yingcheng. Also *L* in the mountains between Guangzhou and Wuzhou.

GUANGXI (GUN) 10.3 (33)
Large areas of karstified *L* occur throughout, especially in the centre and N. The *L* mostly Permian and Carboniferous with some dolomite in the E. *L* extends into Guangxi and Hunan. Well-developed tower karst in the lowlands around Guilin, increasing in height toward the N. Spectacular caves occur in this area and also near the Hongshui River W of Luizhou.

1. **Cross Cave Park, Nongling County**. 24.33N, 105.17E. Spring deposit with bryophytes. Alt. 1,394 m. Z6. Zhang Zhaohui (*unpublished*).
2. **Debao, Debao County.** 22.58N, 106.37E. Series of travertine dams along a tributary of the Zhoujing River. Z7. Yang Hankui *et al.*, (1986) *s*.
3. **Jiaotiandayan Cave, Xinping County**. 24.53N, 110.26E. Cave threshold travertine influenced by algal growth. Z6. Wang Fuxing *et al.*, (1993) *la*.
4. **Jingxi, Jingxi County**. 22.58N, 106.26E. Travertine dams and cascades along a tributary of the Zhoujing River. Z6. Yang Hankui *et al.*, (1986) *s*.
5. **Redsandxiang, Hechi City.** 24.30N, 107.55E. Cave threshold travertine associated with bryophytes and algae. Alt. 385m. Z6. Zhang Zhaohui (*unpublished*).
6. **Seven Star Park, Guilin.** 25.21N, 110.11E. Cave threshold travertine associated with algae and bryophytes. Z6. Zhang Zhaohui (*unpublished*).
7. **Six Villages, Nandan County**. 24.50N, 107.32E. Stalactite associated with mosses at cave threshold. Alt. 880m. Z6. Zhang Zhaohui (*unpublished*).
8. **Pinggou, Pinggou County**. 23.14N, 107.34E. Travertine dams along the Youjing River. Z7. Yang Hankui *et al.*, (1986) *s*.
9. **Yangshuo, Yangshuo County**. 24.40N, 110.27E. Cliff seepages, remora (='aussenstalactit') and threshold stalactite abundant along Lijiang River colonised by algae and bryophytes. Z6. Pentecost (1985). *s, la, lb.*, Wang Fuxing et al., (1993) *la, lb*.

GUIZHOU (GUI) 14.5 (51)
Contains single most extensive area of karst in China amounting to 13,000m in thickness. *L* ranges from Cambrian to Triassic, forming the Yunnan-Guizhou limestone plateau. To the E of Guizhou the plateau attains an average altitude of c.1,000m, increasing to c.2,900m in the W Plateau, dissected by river systems draining into the Yangtze in the N and the Zhu Jiang in the S. Caves and travertines well developed along deep valleys at plateau margin, especially along irregular southern rim S and E of Guiyang. Sites shown on separate Guizhou map (Fig.1b).

1. **Barling River, Guanling County.** 25.51N, 105.37E. Travertine-depositing tributary of the North Pan River with over 20 dams and cascades. Z6. Yang Hankui *et al.*, (1985) *s*.
2. **Beishu-Shanzhahe River, Zhenling County.** 25.59N, 105.41E. At least 18 dams and cascades from the Stone Village to Hecuine, over a distance of 10km. Includes Tianshengqiao Dam, 20m wide and 7.2m high, with travertine cave. Z6. Yang Hankui *et al.*, (1986) *s*. Zhang Zhaohui *et al.*, (1997a,b) *lb*. Zu An and Zu Gang (1994) *ch, in*.
3. **Beishudong Waterfall, Jiankou County.** 27.39N, 108.50E. Travertine cascades under three karst caves on the left bank of the Lingxiao River. Z6. Yang Hankui *et al.*, (1984) *s*.
4. **Chonganjing Periodic Spring, Huangping County.** 26.36N, 107.53E. Deposit 20m wide and 3 to 5m thick covered in plants, from a periodic spring flowing for 8 to 13 min., then stopping for 2 to 3 min. Z6. Yang Hankui *et al.*, (1984) *s*.

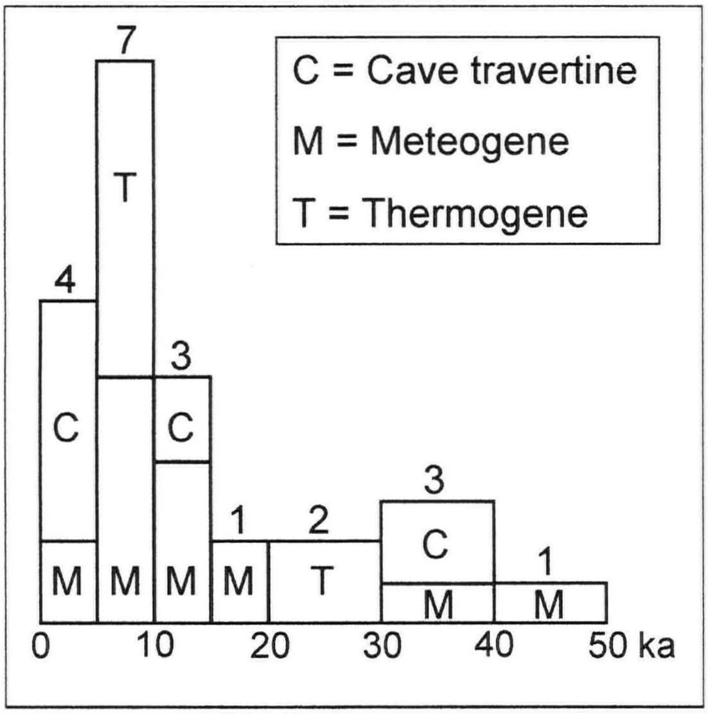



*Figure 5.*
*Travertine 14C dates in China.*

5. **Chuantong River, Guanling County.** 25.51N, 105.37 E. Two inactive dams near the riverbank at Wantong Village. Yang Hankui *et al.*, (1984) *fm, s.*
6. **Chuantonghe Fall, Yongyang County.** 26.54N, 107.28E. Large cascade deposit with deposition rate averaging 5mm a-1. Z6. Mo Zhongda (1984) *dp, s*; Zhang Yinjun *et al.*, (1994) s.
7. **Daqikong Park, Libo County.** 25.09N, 107.48E. Spring deposits and cliff remora with rich cryptogamic flora. Z6. Zhang Zhaohui (*unpublished*).
8. **Doupe Pool Waterfall, Zhenling County.** 26.09N, 105.36E. Ten dams and cascades from Doupe to Maoshui over a length of 2km. Doupe Pool Waterfall is one the widest travertine cascades in the world, 105m in length and 20.8m high, with caves beneath. Z6. Yang Hankui *et al.*, (1984) *s*; Zhu An (1994b) *ch, in*; Zhang Zhaohui (1996) Zhang Zhaohui *et al.*, (1996) *lb*; Pentecost and Zhang Zhaohui (2001) *la, lb.*
9. **Dragon Palace Waterfall, Anshun County.** 26.06N, 105.39E. Cascade deposit 33m high and 10m thick. Z4.Yang Hankui *et al.*, (1984) *s*.
10. **Fengdong Cave, Panxian County.** 25.31N, 104.40E. Cave threshold travertine with rich cryptogamic flora. Z4. Tian and He (1996) *la, lb.*
11. **Flying Cloud Cave, Huangping County.** 26.45N, 107.53E. Large cascade deposit. Z6. Yang Hankui *et al.*, (1984) *s*.
12. **Gaotang Waterfall, Guanling County.** 25.51N, 105.37E. Large deposit near mouth of Gomutang River, 15to 30m wide, 130m high and 3 to 5m in thickness, with travertine cave. Z4. Yang Hankui *et al.*, (1985) *s*.
13. **Geological Team Site 112, Guanling County.** 25.47N, 105.37E. Deposits 14C-dated to 35.9ka. Yang Hankui *et al.*, (1984) *a, do, s.*
14. **Huangguoshu Waterfall, Zhenling County.** 26.08N, 105.36E. Altitude 600-1500 m. The 'Orange Fall', a huge travertine cascade 74m high and over 50m wide and 6 to 10m in thickness on the Dabong River, where it descends the Guizhou Plateau. Large cave travertine cave traverses deposit with U-series dates ranging from 20 to 70ka. Immediately below falls are a series of degraded and eroding dams in a section of captured river, possibly a collapsed cavern. Z6. Waltham (1984) *s*; Zhang Yingjun and Mo Zhongda (1982) dp, s; Yang Hankui et al., (1985, 1986) *Ch, Cl, Dp, Du, S,*; Ford and Pedley (1992); Zhang Zhaohui (1996); Zhang Zhaohui *et al.*, (1996, 1997a,b, 1998) *lb, s*; Tian Youping and He (1998) *la*; Zhang Zhaohui and Pentecost (1999) *lb, s*; Zhang Dian (2001) *ch, dp.*
15. **Huaqing Park, Guiyang City.** 26.35N, 106.40E. Series of dams along the Huaqing River. Z6. Yang Hankui *et al.*, (1985) *s*.
16. **Jumping Cat River, Chinxi County.** 26.49N, 106.07E. Extensive spring crust resembling flowstone at head of valley. U-series dated to 11.5ka. Z4. Yang Hankui *et al.*, (1984) *du, s.*
17. Kaili City 26.26N, 108.00E. Large inactive deposits from the railway station to the city centre covering about 2km2 and 15 to 30m in thickness. Yang Hankui *et al.*, (1985) *fm, fp, penv, s.*
18. **Lousha Gate Mountain, Zunyi City.** 27.21N, 106.51E. Large traver tine fan from mountain foot to Banjio Road, over 2km in length. Z4. Yang Hankui *et al.*, (1986) *s*.
19. **Luchong River Valley, Hezhang County.** 26.55N, 104.40E. The Luchong River deposits travertine in its upper reaches near Huhe Village. Z4. Zhang Zhaohui (*unpublished*).
20. **Maolan National Nature Reserve, Libo County** 25.08N, 108.06E. Many small cascades and cliff remora, much under primary karst forest. Z6. Wang Fuxing *et al.*, (1993) *la*; Zhang Zhaohui (1993b) *lb*; Tian and He (1997); Zhang Zhaohui (1998) *lb, s*; Zhang Zhaohui and Pentecost (2000) *lb.*
21. **Maling River Valley National Park, Xinyi City.** 24.56N, 104.56E. Series of more than 20 travertine cascades with a rich flora along the Maling Valley. Z6. Zhang Zhaohui (1998) *lb, s.*
22. **Mayang River Reserve, Yanhe County.** 26.14 N.,108.07 E. Deposit associated with bryophytes, 300 to 1,100m alt. Z6. Zhang Zhaohui *et al.*, (1997b, 1998) *lb*.
23. **Mountain Cave Head, Zhenyan County.** 26.58N, 108.06E. Four inactive cascades reported by Yang Hankui *et al.*, (1985) *cl, s.*
24. **Qing Dragon Cave, Zhenyan County.** 26.59N, 108.25E. Three inactive dams and cascades close by, about 1km2 in area and 15 to 30m in thickness. Yang Hankui *et al.*, (1985) *penv, s*,
25. **Reigongtan, Xingyi City.** 24.56N, 105.00E. Series of large dams along the South Pan River, over 10km in length, up to 16m in thickness. Z6. Yang Hankui *et al.*, (1985) *s*.
26. **Sibanshao, Guiyang City.** 26.12N, 106.42E. Series of dams near the village. Z4.Yang Hankui *et al.*, (1985) *s*.
27. **Tianxing Bridge Park, Zhenling County.** 26.08N, 105.36E. Series of travertine dams and cascades, many showing signs of erosion, on the Dabong River, 10km below Huangguoshu Waterfall. Z6. Zhang Zhaohui (1996) *lb,s*; Zhang Zhaohui *et al.*, ( 1997) *lb, s.*
28. **Timahidong Beishui Falls, Chengong County.** 27.06N, 108.43E. Series of cascades 30 to 90m in height. Z6. Yang Hankui *et al.*, (1984) *s*.
29. **Xiangzhigou Park, Guiyang City.** 26.35N, 106.40E. Numerous cascades, including Dishuiya cascade with rich flora in the Xianggou Valley, deposits 10 to 40m wide, 40 to 60m high and 5 to 10m in thickness. Z6. Mo Zhongda (1984) *ge, s*; Tian and He (1997) *la*; Zhang Zhaohui (1998) *lb, s.*
30. **Xiaoqikong National Park, Libo County.** 25.07N, 107.47E. Series of 15 travertine dams, cascades and large seepages. Dams undergoing erosion. Z6. Zhang Zhaohui (1993a) *lb, s*; Zhang Zhaohui and Pentecost (1999) *lb.*
31. **Yezhong Monkey Reserve, Shuicheng County.** 26.11 N, 104.50E. Large cascade below cave resurgence, 56m high, 6m wide and 4m thick. Z4. Zhang Zhaohui *et al.*, (1997b) *lb, s*; Zhang Zhaohui (1998) lb.
32. **Yiahe River. Guiyang City.** 26.35N, 106.40E. Small deposits reported. Z4. Zhu An (1988; 1994a,b) *dp, fa, la, s.*
33. **Yuntaishan National Park, Shibing County.** 26.54N, 108.06E. Series of small travertine cascades. Z6. Zhang Zhaohui *et al.*, (1997b) *lb*; Zhang Zhaohui (1998) *lb.*
34. **Zhijin Cave, Zhijin County.** 26.34N, 105.53E. One of largest caves in China with threshold travertine associated with algae. Z4. An Yuiguo et al., (1993) *dp*; He Fusheng *et al.*, (1993) *la, s.* Rong Kunfang *et al.*, (1996) *la.*

HAINAN (HAI) 0.2 (6.2)

Small patches of *L* occur S of Zhanzhou and just W of Wancheng, mostly in dense sub-tropical forest.

HEBEI (HEB) 3.4 (10)
Three large areas of *L*. Mountains centred on Chengde bordering Beijing contain Cambrian L and dolomite. In the SW bordering Shanxi Province the Taihan Shan contains Archaean and Palaeozoic L and dolomites, plus isolated areas W of Beijing including parts of the Taihang Shan.

1. **Fuping, Fuping County.** 38.46N, 114.12E. Spring deposits associated with bryophytes. Z2. An Guanyi and Wang, G. (1989). *lb, s.*

HEILONGJIANG (HEI) 4.1 (10)
Small areas of *L*. Two patches surrounded by igneous rock occur in the Lesser Khingan Mountains, with another area farther S in the hills around Mudangjian.

HENAN (HEN) 1.6 (9.5)
Some *L* in the W and centre of the Province. Cambrian *L* occurs in the hills SW of Zhengzhou. Extensive E-W trending outcrops around Shaangxi, W of the Nanyang mountainous area.

HUBEI (HUB) 5.9 (22)
Large areas of *L*. In the centre, Palaeozoic *L* occurs in the low hills NW of Wuhan, with more outcrops farther W in the Yangtze Gorges with caves near Yichang. To the W, and N of the Yangtze River, Precambrian *L* mountains attain 3,000m alt. Other *L* occurs in two areas in the SE, - the Mufu Shan Range and S of Wuhan.

HUNAN (HUN) 8.2 (27)
In the central area Carboniferous-Permian *L* occurs E and S of Hengyang, including the mountains of Dupang Ling toward Guilin. In the E, Cambrian and Devonian *L* and dolomite extend from the Guizhou plateau, including much of the Wuling Shan Range

INNER MONGOLIA (IM) 5.1 (1)
Few significant outcrops. Include the low mountains W and N of Baicheng and the Greater Khinggan Ling Mountains, with Precambrian and Ordovician L along their S border.

1. **Badain Jaran** . Alkaline hyposaline and hypersaline lakes contain aragonite travertine pinnacles associated with a microbial flora. Arp *et al*., (1998) *la, s.*

JIANGSU (JIS) 0.3 (2)
Small L area in N, bordering Shandong. Karst caves at Yizing, near Tai Hu.

JIANGXI (JIX) 1.8 (5)
Cambrian *L* in the NW in a geologically complex area continuing into Anhui. Includes the Mufu Shan Range. At Jiujiang is Sizhong Shan Cave.

JILIN (KIRIN) (JIL) 0.9 (2)
Cambrian *L* and dolomite on the N Korean border in the Chang Dai San Mountains, with a smaller area of dolomite in the hills around Jilin City.

LIAONING (LIA) 1.6 (6)
On peninsula of Dalian are low hills of Cambrian *L*. In the Qian Shan Range, *L* well developed E of Anshan and the low hills W of Jinzhou (Songling) in the W.

NINGXIA (NIN) 0.4 (2)
Small province with *L* in the N, W of Yinchuan, partly in the Helan Shan Range.

QINGHAI (QIN) 15.0 (8)
Extensive E-W outcrop of Triassic *L* and dolomite together with a large tongue of *L* extending N from the Tibetan plateau. The E-W trending outcrop runs through the high mountains of Bushan Shan (>6,000m alt) and also mountains S of the Qaidam Pendi. South of lake Qinghai Hu, *L* is extensive in the Qinghai Nanshan Range. The tongue of *L* extending from Tibet occurs in several ranges including those surrounding Zhidoi (c.34°N, 96°E) where much ground exceeds 4,000m alt.

1. **Da Qaidam Lake** 37.08N, 95.03E. Hot spring flows into lake with travertine dated to 24ka. Probably thermogene. Z1. Zheng *et al*., (1993) *ch, s.*

SHANDONG (SHD) 1.5 (7)
Archaean and Palaeozoic *L* scattered in the centre and S, including parts of the Tai Shan and Lu Shan ranges.

SHANGHAI
No L of note in small city province.

SHANGXI (SHA) 4.3 (21)
North of centre of the province and extending into Inner Mongolia is Cambrian and Ordovician *L* and dolomite developed in the Yunzhong Shan Range W of Taiyuan. In the E, bordering Hubei an area of Ordovician *L* and dolomite forming main range of the Taihang Shan, E of Taiyuan and Changzhi. Province also contains Archaean marbles.

1. **Women's Gate (Niangtzekuan), Nanweiquan County.** 36.42N, 113.22E. Largest known spring-deposited meteogene travertine in N China, yielding plant impressions and other fossils. Formerly quarried for stone. Powerful karst spring present. Dated to 6ka. Chang (1927) *s*; Barbour (1930) *s*; Waltham (1984) *s*; Chou Youyou (1988) *dp, do, penv, s*; Sweeting *et al.*, (1991) *s*.

SHAANXI (SHAA) 4.1 (10)
Several E-W trending outcrops in the S. Most southerly area forms part of the Micang Shan and Daba Shan Ranges. In the N Carboniferous and Devonian *L* occurs in the Qingling (Tsinling) Mountains, E and W of Ningshan and also in mountains E of Xi'an.

SICHUAN (SIC) 10.0 (20.4)
Limestone occurs in the N, S and W. In the S, bordering Yunnan, Permian *L* occurs SE of Leshan (c. 29°N, 104°E). North of the Daxianling, high mountains (3,000 to 4,000m.) contain much palaeozoic *L*. In the W, a large tongue of Permian *L* extends into Qinghai and runs down the entire W border constituting a large part of the Chola Shan and Shalui Shan Ranges, which exceed 5,000m in places. In the N, extending into Gansu is Triassic L of the Minshan Mountains.

1. **Dalugou, Jiuzhaigou County.** 33.00N, 104.19E. Large series of travertine dams. Z2. Guo Weixing (1988) s; Zhu Xuwen and Zhao Xulun (1990) *s*.
2. **Fairy Pool, Juizhaigou County**. 33.00N, 104.19E. Colourful series of dams and terracettes. Probably thermogene. Z2. Guo Weixing (1988) *s*; Zhu Xuewen and Zhou (1990) *s*.
3. **Garze**. 31.27N, 100.00E. Two sites near the Yalong Jian River. Z2. Lu and Li (1992).
4. **Huanglong National Park, Songpan County**. 32.32N, 103.20E. Series of dams and lakes along a 7km length of river. Some dams 200m wide and up to 20m high. 3,115 to 3,578m alt. Dated to 6ka. Cool thermogene springs (6°C) responsible. Z1. Guo Liang (1987) *ch, dp*; Chen *et al*., (1988) *dp*, is; Ford (1989) *s*; Xuewen and Zhou (1990) *s*; Lu and Li (1992); Liu Zaihua *et al*., (1993) *ch, dp, si*; Lu (1994); Liu Zaihua *et al*., (1995); Yuan (1997) *ch*; Liu Zaihua (1994); Lu *et al*., (2000).
5. **Jiulong, Jiulong County**. 28.49N, 101.29E. Travertine noted. Z4. Lu and Li (1992).
6. **Jiuzhaigou National Park, Juizhaigou County.** 33.00N, 103.54E. Series of 14 travertine-dammed lakes separated by spectacular waterfalls over distance of 20km. Lakes up to 4km long and 1km wide, 2,410 to 4,152m. alt. Pearl Shore dam 310m wide. Z1. Zhu Dehao (1986) *s*; Guo Liyang (1987) *dp*; Guo Weixing (1988) *cl, dp, s*; Zhu Xuewen *et al*., (1989) *ch, dp*; Zhu Xuewen and Zhou (1990)

*ch, cl, dp, si*; Zhang Jie (1993) *dp*; Ning Ning (1996) *s*; Zhang Jie *et al.*, (1997) *s*; Zhang Zhaohui and Pentecost (1999) *lb*; Pentecost and Zhang Zhaohui (2000) *la, lb*.

7. **Kalongguo, Heshui County.** 31.53N, 102.48E. Large deposit along the Kalong Valley. Z2. Guo Weixing (1988) *s*.
8. **Kangding.** 29.51N, 101.59E. Five travertines. Z4. Lu and Li (1992). Hot springs also occur in area.
9. **Munigou Park, Songpan County.** 32.26N, 103.30E. Large travertine cascade, Zhaga Falls descends through mountain woodland then braids to form the 'Water Forest'. Lower in the valley are many fossil travertine cascades, dams and lake deposits with smaller deposits of active travertine to Munigou Village. In the Erdaohai trench a thermogene site is indicated. Z2. Guo Weixing (1988) *s*; Zu Xuewen and Zhou (1990) *s*; Zhang Zhaohui and Pentecost (1999) *lb*; Pentecost and Zhang Zhaohui (2000) *la, lb*.

TAIWAN (TAI) 0.1 (8)

Two bands of *L* run parallel to long axis of island. In the E the Chungyang Shanmo Mountains includes Marble Cliffs, Turoko National Park. Scattered sites in lower mountains to the W. Many thermal springs.

TIANJIN

No noteworthy *L* in small city district.

XINGJIANG (XIN) 29.8 (6)

Large province with extensive *L* in S and W. In S two outcrops of Cambrian *L* extend from the high mountains S of Yutian to the Arkatag Mountains. 500km to the E, mostly in the Kunglung Range at the N edge of Tibetan plateau at 5,000m. Farther W bordering Kashmir and Tadzhikistan *L* exposed in the Karakoram Range S of Kangxui. Farther N they form an arc in the high mountains S of Kashi (5,000 to 7,000m). North of Kashi outcrops are extensive in S part of the Tien Shan Range, mostly >2,000m. Yet farther N, a long WNW-ESE outcrop extends through mountains N of Yining for 500km to mountains N of Bosten Hu, with additional exposures in the Bohoro Shan.

1. **Ruoqiang, Ruoqiang County**. 37.13N, 88.32E. Plio-Pleistocene spring deposits associated with rich fossil flora. Guo Shuang-xing and Gu (1993) *fp, penv, s*.
2. **Yang Chhuan.** Petrifying springs recorded from the N Tien Shan Mountains in the 6th Century AD. Needham (1954).

XIZHANG (XIZ) 46.3 (9)

Largest area of *L* in China, mostly at high altitudes where travertines rarely develop. Several huge elongate outcrops of Cambrian L in E bordering Sichuan. *L* occurs in the Ninjin Shan and the Taniantaweng Shan farther W. Mostly >5,000m alt. *L* also in high mountains E of Bowo. In the region bordering Nepal and Bhutan extensive *L* >5,000m make up much of the Tibetan Himalaya, including Qomolangma Feng (Everest). Also large areas S of Lhasa bordering Puma Yumco and Daryan (both 4,000 to 5,000m.). In south-central Xizhang several large irregular outcrops between Zhongba and Quntang and to the N of Cogen (all c.5,000m alt). Some *L* in the extreme W bordering the Karakoram Mountains, W of Rufog (4,000 to 5,000m).

1. **Amdo, Amdo County.** 32.22N, 91.07E. Warm spring deposits algal travertine over 1km$^2$ up to 50m in thickness in the Sanqu River Valley, dated 5 to 6ka. Probable thermogene. Z1. Zhe Yongtai and You (1985) *s*; Sweeting *et al.*, (1991) *ch,s*.
2. **Bangon Lake, Ritu County.** 33.36N, 79.42E. Large deposits associated with springs. Z1. Yang Hankui *et al.*, (1991) *s*.
3. **Ciangmuzho, Geichi County.** 32.24N, 84.10E. Thick deposits associated with hot springs near Marmi. Probably thermogene. Z1. Yang Hankui *et al.*, (1986) *s*.
4. **Denri County.** 28.36N, 87.08E. Small deposits reported. Z1. Zhe Yongtai and You (1985) *s*.
5. **Dingri** (Tingri) 28.43N, 87.08E. Travertines up to 4,300m alt, dated to 100ka by U/Th. Mean annual air temperature 1°C. Sweeting *et al.*, (1991) *du, s.*; Zhang Dian (1997) *s*
6. **Gu Deixiang, Zoumei County.** 28.26N, 91.26E. Large spring mounds to 25m in height reported with travertine 'sticks' (steep mounds?) 2 to 5m high. Altitude 4,500m. Probably thermogene. Z1. Zhu Dehao (1992) *s*.
7. **Lhasa River, Lhasa.** 29.41N, 91.19E. Some deposition along upper Lhasa River at 4,400m alt. Z1. Zen *et al.*, (1983) *s*.
8. **Marl District, Gegi County.** 32.24N, 81.07E. Spring deposit of travertine 'sticks' (cones?) averaging 2 to 3m high, largest measuring over 7m high and 0.5-1m in diameter. Probably thermogene. Z1. Zhu Dehao (1992) *s*.
9. **Nawantai** (not located). Spectacular dams reported. Yang Hankui *et al.*, (1986, 1991) *s*.
10. Nilong 29.08N, 87.29E. Inactive travertine-cemented colluvium at high altitude figured by Waltham (1996).
11. **Nong Erdizheng, Nima County.** 31.48N, 88.09E. Hot spring deposits associated with mosses at 4,850m alt. Probably thermogene. Z1. Li Xingjang (1996) *lb*.
12. Parochi 28.33N, 86.40E. Laminated deposits on valley floor at 4,300m alt. dated to 100ka. Probably thermogene. Z1. Sweeting *et al.*, (1991) *s*.
13. **Quesang Springs, Quesang Village.** 29.09N, 87.30 E. Hot spring at 48 to 50°C and 4,200m alt. depositing large area of thermogene travertine. Zhang Dian (1997) *ch, s, hyd*.
14. **Small Bantachirandue, Mankan County.** 29.41N, 98.36E. Large deposits in front of limestone cave at 3,800 to 4,000m alt. Yang Yishou *et al.*, (1983) *s*.
15. **Terthapuri** 31.07N, 80.45E. A hot spring deposits travertine. Z4. Waring (1965) *s*.
16. **Yiali Village, Linam County.** 28.09N, 86.01E. Deposits 2 to 4km$^2$ in extent below springs at c.4,300m alt, dated to 7ka. Z1. Zen *et al.*, (1983) *a, penv, s*; Zhe Yongtai and You (1985) *s*; Yang Hankui *et al.*, (1986) *s*.
17. **Zabuye Lake** 31.21N, 84.04E Numerous travertine-built islands and cones in the northern section of saline lake dated to c.8.5ka. Alt. 4,421m. Thermogene, water rich in rare elements. Zheng and Xian (1989) *ch, do, hyd*; Zheng *et al.*, (1993) *ch*.
18. Zhuguo Temple, Changdu County. 31.07N, 97.11E. Large deposit at 4,300m alt. Yang Yishou *et al.*, (1983) *s*.

YUNNAN (YUN) 19.8 (26)

Mountainous province includes W edge of the Guizhou limestone plateau containing several thousand metres of carbonates. Well developed karsts to the S and E of Kunming and N of Dongchuan. Also several large N-S outcrops in the centre, S and W. In the south, *L* occurs in mountains E of Yunjinghong and E of Mangshi, with large cave at Yaogan. In the N, the southern tip of a great arm of *L* extends into Qinghai and occurs around Paishoutou, in high mountains of Hengduan and in the Mian Mian Shan range. Region contains numerous thermal springs.

1. **Beishutai (Paishutai), Zhongden County** 27.46N, 99.45E. Largest site in province near Chungtien, with a series of dams depositing over 1km2 at 3,000m alt. Probably thermogene. Z4. Weijermars *et al.*, (1986) *s*; Zhu Dehao (1992) *s*.
2. **Dadishui Waterfall, Yiliang County.** 24.20N, 103.18E. Large cascade with cave on Baline River, 54m wide and 86m high. Nearby inactive cascade 200m wide and 90m high. Z4. Yang Hankui *et al.*, (1986) *s*.
3. **Dashu Dragon Lake, Mile County.** 24.10N, 103.25E. Large spring deposits reported. Z6. Yang Hankui *et al.*, (1986) *s*.
4. **Hot Sea, Tengchong.** 24.52N, 98.18E. Extensive thermal springs with calcite travertine and other hydrothermal minerals, includes Black Mud Pool (large terrace), Stone Wall Bath (mound), associated with deep faults and previous vulcanism. Thermogene. Z6. Meixiang and Wei (1987) *s*.
5. **Hot Spring, Yiliang County.** 24.41N, 103.07 E. Springs rise at 40°C and deposit much travertine. Z6. Yang Hankui *et al.*, (1986) *s*.
6. **Sadi-Paozi, Lunan County.** 24.35N, 103.13E. Old cascades and

dams 4m in thickness with fossil Mollusca and plants. Yang Hankui *et al.*, (1986) *s*.

7. **Stone Forest, Lunan County**. 24.38N, 103.19E. Small site dated to 17.5ka. Yang Hankui *et al.*, (1986) *du, s*.
8. **Xiaodishui Waterfall, Yinniang County.** 24.39N, 103.17E. Cascade near Dadishui, 60m wide and 20m high. Nearby inactive cascade 200m wide and 60m high. Z7. Yang Hankui *et al.*, (1986) *s*.
9. **Yuanmao, Yuanmao County.** 25.31N, 101.50E. Series of lake crusts and dams, dated to 150 to 310ka. Ceifang *et al.*, in Yang Hankui *et al.*, (1986) *du, s*.
10. **Yulongxue Mountain, Lijing County.** 26.55N, 100.16E. Travertine colonised by algae and bryophytes in mountain seepages. Z2. Zhang Zhaohui (unpublished).

ZHEJIANG (ZHE) 0.9 (4)

Silurian L in the W, Xianxia Ling Mountains and Yaolin Cave, SW of Hangzhou is in the Tianmu Shan.

## ACKNOWLEDGEMENTS

We are grateful to the National Natural Science Foundation of China (NSFC), and the Natural Science and Technology Foundation of Guizhou (NSTFG). Royal Society Exchange Fellowships were awarded to both authors during the preparation of this review (1999), and a Royal Society BP Amoco Research Fellowship was awarded to the junior author during 1999-2000.

## REFERENCES

An Guanyi, Wang G X, 1989. A moss associated with tufa deposition. *Plants*, Vol.5, 41.

An Yuigo, Li Z, He F, 1993. Preliminary research of formation characteristics of speleothems in Zhijing Cave. *Proceedings of the XI International Conference of Speleology*, Beijing, 144-155.

Anon, 1990. *The Conservation Atlas of China*. [Beijing: Science Press.]

Arp, G, Hoffmann, J and Reitner, J, 1998. Microbial fabric formation in spring mounds ("microbialites") of alkaline salt lakes in the Badain Jaran Sand Sea, China. *Palaios*, Vol.13, 581-592.

Barbour, G B, 1930. The origin of the Niangtzekuan tufa. *Bulletin of the Geological Society of China*, Vol.9, 213-220.

Braithwaite, C J R, 1979. Textures of recent fluvial pisolites and laminated crystalline crusts in Dyfed. *Journal of Sedimentary Petrology*, Vol.49, 181-193.

Chang, H T, 1927. *Lapidarium Sinicum. A study of the rocks, fossils and metals as known in Chinese literature*. [Peking: Geological Survey of China.] Edition 2.

Chen, X, Zhu, X and Zhou, X, 1988. A study of isotopes of karst water and travertine deposits at the Huanglong scenic spot. *Carsalogica Sinica*, Vol.7, 209-212.

Chou, Y, 1987. *Formation of Tufa in the Juizhaigou District, Western Sichuan*. Unpublished MSc thesis, Department of Geography, University of Nanjing.

Chou, Y, 1988. *Formation of tufa and palaeoenvironmental significance of Women's Gate*. Unpublished PhD Thesis. Department of Geology, University of Nanjing.

Clark, I D and Fontes, J-C, 1990. Paleoclimate reconstruction in Northern Oman based on carbonates from hyperalkaline groundwaters. *Quaternary Research*, Vol.33, 3209-336.

Dreybrodt, W, Buhmann, D, Michaelis, J and Usdowski, E, 1992. Geochemically controlled calcite precipitation by $CO^2$ outgassing : field measurements of precipitation rates to theoretical predictions. Chemical Geology, Vol.97, 285-294.

Durrenfeldt, A, 1978. Untersuchungen zur Besiedlungsbiologie von Kalktuff faunistosche, ökologische und elektronenmikroskopische Befunde. *Archive für Hydrobiologie, Supplemente*, Vol.54, 1-79.

Edmunds, W M, Taylor, B J and Downing, R A, 1968. Mineral and thermal waters of the United Kingdom. 23rd *International Geological Congress*, Vol.18, 139-158.

Ford, T D, 1989. Tufa – the whole dam story. *Cave Science*, Vol.16, 39-49.

Ford, T D and Pedley, H M, 1992. Tufa deposits of the world. *International Speleological Society of Japan*, Vol.17, 46-63.

Golubic, S, 1967. *Algenvegetation der Felsen*. In: Elster, H J and Ohle, W (eds) *Die Binnengewasser*, Vol.23. E. Schweizerbart'sche Verlagsbuchhandlung, Stuttgart.

Goudie, A S, Viles, H A and Pentecost, A. 1993. The late-Holocene tufa decline in Europe. *The Holocene*, Vol.3, 181-186.

Guo Shuang-xing and Gu, C, 1993. Fossil plants from calcareous tufa and palaeoenvironments in Ruoqiang, Xinjiang. *Acta Palaeontologica Sinica*, Vol.32, 84-87.

Guo Weixing, 1988. Formation and development of travertine in natural scenic, NW Sichuan. *Mountain Research*, Vol.6, 54-59.

He Fusheng, An, Y and Li, Z, 1993. Blue-green algae and primary lithogenesis Zhijing Cave, Guizhou. Proceedings of the XI *International Conference of Speleology*. Beijing, 116-117.

Herman, J S and Lorah, M M, 1987. $CO_2$ outgassing and calcite precipitation in Falling Spring Creek, Virginia, U.S.A. *Chemical Geology*, Vol.62, 251-262.

Irion, G and Müller, G, 1968. Mineralogy, petrology and chemical composition of some calcareous tufa from the Schwabische Alb, Germany. 157-171 in Mueller, G and Friedman, G M (eds) *Carbonate Sedimentology in Central Europe*.[New York: Springer.]

Julia, R, 1983. Travertines. 64-72 in: Scholle, P A, Bebout, D G and Moore, C H (eds) *Carbonate depositional environments. Association of American Petroleum Geologists Memoir*, 33. [Tulsa, Oklahoma.]

Keary, P and Wei, H, 1993. Geothermal fields of China. *Journal of Volcanology and Geothermal Research*, Vol.56, 415-428.

Kerney, M P, Preece, R C and Turner, C, 1980. Molluscan and plant biostratigraphy of some Late Devensian and Flandrian deposits in Kent. *Philosophical Transactions of the Royal Society of London. B.*, Vol.291, 1-43.

Li Bin, Yuan, D, Lauritze, S-E, Qin, J and Lin, Y, 1998. The Younger Dryas event and Holocene climate fluctuations recorded in a stalagmite from the Panlong Cave of Guilin. *Acta Geologica Sinica*, Vol.72, 455-465.

Li Daton and Luo, Y, 1983. Measurement of carbonate rocks distribution area in China. *Carsalogica Sinica*, Vol.2, 147-150.

Li Xinjiang, 1996. *Bryoflora of Xizhang*. [Beijing: Science Press.]

Liu Ming-Gan, 1998. *The Chinese Geographical Atlas*. [Beijing.]

Liu Zaihua, Yuan, D, Dreybrodt, W and Svensson, U, 1993. The formation of tufa in Huanglong, Sichuan. *Carsalogica Sinica*, Vol.12, 185-191.

Liu Zaihua, Svensson, U, Dreybrodt, W, Yuan, D and Buhmann, D, 1995. Hydrodynamic control of inorganic calcite precipitation in Huanglong Ravine, China : Field measurements and theoretical prediction of deposition rates. *Geochimica et Cosmochimica Acta*, Vol.59, 3087-3097.

Lu, G, 1994. Hydrochemical research of cold-water travertine in Huanglong-Jiuzhai scenic spots, Sichuan Province. *Journal of Mineralogy and Petrology (China)*, Vol.14, 71-78.

Lu, G and Li, X, 1992. A study on cold-water travertine surface depositional landforms in Huanglong Scenic Spot, Sichuan Province. *Journal of Chengdu College of Geology*, Vol.19, 55-64.

Lu, G, Zheng, C, Donahoe, R J and Berry Lyons, W, 2000. Controlling processes in a $CaCO_3$ precipitating stream in Huanglong Natural Scenic District, Sichuan, China. *Journal of Hydrology*, Vol.230, 34-54.

Meixiang, Z and Wei, T, 1987. Surface hydrothermal minerals and their distribution in the Tengchong geothermal area, China. *Geothermics*, Vol.16, 181-195.

Mo Zhongda, 1984. A preliminary study on Guizhou karst waterfalls. Tropical Landforms, China, Vol.5, 20-30.

Needham, J, 1954. *Science and Civilization in China*. Vol.3. [Cambridge: Cambridge University Press.]

Pedley, H M, 1990. Classification and environmental models of cool freshwater tufas. *Sedimentary Geology*, Vol.68, 143-154.

Pentecost, A, 1985. Association of cyanobacteria with tufa deposits : identity, enumeration, and nature of the sheath material revealed by histochemistry. *Geomicrobiology Journal*, Vol.4, 285-298.

Pentecost, A, 1992. Carbonate chemistry of surface waters in a temperate karst region: the southern Yorkshire Dales, UK. *Journal of Hydrology*, Vol.139, 211-232.

Pentecost, A, 1995. The Quaternary travertine deposits of Europe and Asia Minor. *Quaternary Science Reviews*, Vol.14, 1005-1028.

Pentecost, A, 1998. The significance of calcite (travertine) formation by algae in a moss-dominated travertine from Matlock Bath, England. *Archives of Hydrobiology*, Vol.143, 487-509.

Pentecost, A and Viles, H A, 1994. A review and reassessment of travertine classification. *Geographie Physique et Quaternaire*, Vol.48, 305-314.

Pentecost, A and Zhang Zhaohui, 2000. The travertine flora of Juizhaigou and Munigou, China and its relationship with calcium carbonate deposition. *Cave and Karst Science*, Vol.27(2), 71-78.

Pentecost, A and Zhang Zhaohui, 2001. A note on freshwater research in China with some observations on the algae from Doupe Pool, Guizhou Province. *Freshwater Forum* (in press).

Preece, R C and Day, S P, 1984. Comparison of Post-glacial molluscan and vegetational succession from a radiocarbon-dated tufa sequence in Oxfordshire. *Journal of Biogeography*, Vol.21, 463-478.

Qin, X, Liu, D, Tan, M, and others, 1998. Grey characteristics of microbanding in Shihua Cave, Beijing and its climatic signification (I). *Science in China, Series D*, Vol.41, 151-157.

Qiu, Y, 1984. Cave deposits and its diagenesis in Xiniu Cave, Zhennin, Guizhou Province. *Carsalogica Sinica*, Vol.3, 55-63.

Rong Kunfang, Li, J, An, Y and He, F, 1996. A study of biogenesis of karst speleothem: an example from Zhijin Cave of Guizhou. *Guizhou Geology*, Vol.13, 177-180.

Spiro, B and Pentecost, A, 1991. One day in the life of a stream – a diurnal inorganic carbon mass balance for a travertine-depositing stream (Waterfall Beck, Yorkshire). *Geomicrobiology Journal*, Vol.9, 1-11.

Sweet, P C and Hubbard, D A, 1990. Economic legacy and distribution of Virginia's Valley and Ridge Province of travertine-marl deposits. 129-138 in Herman, J S and Hubbard, D A (eds) Travertine-marl : Stream deposits in Virginia. *Virginia Division of Mineral Resources*. Vol. 101. [Charlottesville, Virginia.]

Sweeting ,M M, Bao, F S and Zhang, D, 1991. The problem of palaeokarst in Tibet. *Geographical Journal*, Vol.157, 316-325.

Tan, M, Liu, D, Zhong, H, Qin, X, Li, H, Zhao, S, Li, T, Lu, J and Lu, X, 1998a. Preliminary study on climatic signals of stable isotopes from Holocene speleothems under monsoon condition. *Chinese Science Bulletin*, Vol.43, 506-509.

Tan, M, Liu, T, Qin, X and Wang, X, 1998b. Signification chrono-climatique de speleothemes laminés de Chine du Nord. *Karstalogia*, No.32, 1-6.

Tan, M, Pan, G, Wang, X, Qin, X, Teng, Y, Song, L and Lin, Y, 1999a. Stalagmites and environment – preliminary study on the formation of laminated stalagmites. *Carsalogica Sinica*, Vol.18, 197-205.

Tan, M, Qin, X, Shen, L, Wang, X, Wang, Y, Li,,T, Song, L, Wang, L and Liu, D, 1999b. Bioptical microcycles of laminated speleothems from China and their chronological significance. *Chinese Science Bulletin*, Vol.44, 1604-1607.

Tian, Y and He, F, 1996. A preliminary study on microcommunity ecology of karst cyanophyta in mat from Fengdong Cave, Panxian, Guizhou. *Carsalogica Sinica*, Vol.15, 233-238.

Tian, Y and He, F, 1997. Research on waterfall calcareous tufa mats from Xiangzhigou, Guizhou. *Carsalogica Sinica*, Vol.16, 145-154.

Tian, Y and He, F, 1998. A study on biogenetic of calcareous tufa – exemplified by the tufa in Jiuzhaigou, Sichuan and Huangguoshu, Guizhou. *Carsalogica Sinica*, Vol.17, 49-55.

Troester, J W and White, W B, 1986. Geochemical investigations of three tropical karst drainage basins in Puerto Rico. *Groundwater*, Vol.24, 475-482.

Waltham, A C, 1984. Some features of karst geomorphology in South China. *Cave Science*, Vol.11, 185-198.

Waltham, A C, 1996. Limestone karst morphology in the Himalayas of Nepal and Tibet. *Zeitschrift für Geomorphologie* N. S., Vol.40, 1-22.

Wang Fuxing, Cao, J, Huang, J, Jiang, L, Huang Jifu and Wang, J, 1993. *Biokarst*. [Beijing: Geological Publishing House.] 121pp.

Wang Xunyi, 1985. Some characteristics of stable isotopes of oxygen and carbon in speleothems of Guilin. *Carsalogica Sinica*, Vol.3, 149-154.

Wang Xunyi, 1986. U-dating and _18O, _13C features of speleothems in Maomaotou Big Cave, Guilin. *Kexue Tongbau*, Vol.31, 835-838.

Waring, G A, 1965. Thermal springs of the United States and other countries of the world, a summary. United States *Geological Survey Professional Paper* No. 492. 383pp.

Wei, K and Lin, R, 1994. An enquiry into paleoclimatic information from oxygen isotopic profile of Dunde ice core in Qinlianshan. *Geochemistry*, Vol.23, 311-320.

Weijermars, R, Mulder-Blanken, C W and Wiegers, J, 1986. Growth rate observation from the moss-built Checa travertine terrace, central Spain. *Geological Magazine*, Vol.123, 279-286.

Winsborough, B M and Golubic, S, 1987. The role of diatoms in stromatolite growth : two examples from modern freshwater settings. *Journal of Phycology*, Vol.23, 195-201.

Yang Hankui, Zhu, W X and Huang, R H, 1984. The feature of karst waterfalls in Yunnan-Guizhou Plateau of China. *Carsalogica Sinica*, Vol.2, 89-96.

Yang Hankui, Zhu, W X and Huang, R, 1985. Research on travertine formation in the rivers of Guizhou. 39-47 in *Karst Landforms and Caves*. [Beijing: Science Press.]

Yang Hankui, Huang, R H and Zhu, W X, 1986. Tufa deposition facies and types. *Geology of Guizhou*, Vol.6, 47-56.

Yang Hankui, Huang, R H, Zhu, W X and Li P, 1991. Model of environmental facies of continental CaCO3. *Marine Geology and Continental Geology*, Vol.11, 106-113.

Yang Yishou, Li, P H, Zhang, J S, Wang, H P, Jen, C and Chen, Z M, 1983. *Geomorphology of Xizhang*, [Beijing: Science Press.]

Yokoyama, T, Nakai, S and Wakita, H, 1999. Helium and carbon isotopic compositions of hot spring gases in the Tibetan Plateau. *Journal of Volcanology and Geothermal Research*, Vol.88, 99-107.

Yuan, D, 1997. Sensitivity of karst process to environmental change along the PEP II transect. *Quaternary International*, Vol.37, 105-113.

Zen, M, Liu, Z, Wang, F, Xi, J, Liu, Z and Pan, R, 1983. *Introduction to Karst*. [Beijing: Commercial Press.]

Zhang Dian, 1995. Geology, palaeohydrology and evolution of caves in Tibet. *Cave and Karst Science*, Vol.21, 111-114.

Zhang Dian, 1997a. Contemporary karst solution processes on the Tibetan Plateau. *Mountain Research and Development*, Vol.17, 135-144.

Zhang Dian, 1997b. An interpretation of some observations on karst spring regimes and their implication for the underground drainage systems of the Lhasa area, Tibet. *Asian Geographer*, Vol.16, 59-71.

Zhang Dian, 2001. Physical mechanisms of river waterfall tufa (travertine) formation. *Journal of Sedimentary Research*, Vol.71, 205-216.

Zhang Jie, 1993. On bio-effects on the development of karst dammed lakes in limestone areas, Minshan Mountain Range, NW Sichuan. *Journal of Lake Sciences*, Vol.5, 34-39.

Zhang Jie, Nie, X and Li, S, 1997. Significance of karst research to local tourism in Jiuzhaigou conservation. *Carsalogica Sinica*, Vol.16, 386-392.

Zhang Qing-Song, Tao, J, Huang, C and Gu, C, 1990. A discovery of late Cenozoic fossil plants in Kunlun Mountains. *Chinese Science Bulletin*, Vol.35, 1204-1208.

Zhang Yinjun, Chen X, Zhu A. 1994. The experimental study on tufa deposition. *Carsalogica Sinica*, Vol. 13, 197-205.

Zhang Yinjung and Mo, Z, 1982. The origin and evolution of Orange Fall. *Acta Geographica*, Vol.37, 303-316.

Zhang Zhaohui, 1993a. Ecological study on the mosses of the Maolan Karst Forest Area. 90-101 in Zhu Shouqian (ed.) *Ecology Research on Karst Forests*. Vol.1.

Zhang Zhaohui, 1993b. A catalogue of Musci in Maolan karst forest area, Lipo County, Guizhou. *Journal of Guizhou Normal University*, Vol.11, 33-42.

Zhang Zhaohui, 1996. Contributions to the bryoflora of Guizhou, S.W. China: new records and habitat notes on mosses from Huangguoshu karst area. *Journal of Bryology*, Vol.19, 149-152.

Zhang Zhaohui, Wang, Z and Zhu, A, 1996. A preliminary study on bryokarst of caves in Huangguoshu area. *Carsalogica Sinica*, Vol.15, 224-232.

Zhang Zhaohui, 1997a. A catalogue of bryophytes in the Huangguoshu Karst Area. *Journal of Giuzhou Normal University*, Vol.15, 23-24.

Zhang Zhaohui, 1997b. Bryoflora of some speleothems of karst caves in Guizhou, SW China. Proceedings of the 12th *International Congress on Speleology*. Vol.3. La Chaux-de-Fonds, Switzerland : 297-300.

Zhang Zhaohui, Wang, Z, Ran, J and Ling, H, 1997a. A preliminary survey of the bryophytes from Three Black Monkeys Nature Reserve in Guizhou and Guangxi Province, SW China. *Guihaia*, Vol.17, 331-337.

Zhang Zhaohui, Wang, C and Wang, Z, 1997b. Survey of bryophytes in Mt. Yuntai Karst Forest Area, Shibing County. *Guizhou Sciences*, Vol.15, 70-76.

Zhang Zhaohui, 1998. A preliminary taxonomical study on tufa-bryophytes in Guizhou, SW China. *Chenia*, Vol.5, 173-176.

Zhang Zhaohui and Pentecost, A, 2000. New and noteworthy bryophytes from travertine in Guizhou and Sichuan, S. W. China. *Journal of Bryology* (in press).

Zhe, Y and Yu, J, 1985. . [Beijing: Science Press.]

Zheng, M and Xian, J, 1989. *Saline lakes on the Qinghai-Xizang (Tibet) plateau*. [Beijing: Beijing Scientific and Technical Publishing House.]

Zheng, M, Tang, J and Zhang, F, 1993. Chinese saline lakes. *Hydrobiologia*, Vol.267, 23-36.

Zhu An, 1988. *A study of the formation of tufa in rivers*. Unpublished MSc. thesis, Department of Geography, Guizhou Normal University.

Zhu An 1994a. The study of aeration effect on mechanism of fluvial tufa deposition. *Journal of the Guizhou Normal University*, Vol.12, 35-39.

Zhu An 1994b. A special tufa fabric-stratified-algae-support fabric and cause of its formation. *Guizhou Sciences*, Vol.12, 35-39.

Zhu An and Zhu Gang. 1994. Study of scale formation on the surface of hydroelectric installations in a karst region. *Carsalogica Sinica*, Vol.13, 213-216.

Zhu Dehao, 1986. Juizhaigou ravine scenic spot and Plitvice Lake Park. *Exploration of Nature (China)*, Vol.16, 113-118.

Zhu Dehao, 1992. China karst tourism resources and their position in the world. *Carsalogica Sinica*, Vol.11, 332-339.

Zhu Xuewen and Zhou, X, 1990. Deposition of travertines in karst area of Minshan Mt. *Carsologica Sinica*, Vol.9, 250-264.

Zhu Xuewen, Zhang, R and Zhou, X, 1989. Basic characteristics of karst in Minshan Mt., West Sichuan. *Carsalogica Sinica*, Vol.8, 253-260.

CAVE KARST SCIENCE Vol. 28, No.1 April 2001
Transactions of the British Cave Research Association



ISSN 1336-191X

# The sediments of Illusion Pot, Kingsdale, UK: Evidence for sub-glacial utilisation of a karst conduit in the Yorkshire Dales?

**Phillip J MURPHY [1], Robert SMALLSHIRE[2] and Christine MIDGLEY [3]**

[1] The School of Earth Sciences, University of Leeds, LS2 9JT, UK.

[2] Midland Valley Exploration, Glasgow, G3 6AX, UK.

[3] The School of Geography, University of Leeds, LS2 9JT, UK.

**Abstract:** Analysis of the sedimentary fill preserved within the Illusion Pot section of the Dale Barn Cave system indicates that the sediments were derived from the Chapel-le-Dale end of the cave. The sedimentary sequence exposed in the conduit is very similar to those described from sub-glacial eskers, and a possible hydrological connection with the sub-glacial drainage system of the Chapel-le-Dale glacier is proposed. Scalloping superimposed upon speleothems in relict conduits within the system confirms that a second phreatic episode occurred during the cave's development. Speleothem uranium series dates constrain the second phreatic episode to post-date 343,400 BP (+86.0/-47.7ka).

*(Received 25 March 1998; Accepted 21 June 2001)*

## INTRODUCTION

Dale Barn Cave is a remarkable linear cave system orientated approximately southeast-northwest below Scales Moor, passing beneath the southwesterly nose of Whernside from Chapel-le-Dale to Kingsdale (Figs 1 and 2). An account of karst features of the area and of the cave's setting is given by Waltham *et al.* (1997). The cave was explored from Chapel-le-Dale (Crossland, 1975a, 1975b). However, due to the arduous nature of the caving required to reach the far end of the system a new entrance (Illusion Pot) was engineered on the southern side of Kingsdale. As well as facilitating further exploration in the cave, the opening of the new entrance has enabled the study of relatively undisturbed sediments in otherwise highly remote cave passages.

Currently, active cave passages carry streamways from both the Chapel-le-Dale and Kingsdale ends of the cave to a confluence almost directly beneath the topographic divide, before draining to the resurgence of Dry Gill Cave in Chapel-le-Dale. Above the active levels lie a series of abandoned passages. Sediments contained in the northwestern end of the relict high level passages (named Vandals Passage by the original explorers but referred to as the Expressway by Brook *et al.*, 1994) are the main topic of this paper.

Vandals Passage is oriented southeast-northwest and is up to 15m in diameter (Fig.3). It is aligned along a minor sub-vertical fault showing calcite mineralisation, and it terminates to the northwest in a calcite

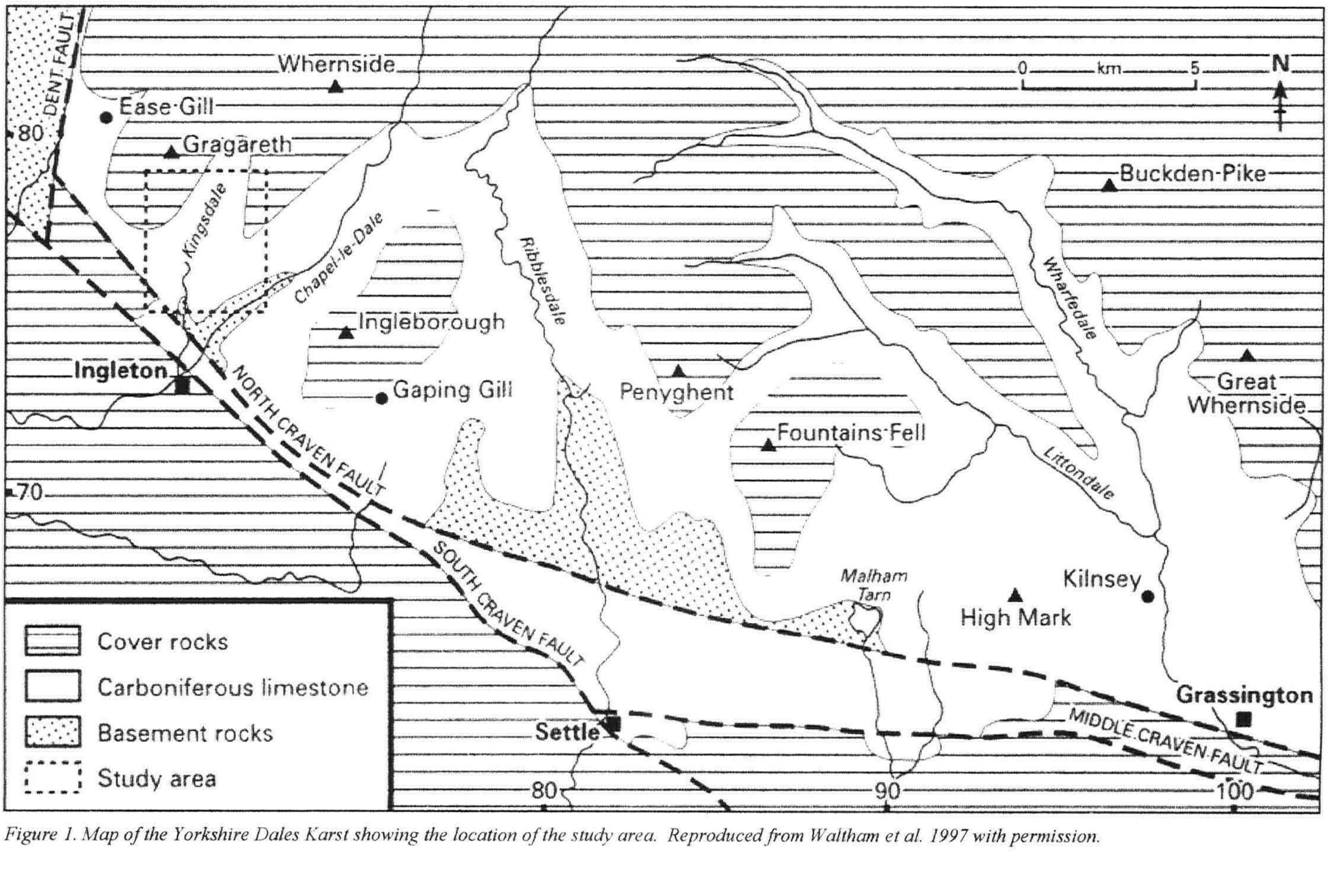



*Figure 1. Map of the Yorkshire Dales Karst showing the location of the study area. Reproduced from Waltham et al. 1997 with permission.*

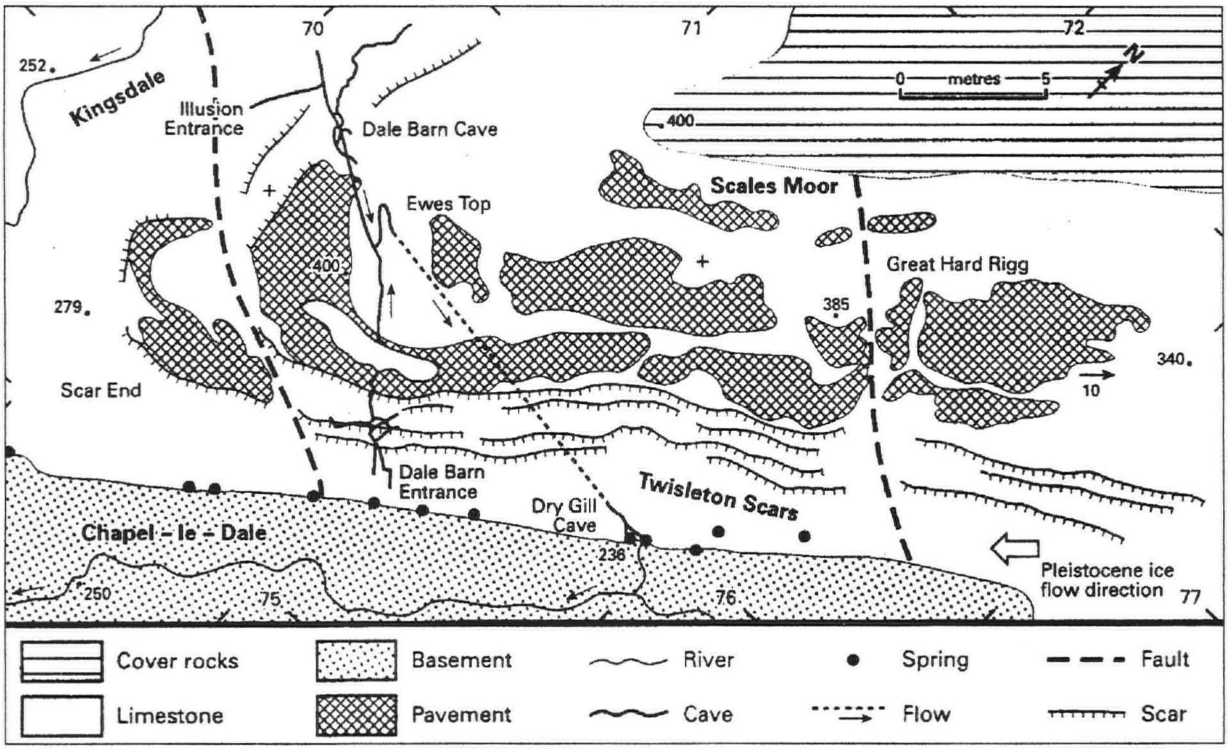



*Figure 2. Geological map of Scales Moor. Reproduced from Waltham et al. 1997 with permission.*

blockage beneath the southern flank of Kingsdale, where radio-location data indicate a depth of only 6m beneath the surface. To the southeast the passage terminates in the block collapse of Rushton Chamber. Relict high-level development can be followed across Rushton Chamber in a low crawl named Perfidia, which is believed to be in the top of the almost totally filled 15m-diameter passage. These relict high-level passages have counterpart relict levels in the Dale Barn Cave end of the system in Chapel-le-Dale. The Illusion Pot entrance enters Vandals Passage from the southeast by a more modest 2 to 3m-diameter passage.

*Plate 1. Scalloped speleothem on the upper southwest wall of Vandals Passage*

## SCALLOPED SPELEOTHEMS

Large speleothems with superimposed phreatic scalloping (signifying a northwesterly flow direction) occur in the roof of Vandals Passage (Plate 1). This indicates that the initially water-filled high-level passages in the Dale Barn Cave were drained, allowing the growth of extensive speleothem deposits prior to resumption of flooded conditions during the second phreatic episode in the cave's history. It appears clear that the overall dimensions of the conduit suffered relatively little enlargement by the waters that were responsible for the scalloping.

## THE SEDIMENTS

The sediment fill of Vandals Passage is on an impressive scale, locally filling the passage almost to the roof. A number of sections through the fill are exposed, and the relatively unvisited state of the cave means that much of the fine detail of the undisturbed sediments can clearly be seen.

Where the sediments form the floor of the accessible passage, a cobble and boulder layer masks the deposits, probably indicating post-depositional removal of much of the original finer-grained material. Evidence of sediment slumping, and the occurrence of erosional remnants of sediment high on the cave walls, indicate that partial removal of the sediments has occurred. Areas of sediment removal and collapse correspond with the positions of avens and sites where large drips of water enter from the roof of the passage. The roof of Perfidia is remarkably uniform; no avens allow water to enter the passage to erode the sediments, so there is very little vertical exposure of the deposits.

In Vandals Passage a slump has led to exposure of a clear 4m-high section of sediment across the passage (Fig.3 point 'A'). The succession revealed consists of alternating units of diamicton and sand and gravel, with very sharp and locally undulatory unit boundaries (Plate 2 and Fig.4). The sand and gravel units are generally well-sorted (Fig.5) and show either cross-bedding or no internal sedimentary structures. Sporadic units of pale grey laminated clay are laterally less extensive than the other units. Lithological analysis of the sediments reveals that they comprise roughly equal proportions of material derived from limestone and from sandstone. However, they also contain up to 10% of chloritised slate and mudstone debris.

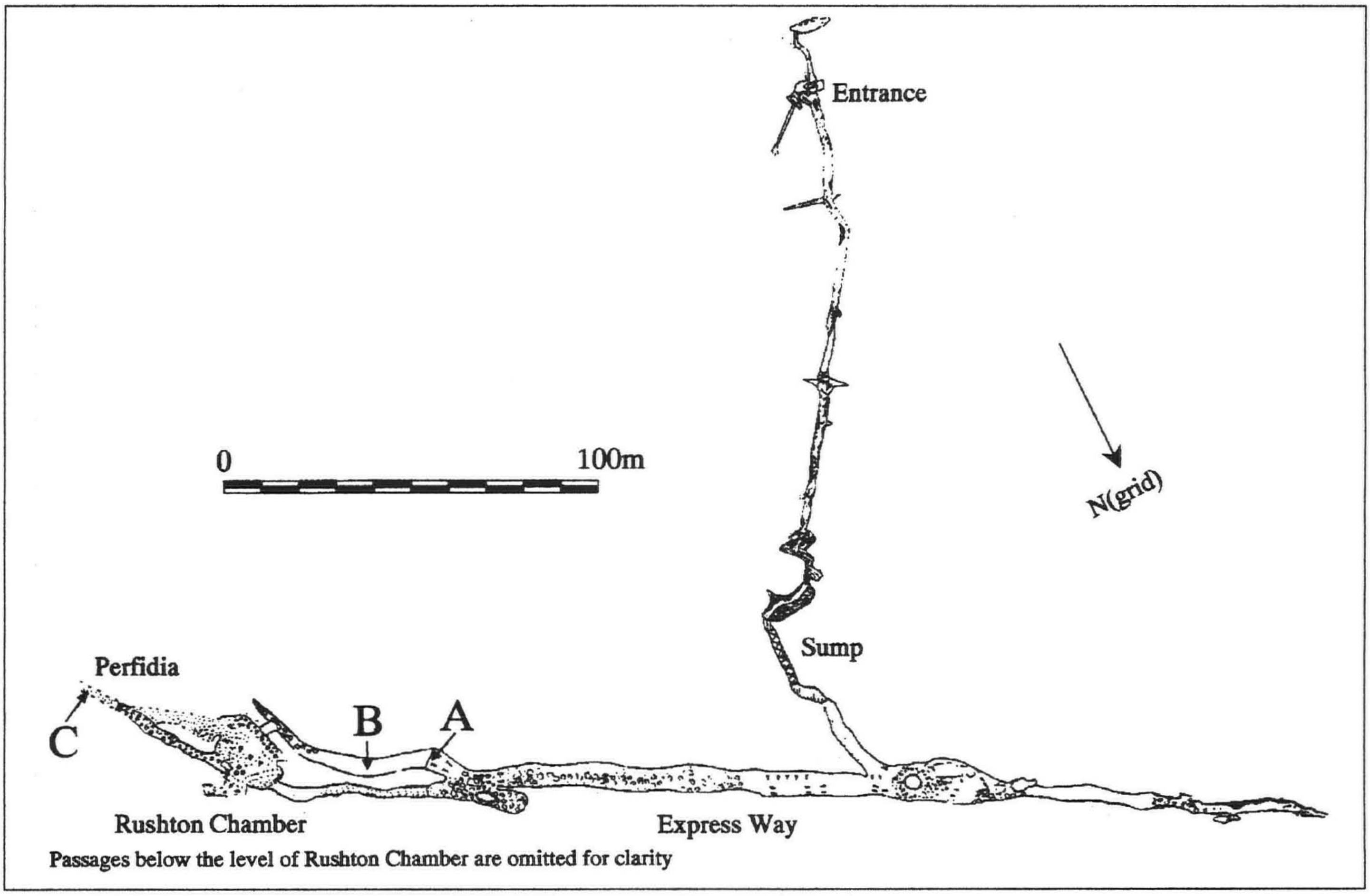



*Figure 3. Illusion Pot Series, Dale Barn Cave. Reproduced from the Northern Cave Club Survey. (BCRA grade 5e) by permission.*

Overlying the vertical exposure are several large dune forms up to 1.5m high and 8m long (Fig.3 point 'B'). These consist of sand and gravel, and show clearly-defined internal structures. The dune foresets dip towards the northwest. A dissected remnant of such a dune form is exposed on the northeastern wall of Perfidia (Fig.3 point 'C'), where the foresets dip towards the northwest. The lithological content of the sands and gravels exposed in the dune forms differs little from that of the units described at point 'A'. Typically, all the sediments analysed contain a relatively small percentage of fine-grained chloritised clasts.

*Plate 2. View of the sedimentary sequence exposed at 'A', Figure 3, The Spade handle is 80 cm long.*

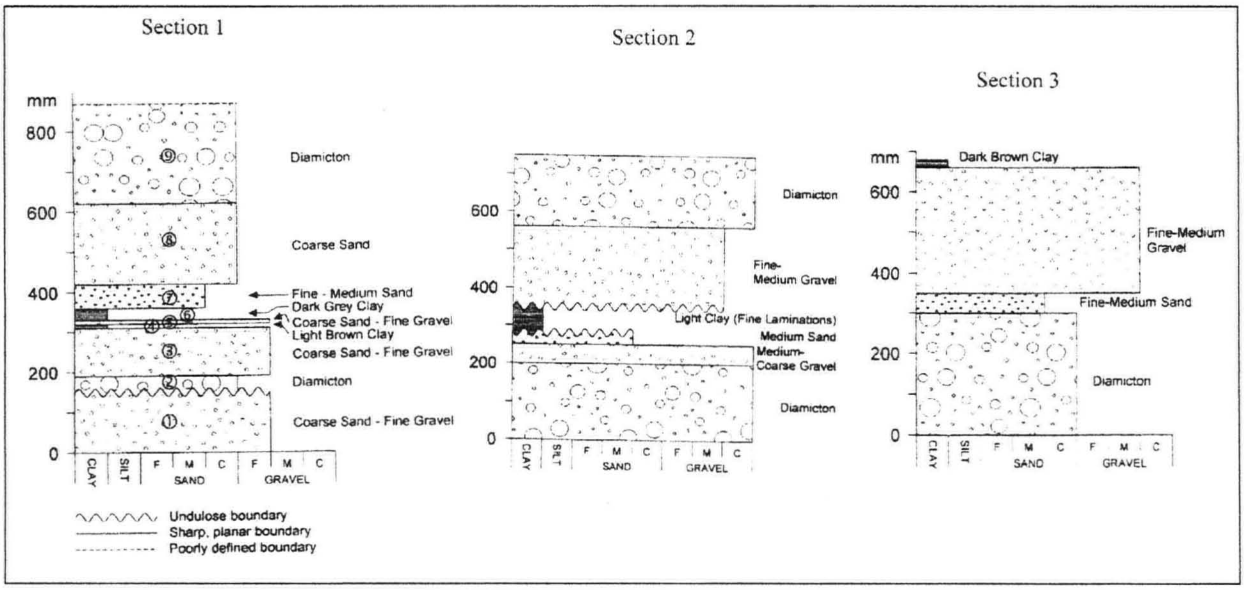



Figure 4. Sedimentary logs of the sequence exposed at 'A', Figure 3

## SEDIMENT PROVENANCE

Eye-catching green clasts, found throughout the sediments being described, are not typical of cave sediments elsewhere in the Yorkshire Dales. Lithologically they are fragments of fine-grained chlorite-bearing meta-sedimentary rocks. The only local outcrops of such lithologies occur within inliers of the Early Palaeozoic Ingleton Group, which occur at the southern margin of the Askrigg Block. Ingleton Group rocks form part of the valley floor in Chapel-le-Dale, but they are not exposed in Kingsdale upstream of Thornton Force. Nonetheless, the possibility that Ingleton Group strata might crop out beneath the superficial deposits forming the valley floor in Kingsdale must be considered.

In the early 1990s cave divers found and explored a connection between the cave systems on the east and west sides of Kingsdale. This connection follows a bedding-guided passage (East Kingsdale Branch), which reaches a maximum depth of 34.5m (Monico, 1995) and is aligned northwest-southeast for much of its length. The presence of cave passage beneath Kingsdale indicates that, beneath the superficial deposits, much of the valley floor is limestone (Fig.6). During the diving explorations no Ingleton Group strata were seen in the floor of the East Kingdale Branch (J N Cordingley, pers. com.).

Thus, the possibility that Ingleton Group strata could form the floor of Kingsdale is limited to the area northeast of Valley Exit Cave and southwest of Kingsdale Head hamlet where rocks of the Great Scar Limestone Group crop out in the bed of Kingsdale Beck (Fig.6). Under conditions of low discharge, Kingsdale Beck sinks into the superficial deposits at a number of points downstream of Kingsdale Head, suggesting that the superficial material is underlain by limestone.

In Wharfedale, 30km east of Kingsdale (Fig.1), a buried outcrop of Lower Palaeozoic strata beneath superficial deposits is inferred on the basis of the occurrence of chloritised metasedimentary erratics within late glacial deposits down valley from Kilnsey (Dakyns, 1890, 1893; Raistrick, 1931). No such erratics are found in the Late Devensian Raven Ray retreat moraine in Kingsdale (Fig.6).

As there is no evidence for the presence of buried Ingleton Group strata in Kingsdale, the most likely source of the Vandals Passage and Perfidia sediments must be assumed to be the Ingleton Group outcrop in Chapel-le-Dale. If so, the sediments must have been transported northwestwards beneath Scales Moor towards Kingsdale. This interpretation is supported by the internal structures of the dune-forms found in the cave and by the flow-sense suggested by the scalloping patterns on the passage walls and on the speleothem.

## MODE OF EMPLACEMENT

Exposure at point 'A' reveals deposits very similar in facies to a chaotic diamicton with little preferred orientation or structure described by Ford and Williams (1989). The top surface of the deposits is abrupt and commonly succeeded by a well-sorted gravel or sand. Ford and Williams (1989) attributed such sediments to the pipefull sliding bed mode of deposition described by Newitt *et al.* (1955). In this situation all the sediment mass was in motion and then deposited simultaneously, with sorting only by the dispersive pressure of colliding particles (McDonald and Vincent, 1972). Similar sediments have been described from sub-glacial eskers (a flow situation analogous to that in phreatic cave conduits) and attributed to the sliding bed mode of deposition (McDonald and Vincent, 1972; Saunderson, 1977). Saunderson (1977) takes the occurrence of such deposits to be diagnostic of water-filled sub-glacial tunnels.

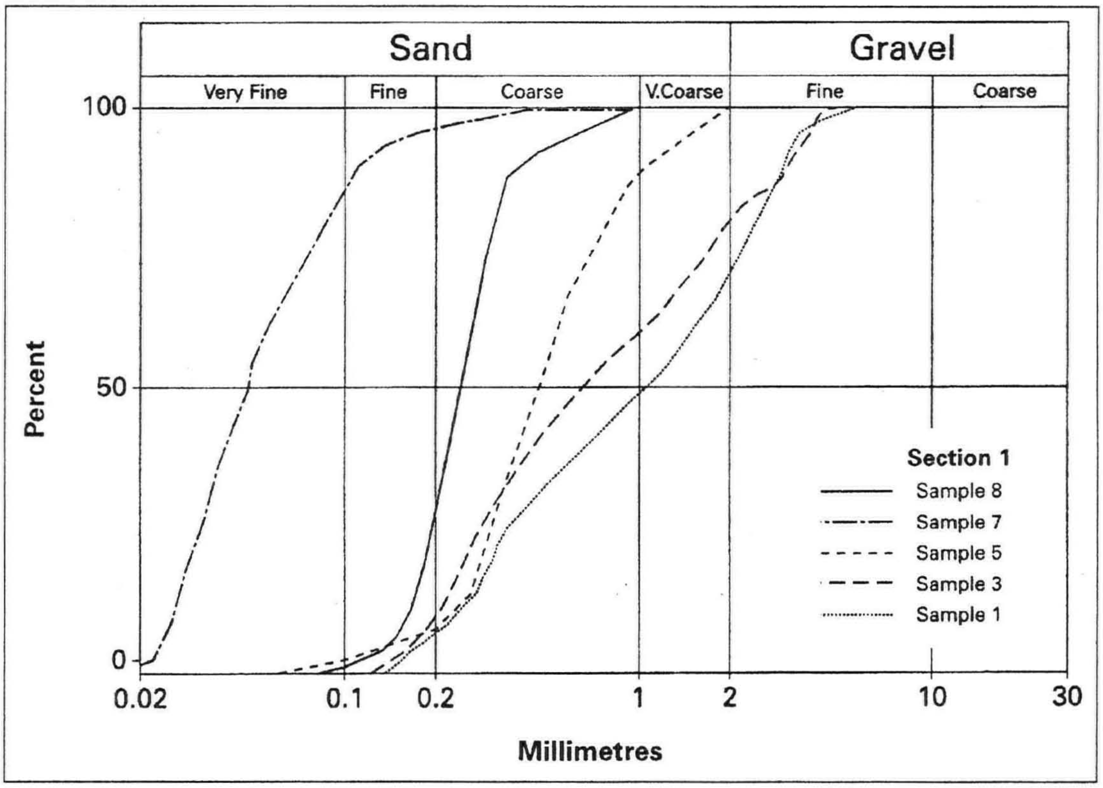
Brennand (1994) studied a number of extensive and well-exposed sub-glacial eskers in Ontario, Canada, and described a sequence dominated by gravels and diamictons with a secondary assemblage of rhythmically alternating sand and gravel units. The internal structure of the units showed significant variation, whereas contacts between the units were commonly very sharp. Brennand (1994) considered the sediments to be the result of deposition from fluidal flow or hyperconcentrated dispersions, and the rhythmicity of the sand/gravel alternations is interpreted as being a response to episodic flood flows.

Brennand (2000) reviewed the sedimentology of the eskers of the Laurentide ice sheet in Canada. Vertically stacked gravel-sand couplets and large gravel dunes, as seen in Illusion Pot, are observed in many of the eskers described.

The clay layers recorded in the exposed sections at Illusion Pot indicate periods of relative quiescence between stronger flows, and the laminations recorded within them may be analogous to varves. Their lack of lateral continuity suggests that they were eroded by the stronger flows responsible for overlying deposits of gravel, sand and diamicton.

Dune forms recorded at points 'B' and 'C' (Fig.3) overlie the sediments exposed at point 'A' and are therefore a younger feature. Development of dune forms is indicative of a relatively low-energy environment. Saunderson (1977) described dune forms overlying a poorly sorted sediment facies within the Guelph esker in Ontario, Canada, where they were related to the energy change accompanying decreased discharge during abandonment of the sub-glacial drainage conduit.

*Figure 5. Cumulative distribution of grainsize curves for samples from section 1, Figure 4.*




The well established technique of determining environmental history of the parent deposit of sediment grains by scanning electron microscope (SEM) analysis of quartz grain surface textures (Krinsley and Dornkamp, 1973) has been used successfully on cave sediments (e.g. Bull, 1989). SEM analysis of the Illusion Pot sediments was undertaken on samples from Unit 9, section 1 (Fig.4). The 0.15 to 0.25mm sieve fraction was used, and the samples were washed in distilled water to remove any adhering clay particles. Brittle fracture facets, typical of glacial deposits, dominated the grain surface textures.

X-ray diffraction analysis of the laminated clay units in Illusion Pot showed that they consisted only of calcite and quartz. This composition is typical of underground clay and silt deposits in glaciated karst regions and such deposits are interpreted as reworked "glacial flour", produced by basal, sub-glacial, ice erosion (Ford and Williams, 1989).

The apparently limited effect of the waters responsible for scalloping the speleothems in Vandals Passage (Plate 1) in enlarging the overall size of the conduit could be due to the depleted aggressiveness of glacial meltwaters (Smart, 1984). Alternatively it is possible that the connection of the conduit to the highly dynamic sub-glacial drainage network was only for a limited time.

## TIMING OF SEDIMENT EMPLACEMENT

Waltham (1990) considered that the Chapel-le-Dale inlier did not exist in pre-Anglian times. If this is so the sedimentary fill of Illusion Pot must be Anglian or younger in age. The scalloped speleothem shown in Plate 1 has a three layer internal stratigraphy. A sample from the middle layer was assayed by standard uranium series disequilibrium alpha counting methods, yielding an age of 343,400 years +86.0/-47.7ka (corresponding to the 'Hoxnian' interglacial of Waltham *et al.*, 1997). This age is consistent with dates obtained from speleothems in relict phreatic tunnels in the Gaping Gill system to the east and the Easegill system to the west (Gascoyne *et al.*, 1983; Gascoyne and Ford, 1984). Vandals Passage was drained prior to this date, and the second phreatic episode post-dates this time.

The lack of clasts derived from rocks of the Ingleton Group within the Late Devensian deposits of the Raven Ray moraine indicates that Vandals Passage was not disgorging sediment into Kingsdale when the moraine was being deposited. If the proposal of a sub-glacial origin for the sediments of Illusion Pot is correct, emplacement during either the Early Devensian or the 'Wolstonian' (Oxygen Isotope Stage 6) is indicated.

## INTERPRETATION

A mechanism that could account for the establishment of a second phreatic episode, and the related sedimentary features described here, is that the Dale Barn Cave system functioned as a sub-glacial conduit. Chapel-le-Dale is a classic example of a glacial trough valley, whereas Kingsdale is much less well incised. This is because the ice flow route into Kingsdale passed over the high divide from Dentdale to the north, possibly leading to a situation where Kingsdale was ice-free while Chapel-le-Dale was carrying a major ice stream from the local ice centre to the north (Mitchell, 1991). This would account for the sediments exposed at point 'A' (Fig.3) having been deposited in the pipefull, sliding bed, mode as described by Ford and Williams (1989). The layered clay deposits would have formed during periods of ponding, when the cave system was not in hydrological continuity with the dynamic drainage system beneath the Chapel-le-Dale glacier. Dune forms, as exposed at the top of the sediment fill, record a decrease in discharge during the final stages of utilisation of the cave by the sub-glacial waters.

A similar case of the utilisation of a pre-existing karst conduit resulting in reversed phreatic flow is described from Storbekkgrotta, Glomdal in Norway by Lauritzen (1983,1984), though no emplacement of sediment by the sub-glacial water is described.

## CONCLUSIONS

The high-level relict passages of Illusion Pot were drained more than 343,400 (+86.0/-47.7ka) years ago.

Subsequently the relict passages were subjected to a renewal of phreatic conditions, during which sediment was transported northwestwards from Chapel-le-Dale towards Kingsdale. The sediments

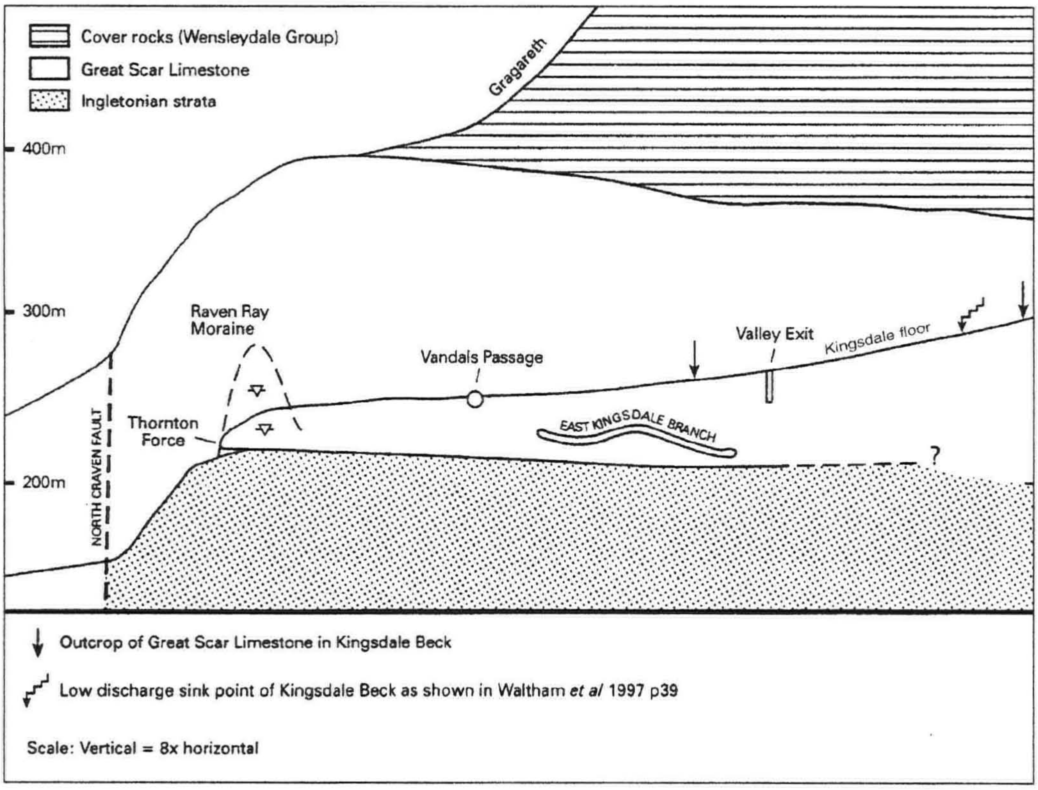



*Figure 6. Section along the course of Kingsdale Beck. Based on Figure 28.3 of Waltham 1986 with permission.*

are analogous to those seen elsewhere, deposited within sub-glacial drainage conduits and preserved as eskers. Thus, the second phreatic episode may have been a result of the utilisation of the pre-existing cave as a drainage channel for the sub-glacial waters of the Chapel-le-Dale glacier.

## ACKNOWLEDGEMENTS


The authors thank Dr S Bottrell, Dr J Best and Dr E Condcliffe of the School of Earth Sciences, and Dr T Murray of the School of Geography, all at the University of Leeds. Dr P Rowe at the University of East Anglia kindly undertook the uranium series dating.


Quaternary stratigraphical terminology used in this paper is that of Waltham *et al.*, 1997.

## REFERENCES


Brennand, T A, 1994. Macroforms, large bed forms and rhythmic sedimentary sequences in subglacial eskers, south-central Ontario: implications for esker genesis and meltwater regime. *Sedimentary Geology*, Vol.91, 9-55.

Brennand, T A, 2000. Deglacial meltwater drainage and glaciodynamics: inferences from Laurentide eskers, Canada. *Geomorphology*, Vol.32, 263-293.

Bull, P A, Daoxin,Y and Mengu, H, 1989. Cave sediments from Chuan Shan Tower Karst,Guillin,China. *Cave Science*, Vol.16, No.2, 51-56.

Brook, D, Griffiths, J, Long, M H and Ryder, P F, 1994. Northern Caves, Volume 3 *The Three Counties and the North-West.* [Clapham: Dalesman.]

Crossland, D J, 1975a. The exploration of Dale Barn Cave. *Northern Cave Club Journal "The Caver"*, No.3, 18-24.

Crossland, D J, 1975b. Through the sump in Dale Barn Cave. *Northern Cave Club Journal "The Caver"*, No.3, 25-32.

Dakyns, J R, 1890. On Silurian erratics in Wharfedale. *Proceedings of the Yorkshire Geological and Polytechnic Society*, Vol.VI, 159.

Dakyns, J R, 1893. Glacial phenomena of Wharfedale between Bolton Abbey and Kettlewell. *Proceedings of the Yorkshire Geological and Polytechnic Society*, Vol.XII, 299-305.

Ford, D C and Williams, P W, 1989. *Karst Geomorphology and Hydrology.* [London: Unwin Hyman.]

Gascoyne, M, Ford, D C and Schwarz, H P, 1983. Rates of cave and landform development in the Yorkshire Dales from speleothem age data. *Earth Surface Processes and Landforms*, Vol.8, 557-568.

Gascoyne, M and Ford, D C, 1984. Uranium series dating of speleothems, part 2 results from the Yorkshire Dales and implications for cave development and Quaternary climates. *Cave Science*, Vol.11, No.2, 65-85.

Krinsley, D H and Doornkamp, J C, 1973. *Atlas of quartz sand surface textures.* [Cambridge University Press.]

Lauritzen, S-E, 1983. *Arctic and Alpine Karst Symposium. Program and Field Guide.* University of Oslo.

Lauritzen, S-E, 1984. Evidence of subglacial karstification in Glomdal, Svartisen. *Norsk Geografisk Tidsskrift*, Vol.38, 169-170.

McDonald, B S and Vincent, J S, 1972. Fluvial sedimentary structures formed experimentally in a pipe and their implications for interpretation of subglacial sedimentary environments. *Geological Survey of Canada paper* 72-77, 1-30.

Mitchell, W A, 1991.*Western Pennines: Field Guide.* [London: Quaternary Research Association.]

Monico, P, 1995. *Northern Sump Index.* [Cave Diving Group.]

Newitt, D M, Richardson, J F, Abbott, M and Turtle, R B, 1955. Hydraulic conveying of solids in horizontal pipes. *Transactions of the Institution of Chemical Engineers*, Vol.33, 93-110.

Raistrick, A, 1931. *The glaciation of Wharfedale. Proceedings of the Yorkshire Geological Society*, Vol.22, 9-30.

Saunderson, H C, 1977. The sliding bed facies in esker sands and gravels: a criterion for full-pipe (tunnel) flow? *Sedimentology*, Vol.24, 623-638.

Smart, C, 1984. Glacier hydrology and the potential for subglacial karstification. *Norsk Geografisk Tidsskrift*, Vol.38, 169-170.

Waltham, A C, 1986. Valley excavation in the Yorkshire Dales karst. 541 to 550 in Paterson, K and Sweeting, M M (eds), *New directions in karst.* [Norwich: Geobooks.]

Waltham, A C, 1990. Geomorphic evolution of Ingleborough. *Cave Science*, Vol.17, No.1, 9-18.

Waltham, A C, Simms, M J, Farrant, A R and Goldie, H S, 1997. *Karst and Caves of Great Britain. Geological Conservation Review series* No.12. [London: Chapman and Hall.]

CAVE KARST SCIENCE Vol. 28, No.1 April 2001
Transactions of the British Cave Research Association


ISSN 1336-191X

# Factors concerning the reliability of the Method of Mixtures in stream studies, shown by three applications

**Roger D STENNER** and **Frances L STENNER**
18 Stafford Place, Weston-super-Mare, North Somerset, BS23 2QZ, UK.

**Summary:** By studying examples when the Method of Mixtures failed, factors concerning essential assumptions were highlighted. Data from three different Method of Mixtures applications were considered.
In considering the first application (measuring stream ratios, and extending the work to map out the stream distribution in caves), conditions that cause changes in water properties are listed. Changes take place in boulder ruckles between the entrance and open cave. In open caves water properties were stable unless: (a) the water mixed with water from another source; (b) rainwater storm surge passed through the cave; (c) hard percolation water flowed over existing calcite deposits, depositing dripstone; (d) stream sediment was stirred up and included with sample; (e) oxidation of dissolved or suspended organic matter took place. The latter is a slow process that has not yet been found in Mendip caves. Unexpected changes in water properties are most likely to be a sign of the presence of a previously undiscovered inlet.
The second application is in the measurement of stream-size by salt dilution, in which uniform mixing is an essential consideration.
The third application is in investigating the characteristics of a stream that cannot be sampled directly.

*(Received 23 November 2000; Accepted 11 July 2001)*

## INTRODUCTION

The Method of Mixtures relates changes in the physical properties of two mixing fluids before and after mixing, to the relative quantities of the two fluids, and hence, in steady streams of mixing fluids, to their relative flow rates. The equation quoted in Section 2.3 (below) is an expression of the basic equation expressing the theory. The method has been used in karst studies for many years, to measure stream ratios (for example Pitty, 1966; Stenner, 1966) and hence to measure changes along a stream passage (Stenner, 1968, 1973), and to investigate obscured inlets joining a stream (Pitty, 1966; Stenner 1973). Measuring stream-size by salt dilution is another application of the method.

Using the Method of Mixtures to measure stream ratios is especially useful in the turbulent streams so commonly found in caves. Caution is needed, because close to the flooded zone, stretches of cave streams may be deep and more canal-like, more similar to lowland streams, where the method is likely to fail because assumptions are not valid.

In this wide range of applications there is a common factor. They all depend upon assumptions that are fundamental to the method. The assumptions are by no means obvious in the context of karst studies. In this paper, the assumptions are discussed in the context of data accumulated during use of the method for three diverse applications. Use in each of these applications revealed important examples of unexpected constraints or unexpected consequences.

### Two essential assumptions

For the Method of Mixtures to be valid, there are two essential assumptions. Firstly, the streams must mix completely and uniformly. Secondly, the properties being measured must be stable. Whenever the Method of Mixtures is used in a new cave application, these two fundamental assumptions must be examined critically afresh, to check their viability in the new application.

Whether or not these two assumptions are valid in any circumstance may not be immediately obvious. They were discussed in reports of studies in St Cuthbert's Swallet, Priddy (Stenner, 1968), and during a 32-trip study in GB Cave, Charterhouse (Stenner, 1973). After recent new studies in St Cuthbert's Swallet and its surface streams, and in Swildon's Hole, Priddy, the quantity of data relating to the Method of Mixtures has increased greatly. The present study re-examines the fundamental assumptions of the method, to discover more about their validity. In particular, data were searched for examples of the method failing. These examples teach us a great deal about the limitations of the method, and teach us to recognise the circumstances when the assumptions may not be valid.

To provide a focus for the validation process, this paper examines three different applications of the method.

1. measuring the stream-size ratio of two streams at a stream junction;
2. measuring stream-size by salt dilution;
3. investigate the physical and chemical characteristics of a stream that cannot be sampled directly (the former St Cuthbert's Stream inlet).

## 1. MEASURING THE STREAM-SIZE RATIO OF TWO STREAMS

Studies carried out between 1965 and 1973 in St Cuthbert's Swallet, Priddy, enabled several sets of stream ratios to be calculated throughout the cave (Stenner, 1968). The stream-size of Plantation Stream (then the largest stream entering the cave) was measured using a rectangular-notch weir (Donnan, 1952) between 1966 and 1969, in high and low flow, in winter and in summer. Using the stream ratios at junctions throughout the cave and the stream-size at Plantation Swallet, the stream distribution throughout the cave on several occasions was calculated (Stenner, 1968). The same method was used in GB Cave in 1968 (Stenner, 1973), using a portable weir near Tyning's Swallet.

When, in St Cuthbert's Swallet, the consequences of the change in course of Plantation Stream were studied (between 1994 and 1997), salt dilution was chosen in preference to a weir to measure discharge (Stenner, 1997). The same method was included in an ongoing study of Swildon's Hole. In both studies the Method of Mixtures was used at every major stream junction and stream inlet, supplemented (wherever appropriate) by direct measurement of the size of the inlet stream. Data concerning stream ratios in the cave systems were gathered in eight trips in St Cuthbert's Swallet between 1994 and 1997, and in seven trips in Swildon's Hole in 1999 and 2000.

| Date | Pulpit Pot | Upstream of Disappointment Pot | Traverse Chamber Choke | Sewer Passage |
|---|---|---|---|---|
| 29/05/94* | 116.4 | 118.0 | ***116.0*** | ***128.0*** |
| 15/6/94 | 146.9 | 147.3 | 152.1 | 154.9 |
| 11/07/95* | ***161.9*** | 177.8 | 171.5 | 175.6 |
| 03/09/95* | ***182.0*** | 203.3 | *(187.0**)* | ***206.1*** |
| 13/2/96 | ***112.6*** | *(147.1**)* | 106.9 | 107.3 |
| 10/3/96 | 134.3 | 131.9 | *(117.3 **)* | ***134.7*** |
| 24/03/96* | ***123.5*** | 160.9 | 119.9 | 121.1 |

*Table 1.1. Changes in total hardness ($10^5 \times M$; ~ ppm as $CaCO_3$) between successive stations in St Cuthbert's Swallet Main Stream between 1994 and 1996. On dates marked * a pulse of storm-water passed through the cave. Data marked ** (also in parentheses) were from samples containing mud, and hence unreliable. Data in bold italics show changes that are in excess of analytical precision.*

### 1.1. Choice of hydro-chemical characteristic

When samples were collected above and below a stream junction, all analyses and measurements should, in theory, give stream-size ratios that agree. The precision of the agreement depends on the precision of the ratios, which is a function of the precision of each measurement relative to the size of the changes around the junction. Data from a junction in St Cuthbert's Swallet have been quoted (Stenner, 1968, p.60, Table 5) in which temperature measurements and data from total hardness and calcium titrations provided estimates for the stream-size ratio of the mixing streams that were indistinguishable statistically.

The precision of a stream-size ratio estimate varies from one measurement to another, and it is impossible to predict which measurements will yield the most reliable data in any particular case. If stream-size ratio studies are included in a wider hydro-chemical study in which many stream characteristics are measured, the likelihood of obtaining a reliable stream-size ratio will increase. For example, on 9/11/1968 in St Cuthbert's Swallet, temperature and total hardness changes around two major junctions near Traverse Chamber were too small to allow calculation of stream-size ratios. However, one inlet stream displayed a high potassium concentration, and potassium data enabled the stream-size ratios to be calculated.

During earlier work in St Cuthbert's Swallet and GB Cave, stream temperatures were extremely useful for calculating stream-size ratios. Mercury-in-glass thermometers had been used, graduated to 0.1°C, but the readings were estimated to ±0.02°C. Temperature differences therefore had a precision of better than ±0.05°C, and temperature measurements commonly yielded reliable stream ratio estimates. In much of the recent work in St Cuthbert's Swallet, digital electronic thermometers with a read-out to 0.1°C were used. The digital thermometers therefore gave temperature change measurements with a precision of ±0.2°C, reducing the value of temperature measurements considerably.

### 1.2. Mixing

The method assumes that the two streams are thoroughly and uniformly mixed. Even turbulent, fast flowing streams commonly mix very inefficiently downstream of a junction. It is essential that the "downstream" data should be collected from downstream of a feature that will ensure thorough mixing of the two waters. Salt dilution (described in Section 2, below) gives results that show clearly how effective the mixing has been. The technique therefore has a special value in teaching its users to recognise the features in a stream that lead to rapid, thorough mixing. For example, in the recent St Cuthbert's studies, 17 of 160 attempted salt dilution measurements failed, but 10 of the failures came in the first 26 attempts, and there have been no failures (so far!) in the Swildon's Hole study. This shows an encouragingly steep "learning curve". However, in this application, the researcher can move to find a suitable site for the standard addition, a flexibility that is not available at a stream junction.

Data concerning mixing are presented in Section 2.6 (below), illustrating the effectiveness of mixing displayed during studies at St Cuthbert's Swallet.

### 1.3. Stability

The Method of Mixtures assumes that the characteristics being measured are stable. To maximise the chances of stability, and to minimise the chances of contamination, it is obvious that stream surveys should be made in the shortest possible time, with small parties moving upstream, preferably with no other parties in the same part of the cave.

In the GB Cave study in 1968 (Stenner, 1973), inconsistent and seemingly impossible results were obtained during one trip, when a downpour took place while the sampling trip was in progress. Similarly, in recent trips in St Cuthbert's during heavy rainfall, temperature and hardness changes were found in the stream between successive sampling points as storm-water flowed through the cave (see Table 1.1). These examples of instability are examined in detail below.

During normal trips (when samples were collected correctly) the hydro-chemical characteristics of streams were stable. When results were searched for more examples of changes in stable conditions, several factors were seen to be particularly relevant. Similar working hypotheses, drawn up in early studies of St Cuthbert's Swallet (Stenner, 1968), and during the study of the hydrology of GB Cave (Stenner, 1973.), have been re-examined during the present study, and are restated in the Conclusion of Part 1, below. Because these hypotheses are important, new evidence concerning them is examined in detail.

### 1.4. Working hypotheses concerning stream ratios

#### 1.4.1. *The stability of hydro-chemical factors in normal sampling trips*

Stability of hydro-chemical factors is fundamental for reliable stream ratio measurements. But, in the Old and New routes in St Cuthbert's Swallet, it is not possible to sample the network of inlets within a short time period. Examining measurements between two widely spaced stations (with no inlets between the two successive stations) provided data about the stability of the measurements.

The following temperatures were measured in the Main Stream in St Cuthbert's Swallet.

i. 28/01/67. Traverse Chamber Choke, 8.52°C; outside Dining Room 8.52°C;
ii. 26/11/67. Traverse Chamber Choke, 8.50°C; Sewer Passage 8.60°C;
iii. 10/02/68. Traverse Chamber Choke, 7.80°C; outside Dining Room, 7.83°C

(Refer to the survey - Irwin, 1991 - for details of sample site locations,).

These results showed the stability of stream temperature, and also showed that the consequences of heavy drips from The Cascade, mixing with the Main Stream a few metres upstream of Everest Passage, were too small to be detected.

However, between 1994 and 1996, total hardness changes were measured between two pairs of stations with no intermediate stream inlets (from Traverse Chamber Choke to Sewer Passage, and from Pulpit Pot to the Disappointment Pot inlet). In every case, changes were observed during trips affected by severe rain-storms. The results are presented in Table 1.1, alongside examples when no significant changes took place.

Results in Table 1.1 show that total hardness in the main stream was stable, except in samples containing disturbed streambed sediments (to be discussed below in section 1.4.4), or when a pulse of storm-water was passing through the cave. For example, during the sampling trip on 3/09/95, there was a heavy rainstorm. Some of the measurements made during this trip are certain to have been affected by the passage of the rainwater surge. In addition to the total hardness anomaly on this date, large changes in temperature, calcium and potassium were recorded between the top of Pulpit Pitch and the bottom of Gour Passage Pitch. In sampling trips in stable weather there were no measurable changes here, unless a bad (i.e. muddy) sample had been collected. On 11/07/95 and 24/03/96, rainstorms caused similar changes between successive stations. Finally, after recent heavy rainfall on 29/05/94, the dam at the Entrance had been left in place for several hours earlier in the day, causing deep flooding of the valley floor. This water was running off during the sampling trip, creating an artificial storm surge while the sampling trip was in progress.

Inlets in Pulpit Passages occasionally had concentrations of total, alkaline and calcium hardness that were lower than those in the surface stream (as, for example, on 15/06/94 and 11/07/95). This may be evidence that when the hardness of the surface stream is unusually high, calcium bicarbonates can be removed from solution (after all, the Pulpit Passage West Inlets emerge from the boulder ruckle in a stalagmite-decorated chamber, trickling over stalagmite). However, another possibility is that in low flow, water may take a considerable time to flow through the ruckle, and the water emerging in Pulpit Passage may have entered the system under a different flow regime, with different hardness. Further sampling may help to resolve this uncertainty.

In recent sampling in St Cuthbert's Swallet, 4 of the 8 trips took place under very high stream flow conditions. Valuable data are, therefore, now available from severe conditions, which have tested the limitations of the assumptions. Even under these extreme adverse conditions, the four wet-weather sampling trips provided positive data. To be specific; although data from well-spaced stations proved that long-term stability did not operate under these conditions, short-term stability at each stream junction was sufficient to allow stream-size ratios at individual stream junctions to be measured with adequate precision.

In any new application in a new study, it is important to gather evidence to examine the stability of characteristics. This may be done by, for example, sampling the stream at the entrance at the beginning of the trip, and again at the end of the trip.

### 1.4.2. *Changes in a boulder ruckle between the surface and inlets in the cave*

The first period of studies in St Cuthbert's showed that significant hydro-chemical changes took place between the soak-away sink and inlets in Pulpit Passage and Arête Chamber. A trace carried out by Drew and Stenner (Stenner, 1968), using pyranine, proved that the small trickles were all derived from the surface stream.

Much larger hydro-chemical changes were found in the ruckle between Tyning's Swallet and the stream inlets in GB Cave. The stream at the surface has a very low hardness, giving this stream a high potential for dissolving carbon dioxide and then limestone. In this cave, the boulder ruckle changes were measured 16 times between February 1968 and December 1968. The newly developed aggressiveness determination was included in the study and the results were important, because they showed that ideas then current on the progressive dissolution of limestone as a stream passed through Mendip caves needed to be revised (Stenner, 1969; Smith and Drew, 1975). The inverse correlation between the increase in total potential hardness (increase of total hardness + increase of aggressiveness) and the stream-size of Tyning's Stream was so close as to preclude other influences. It was concluded that the changes within the ruckle were caused by the dissolution of limestone following the absorption of carbon dioxide by the stream in the ruckle. The relationship described by the regression equations also effectively precluded admixture with harder water as an explanation of the observed changes. Later work, which included the analysis for dissolved gases, gave the final proof that concentrations of dissolved gases are indeed able to change rapidly in streams passing through boulder ruckles (Bridge *et al.*, 1977).

### 1.4.3. *Changes caused when different streams mix*

At first it seemed that there is no way of discovering whether or not water from an additional source joins swallet water in the boulder ruckle. On one occasion in St Cuthbert's Swallet, it was proved that no extra water was added to water from Plantation Stream between the swallet and Plantation Junction (Stenner, 1997, p.16). However, an alternative method has become apparent (Knights *et al.*, 2001, in preparation).

If the change has been caused by dissolution of limestone, the mean increment of total hardness will be numerically equal to the mean increment of alkaline hardness, and there will be negligible mean increase of non-alkaline hardness (or, for example, sulphate). Conversely, a significant change in non-alkaline hardness will indicate the probability that the stream had mixed with water from a different stream.

Applying this hypothesis to streams flowing from the surface to the various inlets in Arête Chamber and Pulpit Passage (all positively tested using pyranine), the changes in alkaline hardness were very close to the change in total hardness, and the changes in non-alkaline hardness were negligible. It can therefore be concluded that there had been no significant external input of water to these streams. But, when water from the Mineries Pool Outflow stream was compared with water at Plantation Swallet, and various increases were tabulated, the following mean changes were calculated (Δ being the symbol for increase):

| | | |
|---|---|---|
| Mean Δ total hardness | = | 33.8 ppm $CaCO_3$ |
| Mean Δ alkaline hardness | = | 36.0 ppm $CaCO_3$ |
| Mean Δ non-alkaline hardness | = | 2.2 ppm $CaCO_3$ |

Significant changes in concentrations of sulphate were also found. These results contrast sharply with those caused by the straightforward dissolution of limestone in Arête Chamber and Pulpit Passage inlets. In 1994 the discovery of a previously unknown tributary stream gave positive proof that the changes between the Pool Outflow and Plantation Swallet (observed between 1966 and 1973) had been caused by addition of water from this completely separate source (Stenner, 1997, pp.18-20).

A significant mean change of non-alkaline hardness (or, for example, sulphate) is therefore an indication that two different streams have mixed. Results derived from a single set of samples might be inconclusive, but repeated sampling can be expected to give a reliable indication.

### 1.4.4. *Changes due to deposition of dripstone*

A decrease in total hardness along the streamway of the inlet, caused by de-gassing of $CO_2$ gas into the cave atmosphere, followed by the deposition of dripstone in the passage, was measured in the White Passage Inlet stream in GB Cave. For example, data from 17/11/68 (Stenner, 1973, p.209) showed that in the Oxbow, the White Passage Stream had a total hardness of 155.2ppm as calcite, and the aggressiveness was –7.8ppm. Downstream, near the Main Stream junction, the total hardness had fallen to 151.6ppm, and the aggressiveness was –8.0ppm. The result confirmed that, although the total hardness in the supersaturated water had fallen, the supersaturated nature of the water had been maintained by a further loss of $CO_2$ into the cave air.

### 1.4.5. *Stirring up stream bed sediments when samples are collected*

When the method for direct measurement of aggressiveness was being developed, it was recognised that if a water sample included streambed sediments, related aggressiveness data would be unreliable. In the recent studies in St Cuthbert's Swallet a new, unsuspected type of error was identified, involving water samples containing clay-like suspensions. In such samples, major errors in data for magnesium, potassium and sulphate were found. This is probably because clays are natural ion exchange media (as discussed in Knights and Stenner, 2001, in preparation). Such errors were found in every sample that had been contaminated by clay-like suspended material. Examples are shown in Table 1.1. **This unexpected discovery has serious implications in hydro-chemical cave studies.** The remedy is that whenever streambed sediments are found in a water sample, the sample must be filtered at the time of collection (a process that invalidates pH and dissolved gas measurements). It is much better to be careful to avoid disturbing the mud in the first place.

### 1.5. Conclusions

The comments on limitations to the assumptions concerning the Method of Mixtures apply to all applications of the method.

In general, the data support the hypothesis that along Mendip-size streamways, physical and chemical characteristics are stable (within the time span of a normal sampling trip). Changes were found in five circumstances;

i. In boulder chokes between surface sinks and inlets in the cave;
ii. At stream junctions (including major drip inlets);
iii. In hard water trickling over flowstone (e.g White Passage stream junction, GB Cave);
iv. At sites where stream-bed mud has been stirred up into the water sample;
v. When stream properties are changing rapidly in response to a rainstorm.

In very long stream passages in other caving regions, there will be sufficient time for slow reactions involving the oxidation of organic solutes to take place, as demonstrated for instance in Ogof Ffynnon Ddu (Bray, 1975), causing changes in levels of dissolved limestone that are gradual, and not detectable in the relatively short Mendip stream passages.

The fundamental stability is important because:

**If at any point in a stream, a sudden change in temperature or water chemistry is observed, that point marks a confluence of waters from different origins.**

## 2. MEASURING STREAM-SIZE BY SALT DILUTION

A simple method is described for measuring stream-size by salt dilution. This method is proposed as a practical alternative to using a portable weir, to be compatible with the overall aim of quantifying the physical and chemical characteristics of the stream being studied. It is suitable for underground use.

At the outset, ready-built apparatus (the Marriott constant-flow bottle) was considered to be impractical for the applications being planned, and would be unsuitable for use underground. The aim had been to find out if a simple home-made constant-head bottle would be sufficiently accurate. Tests on the first trial model showed that the accuracy was good, and the feared problem (vortex formation, with a change in flow-rates) did not occur.

Between 1994 and 1997, 160 stream-size measurements were made at the streams feeding St Cuthbert's Swallet, using salt dilution and the homemade constant-head bottle. Since February 1999 the same method has been used in an ongoing study of the hydrology of Swildon's Hole.

### 2.1. Making and using a constant head bottle

The base of a cylindrical 2-litre plastic mineral water bottle was cut off. A hole was drilled through the cap, and a line was drawn around the bottle 14cm above the neck with a black spirit marker. In later versions, the height of the line was reduced to 9cm, and the precision of the method did not change. The original bottle is shown being used (at St Cuthbert's Stream) in Figure 2.1.

With the hole in the cap closed by a finger, the bottle was filled to the mark with the standard solution. The bottle was held about 50cm above the surface of the stream at a suitable location. A bottle with two litres of the same solution was ready. At the starting time, the hole was uncovered, and solution was added to the constant head bottle at such a rate as to maintain the level at the marked height. The time taken to add the 2 litres was recorded. The rate used in the St Cuthbert's stream study was approximately 0.6 to 0.8 l/min, which could be varied by changing the cap to one with a different sized hole. In recent studies in Swildon's Hole, an addition rate of 1.2 l/min was used successfully in high flow conditions.

After initial practice, no difficulty has been found in achieving a constant addition rate.

Trial measurements were made using a bottle with three water levels 5mm apart. The results proved that temporary minor fluctuations in the liquid level did not cause a significant error.

The solute must be harmless (and preferably must be already present in the stream), must not react with solutes already present in the stream, and must be suitable for accurate analysis. In the two applications

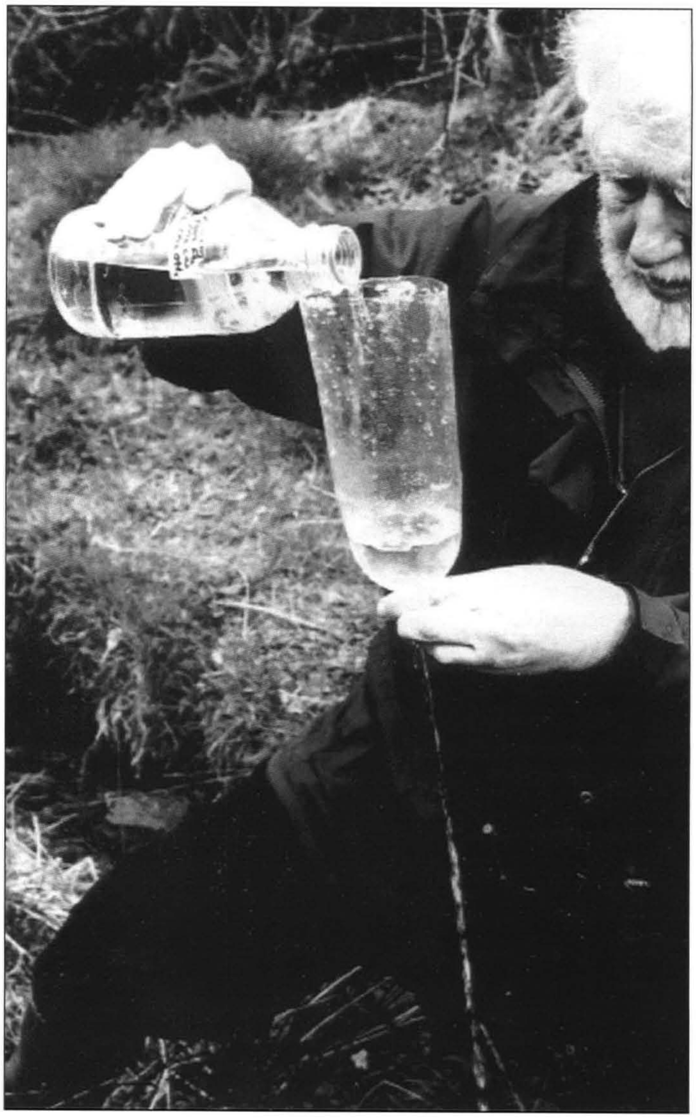


*Figure 2.1. Measuring the discharge of St. Cuthbert's Stream by standard addition*

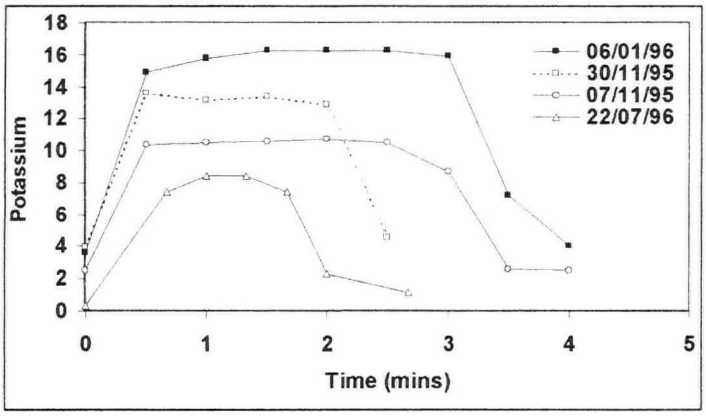



*Figure 2.2. Standard addition at St. Cuthbert's Swallet, Main Stream Sink. Potassium concentrations ($10^5 \times M$) in samples.*

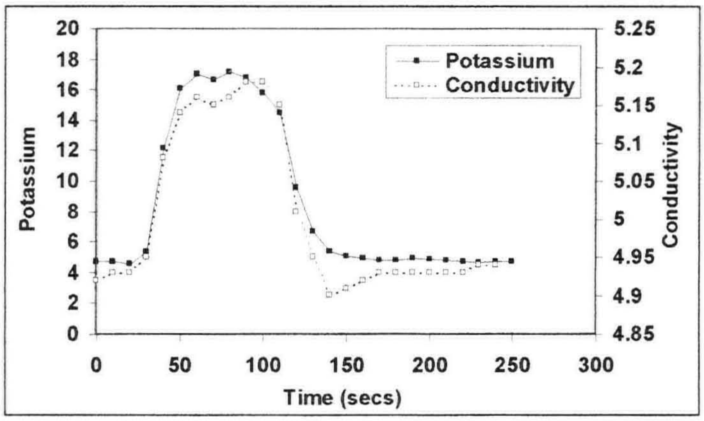



*Figure 2.3. Using Standard addition at Swildon's Hole, comparing potassium concentrations in samples with in situ conductivity measurements.*

mentioned, potassium chloride was chosen because potassium analyses were already part of the analytical program, so no new analyses would be needed to increase an already heavy routine. Additionally, potassium chloride is inexpensive and meets environmental and water quality constraints at the concentrations involved.

### 2.2. Using salt dilution at St Cuthbert's Swallet

Stock 1M standard solution, made from AnalaR KCl in conductivity grade water, was freshly diluted to the chosen concentration. An assistant (whose help was indispensable) collected samples in 25ml bottles at the chosen site (where mixing was expected to be complete).The first sample was taken immediately before any salt was added, and samples were taken at 15 or 20 second intervals during the addition, and for about 2 minutes after the addition was complete.

The samples were analysed by Flame Emission Spectrophotometry (FES), with a Unicam 919 instrument burning acetylene and compressed air.

When a successful measurement had been made, a graph of the results showed a rapid rise to a constant high value, showing that mixing had been thorough, and the rate of addition and the final concentration had been constant. Examples are shown in Figure 2.2.

### 2.3. Calculation of the results

The Molarity of the solutions was used in the calculations.

| | |
|---|---|
| Concentration of solute added from Constant Head Bottle: | a M |
| Concentration of solute in stream before addition: | b M |
| Concentration of solute in stream after addition: | c M |
| Flow rate of solute: | d l/min |
| Flow rate of stream: | $\frac{(a-c)\times d}{(c-b)}$ l/min |

The precision of the potassium analysis was similar to that of the timing.

### 2.4. Discussion of the results

With a stream of about 10 l/sec, 0.025M KCl gave good results, and for a stream of about 100 l/sec, 0.5M KCl was used. The method was successful for flow rates from 100 l/sec to as low as 0.5 l/sec. The method can be adapted for use in larger streams by using larger addition rates and/or greater salt concentrations. When the stream flow was smaller (from 0.5 to approximately 0.1 l/sec) it was more convenient to use a polythene sack and measuring cylinder and measure the stream-size directly.

Natural concentrations of potassium in the streams being studied have sometimes exceeded the final concentrations shown in Figure 2.2. The brief rise in potassium due to these measurements was therefore within the natural range of potassium in these streams.

Common salt could have been used instead of KCl, but higher concentrations would have been needed because of the higher background levels of NaCl in natural streams. Sodium and chloride are both straightforward to determine at the levels that would be used. A fluorescent dye could also have been used, the concentration of the dye after addition being measured by a fluorimeter, but (for reasons stated previously) this was not such a good choice for the studies in which the writers were involved.

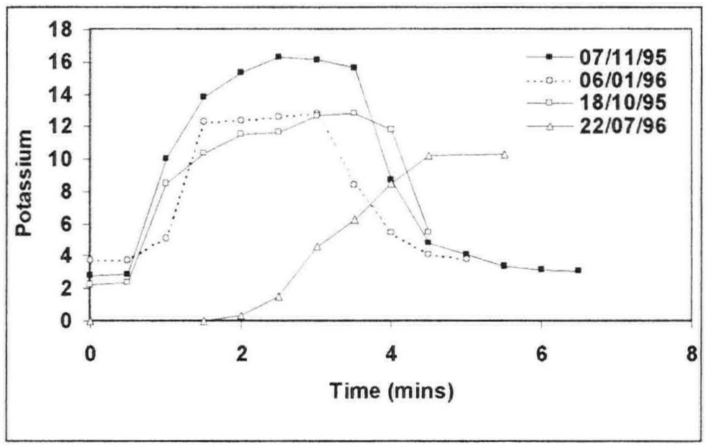



*Figure 2.4. Standard addition at Priddy Mineries Pool Outflow Stream. Potassium concentrations ($10^5 \times M$) in samples.*

The disadvantage of the basic salt dilution method is that there is no direct way of knowing when satisfactory mixing has been achieved. In recent salt dilution measurements at Swildon's Hole, a portable conductivity meter with a high specification was used to determine when conductivity, and hence potassium levels, had reached a steady maximum value. The results of the very first trial of this modification, at Swildon's Hole on 16/05/99, are shown in Figure 2.3 (a "blip" in the results merely indicates where one of the investigators was distracted!). The results showed a very close agreement between the two methods of analysis, although FES was much more sensitive than conductivity. In subsequent salt dilution measurements, the use of the portable conductivity meter improved the collection of samples for later analysis by FES, because it showed with certainty when conductivity (and hence potassium levels) had reached a steady maximum value. Many workers will not have access to a sufficiently accurate and sensitive portable conductivity meter, and will have to depend on later examination of data to prove that mixing in the particular measurement had been satisfactory.

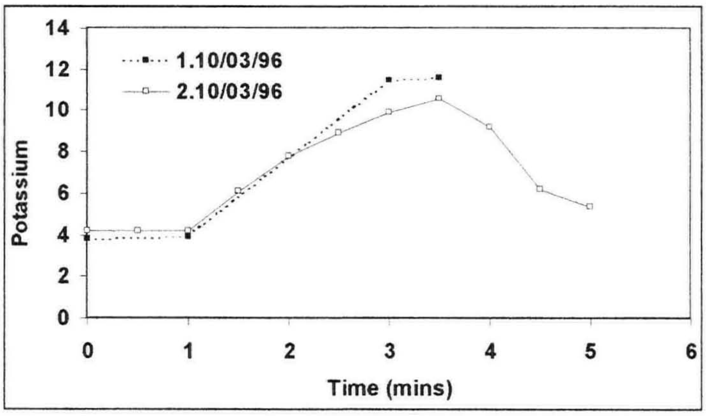



*Figure 2.5. Standard addition at Priddy Mineries Pool Outflow Stream, with postassium standard solution added upstream and downstream of a thrust pool. Potassium concentrations ($10^5 \times M$) in samples.*

## 2.5. Alternative methods of analysis

It would have been possible to use Atomic Absorption Spectrophotometry instead of FES to analyse samples for potassium. Conductivity measurements could have been used with KCl solutions, and this method would have the advantage of providing results in the field. But, as described above, although a high-quality portable conductivity meter was very useful in the Swildon's Hole study, showing when potassium levels were at a steady maximum, its precision was lower than FES data. Conductivity data in this case were relative. Making genuine conductivity measurements in the field is not straightforward.

## 2.6. Achieving uniform mixing in salt dilution experiments

Uniform mixing of the solutions is essential for the successful use of salt dilution. The problem is similar to that encountered when measuring stream ratios (Section 1). It is considered in detail here because, in this application, workers have the extra degree of freedom in being able to choose the best site for making the measurement. Four cases were considered:

1. The stream at Site 1 (30m upstream of the Main Stream Sink at St Cuthbert's Swallet) was a simple, turbulent, shallow stretch of water. The results are shown in Figure 2.2.
2. At Site 2 (Priddy Mineries Pool outflow stream) the stream was wider and shallower than at Site 1, with an irregular bed. Figure 2.4 shows that a longer time was taken to achieve uniform mixing. On one occasion at Site 2 (on 22/07/96, also shown in Figure 2.4), in very low flow (28 l/min by direct measurement), the method failed because uniform mixture was not achieved in the time needed to add 3 litres.
3. Also at Site 2, the effect of a pot-hole in the stream bed is shown. The physical dimensions of the stream-bed are important. The water from Priddy Mineries Pool flows through a pipe in a concrete dam into a splash pool 1.2m wide, 0.3m deep and 1.0m long. The depth of the stream flowing out of the splash pool is (normally) less than 0.1m. The usual routine for stream-size measurement was to add the potassium standard solution at the tail of the pool. To investigate the importance of this detail, the estimation was carried out twice on 10/03/96. First the addition was made as usual at the tail of the pool, then addition was repeated at the pipe in the dam. The effect of the pothole, to seriously slow the achievement of uniform mixing, is shown in Figure 2.5.

## 2.7. Stream depth and stream-size measurement by salt dilution

During the recent St Cuthbert's Swallet studies, conventional weir measurements to enable direct comparisons between the two methods were not carried out. However, in addition to salt dilution measurements, the stream depth was measured at the mouth of the pipe carrying the stream into the cave. The relationship between the stream depth and stream-size was investigated. From 15/08/94 to 3/09/95, the correlation coefficient for 14 pairs of data was extremely close. The value, 0.983, is high enough to be interpreted as showing that the two measurements are alternative measurements of the same quantity. On two occasions in this period when the salt dilution method failed, the regression graph was used to provide the value for the stream-size, and it was used on another three occasions when salt dilution was not attempted. This demonstrated the potential usefulness of a very simple alternative method for estimating stream-size. However, early in September 1995, heavy rainstorms that ended the great drought carried a large quantity of dead vegetation into the culvert, partially blocking it. For the next 4 measurements (13/09/95 to 20/11/95), the effect of the blockage was to destroy the previous relationship between stream depth and discharge. A larger head of water than previously was needed to maintain any given flow value. Parties entering the cave found it difficult to control the stream entering the cave. A digging session removed the blockage, but the previous stream-size/depth relationship was not re-established, and a new stable relationship between stream depth and discharge was not established in the duration of the study.

When using a weir to measure stream-size, likely sources of error lead to an under-estimate of the true value, whereas in salt dilution, likely mistakes result in an over-estimate of the stream-size.

# 3. ESTIMATING THE CHARACTERISTICS OF THE FORMER ST CUTHBERT'S STREAM INLET

Before 1985, the Mineries Pool outflow stream sank at Plantation Swallet. St Cuthbert's Stream, (which drains an area of marshy ground

| | Stenner 1965 to 1973 | | | Atkinson 1969 to 1970 | | | Stenner 1994 to 1997 | | |
|---|---|---|---|---|---|---|---|---|---|
| | Mean | No. | SD | Mean | No. | SD | Mean | No. | SD |
| Temperature °C | 7.4 | 17 | 2.9 | | | | | | |
| Discharge l/min | 102 | 7 | 60 | 170 | 31 | 240 | 522 | 45 | 594 |
| Total hardness ppm $CaCO_3$ | 136 | 22 | 18 | 133 | 33 | 23 | 169 | 45 | 28 |
| Aggressiveness ppm $CaCO_3$ | 0.5 | 10 | 2.1 | 1.2 | | | | | |
| Mg, $10^5 \times M$ | 11.3 | 22 | 2.1 | | | | 17.7 | 45 | 3.6 |
| Ca, $10^5 \times M$ | 124 | 22 | 17 | | | | 151 | 45 | 26 |
| Alkaline hardness ppm $CaCO_3$ | 120 | 20 | 18 | 115 | | | 157 | 44 | 29 |
| Non-alkaline hardness ppm $CaCO_3$ | 15.4 | 21 | 2.8 | | | | 11.5 | 44 | 4.5 |
| $SO_4^{2-}$, $10^5 \times M\ SO_4^{2-}$ | 13.1 | 4 | 0.4 | | | | 11.1 | 41 | 3.6 |
| $NO_3^-$, $10^5 \times M\ NO_3^-$ | 0.5 | 4 | 1.8 | | | | 4.8 | 41 | 3.4 |
| $Cl^-$, $10^5 \times M\ Cl^-$ | 26 | 15 | 3.4 | | | | 28.9 | 45 | 5.1 |
| K, $10^5 \times M\ K^+$ | 6.9 | 6 | 5.6 | | | | 2.9 | 45 | 2.1 |
| Na, $10^5 \times M\ Na^+$ | 32 | 5 | 5 | | | | 29.3 | 45 | 4.5 |

*Table 3.1. Characteristics of the former St Cuthbert's Stream, 1965 to 1973, compared with character - istics calculated from stream-size ratios. Concentrations (total anion divalent) $10^5 \times M$, aggressiveness and hardness, ppm $CaCO_3$, stream-size l/min. $NO_3$ values from 1966 - 1973 by subtracting ($SO_4$ + Cl) from total anion; from 1994 - 1997 by ion chromatography.*

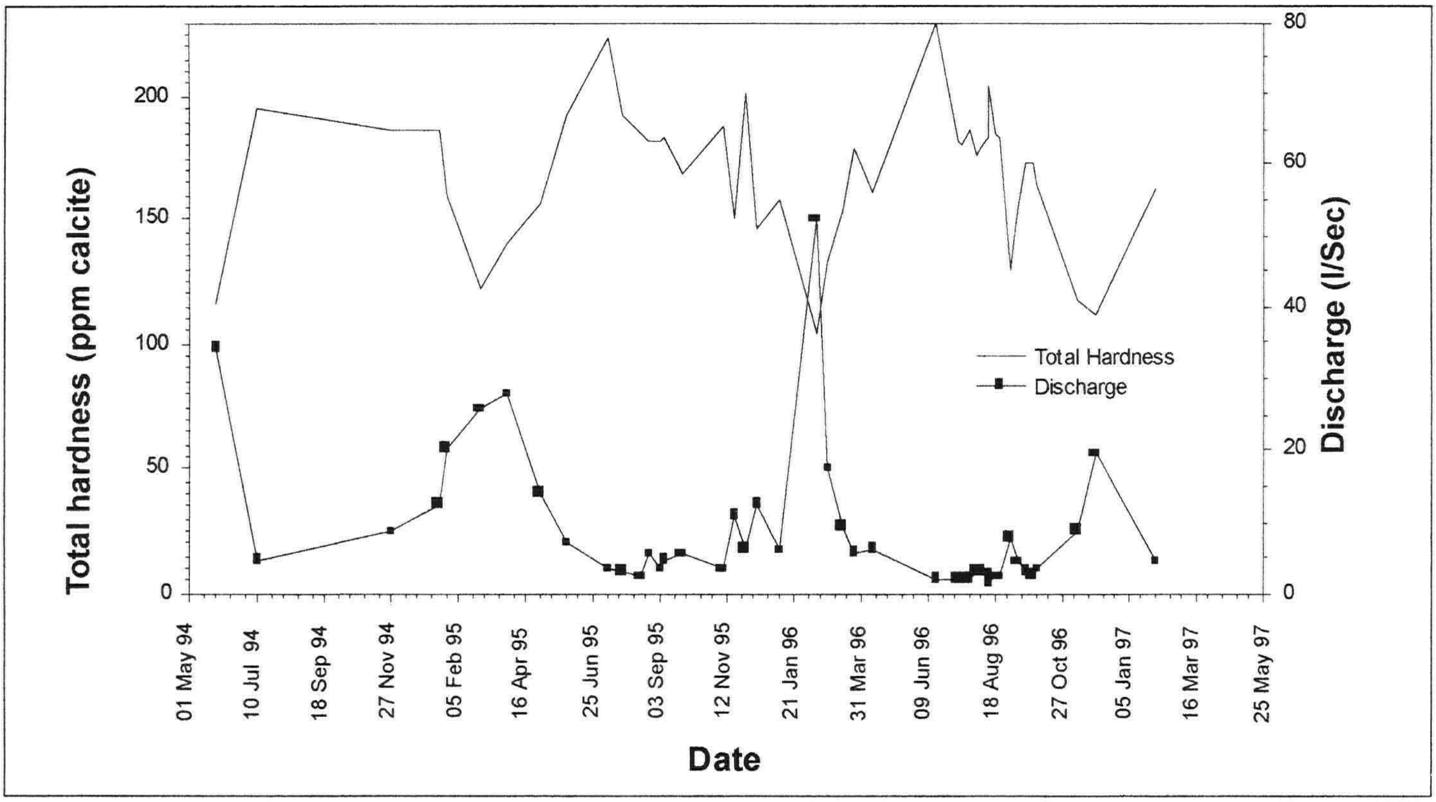



*Figure 3.1 Total hardness (ppm as calcite) and discharge (in litres per second) of the former St. Cuthbert's Stream, May 1994 to February 1997. Total hardness calculated from differences between Mineries Pool outflow and Main Stream Sink, using Method of Mixtures.*

170m northeast of the cave entrance), flowed down the valley to sink close to the cave entrance, with an overflow to the Maypole Sink in wet weather, as described previously (Stenner, 1967; Irwin, 1991). Stenner (1968) and Atkinson (1971) studied the stream between 1966 and 1973, sampling the stream within 60m of the cave entrance. In the marsh where the stream rises, open water was found only in small stretches of isolated trickles, and only at the edges of the marsh did the trickles emerge from the marsh and combine to make the St Cuthbert's Stream.

Since the Mineries Pool outflow stream changed its course, some of its water mixes with water from the St Cuthbert's Inlet stream in the outer parts of the marsh. Mixing of the two streams is finally completed downstream of the marsh. It is therefore no longer possible to sample the old St Cuthbert's Stream directly, except in abnormal severe droughts, when the Pool outflow stream dries up.

The difference between the stream-size at the cave sink and that at the Pool outflow is a measure of the size of the additional inlet water. Although at times leakage from the Fair Lady Well stream makes a contribution to the additional water, the large majority of the extra water is the former St Cuthbert's Stream.

From the stream-size values and changes of the characteristics of the Pool outflow stream between the Pool Outflow and the Main Stream Sink, the characteristics of the additional water were calculated by using the Method of Mixtures. It was assumed that changes took place only as a result of mixture of Pool outflow water with the extra water. Characteristics that change independently, such as temperature and aggressiveness, cannot be studied by this method.

### 3.1. Results

Characteristics of the additional water are presented in Table 3.1. Direct measurements of characteristics of samples of trickles in the marsh are presented in Table 3.2, together with samples from the cave sink obtained when the Mineries Pool Outflow stream was dry.

### 3.2. Discussion of the results

The high mean value for stream-size between 1994 and 1997 is noted. There were several extremely high stream-size measurements in wet weather during this period (values considerably higher than any records from 1966 - 1970, but the stream-size in the great storm of July 1968 was not measured). The high values for calcium, alkalinity and total hardness reflect unusual conditions in the drought summers of 1995 and 1996. High values in the estimated calcium and bicarbonate values in Table 3.2 for 1994 to 1997 are supported by similar values from isolated trickles quoted in Table 3.3. Nevertheless, strong similarities can be seen between the estimated characteristics of the hidden stream (calculated from stream ratios) and those of the former St Cuthbert's Stream (including data by Atkinson, 1971), and recent data from the marsh in Table 3.2. The results support the assumptions made in this exercise.

Data from the non-alkaline hardness/calcium sulphate event surge that followed the 1995 drought (Heathwaite *et al.*, 1999) were examined. Results showed that the added water contained normal levels of sulphate. The calcium sulphate surge was not present in this stream,

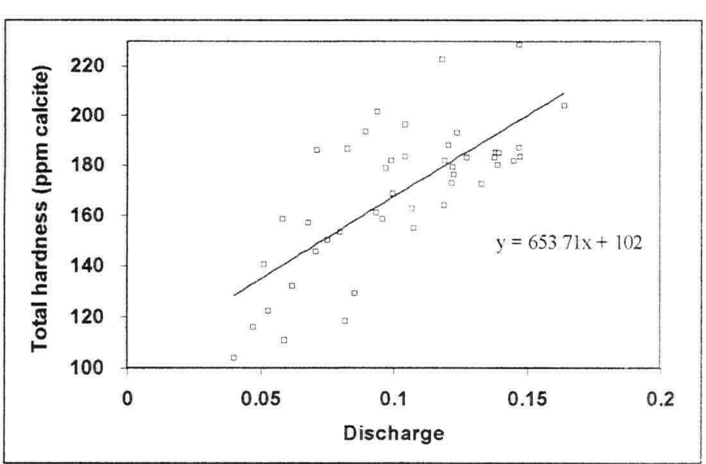



*Figure 3.2. The relationship between discharge (as $Q^{-0.4}$) and total hardness in the former St. Cuthbert's stream, calculated using the Method of Mixtures.*

| | Pool Outflow Dry 1995 | | | Trickles in the Marsh 1996 | | |
|---|---|---|---|---|---|---|
| Date | 13.08 | 24.08 | 3.09 | 13.04 | 3.05 | 30.11 |
| Temperature °C | 12.3 | 13.1. | 10.7 | 9.0 | 10.2 | |
| Discharge l/min | 141 | 324 | 200 | | | |
| Total hardness ppm $CaCO_3$ | 185 | 182 | 182 | 180 | 212 | 210 |
| Aggressiveness ppm $CaCO_3$ | -15.0 | -4.4 | -8.9 | | -2.7 | -5.5 |
| Mg, $10^5 \times M$ | 16.6 | 16.3 | 18.8 | 9.4 | 9.1 | 10 |
| Ca, $10^5 \times M$ | 168 | 166 | 163 | 171 | 203 | 200 |
| Alkaline hardness ppm $CaCO_3$ | 169 | 164 | 171 | 167 | 206 | 203 |
| Non-alkaline hardness ppm $CaCO_3$ | 16.6 | 17.7 | 10.7 | 12.9 | 6.4 | 7.2 |
| $SO_4^{2-}$, $10^5 \times M\ SO_4^{2-}$ | 11.9 | 12.4 | 12.0 | | | |
| $NO_3^-$, $10^5 \times M\ NO_3^-$ | 4.7 | 6.1 | 3.0 | | | |
| $Cl^-$, $10^5 \times M\ Cl^-$ | 25 | 39 | 23 | 34 | 21 | 28 |
| K, $10^5 \times M\ K^+$ | 1.7 | 15.7 | 1.9 | 4.1 | 3.8 | 4.7 |
| Na, $10^5 \times M\ Na^+$ | 30 | 30 | 27 | 21 | 20 | 24 |

*Table 3.2. Characteristics of the former St. Cuthbert's Stream, from 6 samples collected from 1995 to 1997; 3 when the Pool Outflow was dry, and 3 from trickles in the marsh (the source of the stream). Concentrations $10^5 \times M$, aggressiveness and hardness, ppm $CaCO_3$, stream-size l/min.*

and was restricted to water that had actually passed through the Mineries Pool after the drought ended. This proved that this stream (and hence the former St Cuthbert's Stream) did not pass through the Mineries Pool.

The characteristics of the additional water (the former St Cuthbert's Stream) are more similar to those of Fair Lady Well rather than the Mineries Pool Outflow Stream, as might be expected from the similar geology of its source.
Because water can be stored temporarily in marshy ground between the Mineries Pool and the cave sink, it is possible to mismatch the size of the pool exit stream and that of St Cuthbert's Stream. On such occasions, calculated characteristics of the additional stream will be in error. One extreme example was from 30/05/94, when the cave entrance had been dammed earlier that day to help a party entering the cave. A vast volume of water built up in the marshes in the valley bottom. When the dam was opened the stored water was gradually released. The stream-size at the cave sink was measured to be 2,860 l/min. This was a serious mismatch with that at the pool outflow, 800 l/min, and with the stream-size 125m upstream of the cave entrance (after addition of water from the former St Cuthbert's Stream), 980 l/min. Characteristics of the additional water on that occasion, calculated from stream-size at the main stream sink and at the pool outflow, were quite impossible. Among 53 sets of figures, 7 other sets of estimates for the additional water characteristics were also obviously grossly in error, in addition to the results of 30/05/94. It is believed that the natural release of water from temporary storage also led to impossible results in some of the other 7 examples. The 8 datasets were deleted from the database.

The estimate of the stream-size of the additional water was compared with the estimate of the total hardness of this water. The result is shown as a time series graph, in Figure 3.1. The regression equation between the two sets of indirect estimates is shown in Figure 3.2. Figures 3.1 and 3.2 both show remarkably precise co-relationships. Figure 3.1 is very similar to relationships reported elsewhere, and Figure 3.2 is very similar to the relationship found using data by Atkinson (Knights and Stenner, 2001, in preparation). The authors contend that this is an astonishing demonstration of what can be achieved using the Method of Mixtures, in a situation when a stream cannot be sampled directly.

### 3.3. Conclusions

The power of the Method of Mixtures can be seen in this application. It produced data to describe the hydro-chemical characteristics of a stream that can no longer be sampled directly.

## REFERENCES


Atkinson, T C, 1971. Hydrology and Erosion in a Limestone Terrain. Unpublished PhD thesis, Univerity of Bristol.

Bray, L G, 1975. Recent chemical work in the Ogof Ffynnon Ddu system: further oxidation studies. *Transactions of the British Cave Research Association*, Vol.2(3), 127-132.

Bridge, J L, Cooper, C M, Kelly, S D, Marsh, S D and Stenner, R D, 1977. Limestone solution and changes of dissolved gas concentrations at stream sinks of three caves in the Mendip Hills, Somerset. *Transactions of the British Cave Research Association*, Vol.4(3), 355-359.

Ford, D C, 1966. Calcium carbonate solution in some Central Mendip caves, Somerset. *Proceedings of the University of Bristol Spelaeological Society*, Vol.11(1), 46-53.

Donnan, W H, 1952. Some notes on the discharge measurements of small streams. *Cave Research Group Newsletter*, 40, 7-15.

Heathwaite, A L, Knights, A V and Stenner, R D, 1999. A calcium sulphate surge in a stream draining an upland marsh on Mendip (Somerset) following the drought in the summer of 1995. *Proceedings of the University of Bristol Spelaeological Society*, Vol.21(3), 251-267.

Irwin, D J, 1991. *St Cuthbert's Swallet. Bristol Exploration Club*, 82pp.

Knights, A V and Stenner, R D, 1999. The role of ion balances in examining the reliability of analytical data: a case study of Mendip streams (Somerset). *Proceedings of the University of Bristol Spelaeological Society*, Vol.21(3), 235-249.

Knights, A V and Stenner, R D, 2001. Some aspects of the hydrology of streams which drain through St Cuthbert's Swallet (Priddy, Somerset). *In preparation*.

Knights, A V, Sandford, E, Stenner, R D and Williams, J, 2001. Some aspects of the hydrology of St Cuthbert's Swallet, Priddy, Somerset. *In preparation*.

Pitty, A F, 1966. An approach to the study of karst water, illustrated by results from Poole's Cavern, Buxton. *University of Hull Occasional Papers in Geography*, 5.

Smith, D I and Drew, D P, 1975. Limestones and caves of the Mendip Hills. [David and Charles.]

Stenner, R D, 1966. The variations in temperature and hardness in streams in St Cuthbert's Swallet, a progress report. *Belfry Bulletin*. Vol.21(1), 117-200.

Stenner, R D, 1968. Water tracing in St Cuthbert's Swallet, Priddy, Somerset. *Cave Research Group Transactions*, Vol.10(2), 49-60.

Stenner, R D, 1969. The Measurement of the aggressiveness of water towards calcium carbonate. *Cave Research Group Transactions*, Vol.11(3), 175-200

Stenner, R D, 1970. Preliminary results of an application of the procedure for the measurement of the aggressiveness of water to calcium carbonate. *Cave Research Group Transactions*, Vol.12(4), 283-289.

Stenner, R D. 1973. A study of the hydrology of GB Cave, Charterhouse-on-Mendip, Somerset. *Proceedings of the University of Bristol Spelaeological Society*, Vol.13(2), 171-226.

Stenner, R D, 1997. Changes in the distribution of water between surface sinks and stream inlets in St Cuthbert's Swallet, Priddy, Somerset. *Proceedings of the University of Bristol Spelaeological Society*, Vol.21(1), 9-24.

CAVE KARST SCIENCE Vol. 28, No.1 April 2001
Transactions of the British Cave Research Association

ISSN 1336-191X

# The occurrence of *Niphargus glenniei* (Crustacea: Amphipoda: Niphargidae) in West Cornwall, UK

**Lee KNIGHT**
No.1, The Linhay, North Kenwood Farm, Oxton, Nr. Kenton, Devon, EX6 8EX, UK

**Abstract:** Two new records of *Niphargus glenniei* are reported from wells in West Cornwall. This is the first reported occurrence of this species outside Devon since its discovery in 1948.

*(Received 27 April 2001 ; Accepted 5 July 2001)*

*Niphargus glenniei* (Spooner, 1952) is a small, unpigmented and eyeless 'well shrimp' species. It differs from the other three British species of Niphargus [*N. aquilex* (Schiödte, 1855), *N. kochianus* (Bate, 1859), *N. fontanus* (Bate, 1859)] by virtue of the structure of the mandible palp, the form of the telson and uropods, and its smaller size. N. glenniei is sexually mature between 2.5 - 4mm in size (most individuals tend to be around 3mm), whereas other *Niphargus spp.* attain sexual maturity at a size of 4 - 6mm (most mature specimens are around 8mm in size) (Spooner, 1952).

Historically these morphological differences were considered significant enough that several authors have placed the species in the genus *Niphargellus* (Schellenberg, 1938) in common with the continental species Niphargellus arndti (Schellenberg, 1938) and *Niphargellus nolli* (Schellenberg, 1938) (Gledhill et al., 1993). A more detailed discussion of the validity of the genus *Niphargellus* can be found in Gledhill *et al.*, 1993; Spooner, 1952; and Karaman *et al.*, 1994. Until recently *Niphargus glenniei* was only known to occur in the county of Devon. The species is thought to be endemic to southwest England and is afforded a RDB K/5 (red data book listed: insufficiently known / endemic) conservation status (Bratton, 1991).

Prior to 1998 *N. glenniei* had been recorded only from Napp's Cave, near Berrynarbor in North Devon, and from twelve sites in South Devon. These sites included: a spring issuing through metamorphosed slate at Moortown, near Tavistock; superficial riverine gravels in a spit on the upper reaches of the River Plym, at Cadover Bridge on Dartmoor; a well at Moorgate, near South Brent; and several caves and mines, mostly in the vicinity of Buckfastleigh (Gledhill *et al.*, 1993; Knight, 1999; Spooner, 1961). Since 1998, an ongoing project examining the distribution of the species has been undertaken by the author, leading to the identification of an additional five cave records in South Devon, including sites in the Chudleigh, Torquay and Brixham Devonian limestone outcrops (Fig.1).

*N. glenniei* was first observed by Brigadier E A Glennie, in the company of Mary Hazelton, who captured the first specimen, on 19th April 1948. Six specimens were seen in a small, shallow, mud-lined pool on the slope leading down to the Lake in Pridhamsleigh Cavern. The holotype was examined by G M Spooner of the Marine Biological Association, who described it in 1952 (Spooner, 1952). Glennie (1967) states that "*Niphargus glenniei* is a highly interstitial form" as suggested by its thin body, lateral or dorso-ventral flattening and small size. *N. glenniei* is probably widespread within the groundwater of Devon. It is believed that the true habitat of *N. glenniei* is channels of phreatic water in underground rock strata. Following heavy rain it is frequently washed out into streams and pools in caves and mines, where it can more easily be observed and collected (Knight, 1999).

During the summer of 2000 Alma Hathway and Bruce Wotton McTurk, the owners of a private nature reserve at Caer Bran, near Sancreed, West Cornwall, noticed small crustaceans in their water supply, which originated from an old well on the farm (well NGR: SW 4051 2921). They sent specimens to Stella Turk (Environmental Records Centre for Cornwall and the Isles of Scilly). Initially it was assumed that they were *Niphargus aquilex*, which has been recorded

| Date | Location | Description | Sampling Method | Taxa Collected |
|---|---|---|---|---|
| 25/2/01 | Well at Caer Bran Farm, Sancreed SW4051 2921 | A deep covered well, providing water supply for the farm | Collected by Alma Hathway from tap in farm house kitchen | *Niphargus glenniei* |
| 26/2/01 | Chapel Euny Holy Well, Sancreed SW 4179 2929 | A small holy well, approx. 2.5m deep with approx 1m of water fed by a trickle of ground water in a corner of the well. | Sweeps with a long-handled zooplankton net (250μm mesh) | Oligochaeta<br>Cyclopoida<br>*Plectrocnemia conspersa*<br>*Velia caprai* |
| 26/2/01 | Spring in field near Bosfranken Farm SW 3834 2545 | Ground water issues at a point behind a hedgerow, marshy gravel | Sweeps / kick sampling with a zooplankton net. Some gravel also collected and washed through sieves | Oligochaeta, *Pisidium sp.*<br>Chironomidae, Palpomyiini<br>*Psychoda sp.*, *Pericoma sp.*<br>*Phylidorea sp.*, *Cheilotrichia sp.*<br>*Orthonevra sp.*, *Nemoura erratica*<br>*Hydroporus sp. (larvae)*, *Agabus sp. (larva)*<br>*Helophorus sp. (indet female)* |
| 26/2/01 | Springs near Gilley SW 3849 2500 | 3 springs, with a shared issue point. The water is collected by two pipes buried into the ground. Water is then directed to a collecting tank with an overflow | Drift net (250μm mesh) placed in front of overflow for approx. 30 minutes | No fauna collected |
| 27/2/01 | Well near Trevelloe Farm SW 4441 2588 | Ground water up-welling in a small depression beside B3315 | Sweeps with zooplankton net at point of issue | Oligochaeta, Chironomidae<br>Palpomyiini, Stratiomyidae<br>*Pilaria discicollis gp.*, *Nemoura sp. (indet)*<br>*Asellus meridianus*, *Nemurella picteti*<br>*Plectrocnemia conspersa*, *Micropterna sequax* |
| 27/2/01 | Well at Brea Downs SW 3795 2865 | Disused, covered well approx. 11m deep with 6m of water | Three trawls of a 250μm mesh zooplankton net, lowered on a rope | *Niphargus glenniei*<br>Oligochaeta<br>Cyclopoida |
| 27/2/01 | Well at Old Mills junction SW 4579 3447 | A small well beside the Trevaylor Stream. Approx. 1m deep, filled to brim with water. Groundwater up-wells at bottomof well | Drift net (250μm mesh) placed at issue point at bottom of well for approx. 150 minutes | Chironomidae<br>Nemouridae |
| 27/2/01 | Stream in most easterly of Cot Valley adits. Adit entrance: SW 3602 3069 | A small stream that issues from the collapsed end of the adit (within the dark zone) and flows out of the adit into the Cot Valley Stream | Drift net placed at issue point of stream, left overnight | *Velia caprai*<br>*Simulium sp. (indet)*<br>Chironomidae<br>*Folsomia sp.* |
| 28/2/01 | Well at Caer Bran Farm, Sancreed SW4051 2921 | A deep covered well, providing water supply for the farm | Pipe nets (250μm mesh) attached to taps in farm house kitchen and caravan near well. Taps allowed to run for approx. 30 minutes, until header tank had run dry | No fauna collected |
| 28/2/01 | Well at Boleppa SW 4200 3036 | A small well in the garden, approx. 2m deep with approx 1.5m of water. Fed by groundwater seeping in at the bottom of the well | Sweeps with zooplankton net | Oligochaeta, Cyclopoida<br>Plectrocnemia conspersa<br>Asellus meridianus, Anurida sp. |

*Table 1. Site locations, sampling methods and taxa collected*

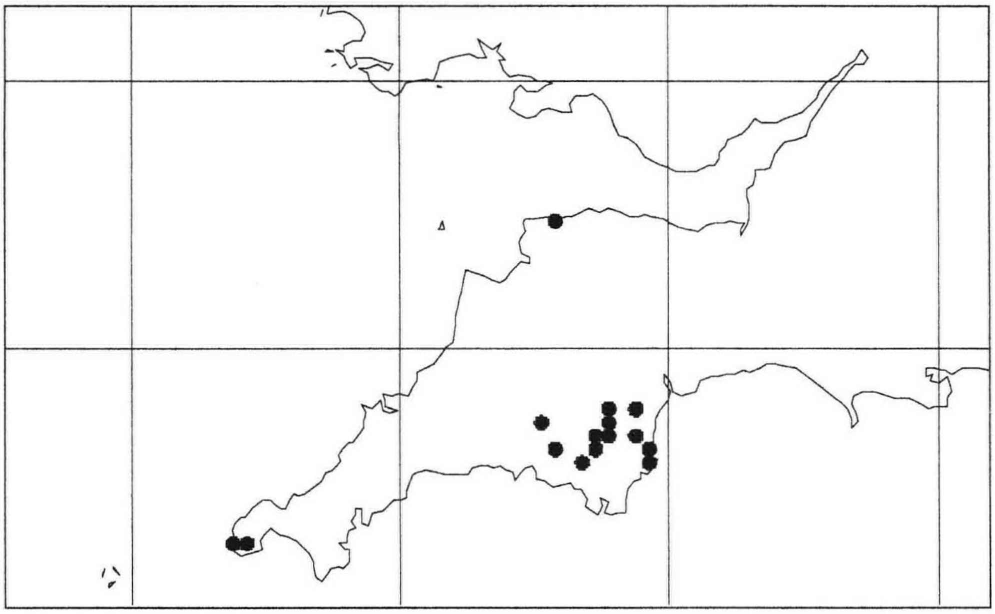


*Figure 1. Distribution of Niphargus glenniei in SW England. The grid lines represent divisions of the Ordnance Survey National Grid.*

from wells in Cornwall and is widespread in the caves and hypogean water of Devon. However, microscopic examination led to an identification of Niphargus glenniei. The identification was subsequently confirmed by Dr Terence Gledhill of the Freshwater Biological Association.

In November 2000 T Gledhill informed the author of this discovery and a preliminary investigation was initiated to determine if *N. glenniei* was present at additional sites in the locality. Sancreed is situated to the west of Penzance, on the Land's End boss of adamellitic granite (Edmonds *et al.*, 1985). The area has numerous wells and springs. On the initial visit the primary emphasis was on these hydrological features. Future visits are likely to concentrate on pools within the many mines in the area.

From 26th to 28th February 2001 eight springs, seven wells and one underground stream, in a mine adit, were visited. These were geographically widespread, covering the area from Penzance to Land's End and from the north to the south coast of the peninsula. Many of the wells in the area are located adjacent to private dwellings and, with the exceptions of Caer Bran Farm and Boleppa, both owned by colleagues of Mrs Turk, these were avoided during this trip. The well at Sparnon was not sampled due to difficulties in accessing the well chamber. Most of the springs were unsuitable for investigation, as no discernible issue point was evident, with groundwater up-welling to the surface in the form of an extensive marshy area. A total of two springs, six wells and the adit stream were eventually sampled. Collection methods varied according to the individual site characteristics (see Table 1 for locations of sites and sampling methods used). *Niphargus glenniei* was found at two of the wells investigated.

Caer Bran farm was visited on 28th February. Pipe nets (250µm mesh) were attached to taps at the farm and the water allowed to run for approximately half an hour. No fauna were collected on this occasion, although Alma Hathway had collected two specimens on 25th February. These were later examined and confirmed to be *Niphargus glenniei*. The second well is a disused well at Brea Downs near Land's End Aerodrome (NGR: SW 3795 2869). The well is approximately 11m deep with about 6m of water. On 27th February a 250µm mesh net was lowered on a rope and three trawls were made through the water. Four specimens of *N. glenniei* (three adults and one juvenile) were collected, along with Oligochaeta and Cyclopoida.

The discovery of *Niphargus glenniei* in West Cornwall is important, as it is the first occurrence of this species outside of Devon, in an area geographically isolated from the next nearest site for the taxon, near South Brent. This reinforces the view, formulated following the author's recent discovery of new locations in Devon, that *N. glenniei* is much more widespread in hypogean waters than previously assumed. It is likely that the species will be found at other sites between the Land's End peninsula and the Devon border. It is also possible that *N. glenniei* exists in Somerset. Holwell Cave in the Quantocks (not far from the Devon border) is situated in Devonian limestone, as are the caves at Buckfastleigh. Both *Niphargus aquilex* and *N. kochianus* (the latter absent from Devon and Cornwall) have been recorded from this cave (Glennie, 1967), although during the last visit by the author (13th June 1998) only *N. aquilex* was recorded. The inherent difficulties of investigating the hypogean fauna are no doubt the main reason for the lack of distributional information for this elusive group of organisms.

## ACKNOWLEDGMENTS

The help of Alma Hathway and Bruce Wotton McTurk, owners of Caer Bran, and of Robin and Sarah Menneer, owners of Boleppa, for allowing their wells to be studied and for their hospitality during the author's visit is acknowledged. Acknowledgement to Stella Turk for identifying the first specimens of *Niphargus glenniei* found in Cornwall and Terence Gledhill who confirmed the identifications. Special thanks to Stella Turk for her hospitality and help. Thanks to the above, Paul Wood (University of Loughborough) and two anonymous referees for proof-reading the manuscript. Additional thanks to Terence Gledhill for his permission to reproduce the line drawing of *N. glenniei*, and thanks to Dr Peter Smithers of the University of Plymouth for producing the distribution map.

## REFERENCES

Bratton, J H (Ed.) 1991. *British Red Data Books: 3. Invertebrates other than Insects.* Joint Nature Conservation Committee. 253pp.

Gledhill, T, Sutcliffe, D W and Williams, W D, 1993. *British freshwater Crustacea Malacostraca: a key with ecological notes. FBA Scientific Publication*, No.52. 173pp.

Glennie, E A, 1967. The distribution of the hypogean Amphipoda in Britain. *Transactions of the Cave Research Group of Great Britain*, Vol.9, 132-136.

Edmonds, E A, McKeown, M C and William, M, 1985. *British Regional Geology, South West England.* 138pp. [London: Her Majesty's Stationery Office.]

Karaman, G S, Gledhill, T and Holmes M C, 1994. A new subterranean amphipod (Crustacea: Gammaridea: Niphargidae) from southern Ireland, with comments on its taxonomic position and the validity of the genus *Niphargellus* Schellenberg. *Zoological Journal of the Linnean Society*, Vol.112, 309-320.

Knight, L R F D, 1999. The hypogean Crustacea of Devon. *Journal of the Devon Spelaeological Society*, Vol.156, 20-25.

Spooner, G M, 1952. A new subterranean gammarid (Crustacea) from Britain. *Proceedings of the Zoological Society*, London, Vol.121, 851-859.

Spooner, G M, 1961 *Bathynella* and other interstitial Crustacea in southern England. *Nature*, Vol.190, 104-105.

ISSN 1336-191X

# Forum

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

All views expressed are those of the individual authors and do not necessarily represent the views of the Association unless this is expressly stated. Contributions to the *Cave and Karst Science* Forum are not subject to the normal refereeing process, but the Editors reserve the right to revise or shorten text. Such changes will only be shown to the authors if they affect scientific content. Opinions expressed by authors are their responsibility and will not be edited, although remarks that are considered derogatory or libellous will be removed, at the Editors' discretion.

## SCIENTIFIC NOTE

## THE OCCURRENCE OF MALACHITE IN JOINT HOLE, NORTH YORKSHIRE, UK.

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

Cave divers have reported the sporadic occurrence of minor amounts of a moderate yellowish green (10 GY 6/4) to brilliant green (5 GG 6/6) mineral, coating gravel size particles in unconsolidated sediments in the active phreatic conduit of Joint Hole main passage, Chapel-le-Dale. X-ray diffraction analysis identified the mineral as malachite ($Cu_2CO_3(OH)_2$). The size of the main passage (commonly 5m by 8m) indicates that it is of considerable age, but has been protected from being drained and subsequently removed by erosion because it lies behind an inlier of Early Palaeozoic metasedimentary rocks (Ingleton Group) forming the valley floor to the southwest.

The sedimentary fill of the conduit was described by Murphy (1999). Unconsolidated sediments occur in isolated bar forms, commonly in the lee of individual boulders, and bedform positions are seen to have changed following flood events. The malachite coatings are friable and it seems unlikely that they would survive entrainment, transportation and deposition of the sediment associated with the high energy conditions of a flood event. Thus, the visible coatings probably indicate deposition of malachite on the gravel sediment that has taken place subsequent to the last flood.

Malachite has been recorded as a secondary deposit in relict conduits, from various localities around the world (Hill and Forti, 1986), but no previous record is known from an active phreatic conduit. Copper carbonate occurrences are widespread in the rocks of the Askrigg Block of Northern England, probably derived as an alteration product of chalcopyrite (Dunham and Wilson, 1985). Around the year 1880 copper ore was mined from rocks of the Great Scar Limestone Group in Dentdale, nine kilometres to the north of Joint Hole (Lings, 1986). Here the ore occurred as crystals and botryoidal masses of chalcopyrite developed inside quartz-lined vugs. Base metal carbonates form wall and floor coatings in the relict phreatic passages of Pikedaw Calamine Cavern near Malham (Raistrick, 1954;Waltham *et al.*, 1997). This occurrence may relate to the redistribution of metal ions by dissolution from primary sulphides in hydrothermal veins during the phreatic phase of the cave's history (Raistrick, 1954; Waltham *et al.*, 1997). Malachite among the unconsolidated sediments of Joint Hole may indicate the ongoing occurrence of such a process in the present day phreatic zone within the rocks of the Great Scar Limestone Group.

## ACKNOWLEDGEMENTS

Thanks to Mr Brian Schofield of the Cave Diving Group, for providing samples, and to Ms L Neve of the School of Earth Sciences, University of Leeds, for undertaking the XRD analyses.

## REFERENCES

Dunham, K C and Wilson, A A, 1985. Geology of the Northern Pennine Orefield: Volume 2, Stainmore to Craven. *Economic Memoir of the British Geological Survey.*

Hill, C A and Forti, P, 1986. *Cave minerals of the world.* [Huntsville, Alabama: National Speleological Society.]

Lings, A S, 1986. Dent copper mine. *The Mine Explorer* (Journal of the Cumbria Amenity Trust), Vol.2, 30.

Murphy, P J, 1999. Sediment studies in Joint Hole, Chapel-le-Dale, North Yorkshire, United Kingdom. *Cave and Karst Science*, Vol.26, 87-90.

Raistrick, A, 1954. The calamine mines, Malham, Yorkshire. *Proceedings of the University of Durham Philosophical Society*, Vol.11, 125-130.

Waltham,A C, Simms, M J, Farrant, A R and Goldie, H S, 1997. *Karst and Caves of Great Britain.* Geological Conservation Review Series No.12. [London: Chapman and Hall].

## BOOK REVIEWS

**Barry F Beck and J Gayle Herring [editors], 2001. *Geotechnical and Environmental Applications of Karst Geology and Hydrology.* Published by A A Balkema, 437pp. ISBN 90 5809 190 2. Price US$90.00.**

Geotechnical and Environmental Applications of Karst Geology and Hydrology is the eight proceedings volume of the Multidisciplinary Conference on Sinkholes and the Engineering and Environmental Impacts of Karst. Like previous proceedings in this bi-annual series of conferences, this volume is designed for professionals that deal with the unique hydrogeological environment of karst terrane.

This proceedings volume is over 400 pages long, divided into eight sections, and includes sixty papers from geologists, hydrologists engineers and planners throughout the United States and fourteen other countries. All authors provided valuable information to the karst community, and the exclusion of any authors not mentioned in this review is due simply to space constraints.

Section 1 contains the keynote paper of the conference (Marinos) and describes the engineering challenges of tunneling and mining in karst terrane.

Section 2, Sinkhole Formation, contains papers that concentrate on sinkhole occurrence (Halliday), cover-collapse sinkholes (Tharp; Cooley), spatial variability (Hyatt *et al.*), human induced sinkholes (Gao *et al.*) and subsidence rates of alluvial dolines (Soriano and Simon). Hubbard provides an interesting paper that overviews karst mapping performed in Virginia and methods used to locate and map sinkholes along with a discussion on sinkhole distribution and karst hazards.

In Section 3, Regional Studies of Sinkholes and Karst, three papers describe the use of a Geographic Information System (GIS) to study karst features (Chenoweth and Day; Gao *et al.*; Green *et al.*). Colombi *et al.* give details on a two-year study that will be conducted in the Lathium sinkhole region of central Italy. The results of the study will be used to develop a numerical model and a conceptual matrix for sinkhole genesis and the development of a sinkhole hazard classification.

The first paper in Section 4, Evaluating the Risk of and Remediating the Damage from Sinkhole Collapse, describes a two-phased karst investigation along a 2,000-foot [c.600m] stretch of U.S. Highway 23 in Michigan (Benson and Kaufman). Two papers describe risk assessment evaluations in karst (Calitz; Lei.). Three papers provide conceptual models at various sites, and Dreybrodt provides a computer model that demonstrates that leakage of dam sites could be caused by dissolution widening of narrow fractures.

Salvati et al. provide a model for sinkhole genesis, and Siegel and McCrackin present a model to determine the interaction of a landfill bottom liner supported by a geosynthetic – reinforced soil above a sinkhole.

Cooper et al. describe how a geographic information system consising of 2D and 3D geological information for Britain is used for capturing geological hazard information to reduce the use of unstable land. Another paper (Tolmachev and Leonenko) stresses the need for improved geotechnical investigative standards when developing on karst terrain in Russia.

Section 5, Groundwater and Contaminant Movement in Karst, contains thirteen papers discussing various tools used to characterize groundwater quality in karst. Bednar and Aley demonstrate that groundwater dye tracing is an effective tool to assess the potential impacts of highway development to karst groundwater resources and associated cave fauna. Currens provides results from a 5-year study regarding the effectiveness of best management practices in agricultural land toward protection of karst aquifers.

Other papers of note in this section discuss the occurrence of coliform bacteria in a karst aquifer in West Virginia (Kozar); mapping of karst groundwater basins in Kentucky's Inner Bluegrass region (Paylor and Currens); legal issues regarding high volume groundwater pumping (Richardson); performance of activated charcoal for detection of fluorescent compounds (Smart and Simpson); use of natural background fluorescence as an aid to dye tracer test design (Smart and Karunaratne); and the effectiveness of geologic barriers for preventing karst water flow into coal mines in north China (Zhou and Li).

Section 6, Treatment of Environmental Problems in Karst, includes three papers that describe remediation methods used at gasoline spill sites (Berry *et al.*; Gillespie; Schaezler *et al.*). A literature review on karst subsurface exploration (Mirabito *et al.*) techniques and a case study for the Merck Landfill cap project is provided. Pope describes void and mitigation strategies used to protect water quality and quantity in Austin, Texas. Another paper describes landfill gas transport in karst (Smith). Worthington and Ford provide test methods for developing a conceptual model for a PCB-contaminated carbonate aquifer in Ontario.

Section 7, Using Geophysics in Karst Investigations, provides the reader with eight papers documenting the use of various geophysical techniques in karst investigations. Methods used include electrical resistivity, thermography, cone penetration tests and 2D electrical resistivity tomography, natural potential mapping, microgravity and electrical tomography, and biostatic low frequency ground penetrating radar.

Section 8, Field Trip Guide. Part 1 describes environmental problems associated with urban development in the karst area of Bowling Green, Kentucky. Part 2 provides a description of the geology and hydrogeology of Mammoth cave.

I recommend this proceedings volume to all individuals interested in, or that work in, the unique geological environment know as karst terrane. This proceedings provides something of interest for everyone, whether it is the application of groundwater dye tracing, subsurface remediation, GIS technology, geophysical techniques, or sinkhole formation. Once again the editors have done a fantastic job of compiling the number of papers presented in this proceedings volume.

## REFERENCE

Beck, Barry F. and J. Gayle Herring (editors), 2001, Geotechnical and Environmental Applications of Karst Geology and Hydrology: Proceedings of the Eighth Multidisciplinary Conference on Sinkholes and the Engineering and Environmental Impacts of Karst, Louisville, Kentucky 1-4 April 2001. 437pp. [Rotterdam, Netherlands: A A Balkema.]

*Reviewed by David M Bednar, Jr., PG, Michael Baker Jr., Inc., Petroleum Square II, 1324 North Hearne Avenue, Suite 255, Shreveport, Louisiana, USA*

**Donal Daly, David Drew, Jenny Deakin, David Ball, Matthew Parkes and Geoff Wright (editors), 2000. *The Karst of Ireland Limestone: Landscapes, Caves and Groundwater Drainage Systems.* Prepared by members of the Karst Working Group. [Dublin: Geological Survey of Ireland.] ISBN 1 899702 41 5. Can be requested free, "whist stocks last", from Dr Matthew A Parkes, Irish Geological Heritage, Geological Survey of Ireland, Beggars Bush, Haddington Road, Dublin 4, Ireland. (003531) 6041493, Fax 6681782. E-mail: matthewparkes@gsi.ie**
**The booklet content is also freely available on the GSI website: http://www.gsi.ie/workgsi/groundwater/karstbook/karst-fra.htm**

Extensive outcrops of limestone cover more than 40% of the island of Ireland, and include some of the finest karst landscapes in Europe. Yet, until recently, there has been little effort to conserve these landscapes. This glossy 37-page A4 booklet, aimed mainly at the casual reader, endeavours to educate ordinary people in simple terms, about the importance of karst landscapes. It covers not only their intrinsic beauty, but also their important as aquifers, as tourist attractions, and as part of the archaeological heritage, as well as discussing their implications for planning and engineering projects.

Karst areas in Ireland are being put at risk from a number of directions, including water pollution, waste dumping, insensitive tourism or other development, vandalism, quarrying and inappropriate drainage. High-profile cases such as the proposed Burren National Park Interpretation Centre at Mullaghmore and the application to turn Poll an Ionian into a show cave, putting its internationally famous stalactite (known affectionately as the 'soggy dishcloth') at risk, have highlighted some of the problems associated with inappropriate development. Without the support of public opinion, these sorts of developments could become commonplace.

The Karst Working Group intends to raise the profile of karst landscapes and their conservation amongst the general public. This booklet is part of that process, and only time will tell how well it will work. Nevertheless, the booklet is one of the better introductions to karst for non-specialists that I have read. The style is generally readable and most of the diagrams are clearly laid out, although necessarily some are a little over simplified for the more informed reader.

The booklet is divided into sections describing what karst is, and discussing its importance in Ireland, followed by individual considerations of the main karst regions. Quite why a section on palaeokarst is placed before the section on karst regions in Ireland is unclear; it would have been better placed towards the end of the book. Following the regional descriptions is a discussion of the engineering and environmental aspects of karst and a section on conservation of the karst landscape. It is excellent to see such a valuable section on groundwater pollution and the engineering and environmental aspects of karst. Whereas many members of the general public will be vaguely aware of how caves form, and perhaps know a little about karst landforms from their school days or show cave tours, most will be essentially ignorant of these aspects of karst. Yet it is these issues that may be most important, especially in rural parts of Ireland, where sinkholes and caves are commonly seen as convenient rubbish tips or carcass disposal sites, not as rapid contaminant flow paths into the aquifer.

Perhaps one of the main shortcomings of the booklet is a general lack of quality maps to show the locations of some of the classic karst features. The map of the Burren in particular could have been clearer and more informative; the shale margin is unclear and there are no indications of major cave system locations. Similarly, cave locations are not marked on the map of the northwestern plateau karsts and no map at all exists for the east midlands, the western lowlands, the southern valley karst or the Ulster Chalk regions. For those lacking a good knowledge of Irish geography, identifying places mentioned in the text can be difficult.

Although some topic areas - notably the role of cavers and caving clubs in discovering, surveying and protecting caves, and the huge amount of effort they put into researching caves - have been glossed over, this booklet does provide a good introduction to karst for the non caver. Hopefully it will be widely distributed and go some way towards educating members of the general public. As a help towards fulfilment of this aim, it is pleasing to see a note that all or part of the document may be reproduced without permission, providing only that the source is acknowledged. Let us hope that this book succeeds in its aim.

*Reviewed by Andy Farrant, British Geological Survey, Keyworth, Nottingham, NG12 5GG, UK.*

**Yonge, Charles J, 2001. *Under Grotto Mountain. Rat's Nest Cave.* Rocky Mountain Books, #4 Spruce Centre SW, Calgary, Alberta, T3C 3B3, Canada. ISBN 0-921102-77-1. Price $19.95 plus relevant carriage charge (contact yonge@telusplanet.net for details), or visit the website at: www.canadianrockies.net/WildCaveTours**
**Also available from Cordee, 3A De Montfort St, Leicester, LE1 7HD, UK. Tel: 0116 2543579; Fax: 0116 2471176**

*Under Grotto Mountain* ... is an unusual sort of caving book, mixing science and history of exploration with abundant anecdote and speculation. I cannot claim that this "review" is what might normally be expected in *Cave and Karst Science*, as I have known and caved with the author for well over 20 years, and some level of bias is inevitable. In fact, when the author gave me a signed copy of the book a few months ago I decided not to review it myself, but to seek the impressions of someone less close to the author and less steeped in cave exploration and the cave sciences. What was needed was an enthusiastic "intelligent lay person" who could read the book and assess its success as a vehicle for delivering a plethora of information, some on highly technical subjects, on a variety of levels. However, following spectacular failure to identify and corner such an individual, rather than see the publication go unremarked and pass into obscurity as just another parochial account of "a cave", the following words are offered. For the reason admitted above, and having made small editorial contributions to parts of the book, I cannot claim a total lack of subjectivity. However, if these words stimulate a second, more objective, review from a different viewpoint, we will arrange for its publication in the future.

Chas Yonge will be known to many UK cavers (certainly of my generation if not among current activists) for his involvement in many and varied cave explorations with the University of Leeds Speleological Association, Sheffield University Speleological Society and the Cave Projects Group during the Nineteen-sixties and Nineteen-seventies. Following migration to Canada to pursue PhD research at McMaster, he continued his explorations there and in many parts of the world, building an ongoing reputation as a committed caver, dedicated cave scientist and karst consultant. Today, among many other interests and activities, he runs Canmore Caverns Ltd, which offers specialised interpretative cave tours in Rat's Nest Cave, near Canmore and Banff in Alberta. He also wrote this book.

First impressions of the book, even before a word has been read, are encouraging. Its format is small (?A5), with soft-back and a coloured cover with pretty decent cave photos front and back. The binding of the c.144 pages seems strong and resilient. The obligatory first flick through the book reveals not only an 8-page block of colour pictures in the centre of the volume but also a healthy content of black and white photographs and text figures. In fact, the main part of the book carries at least one illustration within every 2-page spread, commonly more than one and in some cases as many as three or four. Most of the colour and black and white photos have reproduced well, and some of them are exceptionally sharp and clear, looking good as well as providing the intended enhancement of the text material. The text figures include maps, block diagrams, schematic flow figures, charts and a variety of other diagrams. First impressions are that they are clear and uncluttered, easy to understand and useful. Finally, tucked away under the back flap of the book (which carries a "dynamic" picture of the author) is a folded survey of Rat's Nest Cave, also easy to follow and an invaluable aid in reliving the story of the cave's development and its exploration.

The first few pages of the book are taken up with a very thorough and generous acknowledgements section, a brief Preface (or executive summary), a one-page list of further reading, that will be useful to readers from outside mainstream caving and cave science, and a description of how the book is organised. I was amused to read the author's thanks to two friends, both English teachers, for their help in unravelling long and convoluted sentences. Perhaps they could have helped with the first sentence in this paragraph, which is causing great distress to the software grammar checker! Moving on from the various introductory pages, the author gets stuck into the book's main tasks, and I think the best approach is simply to proceed chapter by chapter.

In *"Touring Rat's Nest Cave"* (Chapter 1) the author takes us through the assembly of a typical tour party followed by an equally typical hike up to the cave entrance. There is a rather detailed description of the cave tour itself, followed by a briefer comment on the downhill stroll back to the Rose and Crown in Canmore to unwind and relive the highlights of the trip! The narrative is fascinating in itself, clearly re-telling a blend of many well-observed actions and incidents. These must be a distillation from many personal visits as well as from guided tours, yet they are embroidered with all the "hooks", "gimmicks" and evocative language that are used by cave tour guides the world over. No offence intended.

Moving on, the well-illustrated *"Caving in the Canadian Rockies"* (Chapter 2) provides a synthesis of some major milestones in the history of local cave exploration. Starting with an early, tricouni-booted early examination of Arctomys Cave (1911) the author moves on to describe some of the more significant facets of the exploration of Castleguard Cave, a system that he clearly knows well. From there he moves to renewed explorations that started in 1971 and led to Arctomys becoming Canada's deepest cave. In this section there is no attempt to duck the darker side of caving, which is raised by inclusion of a brief account of a fatal accident in Arctomys during 1991. Another account follows, describing aspects of the exploration of caves in the Crows Nest Pass area including Gargantua and Yorkshire Pot – where the story of an epic self-rescue is described. More staggering for those who have not been involved in high mountain caving is another story, based on the author's first-hand experience, of a winter trip with the near-legendary Everyday Dave (Dave Thomson). This trip led to minimal finds in terms of new cave, but was seasoned with frostbite for the intrepid explorers as they battled through biting winds at temperatures as low as -47°C! A final paragraph in this chapter hints at the future potential of finding systems deeper than Arctomys, with mention of Close-to-the-Edge, with its 254m-deep entrance shaft and another huge shaft (undescended at the time of writing) beyond.

On the theoretical side the author now turns to the *"Geological Origin of the Cave Rock"* (Chapter 3). In only four brief pages the geological history of the area is synthesised, including a fantasy journey across the still-building Carboniferous reefs in the Panthalassan Ocean on the shores of ancient Laurasia, some 360 million years ago. This is fascinating and imaginative stuff. The history of deposition and tectonic activity, tackled in a step by step manner, is highly informative and succeeds well in emphasising the extreme length of geological time. A couple of simple but effective block diagrams and a chronological table of geological events add to the ease of understanding for "lay" readers.

Perhaps in proportion to the relatively shorter overall timescale involved, Chapter 4, the *"Geological History of Rat's Nest Cave"*, occupies only three pages, including a helpful geological cross-section and another table of events. Again a variety of complex concepts is presented in terms that should be readily understood by those without a cave and karst science background.

Chapter 5, *"Ancient Environments: What the Cave can tell us"*, follows on naturally, and includes introductions to many aspects of past and present cave development theory. Even Bögli's famous mixing curve is re-created and described in readily understandable terms. Within this chapter the author moves on to one of his own pet topics – isotopic dating. Many dates from within Rat's Nest Cave are discussed, and one is left with the distinct feeling that the author is on first-name terms with each of the speleothems involved! It might be argued that, on balance, the consideration of dating is overlong in a lay person's book. If it is, it is also thorough and understandable and, like much of the rest of the book, it is peppered with items of the author's experience and with personal insights of the other scientists that he has met.

Moving on from the "then" of cave development, Chapter 6 looks at the "now" of *"Cave and the Modern Environment"*. Here again the author draws upon a wide knowledge, not only of the background sciences but also of practical examples of the processes and effects involved and their applications in the human context. A section on cave winds might be rather too technical, but it leads nicely into a consideration of radon, with a clear illustration of the uranium 238 decay scheme. The chapter ends with a thoroughly "hands-on" description of cave surveying and a brief consideration of cave radio location as a survey confirmation mechanism, and this brings us to the mid-point of the book.

Most of the colour plates in the mid section have reproduced well and, perhaps in keeping with a book about a partly "tourist cave", many of them show speleothems. Some of these also illustrate other facets of the cave though, and a few other plates show aspects of the cave's structure and form.

Not surprisingly the photo section leads into Chapter 7, *"Mineral Formations"*. After discussing the underlying science of underground mineral deposits the author considers each type of speleothem in turn, quoting examples of each from within Rat's Nest Cave.

Chapter 8 describes *"Cave Life and the Bone Bed"* and is subdivided, not surprisingly but perhaps with a hint of the macabre, into *"the Living"* and *"the Dead"*. The former looks at the modern cave flora and fauna, including the rather endearing *Bushy Tailed Wood Rat* that gave the cave its name. The latter section describes the animal remains found in the Bone Bed, a 2m-thick deposit at the foot of the entrance shaft. It is believed that this bed provides a continuous record of 7000 years of the cave's history. On consideration that bones are also found in passages well away from the Bone Bed, the author suggests that other, currently blocked, entrances may exist, whereas the presence of bats in one remote part of the cave might suggest an open but unknown entrance.

In Chapter 9, humans appear on the scene (*"Human Presence: Pelican Lake Culture*). Relatively few early human artefacts have yet been found in Rat's Nest Cave, but they suggest the presence of aboriginal humans in the area between about 1350BC and 100AD. Possibly the cave provided shelter for transient groups of aboriginal hunters in those early days.

Chapter 10 (*"The Mystery of Hector's Cave"*) moves on more than a thousand years and recounts the story of a possible visit to the cave by European explorers in 1858. Here the author discusses evidence that suggests James Hector and Eugene Bourgeau, part of the Royal Geographical Society's Palliser Expedition (1857-1860) might have encountered Rat's Nest Cave. The evidence is not conclusive, as the author readily admits, but currently known alternative explanations of the explorers' accounts are still less convincing.

Chapter 11 (*"Modern Exploration"*) begins with a recommendation to the reader to *"Pull out the cave map and follow the explorers"* – a suggestion also to be found on the outer back cover. Perhaps to set the scene, it launches immediately into a graphic account of a breakthrough dig at the Birth Canal by Everyday Dave and the almost equally infamous (in some circles) Norman Flux. Having thus grabbed the reader's interest the author switches to a description of the *"Early Trips"*, starting in the 1950s but taking off seriously in the 1970s, mainly by members of the Alberta Speleological Society. In 1979, when it seemed that all open passages had been explored, the first dives in the cave were attempted. Activity continued sporadically along the obvious water route, ending in 1989 at two impassable routes out of Sump 4. The next part of the chapter describes the late Nineteen-eighties exploration of more that 1.5km of passages beyond the Birth Canal dig described previously. Accounts of deeper explorations along a previously overlooked lead that had not been pushed before the excavation of the Birth Canal form the final part of the chapter.

The final chapter (*"Ecotourism and Management of the Cave"*) goes into significant detail about ecotourism in general and about potential and actual impacts upon Rat's Nest Cave in particular. Whereas it's clearly not intended as an alternative source of information to other, purpose-written, cave management books and papers, the chapter provides a useful digest for those with a more casual interest. Tables provided by Jon Rollins, describing *"Areas of concern underground"* and *"Valued ecosystem components underground"* are a particularly useful synthesis.

Following the main text of the book are a useful Glossary of cave-related terms, a section describing *"Caving Organizations in Western Canada"* and an Index covering the various aspects of the cave and its exploration.

Being as objective as possible in a situation where the book's author is a personal friend, where I have contributed directly to the book's evolution, and where my previous knowledge of the cave and the underlying science is greater than that assumed for the target audience, I think that this is a valuable little book, for a number of reasons. In the first place my original reaction was that it was a little too chatty and leant too heavily upon personal anecdote and personal involvement. But the whole thing grew on me. I was able to take a figurative step back and appreciate the scientific explanations for what they were and enjoy the personal glimpses of people, whether they were explorers or scientists. Plus, there really was a feeling of being in the cave. Several past authors have achieved the latter in various ways, but I can think of no other book that has managed to blend aspects of science, exploration and personal anecdote so successfully. No doubt each person reading the book will encounter their own likings and irritations, and perhaps have their own ideas on how it might have been reorganised or otherwise "improved". But for me, considering the target audience, it's pretty near the mark, and should make essential reading for those coming fresh to caving and to cave and karst science.

*Described by Dave Lowe, British Geological Survey, Keyworth, Nottingham, NG12 5GG, UK.*

# 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, Worcestershire, WR13 6LF, UK. Closing dates for applications are: 31August and 31 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 31 January each year..

# BRITISH CAVE RESEARCH ASSOCIATION PUBLICATIONS

**CAVE AND KARST SCIENCE** - published three times annually, a scientific journal comprising original research papers, reports, 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, Nottingham, NG12 5GG, UK, and Professor J Gunn, Limestone Research Group, University of Huddersfield, Queensgate, Huddersfield, HDI 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: Clive G Gardener, 23 Landin House, Thomas Road, London, E14 7AN, 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, Y07 2AT, UK.*

*BCRA Research Fund application forms and information about BCRA Special Interest Groups can be obtained from the BCRA Honorary Secretary: John Wilcock, 22 Kingsley Close, Stafford, ST17 9BT, UK.*