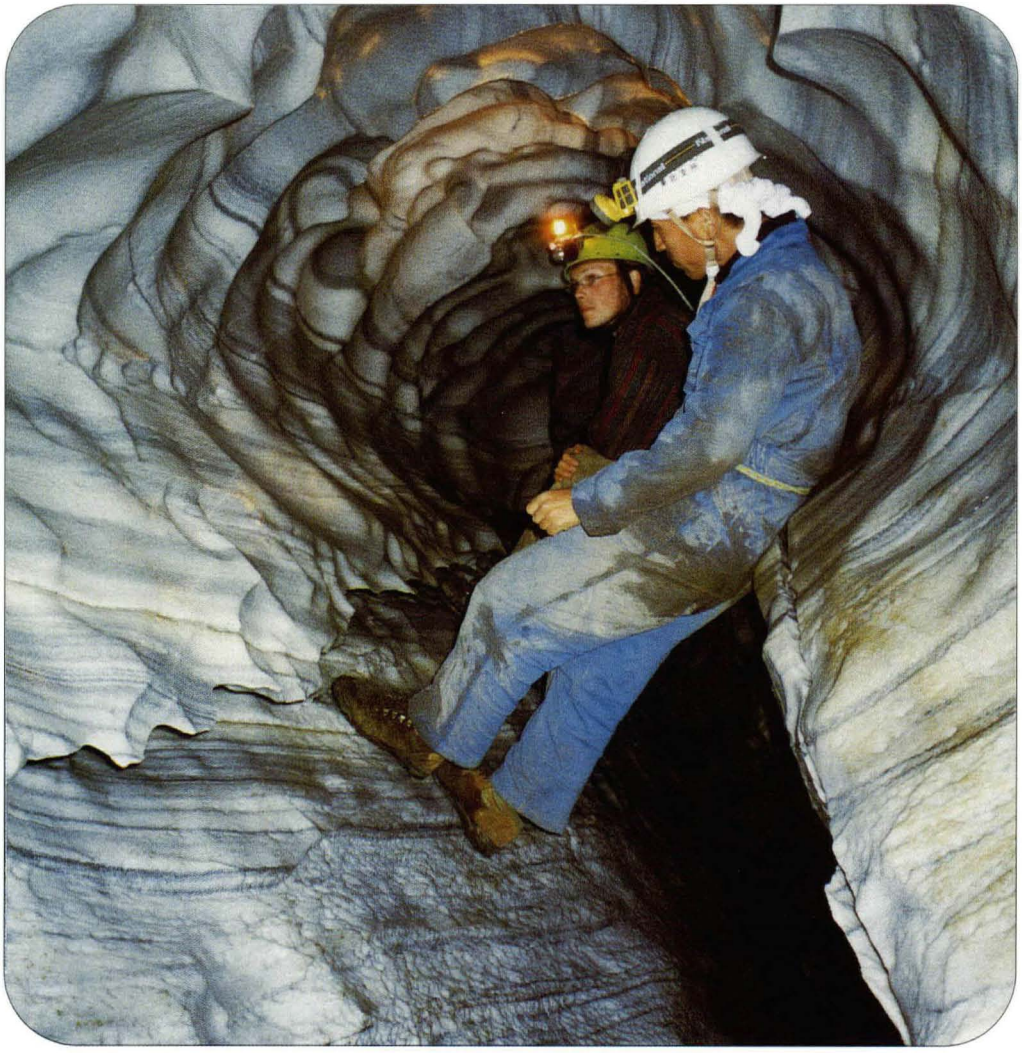
Cave and Karst Science

The Transactions of the British Cave Research Association

BCRA

Volume 24 Number 2 August 1997



Decomposing animals and cave invertebrates
Quartzite dissolution – karst or pseudokarst
Redefining karst and pseudokarst
Climate change : the karst record
Forum

Cave and Karst Science

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

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

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

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

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

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

Notes for Contributors

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

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

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

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

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

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

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

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

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

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

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

Cave and Karst Science

TRANSACTIONS OF THE BRITISH CAVE RESEARCH ASSOCIATION

Volume 24 Number 2 August 1997

Contents

Cover photo:
Fossholet, Upper Glomdal, Norway
Photo by Charles J Yonge (see article by Yonge)
Dynamic vadose passage with active stream in banded marble, Fossholet, Upper Glomdal. The Glomdal valley divides the Svartisen Icecap into east and west portions, and lies across the Arctic Circle.

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

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EDITORIAL

David Lowe and John Gunn

As in 1996, this Summer has been hectic for both of us, with a profusion of symposia and an increasing plethora of new and ongoing research projects in need of fieldwork and interpretation. There can be few, whether scientists or non-scientists, who will have been fortunate enough to participate in more than a selection of the many conferences, congresses and symposia that have been on offer this year, appealing to those with general speleological or geomorphological interests, or to more specific aspects of karst related studies. In the wake of the immensely "busy" 12th International Speleological Congress and its associated excursions, we would particularly like to thank the many individuals from around the world who have commented, generally favourably and enthusiastically, about recent issues of Cave and Karst Science, and about how this publication might develop in the future. We are thinking about their suggestions.

Now that the majority of this year's major international events have passed, with only the photos to be developed and oral presentations to be written up, it is once more time for us to think more parochially about future BCRA activities. The next annual British Cave Research Association Cave and Karst Science Symposium will be hosted by Professor Ian Fairchild, in the Department of Earth Sciences at Keele University, Staffordshire, on Saturday 7 March 1998. Traditionally these BCRA symposia are intended to appeal not only to scientific specialists, but also to all those with a more general but informed interest in a wide variety of cave and karst related topics. The multi-disciplinary approach, and the broad spectrum of participants, allow a healthy exchange of ideas, by means of which non-scientists are informed about recent research trends and results whilst taking the opportunity to bring at least some of the scientists down to earth. In the past we have stressed that the image of a BCRA symposium should lean more towards a semi-formalised forum for disseminating and gathering interesting information than towards a high-powered, ivory-tower, presentation of dust-dry academic reports. The 1997 event, held at Huddersfield University, was attended by interested non-specialists as well as by undergraduate and post-graduate students and a scattering of established scientists, and there were items among a varied programme that must have appealed to everybody who attended.

To make the 1998 symposium a success, the BCRA needs support from two directions. First of all there must be a varied and attractive programme that will help to ensure the second element - a worthwhile level of support from scientists and non-scientists, whether Association members or not. To meet the first requirement we ask potential contributors to come forward now with offers of short presentations (20 or 40 minutes) on any subject related to cave or karst science. If you are not yet ready to contribute in this way, poster papers, displays or preliminary presentations by postgraduate students are equally welcome. Hopefully the response to this and other requests will be sufficient for a lively and entertaining programme to be put together, and this in turn will encourage a worthwhile turnout. In the first instance offers of all types of presentation should be sent to: The Lectures Secretary, T M Whitaker, Greenfoot Barn, Low Bentham, Via Lancaster LA2 7EQ [telephone 015242 62269, or e-mail tmw1@mail.cybase.co.uk]. The cost of entry to the event (including refreshments) will be £7.00 (BCRA members) or £8.00 (non-members), with a discount to half the relevant price for speakers and undergraduate students.

As we reported in the Editorial of the last issue of Cave and Karst Science our forward plan is that the first issue of Volume 25 in 1998 will be a special, commemorative or theme, issue. Thus, we are unlikely to have the opportunity to pre-publish abstracts of the finalised programme of talks scheduled for the 1998 symposium. However, if all goes to plan they will be included in the subsequent edition and potential contributors to the symposium are encouraged to submit a full version of their presentation for possible publication in later issues of Cave and Karst Science. It is worth noting that at least one paper in each of this year's issues was aired first at an earlier BCRA symposium. Presenting papers at the symposia does not guarantee acceptance for publication, but the wide knowledge base of the "average" symposium audience does provide an ideal sounding board for floating ideas and receiving helpful feedback.

Before closing this part of the editorial we must mention that articles and correspondence in this issue continue the ongoing debate with respect to the fabric of karst terminology. As reported in passing in the last issue, an interesting addition to the literature has now appeared, in the form of a theme issue of the International Journal of Speleology, entitled "Gypsum Karst of the World", issued to commemorate the occasion of the 12th International Speleological Congress and the subsequent 4th International Geomorphological Congress. We hope to provide a review of this volume in a future issue of Cave and Karst Science, but for now it is worth pointing out that it includes a chapter in which Alexander Klimchouk argues compellingly that "gypsum karst", commonly assumed to fall outside mainstream karst definitions, is a "true karst".

Finally, before passing to the sombre inclusion below, we would like to take this opportunity to add our congratulations to those undoubtedly already received by our editorial predecessor, Trevor Ford, on the occasion of his recognition by the award of the OBE. All those who know Trevor as a scientist, as an editor and as an individual will know that the award is well-deserved. Without doubt the award represents a personal triumph for Trevor, but equally it constitutes a welcome "feather in the cap" of cave and karst science as a whole. Well done, Trevor.

We thank Clive Gardener for his help in providing the following appreciation.

ROB PARKER: 1962 - 1997

It is with a further sense of great loss to the caving community that we report the untimely death of another leading cave diving explorer, Rob Parker, who died while exploring the Four Sharks Blue Hole, off South Andros in the Bahamas, on 17 August 1997.

Rob developed his underwater skills, from novice to world-class cave diving explorer, in the early 1980s, in partnership with Julian Walker, and under the guidance of Martyn Farr and Rob Palmer. His achievements gained national recognition in July 1985, following his diving in Wookey Hole where, with the brotherly assistance of the American diving technology guru Bill Stone, he pioneered the use of Trimix diving techniques in British cave diving. Here, he established a cave diving depth record of 68m, beyond Chamber 25, and this record remains unbroken to the present day.

As a caver, in the early 1980s Rob joined Clive Gardener in the Chelsea Spelæological Society explorations of Pwll Gwynt and Trident Passage, and in the first serious examinations of the speleological potential of Carno Adit. His contributions to these explorations, as a caver, as a climber and, especially, as a friend, culminated in the discovery of the Borrowed Boots Streamway and the Icing on the Cake formations in Daren Cilau during November 1985. He shared the epic exploration to the most remote subterranean diving site in Britain - the 7th Hour Sump - with fellow cave diver Ian Rolland.

Rob took part in many international caving and diving expeditions, such as those to the Blue Holes of the Bahamas, the Peña Colorada Resurgence to the Huautla System in Mexico, the Cuava de Agua at Tresvisas in the Picos Mountains, the Wakulla Springs in Florida, and to China. His character as well as his impressive diving and climbing efforts made him universally liked, even loved, and admired, but somewhat difficult to emulate! His diving career was abruptly interrupted by the tragic death of Ian Rolland, in Mexico, on March 27 1994, during the Sótano de San Agustín explorations, in which Rob was also about to participate.

From the early 1990s Rob concentrated on developing his climbing abilities, and used his carpentry talents to found and build the Bristol Climbing Centre at St. Werburgh's Church. "Undercover Rock" is now recognised as a leading national centre for the development of climbing skills. Rob was also acquiring film making skills, under the wing of Leo and Mandy Dickinson, with whom he carried out several diving and climbing film projects. The success of his efforts in diving exploration and historical diving camera work led to his invitation to join German NDR Television in the Bahamas for the production of a film on the Blue Holes, dedicated to the memory of his friend Rob Palmer. It was here, carrying the torch for another British cave diving pioneer, that he so cruelly lost his life, whilst returning from an underwater exploration and survey trip, at one of the human frontiers that he so much loved to conquer.

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The effects of decomposing animal remains on cave invertebrate communities

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Abstract: The deterioration and disarticulation of rat carcasses, exposed in caves at Creswell Crags near Worksop, Nottinghamshire, has been investigated over a five-year period, and the involvement of arthropods with the decomposing material examined. Following consumption of soft tissues by dipterous larvae, the fate of the remainder differs according to depth. Animals close to the cave entrance are likely to be mummified. Those deposited farther inside are first colonised by fungi and then attacked by diptera. Disarticulation and skeletalisation usually occur after 2-4 years, if scavengers are excluded. For several years, carrion provides a habitat for both cavernicolous and non-cavernicolous arthropods, the latter disrupting the threshold cave community. In the hypogean region, the over representation of some troglophilic species changes the community structure for at least two years after carcass deposition, although the non-cavernicolous arthropods soon disappear.

INTRODUCTION

Decomposition is responsible for over 95% of community metabolism in terrestrial ecosystems (Putman, 1983) and invertebrates play a vital role in this process. However, most early investigations (Steele, 1927, Duffield, 1937, and Kaufman 1937) concerned carrion and other materials exposed on the ground surface, as did work by Putman (1977). The most comprehensive study of arthropods associated with vertebrate remains (Payne et al, 1965 et seq.) concentrated on carrion decomposition above ground. However, Payne et al (1968) studied pigs buried in coffins. Five carcass stages, each with a specific microcommunity, were identified: fresh, inflation, deflation and decomposition, disintegration and skeletalisation. Carcass weight declined more slowly than on the surface and different organisms attacked the remains. Forty-eight arthropod species were recorded, 26 not implicated in above-ground decomposition.

Biospeleologists have used carrion as bait for cavernicolous arthropods (Peck, 1975). Arthropods attracted to carrion in caves may move or bury it, disturbing cave sediments (Macdonald, 1992) or disrupting archaeological deposits (Atkinson, 1957, Stein 1983). Oligochaete worms may also be responsible for such bioturbation (Thomas and Bottrell, 1992). However, exactly how animals decompose in caves, which are the most important British source of fossil vertebrates, and a key source of information on early humans is poorly understood. Many vertebrates live or over-winter in caves and some use them to cache or eat food (Andrews, 1990), while others simply fall in (Shipman, 1981). Inevitably, some will die there and little is known about how their remains are incorporated into cave deposits

There are also important implications for an environment where lack of energy limits cave populations (Jefferson, 1976).

STUDY AREA

All work was carried out at Creswell Crags SSSI (SK535741), a Magnesian Limestone gorge on the Derbyshire and Nottinghamshire boundary, which is one of Britain's most important archaeological and paleontological sites (Fig. 1).

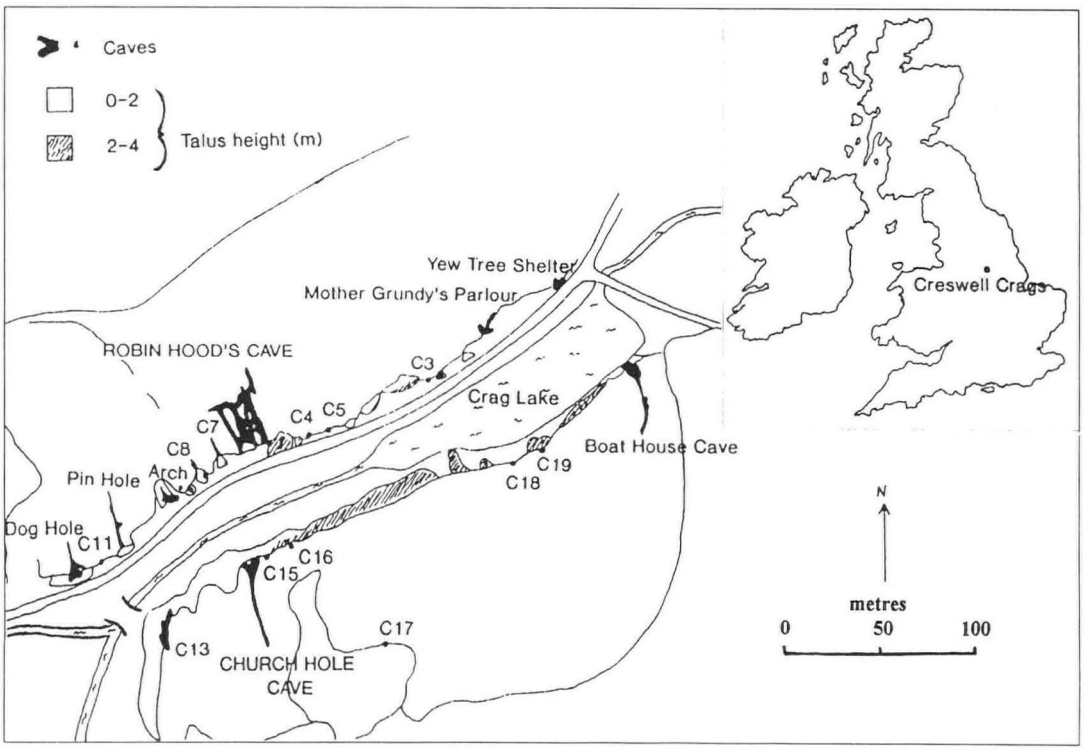

Figure 1. Creswell Crags SSSI, location of major caves.

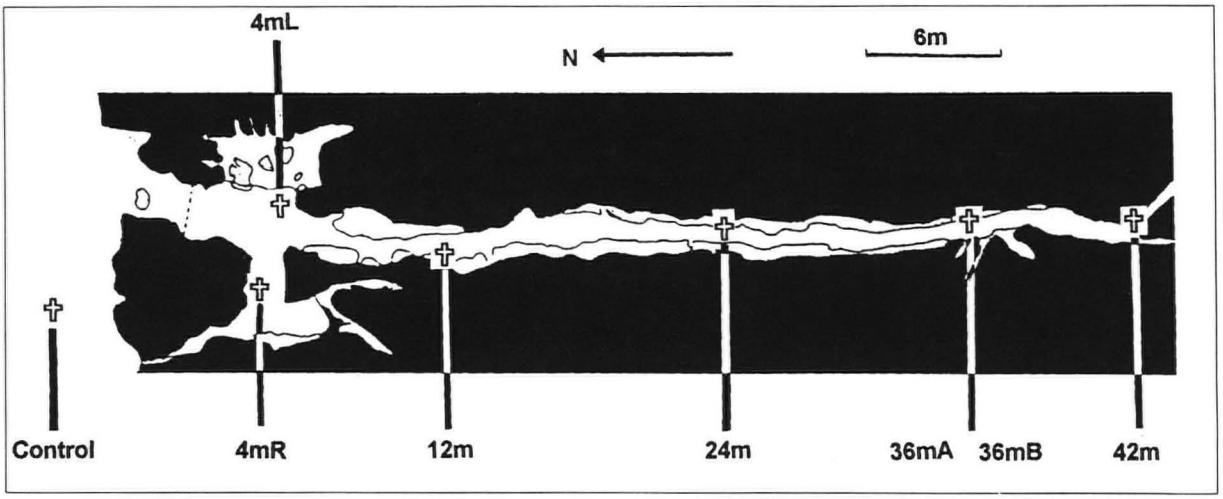

Figure 2. Church Hole Cave, Creswell Crags showing position of rat carcasses. For key see Fig 3.

The caves at Creswell were first excavated by Mello (1876) and Dawkins (1876). The latter concluded that Robin Hood's Cave had served as a hyena den and provided human habitation. Work was also carried out by Armstrong (1949) and Campbell (1969). Investigations in the 1980s have been reviewed by Jenkinson and Gilbertson (1984) and Briggs et al (1985). Particular reference should be made to *Cave Science* (16, No. 3, 1989) largely dedicated to contemporary work at Creswell.

Two caves, situated on opposite sides of the gorge, were used in this study. Long term observations commenced in Church Hole Cave in 1986, with a second, shorter, study in Robin Hood's Cave in 1989.

Church Hole (Fig. 2) is situated in the North facing side of the gorge and is a linear, vadose canyon with a small side chamber 4 metres inside. The roof tapers from 3m high at the entrance to a 1m crawl at 32m, beyond which light does not penetrate. The cave terminates in a chamber backed by a vertical closed chimney at 42m.

Robin Hood's Cave (Fig. 3) on the South facing side of the gorge is the most extensive system at Creswell, consisting of four main chambers connected by a series of passages. The cave is mostly of phraetic origin, with some vadose development. There are three current entrances and the maximum penetration into the cliff is 58m. Since the early 1980s the caves have been protected by metal grilles that deter casual visitors but allow access by invertebrates, small mammals and birds. A comprehensive survey of the invertebrates of Robin Hood's Cave was carried out by Terrell-Nield (1985).

METHODS

Church Hole Cave

On 23rd April 1986, five Sprague-Dawley (white) rats killed by exposure to carbon dioxide, were placed at 4, 12, 24, 36 and 42m into the cave (Fig. 2). A further three rats were positioned as controls outside. Each rat was covered by a dome of 1" gauge chicken wire secured by stones to deter scavengers, which may affect insect succession (Ellison, 1990).

Other investigators, mostly working above ground, have used cats (Illingworth, 1927), sheep (Deonier, 1940), pigs (Payne et al., 1965 et seq.) and humans (Rodriguez and Bass, 1983). Although small rodent carcasses rarely last long enough to illustrate the complete decomposition sequence (Erzinclioglu, 1986), previous observations on pheasants (Terrell-Nield, 1985) indicated that in caves small carcasses could provide sufficient information.

The rats were examined three times per month for three months and then monthly until October 1991, when most of the remains were vandalised. Each time the carcasses were described, photographed and weighed if possible. Fungal cover and dipteran activity were recorded on a 0-5 scale and insect specimens collected for identification. Temperature and humidity readings were taken at floor level at 4m intervals into the cave. Additional rats were placed at 4m and 36m in April 1987.

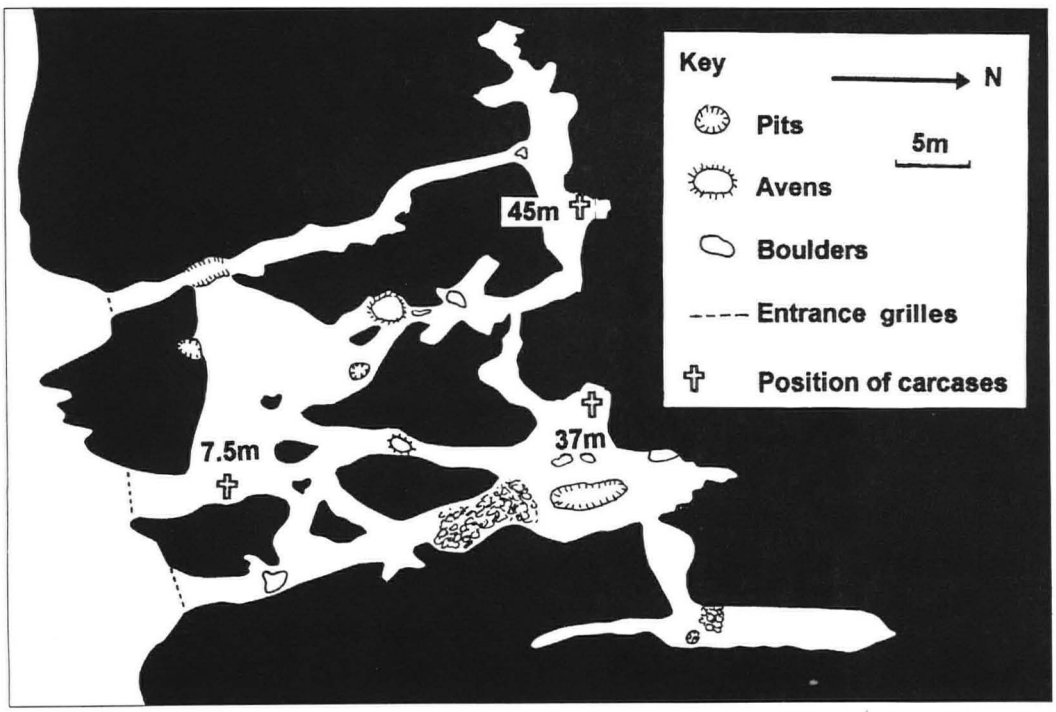

Figure 3. Robin Hood's Cave, Creswell Crags, showing position of rat carcasses.

Robin Hood's Cave

On 9th June 1989, 24 rats were placed in the cave, eight each at 7.5, 37 and 45 metres from the entrance (Fig. 3), where holes in the cave floor allowed perspex tanks to be set level with the surface.

Each 320 x 225mm tank was filled with 50, 100 or 150mm of sieved cave earth, after partly filling the tanks with concrete made with cave sediment. This arrangement allowed the effects of sediment depth on decomposition to be examined (Macdonald and Terrell-Nield, 1991). At each site two control rats were placed on bare rock. All tanks were covered with chicken wire to exclude vertebrate scavengers.

Carcasses were examined each week for 7 weeks, then monthly until May 1991, after which the tanks were removed for excavation, a process described in Macdonald, (1992). On each visit the remains were photographed, weighed, insects collected and temperatures and humidities recorded.

The cave fauna was surveyed by pitfall traps, very efficient at catching invertebrates in caves (Peck, 1976). Six traps each containing 10ml of ethylene glycol-based preservative were set at each site and examined monthly for ten months before the rats were deposited, and then for the following two years.

RESULTS

Church Hole Cave

Temperatures and Humidities

The temperature profile of Church Hole (Fig. 4) typifies a well-ventilated cave, and follows the pattern described by Smithson (1982). The maximum temperatures decline with increasing depth, and the minimum temperatures rise gradually, reducing the range from 11°C at the entrance to 4°C at 42m. At the latter the average annual temperature was 8.3°C, almost the same as at 4m into the cave. However, its 95% confidence limits at +/-0.28°C were less than half that at the cave entrance (8.5°C +/- 0.65), where temperatures were much more variable.

Deeper in the cave the air is almost saturated (Fig. 5), especially in summer. The average humidity is slightly higher than reported for dry caves by Culver (1982), and the similar confidence limits (94.5% +/- 1.68 and 95.6% +/- 1.35) indicate little variation in range between the entrance and 42m.

State of rat carcasses

Decay followed the pattern described by Meginin (1884) and Payne et al. (1968). Although too small to show a "bloat" stage, wet and dry decay phases were evident, as was a putrefaction stage. To these can be added mummification, not usually seen above ground because of weathering and scavengers, except in cases of low temperature preservation (Doyle, 1996). The fate of the Church Hole Cave rats is illustrated in Table 1.

After a 3-10 day "fresh" phase (April 1986 was cold with temperatures of 10°C or less) each carcass began to putrefy, a stage varying from 7 days (controls) to 65 days in the deep cave. Carcasses were almost always colonised by sarcophagus diptera, especially *Calliphora vomitoria* (Tables 1, 2 and Fig. 8). This did not happen to rat 4R, which was buried by *Necrophorus humator* after 20 days. The controls and rat 4L were part stripped by these sexton beetles, but the sediment was too shallow for burial. Animals at 36 and 42m into the cave became breeding sites for *Heleomyza serrata*, which is regarded as a troglophilic dipteran (Jefferson, 1976).

Fungal colonisation (Fig. 6), which for carcasses more than 12m into the cave preceded dipteran colonisation, began with a grey-blue *Penicillium* species. This was followed by a basidiomycete (which never produced spores) and *Mucor haemalis*. Both are white, the former looking like loose cotton wool, the latter erect with typical *Mucor* sporangia. Fungi first appeared where the appendages and head touched the surface. Later, orange *Fusarium culmorum* and dark green *Aspergillus* species were observed. Fungi were visible on the carcasses throughout the experiment, eventually growing on exposed bones.

During *Calliphora* colonisation the fungi deteriorated, although when larvae left to pupate (often taking fur and tissues with them), the mycelia spread onto the surrounding sediment then degenerated. At 42m into the cave, the resting bodies of *Microascus* were observed, these black sclerotia persisting for several years.

The fate of carcasses depended on location. At the entrance, mummification occurred, the skin decomposed gradually over the years, accompanied by slow disarticulation. Farther into the cave, wet decay led to partial disarticulation after the first year (Table 1). Carcasses in wetter cave areas decomposed much more rapidly than in drier regions.

Disarticulation began as the tail bones and mandibles detached. Later, cervical vertebrae separated and the skull gradually moved away from the carcass. Eventually, major limb bones detached. Carcasses deposited between 12 and 36m were largely skeletalised by the fourth year, the

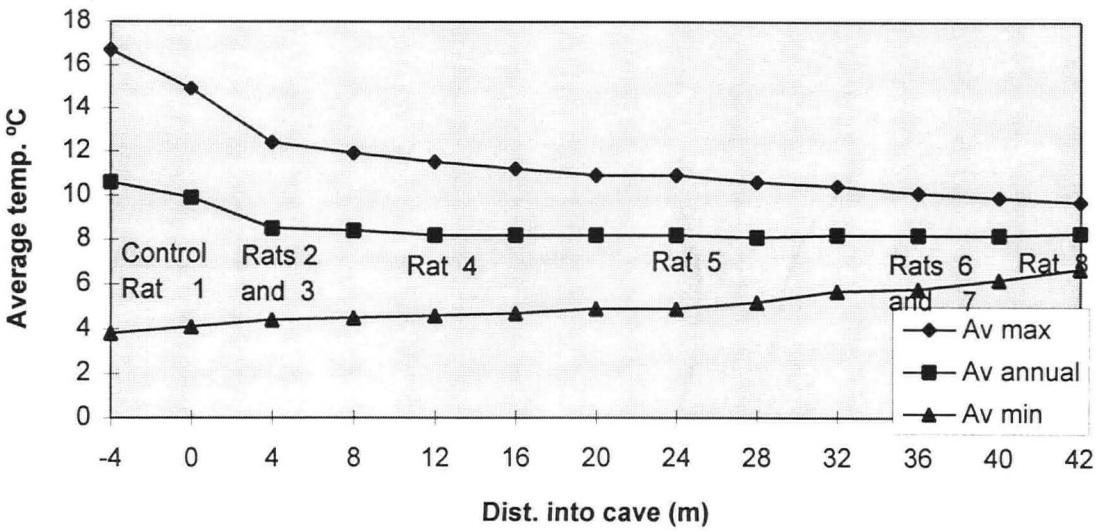

Figure 4. Church Hole Cave, ground temperatures 1986-1991.

Days since deposit	Cont. rat	4 m left	4 m right	12 m rat	24 m rat	36 m a rat	36 m b rat	42 m rat
0	Fresh	Fresh	Fresh	Fresh	Fresh	Fresh	Fresh	Fresh
20	Rancid		Burial		Rancid			
40	Dry	Rancid	Buried	Rancid		Rancid	Rancid	Rancid
60	decay							
80				Wet				
100				decay	Wet	Wet	Wet	Fungal
120	Mumm	Dry			decay	decay	decay	decay
140	-ified	decay				Disart	Part	
160							disart	
180								Wet
200	Skin		Necro.					decay
300	decay		emerg.	Part	Part		Disart	
400	Scav.			disart	disart			
500		Mumm					Skin	Dry
600		-ified				Bone	decom	decay
700			Buried	Skin		and	and	and
800		Part		decay	Disart	skin	dry	skin
900		dis-			and	decay	decay	decay
1000		art		Dry	dry		Bone	
1200				decay	decay		decay	
1400			Spoil					Bone
1600		Dis-	heap	Dis-	Bone	Bones		decay
1800		art	flat	art	decay	spread		
2000		Scav.		Scav.				

Key to terms:

Rancid: with strong odour and active maggot colonisation
Scav: scavenged (carcass removed via non-human or human activity)
Disart: disarticulated, typically tail and/or neck vertebrae separated, followed by limb disarticulation
Necro: Necrophorous investigator
Decom: decomposing/decomposition

Table 1. Church Hole Cave, condition of rat carcasses, 1986-1991.

bones spread over a radius of 0.25m. The trunk region remained intact, although the vertebral column often separated. Exposed bones from the axial skeleton became brown and shiny after 2 - 3 years, but skulls remained white. Although the shallower carcasses were vandalised in 1991, the remains at 24 and 36m were untouched and still partly articulated in 1996. The rat buried by *Necrophorus* would require permission from English Nature for excavation.

Carcass weight provides a more quantitative assessment of decomposition (Fig. 7). Weight loss, due mainly to consumption by dipteran larvae, was very rapid for the controls and slower with increasing depth into the cave, but eventually carcasses averaged 27% of their fresh weight. Typically, a 230-250g rat was reduced to 56-74g, the weight of the skeleton and dried skin. These results agree with those of Nabaglo (1973) where bank voles took twice as long to decay in burrows as on the surface. The slower weight loss in the rats at 24 and 42m is similar to that of pig carcasses from which insects are excluded (Putman, 1983).

Invertebrate colonisation

Thirty-three species of invertebrates, all arthropods, were collected from the carcasses (Table 2). Although the number of colonising species decreased with increasing depth, the proportion of cavernicolous species increased. Some animals bred on the material, particularly flies such as *Megaselia brunneipennis* (Phoridae), which colonises dry carrion, and *Heleomyza serrata* (Heleomyzidae). The major carcass coloniser, however, was *Calliphora vomitoria* (blowflies, Calliphoridae). Dipteran colonisation is illustrated in Fig. 8, which shows that carcasses exposed deep in the cave were not colonised by blowflies until 40-50 days after deposition, maximum larval activity occurring later with increasing depth into the cave.

Collembola such as *Lepidocyrtus* spp were observed on carcass and cave floor fungi whilst other species, for example *Quedius mesomelinus* (Staphylinidae) were seen under the carcasses. Widespread in European

Group/Species	Cont	4L	4R	12 m	24 m	36 m a	36 m b	42 m
Acari, Mesostigmata	3	17						
Araneae, *Lepthyphantes* sp	8	6	60		21			
Isopoda, *Porcellio scaber*	3-13	19						
Oniscus asellus			23	15-36				
Diplura, *Campodea* sp					17			45
Insecta/Collembola								
Hypogastrura purpurea				11				
Lepidocyrtus cyaneus	7-11	4-15		5,49	5-11		13	4-5
L. curvicollis					6	6	19	20
Orchesella sp	10							
Insecta/Lepidoptera								
Hofmannophilia sp.		16			4			
Hofmannophilia sp larvae		17						
Insecta/Diptera								
Bradysia brunnipes				15,29			29-30	
Sciaridae sp larvae						5		
Culex pipiens								33
Megaselia rufipes	3-10	2-33	16-28	1-40			38	
M. brunneipennis adults					15-38	2-52		2-38
M. brunneipennis larvae				3		4		5
Heleomyza sp adults		43	3	68	20-37	11	1-29	2-38
Heleomyza sp larvae							3-4	3-4
Sphaeroceridae				39				
Calliphora vomitoria adults	1							
Calliphora vomitoria larvae	1-2	2		2-3	2-4	3		
Insecta/Coleoptera								
Nebria brevicollis			39					
Pterostichus madidus								52
P. strenuus			39					
Necrophorus humator adults	1	2	3					
N. humator larvae			5-7					
Catops tristis		17						
Choleva glauca		3-21	1-3	1				
Alaeochara lanuignosa		2			19			
Acroton fungi				5				
Lesteva sp				6				
Tachyporus hypnorum	10							
Quedius mesomelinus adults		25	5-11	2-21	2-18	2,30	1-22	4-30
Q. mesomelinus larvae				4-7	2-21	6	6-20	1-8
Philonthus sp	2							
Oxytelus laqueatus		1						
Cryptophagus sp adults	7	7						
Cryptophagus sp larvae					8			
Atomaria sp		15	1					
Total species	11	16	10	13	11	6	6	8
- of which cavernicolous	2	4	3	6	6	5	6	7
Breeding on carcase	1	2	1	3	3	2	4	3
Feeding on carcase	4	7	2	6	4	4	3	2
Feeding on fungi	2	1	0	2	3	1	2	3

Table 2. Invertebrates associated with decomposing rats in Church Hole Cave, 1986-1991.
Numbers in the table refer to the time in months from deposition on which animals were observed.
Entries separated by a dash (-) indicate presence on all visits between the first and last indicated.

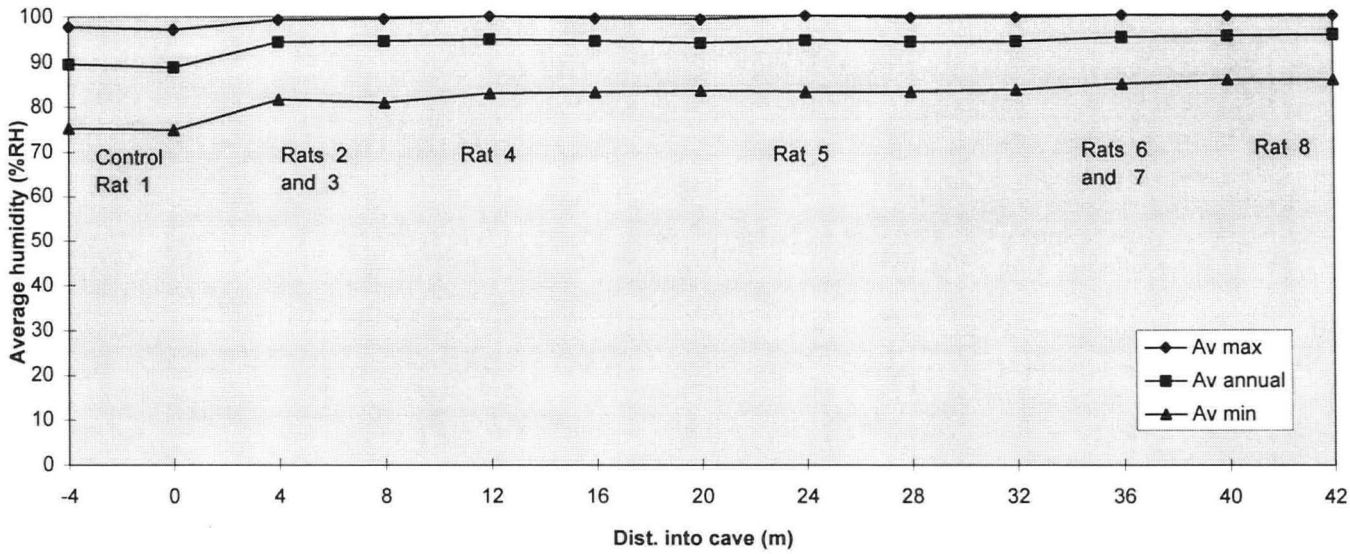

Figure 5. Church Hole Cave, ground humidities 1986-1991.

caves (Hippa et al., 1985) and in the eastern United States (Peck, 1988), this predatory beetle feeds on dipteran larvae and Collembola (Turquin, 1983).

Robin Hood's Cave

Temperature and Humidity

The average temperature over the experimental period was 10.5°C (95% limits +/- 3.5°C) at 7.5m into the cave; warmer than, and more variable than Church Hole Cave at the same depth. At 37m, it was also slightly warmer at 8.7 °C (+/- 1.3). Temperatures were also higher at the third site, 45m into the cave at 9.9 °C (+/- 0.9).

The cave entrance was slightly less humid than Church Hole, at 87.5% (+/- 7.2%), but almost the same at 37m (95.7% +/- 7.4). Although the site at 45m was deeper than at Church Hole, the stagnant cave air here was almost saturated. All figures quoted are annual averages over the two-year study period.

Since carcasses were deposited in June, those at 7.5m experienced higher temperatures than in Church Hole, averaging 13 °C during the active decomposition phase. Carcasses exposed at 37 and 45m decayed at temperatures 1 °C higher than Church Hole for the first 90 days.

State of rat carcasses

The decomposition of the rats 7.5m into Robin Hood's Cave resembled that at 4m into Church Hole, although conditions were drier. *Calliphora vomitoria* larvae were seen 5 to 9 days after deposition and all soft tissues were consumed in the following three weeks. After this much of the hair was shed and moved up to 2.5m by dispersing larvae.

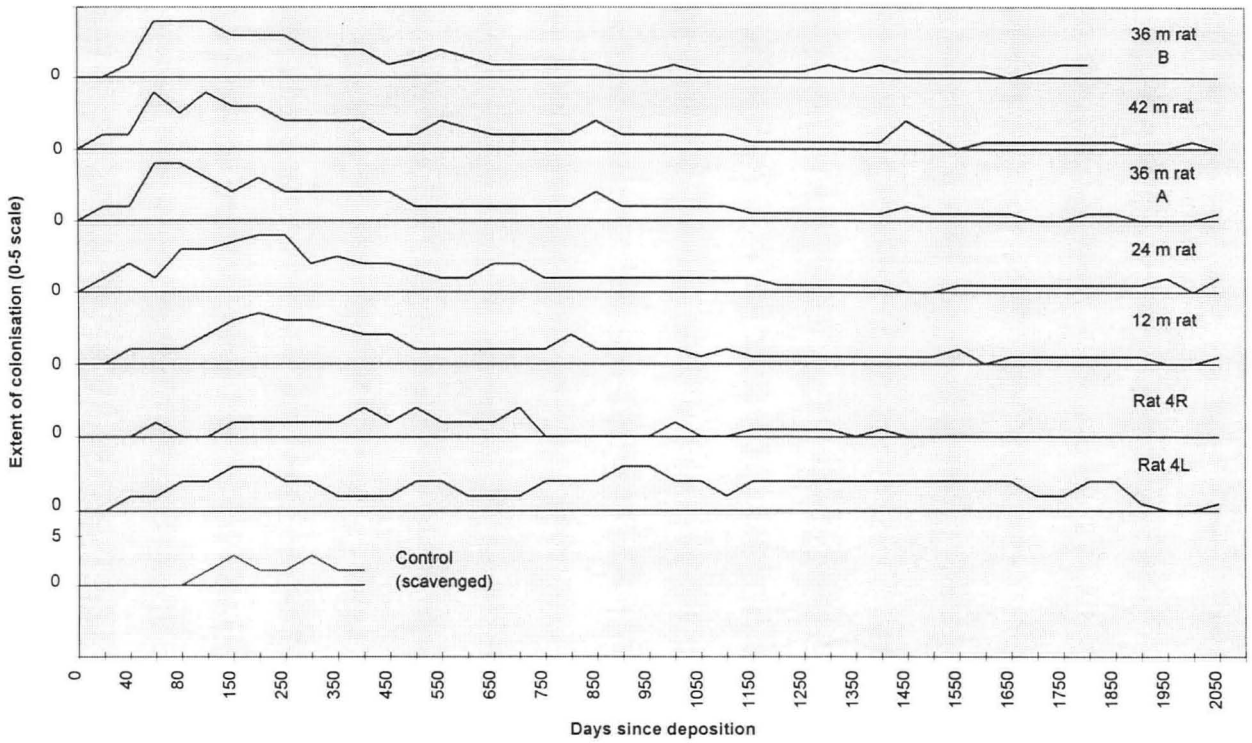

Figure 6. Church Hole Cave, fungal colonisation of rat carcasses, (0-5 scale).

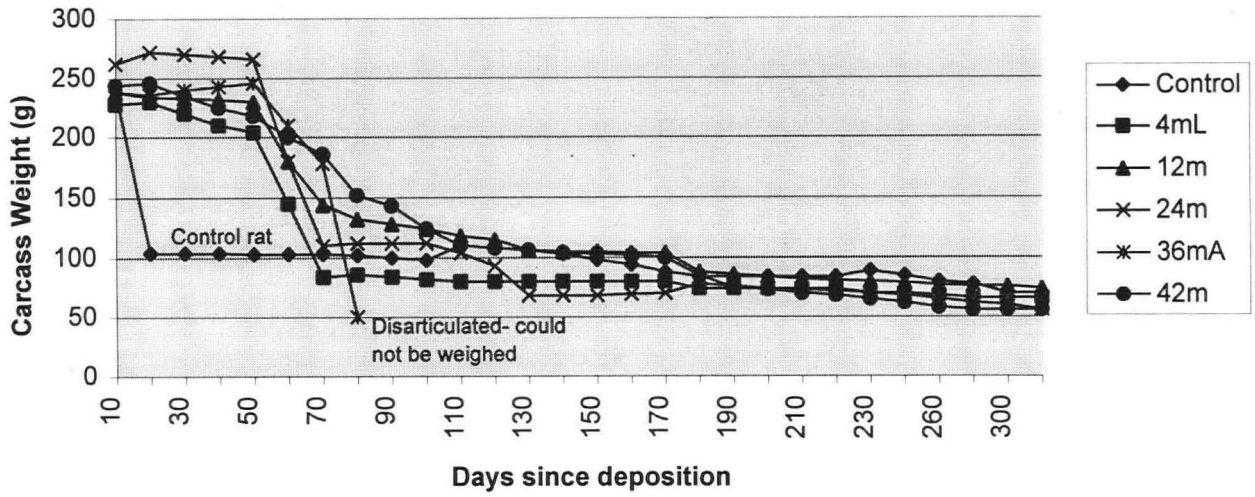

Figure 7. Church Hole Cave, weight loss of rat carcasses during first year.

The carcasses attracted many other insects, but there was no burial by *Necrophorus*. Later, the remains were attacked by moths, especially *Hofmannophilia pseudospretella* (Tineidae), the brown house moth, but the end point was always mummification. All carcasses remained intact and stabilised at 20-25% of their original weight.

At 37m fungal colonisation was rapidly followed by enormous numbers of phorid flies mainly *Triphleba antricola* and *Megaselia rufipes*. The carcasses were then colonised by *Calliphora vomitoria*. In the first two months, carcass weights reduced by 75%. After larval dispersal, fungal decomposition attracted the troglophilic gnats *Lycoriella leucotrica* and *Bradysia brunnipes*, the latter breeding on the carcasses. Finally, dry decay occurred and the carcasses were colonised by staphylinid beetles such as *Quedius mesomelinus* and *Bessobia* sp. and *Cryptophagus acutangulus* (Cryptophagidae). After two years the remains were largely skeletalised, partly or totally disarticulated, but unburied, with sporing colonies of *Fusarium, Microascus* and *Aspergillus*.

At 45m, initial decomposition was fungal and dipteran. Some carcasses were colonised by basidiomycetes and then by *Calliphora vomitoria*. All attracted Phoridae, the same species as at 37m predominating. This colonisation began after 6 weeks and lasted for 5 months. It was followed by the sciarid flies *Bradysia brunnipes* and *Lycoriella leucotrica*, the former breeding on the slowly decaying carcasses. The remaining decomposition was fungal, with a thriving community of mostly troglophilic arthropods. After two years, carcass weight stabilised at 25-30%; all rats were partly or totally skeletalised, disarticulated and covered with a layer of sclerotia from *Microascus*. Minor bones were jumbled, but in half of the carcasses the axial skeleton was intact.

Effects of carcasses on cave invertebrates

Table 3 shows the results of pitfall trapping before and during the decay process and the percentage of species gained, lost or unchanged. Species richness increased at all sites as sarcophagus insects were attracted into the cave. The 7.5m site gained 55 species during the experiment (50% of the total), but lost only 15. At 37m the gain was 32 species, and at 45m 18 species were added, but 11 lost (22% of the total).

Before carcass deposition, species richness declined by almost 50% from the cave entrance to the hypogean region, as observed in 1983-84 (Terrell-Nield, 1985).This pattern persisted during the first year of

	Baseline (10 months)			Experimental year 1			Experimental year 2		
Depth (m)	7.5	37	45	7.5	37	45	7.5	37	45
Total species	49	40	28	59	47	29	39	24	23
Total individ.	637	1000	442	1431	5108	2718	691	3251	2447

Species/Depth	7.5 m	37 m	45 m
% Gained	50	42	37
% Lost	13	30	22
% Unchanged	37	28	41

Note: At 7.5m, 22 of species gained were associated with carrion, including 13 diptera. At 37m, 12 species gained were carrion-associated (11 diptera). At 45m, of the 12 carrion-associated species gained, 10 were dipterans.

Table 3. Species richness, numbers of individuals and community change of arthropods trapped in Robin Hood's Cave before and after carcass deposition.

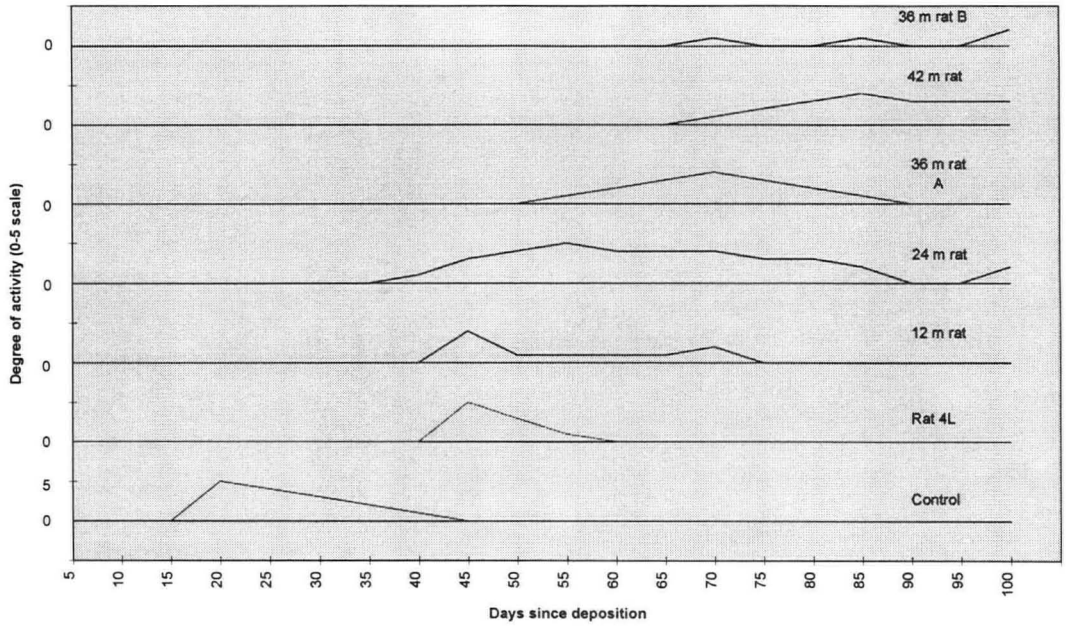

Figure 8. Church Hole Cave, extent of maggot activity in rat carcasses, (0-5 scale).

deposition, but the total number of individuals more than doubled at the front of the cave, increased five-fold at 37m and by six times at 45m. Numbers in the cave threshold decreased almost to the baseline in the second year. There was less decrease in the middle and little at the back.

If population sizes increase much more than species numbers, a measure of diversity such as Shannon-Weaver's H (which takes into account the proportional abundance of each species) will show a decline (Rickleffs, 1996). Fig. 9 shows that the deeper cave regions were particularly affected, since most additional individuals came from a small number of species. This also affects the Evenness, which reaches a maximum of 1.0 when all species are equally present (Odum, 1971). Again, the cave entrance was little affected but the central part of the cave showed a marked decline.

The main species responsible for diversity changes are listed in Table 4. The major introductions are thrips such as Aelolothripidae (known to breed in decomposing material) and the sarcophagus flies *Calliphora* and *Megaselia*. The ichneumonids and braconids are parasites of dipteran and lepidopteran larvae. None of the new species persisted into the second year, although more species were added.

Twenty pre-existing species were strongly affected by the experiment, 14 positively, 6 negatively. The largest increases were seen in the Phoridae, but Brown House moths (*Hoffmanophilia* spp) which attack skins and fur, also increased substantially. Many more thrips and predatory mites (Mesostigmata) were seen, but the latter are commensal on the phorid *Triphleba*. Some fungus feeders such as Collembola, Mycetophilidae and Cecidomyidae increased, the first much more so in year 2. *Cryptophagus ruficornis*, which feeds on dry, mouldy material was stimulated, but the troglophilic *C. acutangulus* declined in numbers.

DISCUSSION

Decomposition is vital to ecosystem energy flow, especially in habitats without primary producers. These studies indicate that animal remains deposited even shallowly in caves decompose differently from those on the surface. Differences in decay are attributable to the cave environment and the difficulty of access to the carrion by non-cavernicolous species. The caves at Creswell are relatively shallow, with only a few troglobitic species (Terrell-Nield, 1985), so many of the arthropods involved in decay were epigeal.

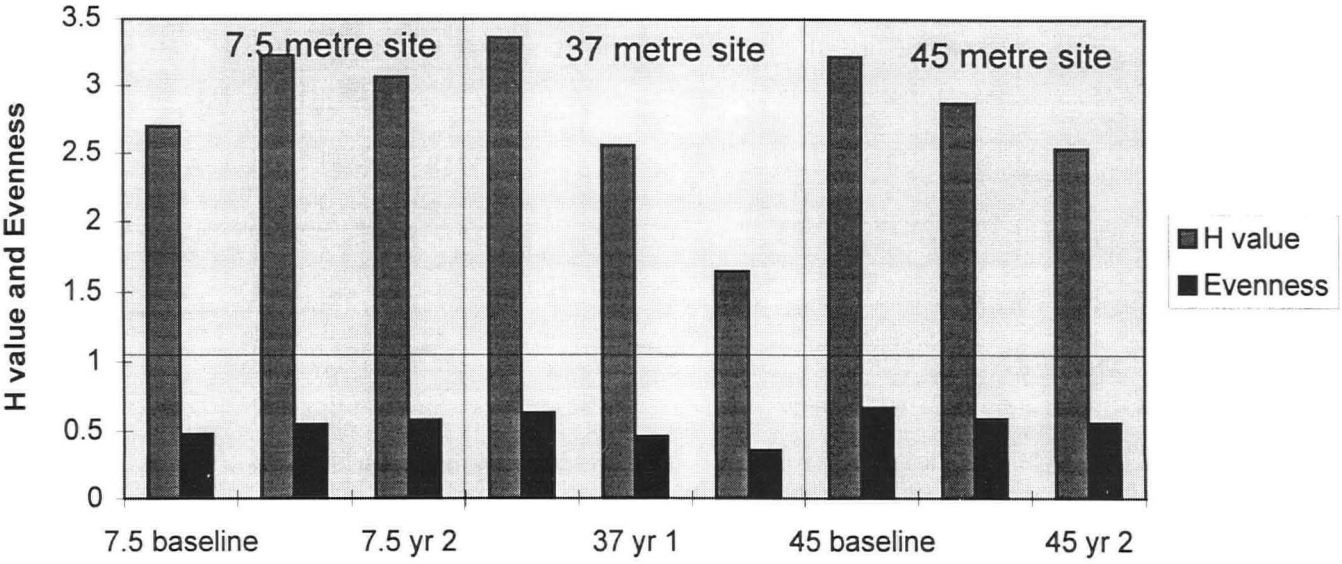

Figure 9. Robin Hood's Cave, effects of decomposing rats on arthropod diversity during the first two years.

a) Major families and species added (+) (represented by more than one individual)						
Depth	7.5m		37m		45m	
Group/Species	Year 1	Year 2	Year 1	Year 2	Year 1	Year 2
Arachnida						
Chthonius ischnocheles		+				
Tegenaria sp		+				
Myriapoda						
Brachydesmus superus						+
Insecta/Thysanoptera						
Aeolothripidae (2spp)	+		+			
Insecta/Diptera						
Psylopus sp (2spp)	+					
Trichosa absurda			+			
Megaselia bifida			+		+	
Calliphora vomitoria	+		+		+	
Insecta/Hymenoptera						
Ichneumonidae (1sp)	+					
Braconidae (1sp)	+					
Pteromalidae (1sp)			+			
Insecta/Coleoptera						
Alaeochara lanuignosa	+					
Oxypoda opaca		+				
Xylostiba monolicornis			+			
Bessobia sp			+			
Omalium excavatum	+					
b) Pre-existing species with more than a 5-fold change over baseline (- = decline, bracketed = lost)						
Arachnida						
Astigmata (Acari, 1sp)	x 8					
Prostigmata (Acari, 1sp)			x - 11	x - 10		
Mesostigmata (Acari, 1sp)	x 24		x 7		x 31	
Cryptostigmata (Acari, 1sp)	(x -2)		(x - 2)		(x -10)	
Porhomma egeria (Araneae)					x -5	
Insecta/Collembola						
Hypogastrura purpurea					(x -6)	
Onychiurus sp						x 7
Lepidocyrtus cyaneus			x 5			x 15
L. curvicollis						x 11
Pseudosinella alba						x 5
Neelus sp	(x -25)		x -9	x -30		
Arrhopalites pygmaeus	(x -13)			x -25		
Insecta/Thysanoptera						
Thripia sp	x 21	x 35				
Insecta/Lepidoptera						
Hoffmanophilia pseudospretella	x 110	x 41				
Insecta/Diptera						
Bradysia brunnipes	x 5				x 22	x 5
Lycoriella leucotrica					x 8	x 5
Triphleba antricola	x 35		x 2130		x 546	
Megaselia rufipes	x 9		x 1099			
Insecta/Coleoptera						
Cryptophagus acutangulus			(- 1)			
C. ruficornis				x 15		

Table 4. Species turnover in Robin Hood's Cave during carcass deposition.

Air temperature is critical in controlling decomposition, since carcass temperature determines the rate of bacterial and fungal development (Nabaglo, 1973). Environmental temperature also affects the metabolism of colonising and associated invertebrates, dipteran larvae developing more slowly at lower temperatures. Just as important, however, are temperature and humidity variation in the cave threshold.

Cave passageways "breathe" (Barr, 1968), because of the density gradient between cooler and warmer air. In summer, denser cool air flows out of the caves, taking with it the odour of decay that will attract necrophagous insects. In both caves, relative humidity became progressively lower and more variable towards the entrance. Here, drying airflows can create an environment lethal to cavernicoles adapted to high humidities (Chapman, 1993), but which provides suitable conditions for mummification before or after dipteran evisceration. The Medico-Legal Society (1976) commented that mummification is likely in warm dry surroundings, especially with air movement.

Desiccation of the remains significantly slows down decomposition because the body becomes too dry to sustain most fungi and insects. It is important for the long-term integrity of the carcass that disarticulation is largely prevented by the encasing and shrunken skin. If the remains are subsequently buried, the skeleton should remain substantially intact even if the skin is decomposed. These events are more likely in the cave entrance, and may be observed above ground in dry conditions.

In the mid part of the caves, decomposition was more complete. Even in dry passages, the humidity of cave air rarely falls below 80% (Culver, 1982). Although these caves have no running and little standing water, continuous drips and limited air circulation often produce summer humidities of 100%. Under these conditions there were clear stages of fungal colonisation, dipteran consumption and wet decay, followed by dry decay. Disarticulation occurred as cartilage and connective tissue were decomposed, but rats deposited close together decayed at different rates, emphasising the importance of local microclimates. Under these conditions, rats lost substantial parts of their skeletons in 2-5 years.

Decomposition in the deepest part of the caves was primarily fungal. Insects initially played a lesser role, leading to relatively gentle decay, especially where carcasses were colonised by Phoridae and Heleomyzidae. The end point was a partly disarticulated but complete skeleton covered in a mass of resting fungal stages. Fungal decay in the hypogean region is thus particularly important for both decomposition and invertebrate populations. This supports findings by Dickson and Kirk (1976) that the abundance of cave-limited invertebrates correlated with the abundance of micro-fungi.

For an animal that dies in a cave, or is carried in by a predator, the extent of consumption by non-cavernicoles will depend on its location. Close to the entrance, dipterans will predominate, but even here carcasses lose weight more slowly than outside, since flies may take longer to find them. The slower weight loss may also be a consequence of lower shade temperatures, which reduce the metabolism of fly larvae.

Flies dispersing from a carcass normally move towards light which will take them to habitats where more oviposition chances are likely. However, in both caves there was a "chain" of carrion. The emergence pattern is akin to an "island effect" where animals disperse along an archipelago. This may explain blowfly colonisation of rats at 45m in Robin Hood's Cave. In contrast, the second rat at 36m in Church Hole Cave attracted only Phoridae and Heleomyzidae. This animal was deposited one year after the first and there was no chain of fresh carrion to lead blowflies to it.

There have been few observations of *Heleomyza* breeding in caves, and several authors doubt that this happens (Hazelton, 1977, Chapman, 1993). In the present study, *Heleomyza serrata* emerged from pupae taken from carcasses at 36 and 45m. However, the larval populations were small.

Later stages of decomposition attracted other diptera, particularly those associated with fungi. Sciaridae were the most prominent group, including cavernicolous species such as *Bradysia* and *Lycoriella*. Associated with the dry decay stage were larvae of the Brown House moth, *Hoffmannophilia pseudospretella*, as well as detritivorous beetles such as Cryptophagus. The carcasses also attracted predators, especially the cavernicolous staphylinid *Quedius mesomelinus*. All stages of the beetle were found under or near the carcasses, the carrion having an important effect on its population.

Other beetles such as Necrophoridae attack only very fresh carrion. They will not breed if there is insufficient sediment for interment. Burial may result in a fully intact skeleton since scavengers do not break up the carcass and there is less chance of weathering or trampling dispersing the remains (Andrews, 1990). Digging may also disrupt sediment stratigraphy, inserting remains in levels to which they do not belong. This post-mortum movement must be considered when interpreting excavated remains (Jenkinson and Gilbertson, 1984).

Decomposing remains thus attracted cavernicolous and non-cavernicolous arthropods from several trophic levels. The main effect was to modify significantly the threshold fauna by the addition of new species and the stimulation of existing ones. Few new species persisted beyond the first year, being closely associated with the earlier stages of decomposition, so this cave region began to return to its previous state. The introduction of non-cavernicolous species into the hypogean regions reduced diversity, but most of the decrease was due to population increase in pre-existing species, an effect still detectable after two years.

The deep cave is a vulnerable, energy-poor environment. The addition of only small amounts of carrion may have profound effects that persist beyond the active decay stage. It is therefore important to consider the effects on cave communities of deliberate or accidental introduction of carrion or any other putrescible material, and take into account carcass location when interpreting animal remains discovered therein.

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Climate Change: the Karst Record - A Conference Review

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Abstract: 71 papers and posters presented (plus a description of 2 field excursions) at Climate Change: the Karst Record, a conference held in the Geology Department at the University of Bergen, Norway, from August 1-4, 1996, are reviewed. Most focused on the systematics, dating and palaeoclimate records of speleothems. Some discussed sediments (other than chemical precipitates), cave ice records, palaeohydrology (passage morphology), surface geomorphology, palaeomagnetism, cave flora and faunal records, and achaeological data. Details of important technical advances were provided. Thermal Ionization Mass Spectrometry (TIMS) is used widely for U-series dating, but U-Pb and Amino-Acid Racemization dating are giving promising results. Considering speleothem palaeoclimatology, stable isotopes of carbon, oxygen and deuterium (for temperature and precipitation) received much attention, as did highly resolved (sometimes better than annual) luminescence records that give solar and other astronomical information via surficial, climate-sensitive, organic products transported in groundwater.

INTRODUCTION

Karst topics have had only a modest, if persistent, role within the wider geoscientific community, for several reasons. On one hand, because of the strenuous nature and perceived danger of their fieldwork, karst scientists are perhaps seen as somewhat "fringe". On the other, difficulties associated with interpreting cave climate records have contributed to their relative lack of prominence in mainstream literature. A body of palaeoenvironmental data from caves has grown, perhaps to a critical mass, with several ground-breaking papers published in leading geoscience journals, and cave climate records now make a real contribution to global palaeoclimatology studies. Additionally there has been, for example, the emergence of the *Karst Waters Institute* in the USA, (partner in this conference with the University of Bergen), the *UIS* congresses, the karst commissions in the *International Geomorphological Union*, various *IGCP* projects, the *Speleothem Pole-Equator projects (SPEP-III)*, projects under *PANASH*, and a proposed *European Science Foundation Network* of karst research groups. The IGCP # 379 commission met to discuss the SPEP-III during this conference.

Thus, the conference was founded on palaeoclimatology, and the important role that cave proxy climate records offer in understanding global climates. Karst caves are unique repositories of palaeoenvironmental information, especially as cave sediments are well protected from surface (especially glacial) erosion. Stable isotopic records from caves can cover extensive time spans and are potentially useful in providing a (continental) climate calibrating framework where only marine and polar records now exist. Furthermore, the close control provided by recent advances in U-Series mass spectrometry dating, and the promise of high-resolution (annual) speleothem luminescence records, may ultimately provide one baseline to which climate records can be pinned. The three day conference featured 71 papers and 23 poster presentations. Significant ongoing work and exciting advances in knowledge and techniques were described in several stimulating sessions

Complementary pre- and post-conference field excursions were made. Excursion 1 (pre-conference) was local and lasted two days. Its itinerary included geomorphology and Quaternary geology in the inner Sognefjord area and the caves and karst of Dummdalen. After the conference the 12-day Excursion 2 included visits to karst localities in Nordland. Both excursion itineraries are supported by extensive literature. Norway's unique glacial karst, typified largely by marble "stripe" formations, provided a unique and thought-provoking perspective for the international audience. Excursion details are provided below.

THE SESSIONS

(see also Appendix)

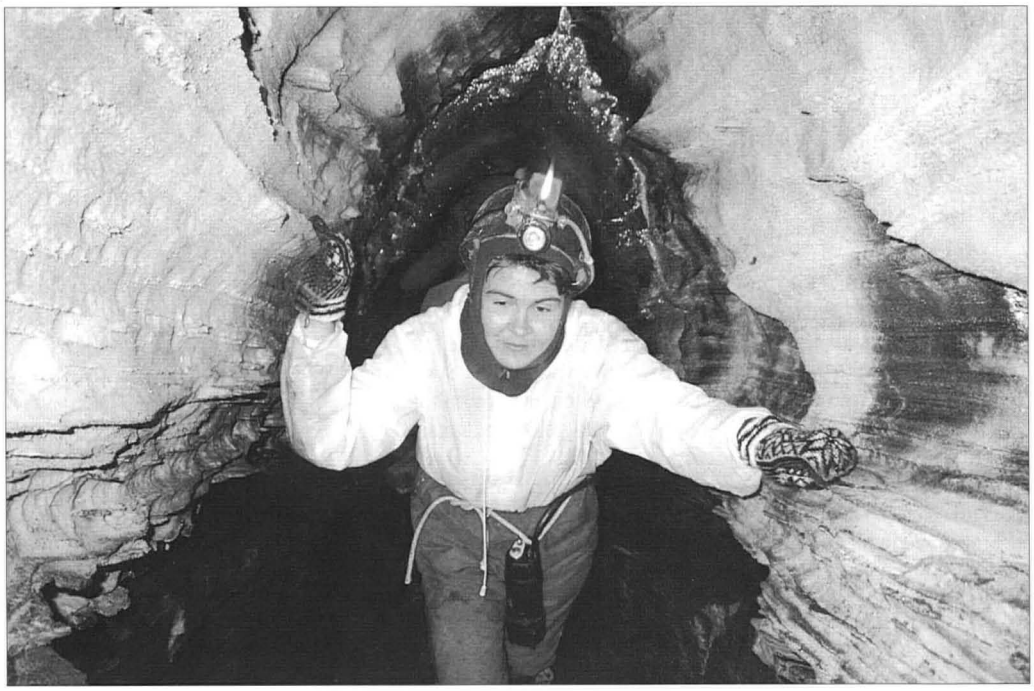
1. Keynotes

These papers provided a state of the art overview. Part of the thoughtful introductory paper by **Stein-Erik Lauritzen** is incorporated in the introduction, and is not repeated.

Derek Ford presented his "house of cards" model for dating cave deposits, in which **absolute** radiometric dating methods (U-series, U-Pb, carbon-14, ESR/TL and AAR) are integrated with relative and marker methods (stratigraphy and geomagnetism). The "house of cards" arises because the $^{230}Th/^{234}U$ method (extending back to 500ka with TIMS) remains the only really reliable method, but is limited to the first part of the Quaternary. Other methods build on this anchor point, except possibly the important Brunhes-Matayama magnetic reversal marker at 780ka (though even this is not datable directly). However, important new work on U-Pb radiometric and Amino-Acid Racemization (AAR) dating, promises to strengthen the "house of cards".

Henry Schwarcz reviewed the contribution of speleothem stable isotopic studies to palaeoclimatology, emphasizing the enormous potential of speleothems as palaeoclimate recorders. To date, most work has focused on $^{18}O/^{16}O$ variations in speleothem calcite. Because several climatic and geochemical factors affect this ratio, attempts have been made to examine deuterium concentrations in speleothem fluid inclusions. These can be considered aliquots of past meteoric precipitation, thus eliminating some geochemical factors. Although $^{13}C/^{12}C$ is measured routinely with $^{18}O/^{16}O$, it has generally been impossible to use it for palaeoenvironmental interpretation. However, new studies of luminescence, and its relation to organics in groundwater, hold promise for this indicator.

Wolfgang Dreybrodt presented mathematical models of speleothems and experimental data, emphasizing the utmost importance of understanding parameters that control growth rate, and how growth rates can be estimated. Growth rates must be well understood to establish accurate chronologies. He showed that they are determined by many parameters but in conflicting ways. For example, increased growth rates caused by climatically induced soil CO_2 increases can be counter-balanced by decreasing temperatures, which reduce growth rates. He further demonstrated that speleothem shape reflects climatic variables. This work, and some calcite fabric work utilizing SEM (below), is important in re-examining some basic premises of speleothem palaeoclimatology. Such studies can aid selection of suitable materials for study.



Passage showing paragenesis in Trollkjerka, Lavangsmarka Karst near Evenes.

Peter Smart closed the proceedings with a critical appraisal of karst climate research, its current status and the direction it should take in the future (**Smart et al**). Several points were raised: (i) records from individual speleothems are inadequate; it is essential to duplicate palaeoclimate records. (ii) A theory must be developed for interpretation of speleothem records that comprise several climatic parameters - the use of complementary proxy records would assist this. (iii) There are needs for field validation, and empirical investigation of palaeoclimate indicators (both spatially and temporally) with time scales of 10-100 years (time scales of 1-2 years do exist), to link Holocene records to present day data. Annual growth banding and historical records have much to offer. (iv) When interpreting $^{18}O/^{16}O$ variations in speleothem calcite, all factors influencing this parameter must be considered - kinetic fractionation, cave temperature, precipitation, storm track, and source temperature. (v) There is a need to recognize, understand and improve signal-to-noise ratios. Criteria such as petrography might help select the best samples. (vi) Reliable growth rate models must be developed. This can be achieved by use more numerous, smaller samples for U-series dating. The integrity of dates must be checked, and here the development of TIMS for $^{231}Pa/^{235}U$ represents a significant advance. Radiocarbon dating should be viewed cautiously, because of the variable origin of speleothem ^{14}C. (vii) It is important to recognize non-linear axial growth of speleothems and establish sample spacing on a time-linear basis - time domain filtering rather than the normally applied space domain filtering. (viii) Sample availability is a serious problem, in actual terms and in consideration of the conservation ethic. Continuous records are hard to find, even in the Holocene, and Quaternary records are interrupted by glacials, so long-term records are difficult to establish. There is a need to characterize and understand hiatuses by petrographical and geochemical analysis.

2. Speleothem Stratigraphy and Chronology

The $^{230}Th/^{234}U$ dating method extends back only 500ka using TIMS (covering only the late Quaternary). Thus U-Pb dating presents an attractive adjunct, because, in principle, it allows dating of material from a few million years to the age of the Earth. **Richards et al** indicated that good concordance is achievable, but only on "ideal" speleothems (with high U/Pb ratios and minimal initial ^{230}Th). One disadvantage of the method for dating beyond 500ka is that initial $^{238}U/^{234}U$ ratios must be estimated.

Still considering speleothem dating, **Hercman** and **Lauritzen** compared and reviewed TL, ESR, ^{14}C and $^{230}Th/^{234}U$ methods. TL and ESR are problematical, providing little or no correlation with Th/U results. This is attributed to the irradiation history of samples being unknown and potentially highly variable. In contrast, 14C dates correlate well with $^{230}Th/^{234}U$ results for ages <20ka, and less well with ages >20ka and <50ka. Younger ages compare well with coral Th/U dates. Surprisingly, all ^{14}C results are lower than counterpart $^{230}Th/^{234}U$ dates, and this is being investigated.

Moving to speleothem stratigraphy, **Baker et al** extended theoretical and laboratory speleothem growth systematics developed by Dreybrodt (above) by applying it in the field. Improved dating precision and annual laminae counting via luminescence have allowed Quaternary growth rates to be determined very accurately. Essentially, their results match Dreybrodt's, demonstrating that $[Ca^{2+}]$ is the key variable determining growth rate. Growth rate was also found to correlate with luminescent intensity, suggesting that organic material disrupts crystal structure, leading to enhanced growth.

Lundberg and **Toscano** described an interesting use of speleothem and coral to constrain the isotope Substage 5a low sea stand (minimum at 83ka) in level and time, using high precision U-series TIMS dating of cave flowstone and coral from Florida and the Bahamas. Flowstone growth throughout Substage 5a was bracketed by cave flooding episodes during higher sea stands, while continuous coral growth occurred more or less at the sea surface. Synthesis of the two record types provides a tight window on date and sea level elevation during that period. The records do not suffer from limited knowledge of reef tract uplift history, and the results indicate sea level at -6.8m asl at this time, rather than +1m asl as claimed in earlier literature.

Lauritzen et al compared speleothem dates from northern Norway (latitude 65°-68°N) and Poland (south of 51°N). While recognizing that comparison becomes more problematical further back in time, a significant latitudinal variation in time-dependent speleothem growth frequency was observed, with an expected greater tendency for speleothem growth inhibition at northern latitudes.

Li et al presented a speleothem record for the last 36ka from Guilin, China. Most of the 21 dates were derived from AMS -^{14}C, concordant at around 35ka with a single $^{230}Th/^{234}U$ α-date. The record is interesting as it not only exhibits significant climatic events recorded elsewhere but also demonstrates climatic oscillations between planetary prevailing wind systems and monsoon systems that occurred during uplift of the Qinghai-Tibetan Plateau. These results bode well for a promising repository of climate information existing within this karst area of >500km^2.

3. "Shopov Bands" and other high-resolution stratigraphical information in speleothems

With recent demonstration that luminescent and visible speleothem laminae have been deposited annually, their physical and chemical study is just beginning, principally because the high resolution chronology they provide is of great interest to palaeoclimatologists. **Shopov et al** reviewed speleothem luminescence resulting from organic acids in groundwater, and shown to be sensitive to solar intensity and surface temperature. One record from Coldwater Cave (USA) exhibits a high correlation between luminescence intensity and the solar luminosity sunspot index. Another, from Rats Nest Cave (Canada), shows reasonable correlation between isotopic cave temperatures and luminescence. The Canadian record can be tied to annual precipitation levels, as the luminescent band-width is resolved to individual years. This feature, when tied to TIMS-^{14}C dating for young speleothems, provides a very precise, if not accurate, dating tool.

Baker et al looked at variation in dripwater luminescence from seven soda straws over two field cycles lasting more than one year. Apart from demonstrating hydrological differences between closely-spaced but unconnected seepage sources with, in some cases, correlated but lagging luminescent records, their results suggest that, ideally, palaeoenvironmental reconstruction should be done on multiple samples. **Genty et al**, pursuing this theme, looked at the speleothems themselves, distinguishing two "end-member" calcite fabrics (white porous laminae and dark compact laminae) with grey between. The "greyness" level correlates positively with luminescence and therefore with organic content. Furthermore, enhanced growth rates are associated with increased greyness, suggesting either that [Ca^{2+}] is mobilized more with increased soil biological activity, or that increased seepage brings in more organics, or that organics disrupt, and thus somehow accelerate, crystal growth.

Ming and **Tungsheng** interpreted the $\delta^{18}O$ record from Chinese speleothems in terms of the monsoon regime switching on and off through recent geological time. Precipitation data from current monsoons yield a $\delta^{18}O$ versus monthly mean temperature very similar (but with opposite sign) to that of $\delta^{18}O/T$ speleothem calcite in thermodynamic equilibrium. They argue that the gradients cancel out and what remains is due entirely to precipitation regimes.

Roberts et al reported on trace elements in Holocene speleothems, studied using laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS). Their results suggest that a coherent trace element record cannot be obtained from coeval stalagmites from the same cave, and that sample-specific processes play a significant role in controlling speleothem geochemistry. Therefore, a much greater understanding of the systematics is required before using, for example, Mg/Sr ratios as a geothermometer.

4. Stable isotopes in speleothems

Determining recent climatic changes in transition zones between arid and humid climates (e.g. the eastern Mediterranean) is a challenge to developing climatic evolution models. Like other transition zones, this area is very sensitive to environmental changes. **Bar-Matthews et al** presented continuous detailed speleothem records from Soreq Cave, dated from 25ka to 1ka BP; a period of global deglaciation resulting in the current Holocene interglacial. In a $\delta^{18}O$ - $\delta^{13}C$ scatter plot, data cluster into six, marginally overlapping, age fields that, essentially, define both temperature and vegetation type (C3 versus C4). This demonstrates that the Soreq speleothems provide an excellent tool for continental palaeoclimate reconstruction in this region.

Frumkin et al presented a continuous, multiple TIMS U-series dated speleothem stable isotope record from Israel, grown during most of the last glacial cycle. They found that the largest amplitude of climatic change occurred between isotopic stages 6-5e, with smaller changes during the last 20,000 years. The $\delta^{13}C$ also suggests shifts in local vegetation type during the large-amplitude climate change. This impressive record matches the oceanic $\delta^{18}O$ curve very well.

In respect of the use of $\delta^{18}O$ - $\delta^{13}C$ scatter plots, **Borsato et al** measured speleothems of various morphologies at various altitudes, from alpine caves in Trentino, Italy. In a relatively linear, positive trend for one cave site, they found a hierarchy such that cylindrical microcrystalline structures < cone stalactites = tip stalactites < soda straws = spray deposits. This suggests that caution be used in interpreting $\delta^{18}O$ - $\delta^{13}C$ and that non-kinetic environments should be carefully selected. The altitude variation of $\delta^{13}C$ is attributed to diminishing biogenic CO_2 and increasing bedrock carbon participation with elevation.

Zazdina Jeskyni Cave (Czech Republic) contains impressive clastic sedimentary fill, with some older material reversed geomagnetically (Bruhes/Matuyama boundary at 780ka). **Kadlec et al** found flowstone interspersed between, and above, younger sedimentary (fluvial) sequences. Dates are concordant with part of isotope interglacial stage 5c (c.100ka) and the beginning of the Glacial 5d (c.114ka), as recorded in foraminiferal cores V 19-30 (Pacific) and V 27-60 (Norwegian Sea). Sediments adjacent to the two speleothem records indicate calcite deposition under very different climatic regimes, supporting the speleothem results.

The prominent white band seen in the upper part of the fjord wall is marble and extends to water level. Opposite, in a thinner marble band, is Norway's deepest cave Ragge-Javri-Raigi (Pit-tarn-cave in Lappish) 580m deep and almost 2km long; near Musken village Hellemofjord.

The massive shaft entrance of Greftkjelen in the Greftdalen Karst (south of Bodo).

Lauritzen made an interesting attempt to generate a Holocene temperature curve for northern Norway from a speleothem TIMS dated between 8500-180 years BP. The $\delta^{18}O$ of speleothem calcite depends upon other factors than temperature; some site-dependent factors must be determined. For this sample, these were calculated based on $\delta^{18}O$ of calcite and mean annual temperature for the present and the Little Ice Age (temperatures around 1.5°C lower). The resulting curve (resolution 125-150 years [5-point running mean], yielding cave temperatures with a maximum of 6°C and a minimum spike at 1°C) compares well with the southern Norway record derived from other sources. However, without the 5-point running mean the profile becomes spiky, suggesting rapid temperature changes of 3 to 4°C. These enigmatic spikes are unexplained. It would be interesting to remove the need to determine factors (other than temperature) affecting speleothem calcite. In principle this can be done by measuring the isotopic composition of fluid inclusions, assumed to be aliquots of groundwater trapped within the calcite fabric during deposition. Extraction and interpretation of this "palaeowater" are fraught with problems, but **Dennis et al** presented results that renew hope for the technique. They demonstrated that water can be extracted from synthetic Iceland Spar, and reported good results from Holocene material of various fabrics from GB Cave (UK). In both cases crushing and vacuum distillation were used to extract the fluids. Previously only the deuterium content of inclusions was measured, because measuring $\delta^{18}O$ in µg quantities of water is difficult, and ^{18}O might exchange with surrounding calcite post-depositionally. Dennis et al's results suggest these difficulties have been largely overcome. The method has great potential for the many dated speleothems already in laboratory collections.

Electron microscopy investigations of speleothem calcite by **Frisia**, in scanning (SEM) and transmission (TEM) modes, allowed recognition of growth and replacement mechanisms as a function of precipitating fluids. From widely-dispersed speleothems, 5 microstructures were identified, of which all but one (large crystals with few defects) indicate rapid growth in far from equilibrium conditions. The cause of rapid growth was felt to be supersaturation at crystal faces in the presence of impurities (organic molecules, cations other than Ca^{2+}, clays etc.). These results, important for understanding speleothem geochemistry, could lead to better strategies of speleothem selection for palaeoenvironmental work.

Bottrell et al showed that metal carbonate alteration products in limestone can provide palaeoclimatic information. Supergene alteration of limestone-hosted sulphides by groundwater can produce relatively insoluble carbonates such as smithsonite ($ZnCO_3$) and cerussite ($PbCO_3$) as well as calcite, as demonstrated by study of a Pb-Zn deposit at Greenhow (Yorkshire, UK). Because more than one carbonate species is present, oxygen isotope analysis can define both temperature of deposition and groundwater oxygen isotope composition uniquely. At Greenhow the three carbonate pairs gave an average of 30± 9°C that, with an inferred $\delta^{18}O$ of -2.2‰ (V-SMOW), suggests alteration under warm conditions such as possibly existed in Tertiary times. Such mineralization is relatively common in limestone aquifers, suggesting that palaeoclimatic information from this source could complement the speleothem record.

5. Cave stratigraphy and palaeomagnetism

Cave sediments - other than speleothems - have been neglected in karst studies, perhaps because they are not immediately aesthetic and their interpretation is commonly difficult. This conference gathered together several recent studies. Working in northern Norway, **Løvlie** and **Lauritzen** noted that mineral speleothems accumulate during ice-free periods, but allogenic sediments can accumulate during periods of complete ice cover. Though difficult to date, such sediments hold information about full glacial conditions, where data are otherwise scarce. Standard palaeomagnetic methods applied to sediments from 10 caves allowed fairly detailed correlation of 5 sections from 4 of the caves, suggesting synchronous sediment accumulation at these sites. Further (with appropriate corrections for geographical location) the sediments could be correlated with Late Weichselian (≈Devensian) varved clays from Soviet Karelia. Sediment accumulation commenced between 16 - 15.5ka, ending between 11.5 - 10.5ka.

Quinif presented a consolidated view of years of such work in the Belgian karst. Caves in low karstic plateaus (eg. in Belgium), accumulate extensive sediments during complete glacial/interglacial cycles, and Quinif devised a scheme for sediment evolution based on the Belgian Middle Pleistocene to Holocene record. During a first interglacial period, soil establishes on the surface and little sediment is carried into caves by rivers. With extensive soil bioactivity and CO_2 production speleothems form. As glacial conditions encroach, extensive soil erosion begins and speleothem growth slows. Wet or dry glacial periods provide either extensive flow (and sediment input) into caves or accumulation of aeolian loess that enters open fissures. Finally, conditions during the next interglacial period match those of the first. A second generation of speleothems forms, and older allochthonous sediments are removed. And so the cycle continues.

In an ongoing palaeomagnetic study of an historical 4-m clastic sediment accumulation in Spiralka Cave (Czech Republic), **Sroubek et al** found a

Karren, Glomfjell Karst.

relationship they believe to be new, coupling ferromagnetic susceptibility (MSferro) to temperature. They do not suggest that temperature affects the concentration and size of ferromagnetic grains (which would intensify the magnetic signal), but rather that erosional processes are affected by temperature. Investigation of these processes is continuing, looking at erosional indicators such as the metals Ti and Zr.

Working with sediments from caves in northern Norway, **Nese** and **Lauritzen** identified 4 lithofacies in Storsteinshola and attempted to correlate these with a "master sequence" previously established in Norcemgrotta: laminated clay and silt (stagnant phreatic), sand (slow circulating phreatic), gravel (vadose conditions with variable flow rate), and polymodal/bimodal unsorted sediments (high energy phreatic). Calcite concretions that developed after sedimentation ceased, yield an imprecise minimum Th/U date of 15.5ka (Weichselian). They conclude that Storsteinshola demonstrates that an wide range of hydrological regimes can be encountered in glacio-karst caves.

Yonge and **MacDonald** examined the potential of using cave ice in isotope palaeoclimatology. Studying the $\delta^{18}O$ - δD systematics of cave ice from 4 (permafrost) localities in the eastern Rocky Mountains (Canada), they concluded that massive floor ice accumulations represent a mixing of hoar frost (unexpectedly highly enriched in ^{18}O and D) derived from warm-season moisture entering the cave, with cave seepage. Because, paradoxically, the warm season vapour regime defines cooler caves at higher elevations, high $\delta^{18}O$ and δD tend to be associated with cooler conditions; an interpretation opposite to the established ice core record.

6. Cave biology and palaeontology

Two theories of how fauna came to inhabit caves have been advanced. Traditional models assume an essentially pre-adapted fauna from forest humus being forced into karstic networks at the onset of glaciation. Modern views assert that species entered caves to avoid physiological stress, competitors, predators or simply because there was free space unsaturated by other species. Either way, climatic changes at the end of the Tertiary and during the Quaternary would have determined cave population distribution in the temperate climatic zone. Thus, for example, distinct faunal populations occupy caves in adjacent glacial valleys. **Moldovan** described three occurrences of micro-speciation of a non-endemic cave beetle (subfamily *Bathysciinae*) during the Quaternary, resulting from glacial downward displacement of forests at 2.3 - 2.1Ma, 1.7 -1.3Ma and 0.9 - 0.8Ma. This demonstrates the potential of using cave fauna as a climatic indicator.

Lien et al studied the lifestyle and morphology of *Gammarus lacustris* G O Sars (Amphipoda) populations outside (epigean) and inside (hypogean) Sandagrotta, in a forest about 400m asl in southern Norway. *G. lacustris* has a widespread holarctic distribution, occurring commonly in calcium-rich or cold lakes. The hypogean individuals, however, exhibit divergent adaptation to cave environments (as do other hypogean crustacea) and may have the potential to be a "model species" similar to *G. minus* in the USA. Extended studies will include DNA and iso-enzymes, to establish the rate and time of morphological divergence between epigean and hypogean populations, perhaps shedding light on "regressive evolution" mechanisms.

Viehmann et al reported on three footprints found impressed into the top of a moonmilk formation in Vartrop Cave, Romania. The moonmilk was dated at 22.4±4.2ka by U/Th, employing an isochron plot to correct for detrital ^{230}Th. This minimum date, together with biometric measurements of the footprints, would suggest a Neanderthal individual, but the footprints are rather too wide. Thus "Vartrop Man" may be a *Homo sapiens fossilis*, retaining some Neanderthalian features, that lived during the Wurm III (isotope stage 2) interglacial. Regrettably, vandals have removed two of the footprints.

Pre-Holocene fauna are rare in Norway, as the high energy glacial environment breaks down fossil material in sediments. Thus, the breaching of Norcemgrotta, a large sediment-filled phreatic cave, during road construction was fortuitous. Within more than 13m of sediment, **Lauritzen et al** identified 3 coarsening-up cyclic units, reflecting various degrees of ice contact (or cyclic variation in hydraulic conditions in the overlying glacier). Various sediments were subjected to palaeomagnetic analysis and ^{14}C or U/Th dating. Faunal assemblages from the so-called *Ursus* horizon, capped by calcite concretions, U/Th dated at 70ka, suggest a cold glacial/marine regime (favouring polar bear, arctic fox, Greenland seal and arctic birds) mixed with a warmer, vegetated regime (favouring marten, field-mouse and wolf). Overall, the analyses suggest an interglacial/glacial transition before 70ka, indicating marine stage 5a and/or 5e.

Rojsek touched on a subject needing much greater attention from speleologists and cave managers - preservation of clastic cave sediments that lack the obvious aesthetic appeal of speleothems. In a philosophical discussion, he proposed strategies for inventory and conservation of important deposits as a natural heritage, using examples from Slovenia.

7. Regional karst and cave analyses

Shopov reported on the UIS *Commission on Physical Chemistry and the Hydrogeology of Karst* working group, dedicated to studying "speleothem records of palaeoenvironmental change". Such changes include temperature, soil, precipitation, sediment, tectonics, solar insolation, geomagnetic field, plant type and distribution, pollutants, sea-level change, hydrothermal activity, cosmic ray flux, cosmogenic isotope production, and supernova eruptions. Shopov asserts that speleothems are commonly superior to other Quaternary palaeoenvironmental archives, particularly their time resolution, which can be as short as a few hours.

Tufa deposits are rarely used as stable isotope palaeoclimate records because, commonly, they are not deposited in equilibrium. However, **Hladikova et al** found a large tufa mound in the Bohemian karst displaying little axial and lateral variation in $\delta^{18}O$ (-7.3 to -8.3‰ PDB) and $\delta^{13}C$ (-7.9 to -10.5‰ PDB), suggesting deposition in equilibrium. The $\delta^{18}O$ seems to have been controlled largely by the source water, rather than by temperature. Four independent dating methods (^{14}C and U/Th on carbonate, archaeological on pottery, and AMS on charcoal) were applied, establishing an unequivocal record from 8,000-2,500 years BP. Apparently early tufa deposition was during the Late Atlantic climatic optimum, changing during the so-called Epiatlantic, with a moister climate affecting the later part. This record accords with molluscan assemblages and the Camp Century Greenland ice core, and compares well with a calcareous tufa in southern Poland.

Holmgren pointed out the need for precisely dated, high-resolution proxy climate records in the southern hemisphere. Africa has few palaeoenvironmental sites, but an ongoing project is reconstructing Quaternary changes using speleothems from Tanzania, Botswana and South Africa. Radiocarbon and U/Th dates, with $\delta^{18}O$ and $\delta^{13}C$ from a single speleothem in Lobatse Cave (Botswana) yield a record broken by three prominent hiatuses (drier periods) from 51-43, 38-35 and 27-21ka. The $\delta^{13}C$ suggests shifts in plant type from C_4 to C_3, indicating wetter periods of winter rainfall at 51-47, 27, 25 and 23.5ka. $\delta^{18}O$, increasing from around -7 to -4‰ PDB, indicates a temperature *decrease* of about 2°C. The climate pattern after 27ka supports a palaeoclimate model (from less substantial, more northerly, data) where equator-wards migration of the westerlies increased winter rainfall over the southern summer regime, but led to drier conditions north of the boundary. Strengthening of the westerlies then led to cold, dry conditions during the Last Glacial Maximum at 20ka, ending in a wetter episode from 16-13ka. (data from a second speleothem).

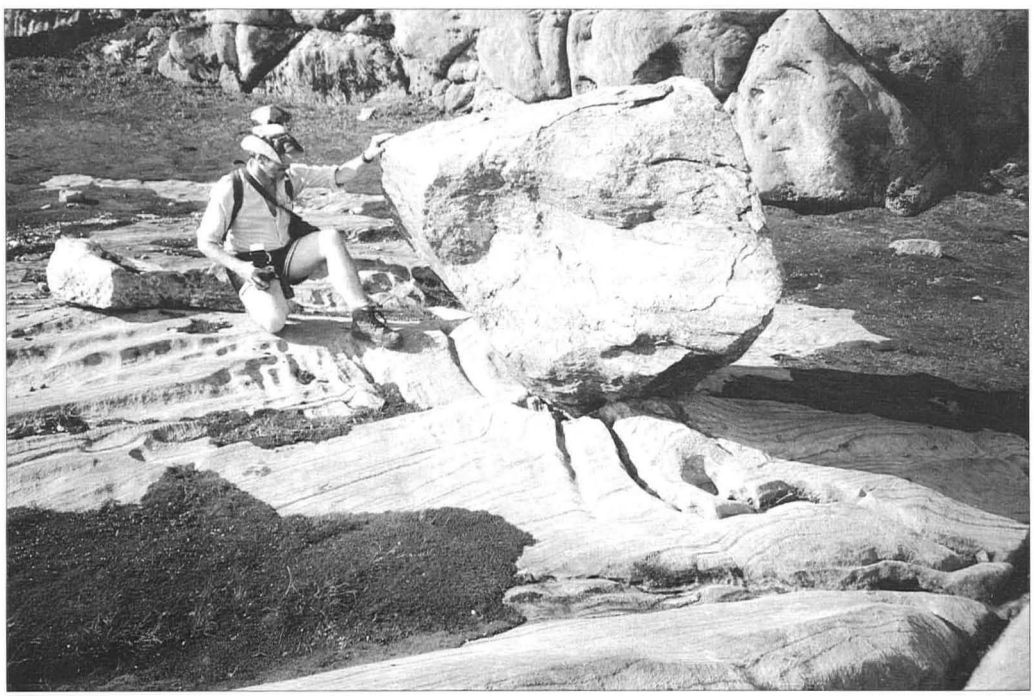
Sauter et al developed a numerical model that simulates changes in hydraulic conductivity during karst system genesis, and applied it to a known, "typical" karst aquifer in the Swabian Alb. The model integrates a large dataset comprising hydraulic boundary conditions, climate controlling inputs (groundwater recharge, CO_2 partial pressure, and temperature) and initial geological-lithological conditions. Preliminary results, though promising, suggest that simulation of flow in less permeable parts of the aquifer, especially in a headward direction, must be considered.

Mihevc and **Lauritzen** examined the Slovenian Kras Plateau, an unglaciated, low lying area, dominated by blind valleys and caves with catchments on non-carbonate rocks. In this setting, partly due to climate change, cave sediments are a function of what was previously termed "Pleistocene infilling" and "Holocene outwashing", but without absolute dates to confirm this hypothesis. However, the local caves contain long stalagmites and sinter dams, some breached by present-day streams. Preliminary U/Th (αdating gives 70-80ka or >350ka for the dams; stalagmites are much younger (initiated between 16-10ka). The former were probably deposited during drier periods with slack water flows, and the latter at a time of clastic sediment infilling. The stalagmites exhibit interesting features, such as flood hiatuses and detrital layering. Work continues to refine the dating (using TIMS), and to establish a stable isotope climatic record

Focusing on regional morphogenic levels and massive paragenetic development (~10m vertically) in a major palaeospring (Storsteinshola, bordering the Kjopsvik karst), **Lauritsen** and **Lauritzen** interpreted Quaternary landform evolution around Tysfjord (Norway). Glacially derived cave sediments triggered paragenesis, and by implication a catchment much larger than today's, related to glacial ice contact in Tysfjord, formerly existed. Correlation between the palaeospring and valley remnants implies a considerable age for speleogenesis. Interestingly, these workers can relate events at Storsteinshola to other relict caves in northern Norway, and to various regional morphogenic levels imposed since pre-Tertiary uplift. Norwegian karstification postdates the dissection of a paleic surface that led eventually to the present fjordal landscape.

Zupan described the history of absolute dating, started around 1971, in Slovenia, home of the Classical Karst. Some 60 speleothem Th/U, radiocarbon and ESR dates have been measured from 11 caves, giving dates ranging from 0 to >350ka.

The 26.4 km^2 Matienzo depression contains 200km of explored passage, thought to have evolved since >1.8Ma. Six distinct phreatic levels (the



Glacial erratic on a karst pedestal giving an indication of post-glacial surface lowering, Glomfjell Karst.

Karren, Glomfjell Karst.

lowest, currently active, designated zero) with extensive clastic sediment suites have been identified. The latter have been studied using various techniques. Magnetic susceptibility measurements allow correlation of sediment suites, enabling passage role in a given phreatic phase to be determined. Measurements are complemented by accurate survey work (establishing levels) and dating of passage abandonment (utilizing U-series, archaeological inferences, TL and morphometric analysis). Initial results give the oldest level 5 at 1.8Ma, level 2 at 26.2ka, level 1 at 17.5ka and level 0 active. Quin's preliminary work demonstrates the potential value of applying cave morphometry and sediment studies to describing long-term, regional palaeological changes - in this case Quaternary climatic changes in northern Spain.

Zupan and **Kranjc** studied a mixed-mineralogy red palaeosol sandwiched between karstified Cretaceous limestone basement and a shallow-sea carbonate deposit on Ist Island in the Adriatic Sea. The palaeosol represents a significant interruption of sedimentation under warm climatic conditions, probably adding to information about documented immersions in Middle Dalmatia after the Mid Eocene. Further work may confirm the palaeosol as pre-Pleistocene, providing an important link in studies of tectonics and sea-level change in the Adriatic, and improving understanding of recent surface karstification.

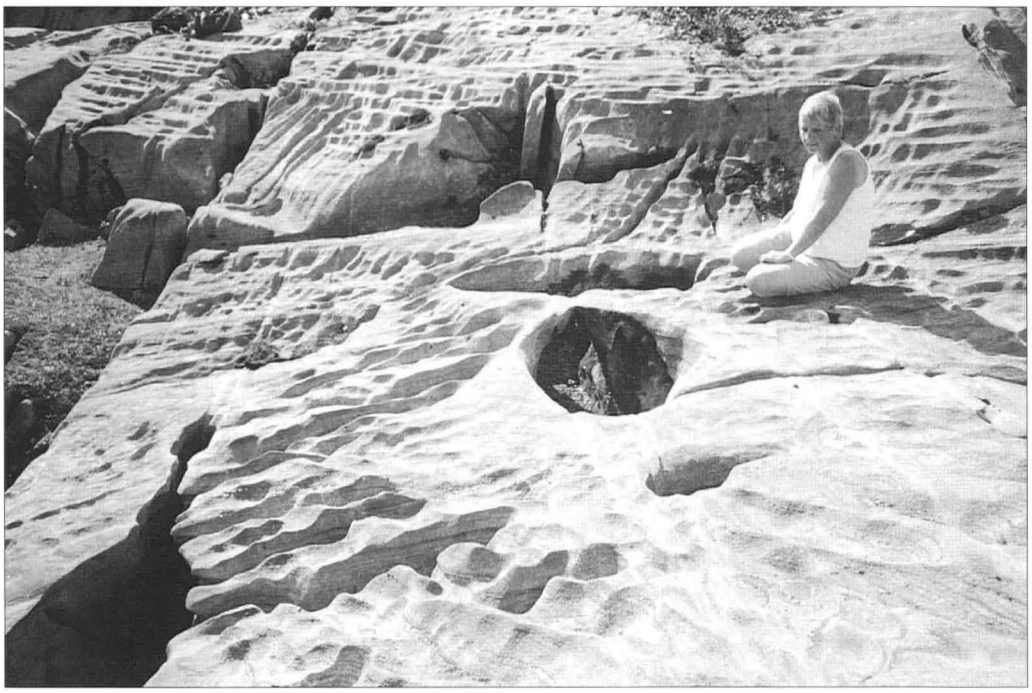
Benischke presented observations from caves on the As Sulb Plateau (part of the Eastern Arabian Shelf Platform), a currently arid are that underwent uplift in Eocene times, triggering karstification. Miocene clastic rocks blanket the Paleocene Umm er Radhuma limestone and dolomite formations, which contain shafts and bedding-directed phreatic tubes. Cave development was characterized by alternating wet and dry climate regimes, with overall increasing aridity lowering the water table to 100-180m below the surface. Intense denudation eventually intersected the caves, sediments were transported deep inside and large flowstone deposits were left near the surface, just under the clastic mantle. Speleothem dates will help establish the chronology.

Gently-dipping Upper Silurian to Middle Devonian carbonates cropping out across the Helderberg Plateau (New York State, USA) suffered multiple glaciations during the Pleistocene and support a well-developed karst. 29 Th/U speleothem dates measured by **Lauritzen** and **Mylroie** from 4 caves along a 50km strike-bound WNW to ESE traverse confirm pre- and post-Last Glacial cave development. There are unexpected date clusters in the 207-170ka and 56-100ka ranges, with some dates >350ka indicating cave survival through multiple glaciations. Deposits from the Last Interglacial are lacking.

Williams' fascinating study from New Zealand's fjordland karst, provided an interesting comparison with similar settings in Norway. A 230ka record of 7 glacial/interglacial events is underpinned by 27 speleothem dates from material interbedded with sediments in Aurora Cave. With 5 advances in the 90-15ka interval, New Zealand's last glaciation appears more complex than previously supposed. Apparently the cave was overlain by up to 600m of ice, but was partially uncovered towards the close of the Last (Otira) Glaciation, allowing re-excavation of sediments by glacial streams. The Aurora material indicates several relatively short-lived glacial advances with intervening interstadials. Results agree with ice-core isotope records, but do not support synchroneity of onshore/offshore events.

Richards et al compared submerged speleothem climate records from the Bahamas with other speleothem data, U/Th (TIMS) ages of coral reefs, and deep-sea core ^{18}O records. All yield important sea-level and palaeoclimate information for the Mid and Late Pleistocene. The Bahamas are stable tectonically so, because calcite is only deposited subaerially, speleothem dates and levels provide important constraints on sea-level. Non-depositional hiatuses mark high sea-stand inundation, arid periods, periods of no soil cover, or fissure blockage. Growth initiation after high sea-stands occurred at 384, 315, 190 and 80ka, corresponding to isotope stages 11/10, 9/8, 7/6, and 5/4. Numerous hiatuses during stage 8 indicate sensitivity to climate change. Few studies of U-Th dissolution and precipitation systematics in such carbonate platforms exist. Decreasing $(^{234}U/^{238}U)_0$ along the growth axis of one speleothem is attributed to closed-system decay of overlying carbonates since deposition, with a $^{234}U/^{238}U$ similar to modern seawater.

Mylroie et al continued the theme of carbonate islands, where karstification is constrained by limited area (mainly meteoric recharge), glacio-eustatic sea level changes and fresh-water lenses. After identifying three hydrological island types: carbonate islands, carbonate cover islands (overlying non-carbonates in the vicinity of past and present sea levels) and carbonate (reef) rimmed islands, they concentrated on the former, citing examples from the Bahamas and Isla de Mona, Puerto Rica. These islands provide simple examples of spatially-limited autogenic recharge creating a fresh-water lens with apexes at sea level. Karstification occurs at the land surface (epikarst), pit caves occur within the vadose zone, and flank margin caves occur at the lens apexes. The latter are useful for sea-level study. Most lie below sea-level (with speleothem dates between 89 and >350ka), but some are above and can be dated to the 125ka (isotope stage 5e) high sea stand. Palaeosols (fossilized epikarst) associated with glacio-eustacy are useful for climate reconstruction via



magnetostratigraphy. They hold promise for extending dating beyond 350ka, as on Isla de Mona, where an inferred age of 1.7Ma has been determined.

Little work has been done on isotopic palaeoclimate reconstruction for speleothems from low latitude caves, probably because, among other factors, rapid growth in such environments leads to non-equilibrium systematics. Fischer et al recognized the problems, and went on to consider variations in the $\delta^{18}O$ of tropical cave calcite provided that equilibrium is achieved, ie. (i) no change in time would be observed or, (ii) the change might be only due to temperature of deposition or, (iii) the so-called Amount Effect peculiar to the tropics might dominate. They presented a broken $\delta^{18}O$-$\delta^{13}C$ record from Forbes Cave, NW Queensland, dating back to 55ka (with most growth between 0-2.5ka). The striking feature of their data is that the $\delta^{18}O$-$\delta^{13}C$ essentially march in step along the growth axis with an amplitude around 2‰. While this would be a secondary criterion for non-equilibrium deposition (the first being a correlation of $\delta^{18}O$ and $\delta^{13}C$ *along* a growth layer), they feel it should be re-examined in the light of a similar record from Israel that could be matched to complementary palaeoclimate records. Speleothems from both places had grown in a 100% humidity environment. In summary, tropical speleothems, in contrast to higher latitude deposits, may provide valuable and different records of climate history.

Jewel and Wind caves are in a central continental location, and contain abundant speleothems. **Ford et al** described isotopic records from a hydrothermal calcite and a vadose calcite. The former yields a continuous record from 330-160ka (8 U-series TIMS dates) in only 2.4cm thickness of material, similar to a well-known hydrothermal calcite palaeoclimate record from Devil's Hole, Utah. The $\delta^{18}O$-$\delta^{13}C$ record splits into two. The 325-225ka portion is a uniform "plateau" (perhaps signifying over-riding hydrothermal effects). The 225-160ka portion is lower in value, varying some 3‰ in $\delta^{18}O$ and displaying a negative correlation between $\delta^{18}O$ and $\delta^{13}C$ (probably due to palaeoclimate changes). The vadose calcite flowstone, 12cm thick, yields a discontinuous but detailed palaeoclimate record from 470-92ka (12 U-series TIMS dates) with a maximum resolution of 300-500 years. Isotope stage 5e, which lasted, with a number of excursions, from 129-119ka, is identified in the record, and Marine Termination II is signaled by an increase of 3‰ in $\delta^{18}O$ from 131-129ka. Growth in the previous interglacial (isotope stage 7) displays abrupt shifts of up to 4‰ in $\delta^{18}O$ occurring at 210, 192 and 178ka. Clearly, these sites offer a tremendous opportunity to establish a multiple, reliably-dated, detailed continental palaeoclimatic record, perhaps more than matching those of the cornerstone marine and ice cores.

8. Poster Presentations

Atalay presented a broad view of karstification in Turkey since initiation during uplift at the end of the Mesozoic. Several large-scale features, such as the fresh-water lakes of Beysehir and Egirdir, relate to this tectonism. Uplift and fracturing have allowed extensive drainage routes to develop, some of which drain lakes and traverse the Taurus Mountains to resurge at the Mediterranean. Aeolian materials associated with the karst indicate a cold dry climate towards the end of the last glacial period.

van Beynen described ongoing work towards characterizing high and low fluorescence in speleothems. Optical fluorescence intensity has been ascribed to relative concentrations of soil-derived organic acids (humic and fulvic) deposited in the speleothem, providing a measure of climatic conditions, but this has not been fully demonstrated. Speleothems with a wide range of hues, from clear white to almost black, were collected, and a spectrophotometer working at a widened band width of 200-550nm was used to excite the full fluorescence range. Removal of organics for chemical and fluorescence analysis, provided information about the "remaining" fluorescence (eg. from trace metals), and gave some understanding of the correlation of organic acids to fluorescence.

Godawa Stormark described the occurrence of considerable accumulations of fossil bats (*Mammalia: Chiroptera*) from Pliocene/ Pleistocene localities in the Krakow-Wielun uplands (southern Poland). A species new to Poland (*Myotis steiningeri*), common in the Late Pliocene/Early Pleistocene, was recognised, and this is similar to *Myotis bechsteini*, commonly reported from the same period.

Goede and **McCulloch** reported strontium variations showing a marked bimodal distribution in a Tasmanian speleothem, indicating two distinct sources, one persistent (from overlying limestone) and one intermittent (believed to be aeolian). Speleothems might thus provide sensitive indicators of dust fluxes during the Quaternary. As strontium also derives from sea-spray, its variation may relate to changing coastline position accompanying sea-level change.

Few studies concerning the physico-chemical and biological controls of speleothem sedimentation exist. **Gradzinski et al** presented preliminary results from Poland regarding the reconstruction of environmental controls and microfacies variation. Their premise is that each microfacies should reflect a given environmental characteristic: hydrodynamic, temperature, chemical composition, impurities, microbial activity, and so on. Resultant microfacies they have observed and defined include moonmilk, botryoidal or columnar fabrics, rhythmic lamination or blocky textures. Potentially,

interpretation of these fabrics can add palaeoclimate information to complement other records, such as luminescence and isotope. **Gradzinski** continued this theme (with others), finding that black laminae in speleothems from caves in the Cracow-Wielun Uplands have a charcoal and organic component (identified by UV) related to human activity. Occupation was probably from the Palaeolithic to the Middle Ages, based on other material in the caves.

Miroslaw-Grabowska examined the stratigraphy of a 5m-thick sediment in the Bisnik rock-shelter. She divided the unit into 3, dated by geological, archaeological and palaeontological means. Layer I accumulated during the Warthanian (around 150ka) when the site was cavernous, Layers II and III accumulated during the Eemian interglacial and the Vistulian, after the cave collapse formed a rock-shelter. Elements of layer II, and Holocene archaeological material at the top of the unit, can be correlated with sediments in other Polish Jura caves. Bisnik is an important new Palaeolithic site, as climatic changes and geomorphological processes can be reconstructed in its vicinity. It is, for example, the first site in the Polish Jura to yield Acheulian-type flint tools.

Hercman et al undertook geochemical analysis of detrital layers in two Polish speleothems to study breaks in deposition. Generally, increased Mg, Al, K and Fe were observed, with a significant increase in Si symptomatic of a locally known feldspars and mica provenance (mica, feldspar and quartz occur at the base of one deposit). Some dark layers, low in these ions, are thought be due to organics. Interestingly, in some of the broad pale banded calcite they found characteristic marginal zones showing ionic enrichment that may reflect migration from adjacent detrital layers or organics.

Frequency histograms for (mainly) U/Th speleothem dates are important and sensitive palaeoclimate reconstruction tools, whether indicating initiation of rapid growth during warm, humid climates, or interrupted growth during glaciations. Historically (since 1970) dating uncertainties were ignored, but later (1983) dating errors, as normal distributions, were incorporated. **Hercman** and **Walanus** pointed out the marked asymmetry in dating errors, especially as the limit of the method is approached at around 400ka, and suggested that assumption of normal distributions is inappropriate. Their "randomization" method for frequency histogram construction utilizes $^{230}Th/^{234}U$ and $^{234}U/^{238}U$. A "randomized" set of mean ages is generated from each pair, with a normal error distribution. Finally, all data are plotted as a frequency histogram, wherein, if the randomization number is high enough (say 30,000), a smooth probability distribution function is generated.

Annual or better stratigraphical and chronological resolution can be attained using techniques such as speleothem luminescence. There is interest in achieving similar resolution from stable isotopes, where previously, at best, many-year resolution was acquired with a fine drill. **Lauritzen** and **Kihle** attempted to obtain annual resolution stable isotope speleothem data using a laser ablation microprobe. This samples down to μm dimensions, removing CO_2 thermally from calcite for analysis. Non-constant fractionation of carbon and oxygen isotopes so removed (a problem previously encountered with thermal decrepitation) seems not to be a problem with this particular method, perhaps due to the high temperatures involved. It yields reproducible results and errors comparable to established methods.

The 700m-thick Akka limestone unit occupies a 50km by 1-4km strip formed on Triassic basement in the Kitakami Mountains (northeastern Japan). **Okamotu** documented environmental change on the karst since the last glacial, based on tephra ages. Two major periglacial mass movement episodes are identified at 50ka and between 30-10ka. Tephra removal by soil creep during the Holocene is thought to reflect deforestation, and human occupation is recognized since 50-40ka, with extensive activity during 5-6ka.

The Romanian cave *Ghetarul de la Scarisoara*, at an altitude of 1165m, contains a large volume of perennial cave ice. During the summer, winter snow that has entered the cave melts, forming a water film on existing ice. This collects soil, pollen and so on, and a layered ice structure has developed (pollen dated to 3000 years BP). Thicker, more vegetated, layers are assigned to warmer, wetter periods such as the so-called Black Sea Histrian transgression in the first part of this millennium. **Racovita** described 10 years of observation at the cave, where floor ice levels oscillate at two superimposed frequencies, appearing to track cave temperature. The first cycle is annual (amplitude <5cm); the second is about 7 years (amplitude <20cm peaking in 1987). Careful analysis of ice and contents might allow cycle data to be extended back in time, potentially aiding study of short-term meteorological cycles.

Shopov et al (1) found a good correlation (0.8) between speleothem luminescent intensity and the Standard Calibration (Residual) $\Delta^{14}C$ Record derived from dendrochronology. Atmospheric ^{14}C arises from cosmic rays, whose flux is modulated by the solar wind. Analysis of a Bulgarian speleothem enabled reconstruction of the cosmic ray flux (CRF) for the last 50ka. Further, a 6.5ka supernova eruptions record with a 20-year resolution was generated using data from Cold Water Cave, Iowa, USA. This was achieved by subtracting an inverted luminescent solar activity record from the $\Delta^{14}C$ record, leaving only the galactic cosmic ray flux (GCRF). This record agrees with supernova data from other sources, so it is concluded that GCRF emanates mainly from such eruptions, with no Big Bang component. As geomagnetic field intensity (GFI) is modulated by the solar wind and solar magnetic fields (related to solar intensity), speleothem luminescence (coupled to soil organic activity also related to insolation) should give a proxy record of the GFI. **Shopov et al (2)** used the Bulgarian speleothem to generate such a record, finding a correlation of 0.78 between luminescent intensity and an independent record of GFI dipole variation. NASA have used the Bulgarian record, along with satellite measurements, to calibrate the Solar Constant for the last 10,000 years.

Shopov et al (3) proposed a new technique - phosphorescence time-resolved photography - to study thermal and uplift history of thermal caves. Essentially the technique relates phosphorescence to temperature-dependent epithermal mineralization in speleothems, which, with absolute dating, should yield the thermal history of the deposit. Results agree well with stable isotope data from hydrothermal speleothems from the USA and Hungary.

Shopov et al (4) compared speleothem growth rates in Rats Nest Cave, Alberta, Canada over the last 120 years with precipitation variations at a nearby site (Banff), finding a correlation of 0.57. Luminescent intensity variations highlight annual speleothem growth bands used, with the Banff data, to construct proxy annual precipitation records for the last 280 years at the cave. By "tuning" the luminescence data with the GFI dipole record of the Bulgarian speleothem (above), growth rates for that deposit were determined. At 7-6ka growth rates were 53 times higher than today - could this reflect the "Biblical Deluge"? Similar work at Cold Water Cave (USA) suggests increased precipitation between 6.4-2.5ka.

Tarhule-Lips and **Ford** investigated "condensation corrosion" as a speleothem dissolution mechanism in caves on Cayman Brac (Cayman Islands). The speleothems yield TIMS U/Th dates from 20 to >350ka. The caves are out of reach of marine storm surges and meteoric input, yet the speleothems exhibit resolution at hiatuses and at margins where they have stopped growing. Humidity would have been the only source of water for calcite dissolution. Gypsum suspended for one year at selected cave sites lost from 5 to >10 weight %, while a sealed control lost <0.17 weight %. Microclimate measurements were undertaken in the knowledge that for significant condensation corrosion to occur a high CO_2 content, humidities close to 100%, and a strong thermal gradient are required. While growth cessation/dissolution cannot yet be correlated with glacial/interglacials, work continues elsewhere to see if the phenomenon is widespread.

Karren, Glomfjell Karst.

Mg/Ca and Sr/Ca variations in seepage water, while being functions of whether bedrock is limestone or dolomite (with a lower Sr content), also appear to vary on the basis of residence time. For example, **Tooth et al** found fast leachates to be antipathetic to slow leachates, which exhibited higher Mg/Ca and Sr/Ca, possibly due to incongruent dissolution. Soda straws have been found to exhibit variable 2-5mm annual banding, attributed to water supply increases. However, these workers did not find the Mg/Ca and Sr/Ca correlation that might be expected in such cases. They extended their studies to include Ba and Na (as well as Mg, Sr and Ca) and found some covariance between Ba, Mg, Na and Sr in a portion of a Belgian soda straw and between Ba, Mg, Na (but not Sr) in an Irish soda straw. They emphasize a need to understand the chemical systematics in the soil and karst zones, but that the ion record has potential for past climate interpretation. In a stable isotope geochemistry study of Holocene speleothems that might be considered complementary, **Verheyden et al**, emphasized the need for measurement of current parameters, such as recent calcite, seepage, cave air, temperature, and vegetation cover.

An extensive system for monitoring karst infiltration from the surface to the water table has been set up in the Aggtelek karst (Hungary). **Zambo** found that infiltration from forested areas is 1-12 hours delayed over that from grasslands, and infiltration into 0.5m-depth of soil can vary from 0-44 hours, depending upon soil humidity. Within the karst, water supply variations are found to be progressively smoothed with depth, but rhythmical variations are still observed at the water table. The latter are thought to reflect lunisolar effects that disturb the karst reservoir. Detailed analysis of karst infiltration and mathematical modelling have allowed average limestone dissolution values to be determined.

THE EXCURSIONS

Excursion 1 (Leaders: Inge Aarseth, John Mylroie and Stein-Erik Lauritzen) Geomorphology and Quaternary Geology of the Inner Part of the Sognefjord Area and an Introduction to the Caves and Karst of Dummdalen (30-31 July, 1996).

This trip viewed geomorphology and Quaternary geology along the innermost fjords of western Norway, the Alpine landscape that rises to 2,500m and the karst of western Jotunheimen. There are three major geological units: over-thrusted rocks of the Jotun nappe complex, Cambrian/Ordovician schists with marbles, and Precambrian gneisses and granites. The landscape reflects underlying bedrock structures, as demonstrated by the trends of fjords, valleys and prominent mountain escarpments. Alternating glacial and fluvial erosion caused glacial overdeepening of valleys and valley piracy, and produced thick glacio-fluvial deposits (some terminal moraines from the last glaciation are 400m thick).

The Dummdalen caves and karst occupy a thin contorted and discontinuous band of Cambro-Ordovician marble (*stripe karst*) sub-parallel to the Dummdalen valley. Its outcrop lies between 1,350m asl at the headward end and 960m asl at the valley's interception with the larger Breiseterdalen valley, where there is a large karst spring. Local summits exceed 1600m. The marble contains nine major caves. Four are river caves carrying the valley stream underground to the karst spring, and five are relict phreatic segments. Currently the river caves are very active; flooding occurs at peak discharge. Roches moutonnées trends indicate that the last dominant ice movement was up-valley, but no evidence for subglacial reversed-flow in the relict caves (demonstrated elsewhere in Norway, eg. Glomdal) has been observed. The relict caves show considerable vertical development (possibly in a sub-glacially raised water table, but with development always towards the Breiseterdalen valley), and paragenetic features associated with inwashed glacial sediment.

Excursion 2 (Leaders: Stein-Erik Lauritzen and John Mylroie) Karst Landforms and Caves of Nordland, Northern Norway (5-16 August, 1996).

Comprehensive details of this extensive field trip are provided in the field guide (Lauritzen, 1996) and in some of the conference presentations; this précis imparts the flavour of what the 26 participants saw. The itinerary, starting at Evenes and finishing at Bodø, ranged from 68°N to just south of the Arctic Circle, which traverses much of the Norwegian karst. Sites were reached by bus, ferry or boat, or on foot, with overnight stops in hotels and campground chalets.

Except for a few areas of relatively unaltered limestone outside the Caledonian orogenic belt near Oslo, most of Norway's karstifiable carbonate rocks are extensively mineralized and folded, regionally metamorphosed calcite and dolomite marbles. Tectonic overprinting produced the unique structural geology of Norway's karst: fracture guidance and stripe morphology. Stripe karst is characteristically Norwegian, comprising thin (<10m) but laterally extensive (>kms) carbonate bands, commonly tightly folded and steeply dipping, with extensive allogenic catchments. Karstification occurs along fractures (faults and shear joints) and relates strongly to lithological boundaries (commonly thrust features) between marble and schists. Most karst

Grey marble karren, Upper Glomdal. The Glomdal valley divides the Svartisen Icecap into east and west portions, and lies across the Arctic Circle.

development is, necessarily, from allogenic drainage, but substantial carbonate areas (>km^2) have been modified by autogenic drainage. Examples visited on the excursion are Saltdal and Glomfjell. Glomfjell is outstanding for its lapiaz, karren, and raised features (erratics perched on pedestals, and upstanding siliceous veins) used in calculating karst denudation rates. Problems of dam construction on stripe karst were illustrated at Glomfjell. To encompass the complete karst size-range, large features were visited, such as the relict poljas and major sink of Trolljerka (Lavangsmarka karst near Evenes), and the huge sinks of the Plurdal karst.

A dominant factor in karst evolution has been multiple glaciation. Cave development is greatly influenced by ice contact, largely due to basal water flow, especially under temperate glacial conditions. With present day glacier retreat, caves have been largely drained, affording unprecedented opportunities to study cave hydrology. The excursion visited several major caves, including: the complex, 11km-long Oksola (at Fauske), the 580m-deep Raggejavriraigi (reached by boat at Hellemofjord), the 3km-long multi-entrance looping phreas of Harmarnesgrotta (at Rana) and the brilliant white-marble Storbekkgrotta, which contains remarkable pendant fields. These stimulated discussion among the participants, especially as they have been well studied by Lauritzen and others. The caves vary from those with complex hydrologies (eg. Okshola) to the "ideal", supposedly simple, single karst conduit, such as the underground outlet of Lake Glomdal (Jordtulla), draining a 27km^2 basin through a 560m-long, 5-6m-diameter tube. (The latter is actually far from simple, as work by Lauritzen, Atkinson and Bottrell demonstrates.)

Besides passage morphology, participants saw cave sediment study sites, and evidence of armouring by glacial sediments that led to massive paragenesis in caves at Kjøpsvik, Tysfjord (see papers above by Lauritsen and Lauritzen; Lauritzen et al).

This discussion does little justice to 12 days of study in superb mountain scenery, but hopefully it will raise awareness of the uniquely Norwegian karst type. The Field Guide is strongly recommended reading.

ACKNOWLEDGMENTS

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APPENDIX

List of papers (grouped by topic) and posters presented during the Bergen conference

1. Keynote papers

Lauritzen, S-E	Climate Change: The Karst Record (Introduction)
Ford, D C	Dating cave deposits
Schwarcz, H P	Paleoclimate inferences from stable isotopic studies of speleothem
Dreybrodt, W	Chemical kinetics, speleothem growth and climate
Smart, P L, Roberts, M S, Baker, A and Richards, D A	Palaeoclimatic determination form speleothems - a critical appraisal of the art. (By way of closing remarks by P L Smart)

2. Speleothem Stratigraphy and Chronology (Chair: Paul W Williams)

Richards, D A, Bottrell, S H, Cliff, R A and Strohle, K D	U-Pb dating of Quaternary age speleothems
Baker, A, Genty, D and Barnes, W L	Recent stalagmite growth rates: cave measurements, theoretical predictions and the environmental record
Hercman, H	Comparison of speleothem dating by TL, ESR, ^{14}C and $^{230}Th/^{234}U$ methods
Lundberg, J and Toscano, M A	Caves and coral: high precision dating of flowstone and coral reefs constraining the 5a sea level in Florida and the Bahamas
Lauritzen, S-E, Hercman, H and Glazek J	Preliminary comparison between Norwegian and Polish speleothem growth frequencies
Li, B, Yuan, D, Quin, J and Lin, Y	A high resolution record of climate change since 36,000 years BP

3. Shopov Bands and other High-Resolution Stratigraphic Information in Speleothems (Chair: Derek C Ford)

Shopov, Y Y, Tsankov, L, Geogiev, L N, Damyanova, A, Damyanova, Y, Ford, D C, Yonge, C J, Krouse, H R K and MacDonald, W D	Speleothems as natural climatic stations with annual to daily resolution
Baker, A, Barnes, W L and Smart, P L	Luminescence and discharge variations in stalagmite dripwaters, Bristol, England
Genty, D, Baker, A, Barnes, W L and Massault, M	Growth rate, grey level and luminescence of stalagmite laminae
Ming, T and Tungsheng, L	Monsoon data from oxygen isotope of speleothems in East China - An example from Beijing Shihura Cave
Roberts, M S, Smart, P L, Perkins, W T, Pearce, N J G and Hawkesworth, C J	Trace elements in Holocene speleothems

4. *Stable Isotopes in Speleothems (Chair: Helena Hercman)*

Bar-Matthews, M, Ayalon, A and Kaufman, A	Late Quaternary paleoclimate in the Eastern Mediterranean - stable isotope systematics of Soreq Cave speleothems
Borsato, A, Spiro, B, Longinelli, A and Heaton, T	Isotopic composition of present-day alpine speleothem from Trentino (NW Italy): A key for paleoclimatic interpretations in ancient speleothems
Dennis, P F, Rowe, P J and Atkinson, T C	Isotopic composition of paleoprecipitation and paleogroundwaters from speleothem fluid inclusions
Lauritzen, S-E	Calibration of speleothem stable isotopes against historical records: a Holocene temperature curve for north Norway?
Kadlec, J, Hladikova, J and Zuk, K	Isotopic study of cave carbonates from Moravian Karst, Czech Republic
Frumkin, A, Ford, D C and Schwarcz, H P	Paleoclimate record from the Mediterranean desert border karst, Israel
Frisia, S	TEM and SEM investigation of spelothem carbonates: another key to the interpretation of environmental parameters
Bottrell, S H, Menys, J and Crowley, S F	Paleoclimatic information in alteration assemblages of limestone-hosted base metal deposits

5. *Cave Stratigraphy and Paleomagnetism (Chair: Wolfgang Dreybrodt)*

Løvlie, R and Lauritzen, S-E	Late Weichselian paleomagnetic chronostratigraphy of sediments in four cave systems in Nordland, N-Norway
Quinif, Y	Complex stratigraphic series in Belgian caves: correlation with the paleoclimatic variations during the Middle and Upper Pleistocene
Sroubek, P, Diehl, J F and Kadlec, J	do cave sediments from the Spiralka Cave (Czech Republic) record environmental change?
Nese, H and Lauritzen, S-E	Quaternary stratigraphy of the Storsteinhola cave system, Kjøpsvik, north Norway
Yonge, C J and MacDonald, W D	The potential of cave ice in isotope paleoclimatology

6. *Cave Biology and Paleontology (Chair: Joyce Lundberg)*

Moldovan, O	What can cave beetles tell us about the climate?
Lien, A M, Østbye, K and Østbye, M	Life cycle and morphology of an epigean and a hypogean population of *Gammarus lacustris* G. O. Sars (Amphipoda) in south Norway
Viehmann I, Lauritzen S-E and Onac, B P	The Vartrop Cave Man and his radiometric age
Lauritzen, S-E, Nese, H, Lie, R W, Lauritsen, A and Løvlie, R	Interstadial/interglacial fauna from Norcemgrotta. Kjøpsvik north Norway
Rojsek, D	Conservation of cave sediments

7. *Regional Karst and Cave Analyses I, II and III (Chairs: Simon Bottrell, Peter Smart and Tim Atkinson)*

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8. *Poster Presentations*

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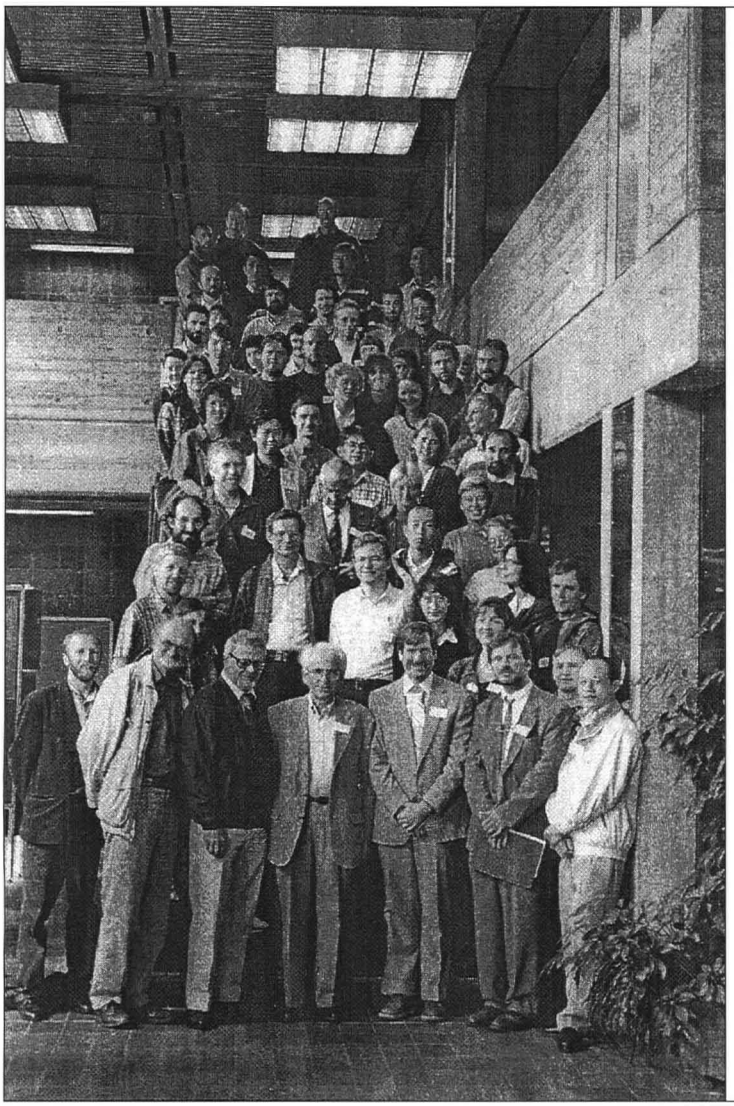

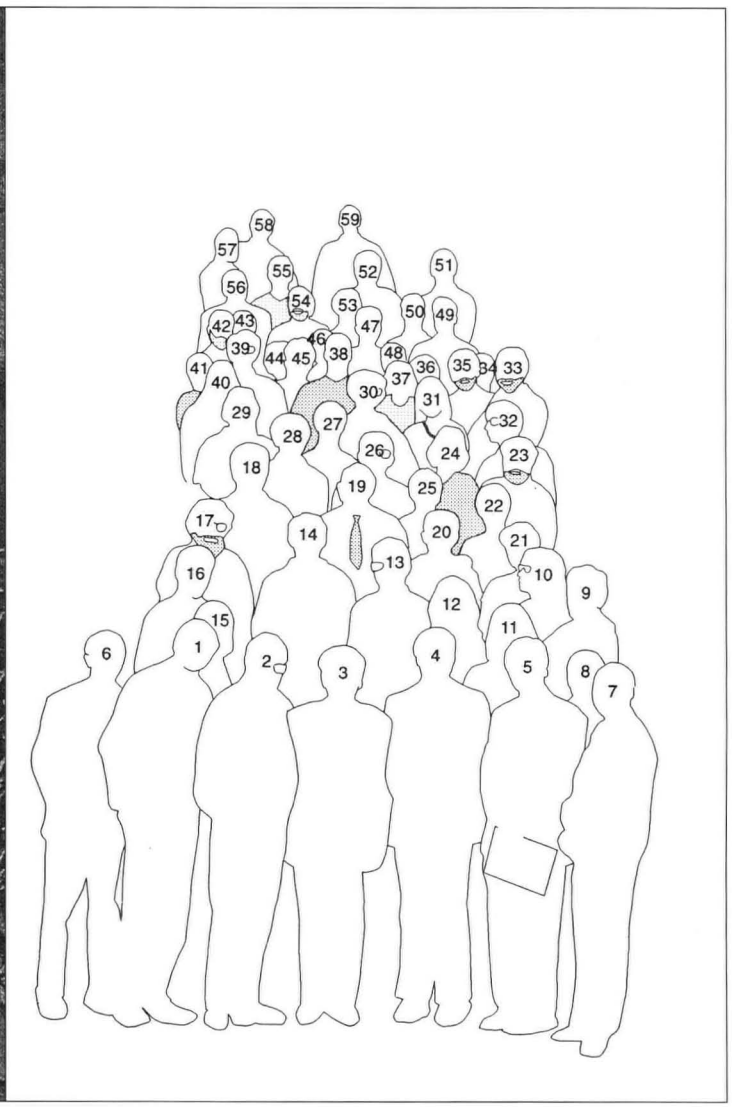

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Quartzite dissolution: karst or pseudokarst?

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Abstract: A wide range of landforms of great similarity to limestone karst is found on many of the world's quartz sandstones and quartzites. These landforms have often been dismissed as pseudokarst, but recent investigation shows that the dissolutional removal of silica, even quartz, under earth-surface conditions is a critical process in their formation. They must therefore be regarded as true karst features. Recognition of these genetically similar forms on quartzose rocks now demands the worldwide adoption of a less restrictive, process-based, karst definition. Direct evidence for this near-surface dissolutional weathering is not common. Examples of this process are reviewed here, along with further evidence for the dissolution of silica from within the quartz sandstones of the Sydney Basin in temperate south-eastern Australia. Some of the complex processes by which dissolution attacks the rock remain unclear. However the solubility, thermodynamics, fluid throughput and physical removal of detritus are all critical factors in the formation of what can only be termed karst on quartzites and quartz sandstone.

INTRODUCTION

Detailed study of the calcareous karst of central and eastern Europe began several hundred years ago (reviewed by Shaw, 1992) and has since developed into a highly structured field of research (e.g. Sweeting, 1972, 1981; Jakucs, 1977; Jennings, 1985; Ford and Williams, 1989). It was perhaps unfortunate though that most early definitions of karst, many of which still linger today, were essentially restricted to carbonate bedrock, because it was not long before a range of similar landforms started to be identified on quartz-rich rocks. These non-carbonate morphologies, whilst commonly identical in size, shape and apparent formative process to their limestone analogues, were therefore dismissed as pseudokarst. That is to say, they were considered to be like karst, but only a scientific curiosity and not generally worthy of detailed study. However, even though dissolutional processes have now been demonstrated as a causative agent in the genesis of many of these forms on quartzose rocks, many geomorphologists and geologists following conventional wisdom, have been loath to change their outlook (eg., Marker, 1976; Vítek, 1979; Pouyllau and Seurin, 1985; Osborne and Branagan, 1992; Yanes and Briceño, 1993).

This paradox of dissolutional landforms on some of the world's most insoluble rocks mimicking those on some of the most soluble, both in appearance and scale, has become increasingly difficult to ignore in recent years, yet little attention has been given to the detailed study of the landforms themselves or the dissolutional processes involved. It appears that this may be because of a long-standing and, as it now seems, falsely grounded assumption that quartzose rocks are of extremely low or almost negligible reactivity and, unlike limestone, are "*practically immune to chemical weathering*" (Tricart and Cailleux, 1972, p.152). Yet, during the last three decades the large scale dissolution of silica, including the least soluble quartz, has been demonstrated clearly and repeatedly as being critical to the development of the great quartzite karst landscapes of Venezuelan Roraima (White et al, 1966; Urbani and Szczerban, 1974; Chalcraft and Pye, 1984; George, 1989; Briceño and Schubert, 1990) and those on the quartz sandstones of Tchad in central Africa (Mainguet, 1972), the Arnhem Land and Kimberley regions of northern Australia (Jennings, 1979; Young, 1986, 1987, 1988) and the Sydney region in south-eastern Australia (Wray, 1995). See Wray (1997) for a detailed review.

THE PROBLEMS OF KARST TERMINOLOGY

Considerable terminological difficulties are inherent in the question of what exactly constitutes karst (Twidale, 1984). Many definitions of karstification are restricted to discrete rock or landform types on lithological or morphological grounds (e.g., Dreybrodt, 1988; Ford and Williams, 1989; Self and Mullan, 1996), but such definitions may not always be appropriate. Absence or scarcity of surface drainage, collapse features, caves, grikes, runnels and speleothems are distinctive, but they are not peculiar to karst (Twidale, 1984). Gams (1989) went as far as to state that certain surface landforms are regarded as typical in karst regions but are not essential. He thought that only two phenomena are essential: efficient dissolution of rock and karst drainage.

In recent years several wider-ranging, process-based, definitions that are not restricted by rock type or landscape morphology have been proposed. Sweeting (1972, p.5) stated that: "*... the sinking of water and its circulation underground is the essence of the karst process ...*" but also followed with "*... this process is dominated by a chemical (solutional) activity, and true karst landforms result largely from the action of one erosive process, namely solution*". Grimes (1975) argued that true karst could occur on lithologies other than limestone provided that dissolution was the dominant process, and Gams (1989, p.169) felt that "*... the processes which control the shape of the landscape can include non-karst processes and are not restricted to solution. However, solution remains the most intensive geomorphic process.*".

Ford (1980, p.345) went further, qualifying the importance of dissolution by noting that "*... true karst forms are distinguished from pseudokarst forms by the necessity of rock solution. True forms may be excavated entirely by aqueous solution, or other processes may contribute largely to their dimensions; but where this latter applies, solution plays an essential precursor or 'trigger role'*". Jennings (1983, p.21) similarly noted the importance of dissolution by stating that karst is the "*... process, solution, which is thought to be critical (though not necessarily dominant) in the development of the landforms and drainage characteristics*" of an area. He later followed with: "*... karst is a terrain with distinctive landforms and drainage arising from greater rock solubility in natural waters than elsewhere ... Solution is not always the most prevalent process in karst, nor is it necessarily the dominant one, but it does play a more important role here than in other kinds of landscape*" (1985, p.1).

More than just the presence of dissolutional weathering is therefore required for sandstone karst development, for dissolved silica is present in most natural waters (Aston, 1983). The dissolution must "*... contribute largely ...*" and act in a way that is a "*trigger role*" (Ford, 1980) or be "*... critical (but not necessarily dominant)*" (Jennings, 1983) in the preparation of the rock leading to the development of landforms that otherwise would not arise. A variety of chemical and physical weathering processes are involved in the development of limestone karst landforms (Jennings, 1985; Ford and Williams, 1989) and, similarly, dissolutional landforms on quartz sandstones or quartzites are also formed by a variety of physical

and chemical processes. But the common factor that sets them apart from more general sandstone weathering is the critical action of chemical dissolution.

Wray (1997) presented a wide-ranging and comprehensive analysis of the worldwide distribution and morphology of karst on quartzite and quartz sandstones. This review demonstrates clearly that landforms are found on quartzose rocks that are comparable in type, form and scale to those described from many limestone regions. The present paper examines the evidence for dissolutional weathering within some of these quartz sandstones.

EVIDENCE FOR KARSTIC DISSOLUTION OF QUARTZITE AND QUARTZ SANDSTONE

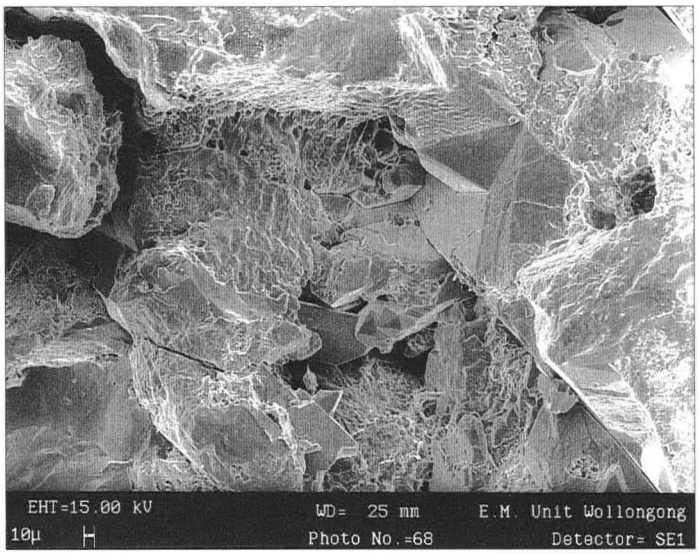
Many examples of silica dissolution within deeply buried quartz sandstones are found in literature describing petroleum occurrences, but unquestionable proof of the dissolutional removal of silica from such rocks under near-surface conditions is rarer. However microscopic evidence from several locations shows clearly that slow near-surface dissolution of quartz, 'arenisation' in the terms of Martini (1979), occurs typically along crystal boundaries, freeing individual sand grains that are ideally suited to removal by flowing water.

In the hot, wet, tropical area of central Venezuela, large table-mountains of the Precambrian Roraima Group orthoquartzites display some of the world's most highly developed and striking quartzose karst landforms (see George, 1989). White et al (1966) argued from petrographical evidence that quartz within these rocks was hydrated to much more soluble opal and then removed in solution. Scanning Electron Microscope (SEM) examination of these quartzites (Chalcraft and Pye, 1984) revealed a widespread and intense crystallographically controlled microscopic attack of detrital quartz grains and overgrowths. Clear evidence was found that widening of grain-to-grain contacts, coupled with etching and corrosion of both quartz grains and cement, eventually leads to the freeing of individual detrital grains. Chalcraft and Pye (1984) rejected the White et al opal hydration mechanism, and demonstrated the direct dissolution of quartz grains and silica cement without an intermediate hydration phase. They also showed that while there is preferential dissolution along joints, beds and lithological contacts, cracks at all scales provide foci for water flow and pathways for dissolution.

Ghosh (1991) found that surface outcrops of weathered Roraima quartzites display an excellent network of lamellar porosity formed by dissolution of quartz cement along overgrowth boundaries. However, samples from deep below the surface show abundant welding of grains by a pervasive syntaxial quartz cement with sutured grain-to-grain contacts. This variation in weathering between surface and buried samples demonstrates that this quartz dissolution is a surface phenomenon, and did not originate at depth in a process similar to that recently recognised by petroleum geologists in the formation of secondary sandstone porosity (Pye and Frinsley, 1985; Shanmugam, 1985; Burley and Kantorowicz, 1986; Hurst and Bjorkum, 1986). However the resultant dissolution features under both circumstances are quite similar.

Wilson (1979) presented SEM images of minute v-shaped chemical etch pits on the quartz grains of the Millstone Grit of South Wales. He attributed these to slow dissolution by fluids of high pH seeping along cleavage and/or fracture planes, and presented evidence for the formation of similar features in the laboratory. Battiau-Queney (1984) also found that the Grit had suffered a long subaerial weathering, possibly under a hot wet tropical climate, resulting in this quartzite being extensively weathered.

Burley and Kantorowicz (1986) analysed microscopic quartz grain surface features (including small pits, notches and larger embayments) produced by dissolutional attack on deeply-buried sandstones. They found a tendency for corrosion to be more intense on those surfaces with a high free-surface energy, such as grain peripheries, along fractures and at crystal boundaries. Two mechanisms of quartz corrosion were proposed.



SEM micrograph showing intense dissolutional attack within the early Permian Snapper Point Formation at Jervis Bay, south of Sydney, Australia. The amount of quartz overgrowth within these sandstones is quite high, but without total elimination of effective porosity. Greatest dissolutional attack is in areas of high free-surface energy (detrital grains, overgrowth faces and edges); however many of the overgrowths, especially prism faces, are only slightly corroded. Cement and overgrowth sutures binding the sandstone have begun to dissolve leaving narrow voids between grains, resulting in a reduction of strength and the production of a sandstone ideally suited to increased physical erosion along joints. Field of view 250µm.

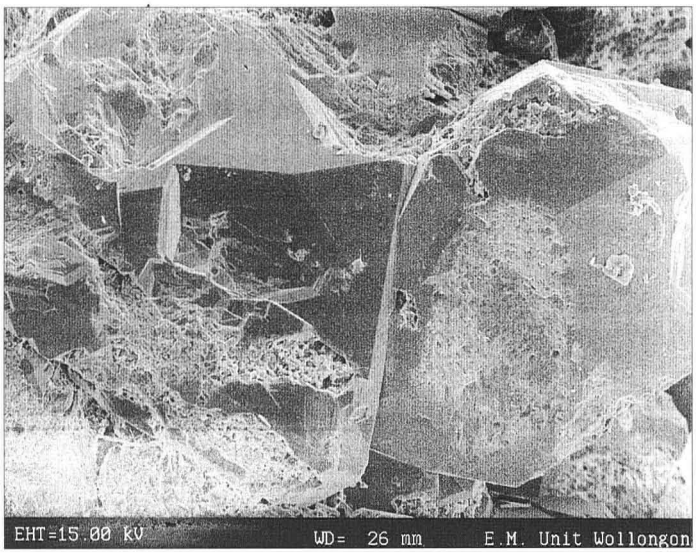
The first, "*transport controlled dissolution*", is influenced by the rate of transport of fluids to and away from the reactive surface, or the reaction rate at the surface. This results in rapid, non-specific corrosion at all available sites, and is typical of attack by strongly concentrated solutions. "*Surface reaction controlled dissolution*" is generally more specific, tends to produce crystallographically controlled features, such as well defined v-shaped pits, and is typical of slow dissolution.

An SEM investigation of the regional extent and intensity of quartz sandstone etching in the seasonally-arid east Kimberley region of northern Australia (R W Young, 1988) provided graphic evidence of such surface-reaction and transport controlled dissolution features. Young (1988) also noted that Hurst and Bjorkum (1986) had challenged the ideas of Burley and Kantorowicz (1986) by arguing that quartz dissolution rates are too low for transport-controlled etching, emphasising that etching will concentrate at the sites with the highest free-energy, and quartz overgrowth lowers the surface free-energy of a detrital grain. Brady and Walther (1990) and Withe and Peterson (1990) also supported the proposition that silica dissolution occurs preferentially at high-energy surface sites such as defects, and is controlled by the density of such defects. Dissolution should therefore be most rapid at the greatest concentration of detrital grain surfaces, face-corners and edges of overgrowths.

Though R W Young (1988) found widespread dissolution in these high-energy locations, he also found that the intensity of quartz etching in the Kimberley region was variable and more closely related to the primary porosity of the host rock. The more porous sandstones display a higher potential for the penetration of corrosive solutions, with subsequent deep weathering that alters the geotechnical properties of the sandstone.

Intense silica dissolution has also been demonstrated in highly quartzose sandstones of the humid-temperate Sydney region of south-eastern Australia. Tropical conditions have been absent from this area for tens of millions of years (Bird and Chivas, 1989), yet A R M Young (1987) published clear SEM evidence for near-surface dissolution of detrital quartz grains, overgrowths and high free-surface energy grain and overgrowth boundaries. As voids are widened by dissolution detrital sand grains are loosened and removed easily by flowing water.

SEM micrograph showing intense 'transport controlled' etching within the early Permian Snapper Point Formation at Jervis Bay, south of Sydney, Australia. Much of the overgrowth is highly corroded, though other areas are only slightly etched. Field of view 250μm.



SEM micrograph of well sutured but still highly permeable Nowra Sandstone from south of Sydney, Australia. Intense non-selective dissolution is seen on the high free-surface energy grains and overgrowth faces or edges, but lower energy faces display lesser attack. Because of the dissolution this sandstone is very friable in tension and shear, but the interlocking nature of the grains still imparts a high compressive strength. Granular disintegration of this sandstone gives rise to a tower morphology very similar to that illustrated by Young (1986) in the Bungle Bungle Range in the Kimberleys of north-western Australia. Field of view 100μm.

Wray (1995) studied the sandstone landforms of the Sydney region in more detail, finding widespread microscopic evidence for intense, but spatially variable, dissolutional removal of silica. Etching within many surface sandstones is much higher than reported from deeply-buried sandstones in this region. In fact, the type, location and intensity of near-surface dissolutional weathering is very similar to that reported from the tropical and seasonally-arid regions noted above. The same small crystallographically controlled pits are seen, along with many larger areas of non-specific dissolution. Grain contacts, overgrowth boundaries and other discontinuities or defects are much more corroded than most overgrowth faces, but even some overgrowth faces are etched, especially in the most weathered sandstones, most commonly on the rhombohedral faces.

The primary porosity of these sandstones is also a major factor governing the intensity of dissolutional weathering and the landforms that later develop (Wray, 1995). Attack of the overgrowths and cement changes the physical properties of the sandstone. Sandstones with little interconnected void provide few pathways for water penetration and are usually only mildly weathered close to the rock surface. Sandstones with a high degree of effective porosity commonly display striking karstic morphology. They are generally very highly etched, their grains are only weakly held, and the rocks have lost much of their physical strength and resistance (Wray, 1995).

Whilst it is undeniable that dissolutional etching and removal of silica from quartz sandstones is found in many locations, it is also necessary to assess the degree to which such dissolution is necessary in the formation of karstic landscapes.

Briceño et al (1990, p.192) discussed the geology and surficial geochemistry of the landscape in the Roraima area, observing that the complex karstic landscapes developed primarily because of the weathering of the quartzites: "*... mainly by solution of siliceous cement in sandstone, which released sand grains*". Once this cement dissolves, the rocks become very friable and ideally suited to erosion by flowing water channelled preferentially along zones of weakness such as joints and bedding planes. These findings indicate unequivocally that formation of this topography has been dependent upon the effects of "*... chemical weathering, together with the constant removal of detritus*" (Briceño et al, 1990, p.179). Briceño and Schubert (1990, p. 131) examined the geomorphology of Roraima, finding once again that dissolutional weathering of the quartzites, coupled with removal of the detritus produced by flowing water, are the critical landscape forming processes: "*The surface is intricately sculptured, in large measure due to exploitation of fractures by solution of the siliceous cement of the quartzite*".

In South Africa Martini (1979) provided clear evidence for the integral nature of dissolutional weathering allied with removal of detritus under vadose conditions in the development of karst in the Black Reef Quartzite. Mainguet (1972) and Busche and Erbe (1987) also argued for the pivotal role of intensive dissolutional removal of silica in the formation of the widespread sandstone karst of the south-central Sahara.

R W Young (1986, 1987, 1988) also showed that sandstone etching is widespread in the Kimberley region of northern Australia and illustrated clearly that variations in landform morphology are dependent on the intensity of dissolutional weathering and the resultant geotechnical properties of the weathered sandstones. Where dissolution has been most intense - "*... granular disintegration of sandstone is dominant, as in the Bungle Bungle massif, (and) symmetrical towers and aretes, often separated by flat-floored embayments, are formed. As granular cohesion increases and the enlarging of fractures becomes the dominant process, the shape of the towers and ridges becomes more irregular until they merge into Mainguet's 'ruiniform' terrain. On highly indurated sandstone, like those of the Cockburn and Osmond Ranges, cliff and cave assemblages are dominant*" (p.216). It is therefore clear from Young's analysis, like those in Venezuela and Africa, that dissolutional weathering of the Kimberley sandstones has been a critical factor in the development of this region's landscapes, and that variations in the intensity of dissolution have a marked influence on the erosion of the landscape and the resultant landforms.

Like Young, Wray (1995) also found that the range of karstic features on quartz sandstones in the Sydney Basin of temperate southern Australia is reflected in the variable intensity of dissolutional weathering. The most highly weathered sandstones are quite friable, with grikes, runnels, basins, small caves, speleothems and even tower karst not uncommon. Where the dissolution is less intense the sandstones retain much of their cement and sutured overgrowths, and are more robust, less liable to

granular disintegration, and only rarely display any karstic features. The variability in dissolutional weathering is therefore clearly a very significant factor in landscape development on these sandstones. A forthcoming paper will discuss these aspects in more detail.

THE DISSOLUTION PROCESS IN QUARTZOSE KARST

Dissolutional weathering is undoubtedly a highly significant, even critical, stage in the silica karst process. But, though the locus of attack within the rocks is generally clear, some of the detailed mechanisms of this arenisation are complex and still not fully understood.

The equilibrium solubility of silica and especially quartz is low (amorphous silica 100-140 mg/l, quartz 6-14 mg/l at earth-surface temperatures) (Yariv and Cross, 1979). But solubility is not the only controlling factor. Thermodynamics and reaction kinetics are also critical in the formation of silica karst. Martini (1981) has argued that the rate of reaction is just as important as the total solubility; a faster reaction rate limits the distance solutions can penetrate the rock before saturation, resulting in arenisation close to the surface and a general surface lowering rather than deep karstification. Slower rates allow greater water penetration and joint widening without surface lowering, and still-slower rates lead to crystal boundary dissolution with a deep general weathering of the rock. Voids along crystal boundaries are very narrow and water circulation is very sluggish, with saturation being reached after only a very short distance unless the reaction kinetics are very slow. If the silica dissolution rate was slower still, without changing the total solubility, Martini believes that quartzite karst would be much more common.

Moreover, the bulk removal of silica is dependent not only on its solubility and kinetics, but also on the rate at which water moves through the rock. Douglas (1969) demonstrated that the silica load of rivers is dependent upon runoff, and thus upon rainfall. Douglas (1978, p.230) later commented that: "*the importance for the rate of solution of relatively rapidly moving water has been demonstrated in limestone terrains ... but it is equally significant in silicate areas. ... the rate loss of ions from silicate minerals to waters is controlled by the speed at which dissolved ions are carried away from the surface of the mineral*". Rimstidt and Barnes (1980) also emphasised the importance of this 'flushing rate'.

It therefore appears that the rate or volume of water movement through the region is one of the keys to the problem; the higher the water throughput the higher the expected rate of silica removal. Where water throughput is high, silica remains mobile and may enter streams and be removed from the area, whereas where flushing rates are lower it is not removed as effectively, and may be reincorporated in the neoformation of clays (Young and Young, 1992). However, constant increase in the rate of water throughput will not result in a constant increase in dissolved silica. Flushing accelerates the dissolution of minerals only up to a still unclear limiting rate beyond which additional through flow of water has virtually no effect, and dissolution is controlled by mineral reactivity (Berner, 1978). This may be seen in the similar degree of quartz etching achieved under vastly different rainfall regimes in the tropical, semi-arid and temperate sandstones discussed above.

But even on the very highly karstified quartzites of Roraima limited field measurements indicate that the chemical conditions under which the karst is forming are at odds with laboratory results, which indicate that highly alkaline conditions are necessary to achieve significant silica dissolution (Krauskopf, 1956; Siever, 1962; Yariv and Cross, 1979). Pouyllau and Seurin (1985) argued for silica dissolution occurring under hyper-acid conditions, but they could provide only limited evidence for the existence of slightly acid conditions. Likewise, Chalcraft and Pye (1984) and Briceño et al (1990) found natural waters at Roraima to be only slightly to moderately acidic.

Field measurements of dissolved silica by Chalcraft and Pye (1984) also showed dissolved silica levels to be quite low (<1 to 7 mg/l). Similar levels of dissolved silica are also recorded from quartz sandstone terrains in Tchad (Mainguet, 1972), Arnhem Land (Noranda Ltd., 1978; Dames and Moore, 1981), and the Sydney region (Johnson and Johnson, 1972; Johnson, 1984; Wray, 1995), even though precipitation regimes differ dramatically between these areas. These results all indicate that silica is being dissolved only slowly, and suggest that these landscapes have formed by slow dissolution over a very long period.

This factor of slow but very prolonged dissolution is one that has all too commonly been ignored, and the low solubility and slow dissolution rate of silica, especially quartz, was believed to preclude formation of karstic landforms on these 'inert' rocks. Though Self and Mullan (1996) have argued for the rapid development of some karstic features on the Fell Sandstone of northern England, in the areas where the most extensive and highly developed quartzose karst are found (notably South America, Australia and Africa) the available evidence indicates that slow rates of dissolution have been offset by very long periods of sub-aerial weathering (Chalcraft and Pye, 1984; Busche and Erbe, 1987; Young, 1986, 1987, 1988; Briceño et al, 1990; Wray, 1995).

Long periods of arenisation result in a rock that eventually becomes incoherent and is thus highly suited to physical erosion. Martini (1981) notes that karst on quartzite cannot form by dissolution alone, and Jennings (1983) emphasised that while dissolution is critical it actually removes only a small proportion of the rock (about 10 to 20% of rock bulk). The carbonation of limestones leaves behind little residue but the chemical attack of water on silicate rocks produces large volumes of residue, loosened by dissolution, that must be removed by physical transport (Jennings, 1983). Therefore, a plentiful supply of flowing water is necessary, preferably under vadose conditions. Physical erosional processes are thus just as important, if not more important, in the formation of quartzose karst as they are in other quartz sandstone regions.

CONCLUSIONS

Distinctive landforms that have developed on many quartzites and quartz sandstones around the world are virtually identical in form and genetic formative process to many landforms developed on limestones (Wray, 1997). It has become ever clearer during the last three decades that use of the term karst can no longer be restricted to describing carbonate terrains. It has also been argued increasingly that karst should not be reserved for the description of specific landscape morphologies, but should be seen more as the process of significant rock dissolution.

Viewing karst more as a process, rather than purely as a morphology or lithology, no longer restricts use of the term artificially to describing particular landforms or rock types. Because it is dissolution that endows karst with its particular characteristics, process-based definitions should now be advocated, thus allowing recognition of the critical genetic process whilst incorporating the essentials and avoiding the limitations of other karst definitions. Such process-based definitions also allow a more natural grouping of landforms that display a similar mode of origin and feature morphology within a range of rock types. This type of definition is thus consistent with geomorphological terminology employed for other landforms (Löffler, 1978).

A significant component of rock dissolution affecting landform development is the key element, critical to karst development. Although pseudokarst features bear a close resemblance to karst forms, they evolve in response to other dominant processes and the action of rock dissolution is not necessarily involved in their formation. Now that widespread karst on quartzites and quartz sandstones has been clearly recognised the blanket application of the term 'pseudokarst' is commonly unjustified. However, as argued by Twidale (1984) for dissolutional landforms in

granite, until the formative processes are known the immediate application of the term karst to landforms with karst-like morphology may be over simplistic. Therefore, the use of distinctive names that are available and established in the literature may be preferable (Twidale, 1984).

Although dissolutional processes that act upon quartzose rocks are very different to those affecting carbonates, silica dissolution has been, and will continue to be, clearly demonstrated as having an integral role in the development of sandstone karst. Hopefully, the recognition of increasing numbers of these landforms as true karst, not pseudokarst, should prompt further much-needed critical investigation, especially of the complex chemical interactions and geotechnical effects of dissolution under a wider range of geological, geographical and climatic settings.

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Redefining the boundary between karst and pseudokarst: a discussion

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Abstract: Self and Mullan (1996) wish to redefine the concepts "**karst**" and "**pseudokarst**" in terms of purely physical characteristics rather than their traditional meaning, which involves both landform and process. It is argued here that their usage of "karst" would be more appropriately termed "karst terrain" and that "karst" is best kept as a combination of terrain and process, with a process-based division into "true" karst and "pseudokarst" where this is feasible. If a separate term is wanted for features such as talus caves, which have a distinctive morphology as well as a separate process, then "quasikarst" is suggested.

INTRODUCTION

Self and Mullan (1996) refer to the diversity of existing definitions and classifications of karst, and perceive problems with the term "pseudokarst" being applied to some limestone terrains or to some limestone cave passages formed by processes other than dissolution. They therefore wish to redefine the concepts "**karst**" and "**pseudokarst**" in terms of purely physical characteristics rather than on the basis of their traditional meaning, which involves both landform and process elements.

THE CONCEPTS UNDER DISCUSSION

Part of the confusion in the existing terminology, and in the recent discussion by Self and Mullan, exists because "**karst**" has been used and defined at several levels of meaning. The different concepts involved are:

Karst:	A union of terrain and process;
Karst processes:	Traditionally solution, but includes other process as well. Some definitions put emphasis on underground removal of material by any process;
Karst terrain:	A suite of characteristic physical features;
Karst feature:	A cave, doline, blind valley, karren, underground drainage etc.
Pseudokarst:	A union of terrain and process;
Pseudokarst processes:	Mechanical erosion, piping, mass movement and tectonics, phase change (lava tubes, glacier caves, thermokarst, ablation features), wave action (sea caves), mining, weathering processes, wind action;
Pseudokarst terrain:	A suite of physical features;
Pseudokarst feature:	A particular cave, sinkhole etc.

Depending upon the author, or on the context, the word **karst**, when used on its own, can sometimes mean the general concept, and sometimes only the terrain or only the process. In a discussion of terminology such as this care is needed to indicate just which concept is being referred to. In this discussion "**karst**" is used (on its own) to mean the complete concept - landform and process; "**karst terrain**" is used when discussing only the suite of observed physical features, and "**karst process**" in discussing the deduced origins. The same approach applies to "**pseudokarst**".

PRIOR USAGE

Karst

To define "pseudokarst" one must first define "karst". As Self and Mullan (1996) indicate, there have been many and varied uses of the term "karst". However, most definitions cite reference both to landforms and to process. However, where authors define "karst" only as a landform, they are really referring to the concept of "karst terrain" rather than to the overall concept. Likewise, a definition of "karst" based purely on process would seem incomplete.

There seems little argument that the special landforms that characterise **karst terrain** include:

(a) *on the surface:* various types of closed depression, stream sinks, springs and karren, and a lack of integrated surface drainage; and

(b) *below the surface:* caves and an underground drainage.

Some authors would require that specific features (such as underground drainage, or closed depressions) be present, while other features (such as karren) are generally considered to be optional and not definitive where found on their own. Note that "underground drainage" refers both to a physical feature (the stream and its conduit) and to a process, so that including this in the definition of a "karst terrain" does imply genetic connotations. Also, the presence of underground drainage is commonly a deduction rather than a direct observation; which makes it less suitable for inclusion in a purely descriptive definition.

Traditionally, the dominant **karst process** has been stated as either "dissolution" or, less commonly, "underground erosion". As Self and Mullan point out, recent work has shown that dissolution is not the only process that occurs in karst terrains, nor is it necessarily the dominant process. None the less, the bulk of the world's karst terrains are found on

soluble rocks, so dissolution **is** the characteristic process, and it seems reasonable to use a special term ("pseudokarst") where this is not the case. Perhaps dissolution should now be regarded as the "initiating process", to allow for the possibility of other processes becoming dominant in later stages of the evolution of the landform.

In the past some definitions have specified limestone as the parent "karst rock", but this seems to have fallen out of favour. Such a definition leaves karst terrain on gypsum and other soluble rocks as candidates for "pseudokarst", and this approach was used by Sweeting (1972, p.306). This problem was addressed in Europe by Anelli (1963), with the introduction of a three-way division of karst terrains into: "**holokarst**" (or just "karst") developed by dissolution of limestone, "**parakarst**" formed by dissolution of other rocks, and "**pseudokarst**" for terrains developed by other processes. This usage has been summarised by Silvestru (1990), and has been used for many years as a basis for classification in the Speleological Abstracts published by the Union Internationale de Speleologie (UIS). The UIS Speleological Abstracts also use a term "**hypokarst**" for glacier caves and lava tubes. Philipp Häuselmann (pers. comm.) indicates that the term "hypokarst" was apparently coined by Cigna (details not supplied) for karst-like features formed by a process of phase change within a single material (melting of ice or solidification of lava), as distinct from "parakarst", which involves reaction of two components (rock and water), and "karst", which involves three components (rock, water and carbon dioxide).

Unpublished reports are acknowledged as being unsatisfactory sources; however, a memorandum circulated by Quinlan in 1966 is of particular interest and so is summarised here. He sent out a request for definitions of both karst and pseudokarst, and compiled the responses from 18 North American karst scientists, along with translations of three European definitions. Most of them defined "**karst**" as both landform and process (dominantly dissolution), but a few also regarded underground drainage as critical. Only two specifically excluded dissolution: one defined karst purely as a terrain, and the other emphasised underground erosion by **any** process. Both these regarded "pseudokarst" as therefore being an unnecessary term. By contrast, another contributor specifically excluded underground drainage as the primary basis of the definition. Given the present-day emphasis on mechanical erosion in caves, it is notable that several respondents in 1966 emphasised that dissolution was not the only process, and Quinlan's own definition referred to "...a group of processes - chiefly solution, but also including **solution-induced** suffosion, precipitation, corrasion, transportation, deposition, subsidence and collapse" [current author's emphasis]. Quinlan's definition and classification were later published in an AAAS symposium (Quinlan, 1966), but the present author has not seen that paper.

Note that if "underground erosion" rather than "dissolution" is specified as the essential element of the karst process, then an important restriction is placed on the scope of "pseudokarst".

Most recent usage of "karst" has been similar to that of Quinlan's respondents; with an emphasis on both terrain and process. Self and Mullan cite a number of text-book definitions of karst, but say that only one - that of Ford and Williams (1989) - gives a process-independent definition. However, the quote they give from Ford and Williams (1989) is misleading. Ford and Williams define karst in the first paragraph of their book as: *"Karst is a terrain with distinctive hydrology and landforms arising from a combination of high rock solubility and well developed secondary porosity"*. The passage cited by Self and Mullan comes from the end of a paragraph on the following page, in which Ford and Williams discuss the origin of the term in the *Kras* region of the former Yugoslavia, and its subsequent extrapolation to similar terrains elsewhere in the world. Ford and Williams are merely summarising the characteristic physical features of a **karst terrain**, but as they have already defined **karst** as both a terrain <u>and</u> a process, this cannot be considered a general definition.

Pseudokarst

Halliday (1960) was probably responsible for introducing the term "pseudokarst" into English-speaking and speleological circles. He refers to earlier usages, in Europe, dating back to the 1930s. However, in an unpublished memo in 1966, Quinlan claimed that the term was "...first proposed by von Knebel (1906, p. 182-183) with reference to the hydrology of certain lava terrains". Halliday (1960) used pseudokarst for "...features of non-solutional origin which are analogous to those of areas of karstic geomorphology".

Most of the contributors to Quinlan's unpublished memo in 1966 defined "pseudokarst" as karst landforms derived by a different (non-dissolutional) process, or forming in non-soluble rocks - which amounts to the same thing. A few said that "pseudokarst" was simply "non-karst", and the respondent who used a karst definition based purely on landform considered the term unnecessary, as did the one that defined the karst process as underground erosion by **any** means.

Authors who defined karst as being restricted to limestone rocks tended to class dissolutional features in other rocks as "pseudokarst" (e.g. Sweeting, 1972), but that approach seems to have been discontinued, with non-limestone dissolution now included either in "karst" or in "parakarst".

One major objector to the use of pseudokarst for a range of non-dissolutional landforms was Otvos (1976). His objection was twofold: firstly a justified objection to the extension of the term by some people to minor features (such as solution pans) or to extreme cases, such as areas that lacked surface drainage but showed no other "karst" landforms; and secondly, one based on his feeling that "pseudokarst" should mimic not only the karst landforms, but also the process of underground erosion. On this basis he advocated that only thermokarst and landforms due to piping qualified as "pseudokarst", and excluded (as "non-karst") features such as glacier caves and lava tubes.

ETYMOLOGY

The prefix **pseudo** comes from a Greek word meaning "false, falsely". According to the Shorter Oxford English Dictionary, its use in scientific combinations is to indicate close or deceptive resemblance to the thing referred to, without real identity or affinity with it. This fits well with the existing usage of "pseudokarst" for landforms that look like karst landforms, but which differ in their origin (process) or fundamental composition (parent rock).

If a non-genetic term is required for landforms that are similar to karst but not quite the same in appearance, then the prefix **quasi** might be more suitable. **Quasi** is from a Latin word meaning "as if, almost". Thus in **quasi** the emphasis is on the similarity rather than on the (possibly hidden) difference implied by **pseudo**.

In the European term "parakarst", **para** comes from a Greek word meaning "by the side of, beside". It does not come from the Latin word meaning "protection" (as in parachute). The prefix **hypo** comes from the Greek root meaning "under", but which is used in modern formations in the sense "under, beneath, below" and also "to some extent, slightly, somewhat". In "hypokarst" it seems to imply "less complex" or "fewer components" than the processes of parakarst and karst.

The etymology of **karst** has been described by others, and does not help in the definition as it comes from a place name, which in turn is from a word meaning simply "rock".

DISCUSSION

In the following discussion it is advocated that "**karst**" should be used in the sense of both a terrain and a process, and that "**karst terrain**" should be used where a non-genetic descriptive term is needed. Quinlan is followed in defining the **karst process** as "dissolution and other dissolution-induced processes" - these other processes can also operate in pseudokarst, but there they are not "dissolution-induced". "Pseudokarst" is used in its traditional sense of "a karst terrain that has formed by non-dissolutional process", with the addition that the processes are also "not dissolution-induced".

However they are defined, the distinction between "karst" and "pseudokarst" is a "bald-hairy" one, in that there is a continuum of sites showing the full range from obviously dissolution dominated processes to completely non-dissolutional processes. The boundary must be an arbitrary and subjective one, and some borderline sites will be difficult to classify. This problem would also occur with Self and Mullan's attempt to distinguish the two types on purely physical character - all gradations occur. If "pseudokarst" is defined on the basis of parent rock it also creates "borderline" problems when, for instance, considering karst terrains on silicate rocks, which are soluble in some environments but not so in others.

Self and Mullan (1996) argue that "karst" should be re-defined in a non-genetic manner. Their reasons are the diversity of existing definitions and classifications of karst, and perceived problems with the term "pseudokarst" being applied to some limestone terrains or to some limestone cave passages formed by processes other than dissolution. There certainly have been arguments about the most appropriate definition of "karst" but, none the less, the majority of usages have included both terrain and process. To try to restrict the term's usage only to terrain will add to the confusion. If a river passage in a cave can be shown to have formed entirely by mechanical (or other non-dissolutional) processes then this author would argue that referring to that passage as "pseudokarst" is not "absurd" but, on the contrary, is a valid and useful way of emphasising the lack of dissolution. The host area as a whole would still, presumably, be referred to as "karst", as it would be a "karst terrain", and dissolution would have been the distinguishing process in its origin. In fact, it must be suspected that even such supposedly non-dissolutional major stream passages **originated** as dissolutional tubes (how else?), and that dissolution continues to be active, even though it is now overshadowed by mechanical erosion.

Self and Mullan say that "identical landforms ... should be classed together". Agreed - but class them as "karst terrain" and then use the terms "karst" and "pseudokarst" (and its sub-classes) to subdivide the terrains on the basis of process where process can be deduced. They also say that genetic classifications only hinder understanding. This is only true if classifications are applied too early in a study. Describe firstly the physical features, decide whether they warrant being classed as "karst terrain" and, only then, try to deduce and classify the processes. In some cases the processes acting in an area may not be obvious, in which case call it a "karst terrain of uncertain origin". If there are multiple processes, and the area falls near the ill-defined boundary between "karst" and "pseudokarst", then it is best not to force it into one category or the other, but to describe it as a "karst terrain formed by both karst and pseudokarst processes" and give the details. Classification is not everything.

Self and Mullan give examples of two problem areas. The initial problem with the Cotswolds would seem to be whether the area even qualifies as a karst terrain. Gull caves are small and not common, and, although they mention sinkholes, it seems that they are fairly rare. Hence the area is marginal as "karst terrain". The gulls are formed by non-dissolutional processes, and therefore could be called pseudokarst **features** even if one does not count the region as a karst **terrain**. There is no problem with application of the existing process-based usages of "karst" and "pseudokarst" here. It is irrelevant that the area is developed on limestone, as that parent-rock criterion is now seldom used to define "karst".

The Northumberland area would seem to have a range of karst **features**, and so qualifies as karst **terrain**. If the deduced process is mechanical erosion following preparation by chemical weathering, then it qualifies as "pseudokarst" - though, as one could argue that chemical weathering involves some dissolution, then it lies closer to the karst-pseudokarst boundary than other areas with more distinctive processes. Thus, the Northumberland area would be classed as "karst terrain produced by pseudokarst processes" or "pseudokarst" for short.

Finally, having argued for a redefinition of karst as a terrain without genetic connotations, Self and Mullan say "...what then of pseudokarst?". They then attempt to redefine it in non-genetic terms as "features that are superficially similar to karst, but have some unique element that is not found in karst". Presumably they are talking about physical elements. They then spoil their entire argument by producing a list of "pseudokarst features" that they define in mainly genetic terms. Initially, for tectonic caves and gull caves, they try to justify the non-genetic approach by citing the fit features of the walls - but these have been noted in the descriptions primarily because they are indisputable evidence of the process. They then go on to include lava caves because they "form while the host basaltic magma is solidifying, and are therefore primary features", and sea caves due to the "surging action of waves". These are both blatantly genetic definitions.

It must be agreed that talus caves have a distinctive morphology (the cavities are essentially an "inter-granular porosity" on a huge scale!) and they probably deserve a classification separate from both karst and pseudokarst. Wind and weathering caves are usually small features and invoke that other contentious argument: namely "the distinction between a cave and a rock-shelter". It was an interesting coincidence that a paper by Hunt (1996) describing "tafoni" appeared next to that of Self and Mullan (1996). Many speleologists would argue that the tafoni described by Hunt would not even qualify as caves, let alone "karst" or "pseudokarst". For referring to features, such as talus caves and tafoni, that are distinct in appearance from both karst and pseudokarst caves, this author would suggest the use of a separate term: **quasikarst.**

CONCLUSION

Self and Mullan are worried by the need for a non-genetic term for karst features and landforms. It is suggested that rather than redefine "karst" they should adopt the term "karst terrain", and retain "karst" in its generally used connotation of both a terrain and a process (perhaps modifying the process definition to include both "dissolution" and "other dissolution-induced processes"). The existing distinction between karst processes and pseudokarst processes is a very useful one, and should not be converted to one based on physical features. Where a karst terrain exists and the processes are clear-cut, "karst" can be used as a shorthand for "karst terrain formed by karst processes" and "pseudokarst" as shorthand for "karst terrain formed by pseudokarstic processes" Where the processes are unknown or complex, then a description such as "karst terrain of uncertain/complex origin" can be used. Where an area fails to qualify as karst terrain, an individual feature can still be referred to as (for example) a "pseudokarst cave", or a "karst doline", if its genesis is obvious. If not, then it should just be called a cave, or a closed depression, or whatever, and described as clearly and completely as possible.

Some features, such as rock shelters of various origins and talus caves, are sufficiently different to perhaps be excluded from the karst nomenclature entirely. Though, as these may still have speleological or archaeological interest, they will continue to be described in the karst and cave literature. If a separate term is considered necessary for these "karst-like" features then adoption of the term "quasikarst" should be considered.

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CAVE AND KARST SCIENCE Vol. 24, No.2, August 1997
Transactions of the British Cave Research Association

Forum

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

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Editors' note:

Cave and Karst Science Volume 23 Number 2 included a paper (by Charlie Self and Graham Mullan) that re-examined the concepts and definitions of karst and pseudokarst. Their discussion and conclusions generated significant international interest among those concerned with this area of study, and prompted a varied correspondence. Most of these communications have not been copied to *Cave and Karst Science* for publication in *Forum*, but the gist of the points that were made can be gathered from the various replies and letters to the editors that are reproduced, with only minor edits, below. Aside from the background exchange of letters, we received another view of the same subject in a paper from Ken Grimes (partly responding to the Self/Mullan views) that appears elsewhere in this issue Subsequent to most of the correspondence, a paper dealing with specific aspects of the same broad topic was received from Robert Wray, and that too appears elsewhere in this issue.

We have no doubt that this controversial and commonly highly subjective issue will continue to attract interest from a variety of specialists, and we will continue to devote space to any relevant correspondence, subject to considerations of balance and demand for space to cover other topics.

From: Graham Mullan
Date: 9 April 1997
Subject: Karst & Pseudokarst

[Copy of letter to Dr Bernasconi]

Dear Dr Bernasconi

I thank you for your letter of 24th March concerning our recent *Cave and Karst Science* paper "Redefining the Boundary between Karst and Pseudokarst", and for the copy of Dr Cigna's paper. [*Editors' note*: This paper - Cigna, A A, 1978. A classification of karstic phenomena. *International Journal of Speleology*, Vol.10 (1), 3-9. - is discussed in the correspondence below.]

I admit that we had not come across this paper before. Regrettably the *International Journal of Speleology* is not commonly available in this country. I know that our Society attempted to set up an exchange with our own *Proceedings*, but this came to nothing. I know we cannot afford to purchase it.

However, having read the paper, I do not think that it would have changed our analysis. As with so many of the other authors that we did cite, Dr Cigna has relied wholly upon the chemical processes involved in karst geomorphology, and has ignored the physical processes. It is our contention that these are of equal import and that the relative importance of physical and chemical processes in producing any given feature are functions of climate, water supply and time, rather than of rock type. Given, also, that the vast majority of sites have not been subject to the sort of stringent analysis that could determine precisely what processes were involved and in what proportion, we feel that the various sub-classes of karst that he quotes may well be misleading.

Thus some of the large river caves of South-east Asia would doubtless be classed by this scheme as merokarst, yet closer analysis might show that most of their volume is due to physical erosion by fast powerful streams - which would make them pseudokarst!

This paper seems to have stimulated a certain amount of discussion in various quarters. If that is so, then we have surely done our job well.

Yours sincerely

Graham Mullan

From: Graham Mullan
Date: 17 April 1997
Subject: Pseudokarst

Dear Editors,

I believe that the earlier paper by Ken Grimes must be: "Pseudokarst: definition and types" (*Proceedings of the 10th Biennial Conference of the Australian. Speleological Federation*, Brisbane, 6-10). It was not too difficult to trace as David Gillieson draws on it in his new book.

If Gillieson's interpretation of it is correct, then yet again it gives a perfectly adequate classification of what happens generally in non-carbonate rocks, excludes solution processes in quartzites (they are karst) and completely ignores the idea that similar weathering processes inevitably also occur in carbonate (etc.) environments and must be responsible for a significant proportion of karst landscape formation.

Because this last point has been missed by so many of those who have responded to us, Charlie has suggested that we restate this central tenet of our argument. He is drafting something along these lines. When we have agreed its form, we will send it on.

None the less, I would still very much like to see Ken Grimes' new paper.

Graham Mullan

From: Charlie Self
Date: 14 May 1997
Subject: Karst and Pseudokarst

Dear Editors,

Below is a reply for the purposes of publication. We have had, in all, correspondence from Bill Halliday (with several photocopied papers), Peter Swart and Dr. Bernasconi, all of which are referred to in the reply. A certain amount of other information, not immediately germane to the reply, such as Bill Halliday's comments on Eraso's belief that glaciospeleology is karstic, and Otvos's complete dislike of the term "pseudokarst" is contained therein, so we may be able to expand our reply should more comments be forthcoming.

One of the stimuli that provoked us to write our paper "Redefining the boundary between karst and pseudokarst" was an earlier paper in *Cave and Karst Science*, where traditional definitions were offered (Marker and Swart, 1995): essentially that karst is formed by water flowing through soluble rocks, pseudokarst by water flowing through generally insoluble rocks. With such definitions, the boundary between karst and pseudokarst is not at all clear, while tectonic and volcanic caves are not even classed as pseudokarst. Our new definitions have met with agreement in some quarters (notably Peter Swart) but some correspondents seem to have missed the point of our argument entirely. It may be helpful if we abstract and rephrase the core of our argument.

Caves are defined as natural underground cavities large enough to be entered by man. This definition is independent of rock type and is not restricted to any one genetic process. The surface landforms known collectively as karren are found in many different lithologies but geographers use the same terminology for them all. In contrast, karst has traditionally been described genetically as a set of landforms created by dissolution of the bedrock. Bill Halliday writes that in America, quartzite caves are thought to be of dissolutional origin and therefore karst. A division here between quartzite (karst) and other sandstones (pseudokarst) does not seem logical to us.

Our argument is that karst is formed by a number of processes working in combination. We accept that during the early stages of formation of a cave in limestone, chemical weathering and dissolution are likely to dominate. As the cave gets bigger, physical erosion becomes more important. It seems quite possible that large river caves, fed by flood-prone and sediment-laden surface streams, develop mainly by physical processes. We do not know this for sure, because comparative quantitative studies have not been made. What is not in doubt is that physical erosion does take place in limestone caves.

The balance between chemical and physical erosion does not depend solely upon lithology. Climate and hydraulic gradient, we would argue, are of equal importance. Chemical and mechanical weathering combine to produce caves in arenaceous rocks, where differences in lithology and cementation cause wide variations in the chemical/physical erosion balance. Though the bulk of the material may be removed as suspended particles, it is wrong to say that physical processes dominate. Chemical processes weaken the structure of the rock (arenisation) and make it susceptible to erosion. Again, we know of no quantitative studies of the chemical/physical erosion balance. To define karst on the basis of presumed genetics, when only one process has been studied, is bad science.

Genetic definitions are inflexible and can lead to some absurd situations. Dr Bernasconi has drawn our attention to a paper (Cigna, 1978) that demonstrates very clearly some of the problems inherent in genetic definitions. Here, karst is deemed to be dissolution of rock by water and carbon dioxide (a three component equilibrium) and the term is restricted to carbonates. Silica is sparingly soluble in water (a two component system), so quartzite caves are termed parakarst, as are caves in evaporites such as salt and gypsum! Cavernous sandstones and caves of physical weathering origin are listed as pseudokarst, alongside mass movement caves.

In theory, Cigna's proposals seem clear and logical, but they are of no practical use. How would one classify a cavernous quartzitic sandstone, discovered during an expedition? Ask for a research grant to study the genetic processes in operation, an answer to be given in three years?

The advantage of describing a karst terrain in morphological terms is that the definition will not be affected by changes in our understanding of the processes by which it is formed. It also allows pseudokarst to be more clearly defined. A common definition at present is "... *karst morphology formed by processes other than dissolution*". Much of what is now studied as pseudokarst (eg. lava tubes, gulls) does not have karst morphology. It seems to us far better to redefine pseudokarst as landforms that superficially resemble karst. Pseudokarst then becomes the collective term for distinct landforms that are independent of and different from karst, rather than a repository for landforms that do not fit current genetic theories of karst.

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Charlie Self and Graham Mullan

From: Charlie Self
Date: 25 June 1997
Subject: Karst and Pseudokarst

Dear Editors,

I have a postscript to our correspondence article about the karst and pseudokarst paper:

In our paper, we stated that gull caves are formed by extension of the strata during cambering. In this instance, we seem to have inadvertently used genetic language. In a recent lecture to the Ussher Society, Denys Brunsden (1996) used the non-genetic term "lateral spreading" when discussing the caves of the Isle of Portland. In his model, deep-seated failures within the Kimmeridge Clay may be responsible for gull formation in the overlying limestones. In the Cotswolds region described in our text, cambering is widely present and is the obvious agent of mass movement. Our mistake was to use the same language for the common case as for the general case.

REFERENCE

Brunsden, D, 1996. Landslides of the Dorset Coast: some unresolved questions. *Proceedings of the Ussher Society*, Vol. 9, 1-11.

Regards,

Charlie Self

The following correspondence from Arrigo Cigna was received as this *Cave and Karst Science* Issue was almost complete, and is included here for completeness, without comment or response.

Arrigo A Cigna
Fraz. Tuffo
I-14023 COCCONATO AT
Italy

25 August 1997

Dear Dr Lowe,

I have read with interest the paper on the definition of karst and pseudokarst published in Volume 23, No. 2 of "Cave and Karst Science". I have been interested in this field since some years ago and I have proposed a classification as independent as possible from subjective evaluation to avoid any possible contradiction.

Please find herewith enclosed a copy of two papers of mine concerning this argument. [See references below.] The second one (i.e. the one published in 1984-85) has a slightly different classification because the words "holokarst" and "merokarst" have been no longer used. In fact, some colleagues pointed out that such words have already been widely used in literature with different meanings and therefore their inclusion in my classification could have caused additional confusion.

Obviously such a classification should be applied according to the most relevant process occurring in the case under consideration, otherwise every "karst" phenomenon would be included as "hyperkarst", because it is always possible to find the presence of additional phases, at least as "trace phases".

Sincerely

Arrigo A Cigna

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Cigna, A A, 1978. A classification of karstic phenomena. *International Journal of Speleology*, Vol.10, 3-9.

Cigna, A A, 1985. Some remarks on phase equilibria of evaporites and other karstifiable rocks. *Le Grotte d'Italia*, Vol.(4) XII, 201-208.

BOOK REVIEW

CIGNA, A A.,(Ed), 1996. *Proceedings of the International Symposium Show Caves and Environmental Monitoring* held at Frabosa Soprana (Cuneo, Italy), 24 - 26 March 1995. 212 x 298mm, ix + 389 pp, maps, illustrations, tables. Available from Stazione Scientifica di Bossea, CAI Sezione di Cuneo, P.za Galimberti 13, Italy.

The traditional function of a show cave is to make money for its proprietor, and I have no quarrel with this philosophy. In the days when only the very wealthy could afford to travel, cave tourists were probably so few in number that their impact on the caves visited was minimal. However, during the past three decades the world tourist industry has boomed; and with it has come increasing pressure on the fragile cave environment.

Alongside this increase the concept of sustainable tourism has developed. It does not matter what the attraction is, there comes a time when the visitors become so numerous that they destroy that which they come to see. If the attraction is a stately home, builders can be sent in to effect repairs. If it is a natural attraction, such as a garden or game park, given enough time the biological damage can be repaired. If it is a cave that is damaged by tourists, the damage will probably never be made good.

Visitors damage caves at the macro- and micro- levels. The macro-level includes such voluntary acts as removing speleothems, dropping litter and writing graffiti. These acts should easily be preventable by supplying suitable education and imposing good supervision. Micro-level damage is more subtle, and not immediately apparent to the visitor. It is the changes in carbon dioxide, temperature and humidity, induced by the presence of tourists in the cave, which slowly affect the rate of formation or destruction of speleothems.

This report contains 30 papers from 9 countries. They discuss not only the results of the environmental monitoring of show caves, but also the methods and instruments available.

The uninitiated might ask why monitoring is necessary. If the damage to the cave is not quantified, steps cannot be taken to minimise or rectify the damage. No two caves are alike - but the principle of conservation is common to all. The skill in managing a show cave lies in balancing the conflicting demands of presentation and those of preservation. These Proceedings should be in the office of every show cave proprietor and manager. They will tell them what needs to be done, why it needs to be done, and how to go about it. Only then can a long-term management plan be prepared, to ensure the continued profitability of the cave.

Reviewed by Dr. S A Craven, 7 Amhurst Avenue, Newlands 7700, S. Africa.

SCIENTIFIC NOTE

Members of the Yorkshire Geological and Polytechnic Society auguring at Turn Dub, Horton in Ribblesdale, North Yorkshire. Taken by Godfrey Bingley in September 1902.

Please find enclosed a print taken from an old 3.25 x 3.25 inch lantern slide, and a short explanation of its origin and significance. I believe that this image has not been published before, and wondered whether it might be of interest to the readers of *Cave and Karst Science*.

As part of the investigation into the underground waters of north west Yorkshire undertaken by the Yorkshire Geological and Polytechnic Society between 1900 and 1904, a number of borings were made between Turn Dub (NGR SD 797 749) and the River Ribble. Details of the work are provided by Dwerryhouse (1904, p.279) and extracts that subsequently appeared in the latter article were quoted by Lowe (1903, p.44).

The hand boring apparatus seen in the photograph proved to be ineffective in penetrating the boulder clay deposits of the Ribble valley, and the services of a professional well sinker were employed to finish the job. Rockhead, on Carboniferous limestone, was reached at a depth of eight feet (c.2.44m) below river level.

Godfrey Bingley was elected to the Yorkshire Geological and Polytechnic Society in 1895. He was a highly skilled and prolific photographer. Following his death in 1927 his extensive photographic collection was cared for in the Department of Geology at the University of Leeds. More recently, this photograph, one of the few remaining original lantern slides, was saved from destruction, and is now under the care of Mr P J Murphy.

REFERENCES

Dwerryhouse, A R, 1904. The underground waters of North-West Yorkshire. Part 2. The underground waters of Ingleborough. *Proceedings of the Yorkshire Geological and Polytechnic Society*. Vol.XV, Part 2, 248-292.

Lowe, G T, 1903. Alum Pot. *Yorkshire Ramblers Club Journal*, Vol.2, No.5, 35-47.

An obituary to Godfrey Bingley appears in: *Proceedings of the Yorkshire Geological Society*. Vol.XXI (1927-1930), p.344.

Phil Murphy
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THESIS ABSTRACTS

WRAY, R. A. L., 1995

Solutional Landforms in Quartz Sandstones of the Sydney Basin,

Unpublished PhD thesis, University of Wollongong, 381 pp.

Solutional landforms have been described for over a hundred years from limestone terrains and are termed karst. In many tropical regions landforms of similar morphology but on highly siliceous sandstones and quartzites have also recently been identified. The similarity of many of these features in morphology and also in genetic solutional processes to those on limestone has prompted recent calls for these quartzose landforms to also be regarded as true karst.

Although not unknown in temperate latitudes, these highly siliceous solutional landforms have been most commonly studied in present-day tropical regions, or areas believed to have been tropical in the recent past. This concentration of research in hot-wet areas, allied with the long held assertion of the insolubility of silica, especially quartz, led to a belief that tropical climatic conditions are necessary for karstic solution of these rocks. However, some of these quartzose solutional landforms are known in areas of temperate climate where there is little evidence for prior tropical conditions. A comprehensive worldwide review of these landforms, and the processes involved in their formation, has not previously been conducted and forms the basis from which this study stems.

The Sydney Basin in southeastern Australia has had a stable temperate climate for much of the Cainozoic with no evidence of tropical climate. The highly quartzose Permo-Triassic sandstones of this area have little carbonate, but nevertheless display a wide range of landforms morphologically similar to those both on limestones and also tropical quartzites These include large bedrock towers, grikes, caves, smaller solution basins and runnels, and even widespread silica speleothems. This study describes the morphology of this suite of landforms in detail, and provides a comparative analysis of these sandstone forms to those reported from quartzites of tropical areas and also their limestone analogues. Various microscopic and natural water chemistry analysis are then utilised in examining the poorly understood natural processes responsible for their formation. The process of sandstone solutional weathering in the Sydney Basin is also compared with that reported from the tropics, finding very little difference in either the form or magnitude of attack between these two climatically distinct regions. No previous studies have examined the wide range of solutional features found on quartz sandstones in one region of a climate comparable to Sydney, nor the processes involved in the genesis of these forms.

PERRIN, D., 1997

The Climate of the Marble Arch Caves, County Fermanagh , Northern Ireland

BSc (Geography) dissertation.
[Available from Department of Geographical and Environmental Sciences, The University of Huddersfield, Queensgate, Huddersfield HD1 3DH]

The Marble Arch cave is a high energy cave located in County Fermanagh, Northern Ireland. The first 500 metres of the system has been opened as a Showcave for approximately 13 years and has been visited by over half a million visitors since opening. Microclimatic investigations over a six month sampling period (31.7.96-10.1.97) found that the cave has a variable microclimate in response to, the surface climate, the caves hydrology and influences within the Showcave.

High positive correlation coefficient's were attained between the cave and surface air temperature. As distance increased into the cave correlation coefficients' decreased indicating a time lag. Air temperatures varied on both a temporal and spatial scale. Summer air temperature ranges of 2.1°C were noted between sites within the cave which increased to 7.1°C during the winter season. The cave air temperature changed progressively from the entrance to the interior, decreasing in the summer and increasing in the winter months. During the summer months the mean surface air temperature (17.4°C) was greater than the cave mean air temperature (10.8°C). In the winter months the mean surface air temperature (1.9°C) was less than the cave mean air temperature (7.2°C). Site variability was generally greater during the summer months indicated by higher Coefficient of Variations.

The 'chimney effect' is noticeable in some parts of the cave as a result of surface and cave air temperature differences. Airflow within the cave changed direction in response to seasonal air temperature variations, flowing out of the cave during summer months and into the cave in the winter. Other processes such as the 'Entrainment Effect' were also evident. Airflow throughout the cave was generally weak, although in some parts of the cave was noticeable as a 'wind'.

The main river flowing through the cave was responsive to the seasonal cave air temperatures. During the summer months the water temperature once entering the cave decreases by approximately 2°C and increases by up to 7°C during the winter months. A relatively constant seasonal water temperature is maintained whilst travelling through the cave.

The largest air temperature variations occurred within the Showcave in which the presence of tourists and electrical lighting are believed to be partially responsible, the latter of which being the greater contributor. Results show that a tour of 18 people on average increased the surrounding air temperature by up to 1.3°C. The effect was reduced when a tour was moving past a point rather than remaining stationary in the same place.

Electronic lighting increased the overall air temperature throughout the Showcave. Each type of light used within the Showcave influenced the air temperature up to a metre away from the light source. Air temperature increases around the lighting was a result of the type of light used rather than the bulb wattage installed. In some cases the air temperature remained 2°C higher than the mean cave air temperature 1 metre away from the light source.

CAVE AND KARST SCIENCE Vol. 24, No.3, December 1997
Transactions of the British Cave Research Association

Forum

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SCIENTIFIC NOTES

TROW GILL GORGE, INGLEBOROUGH, NORTH YORKSHIRE - ITS ORIGINS RECONSIDERED

Phil MURPHY
School of Earth Sciences, University of Leeds, Leeds, LS2 9JT, UK

Abstract: The spectacular gorge of Trow Gill has attracted much speculation over its origins. Opinion has varied between cavern collapse, fluvial incision or a combination of both mechanisms. A possible alternative origin, as a fluvially modified pocket valley, is proposed.

Trow Gill is a gorge situated on the southern flanks of Ingleborough (Yorkshire, UK) that is incised into massively bedded carbonates of Great Scar Limestone facies. It is one of a number of such gorges found on the southern margins of the Askrigg Block, and is one of the better known, due to the footpath from Clapham village to the summit of Ingleborough passing through it. The gorge is imposing, with cliffs up to 30m high and a floor that rises 50m in a horizontal distance of around 200m. The gorge is only 3m wide at its upstream end, and it bells out to 40m wide at its downstream end (Fig. 1).

The origins of Trow Gill have received the attention of several workers over the years, a broad review being published by Waltham et al. (1997). Sweeting (1972) favoured an origin due to erosion by glacial meltwater, with a contribution from cavern collapse. Glover (1974) favoured a wholly subaerial origin, on the evidence that the gorge profile is unlike that of any known caves and the lack of collapse debris. Waltham (1970) speculated that the gorge may be a collapsed cavern, but in 1990 he rejected the cavern collapse model on the grounds that there is no positive evidence of collapse and because stream moulins are present high on the walls of the narrowest section of the gorge. He interpreted the gorge as being the steepest, and therefore the most entrenched, section of a subaerial valley.

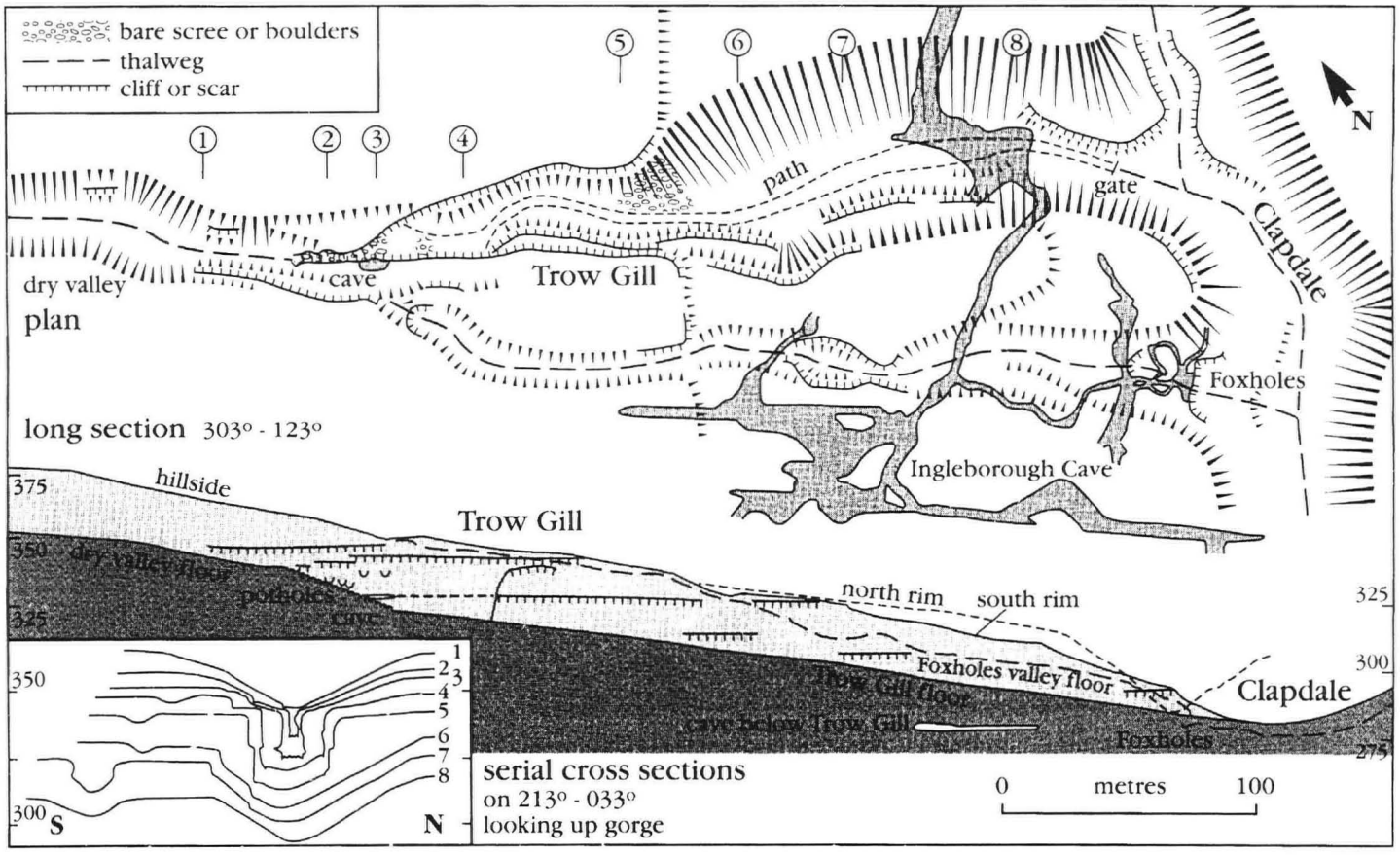


Figure 1. Topographic map and projected long profiles of Trow Gill and the underlying caves. Some of the cave passages have been omitted to improve clarity and all the caves lie below the level reached on the serial cross-sections. The thalweg down Trow Gill lies along the centreline of the path. Reproduced from Waltham et al. (1997) with permission.

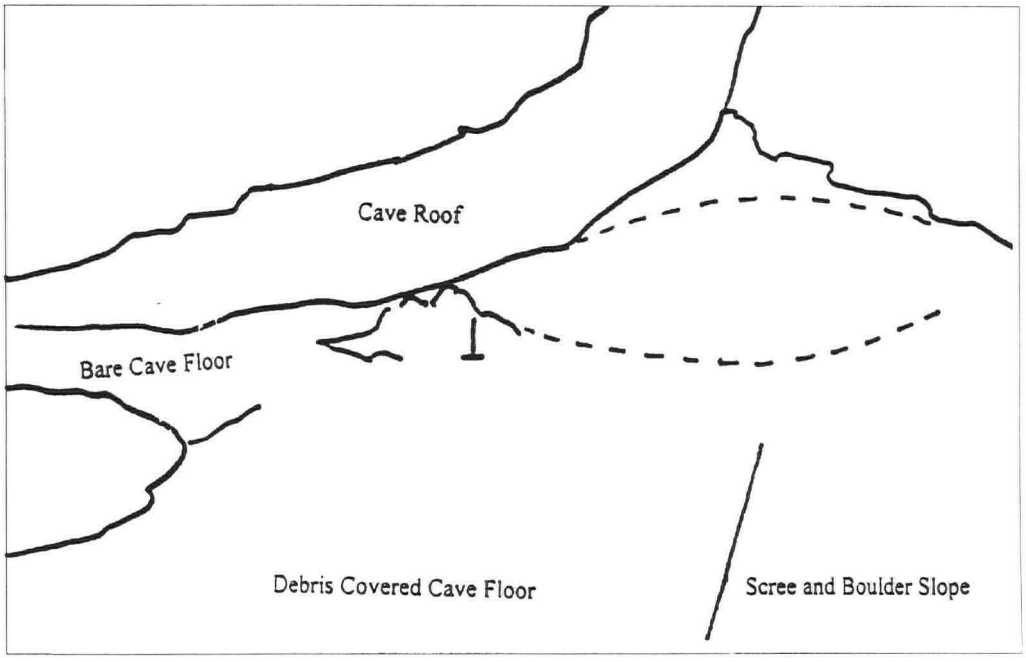
Figure 2. View of Trow Gill Cave and scree slope looking north west, with the narrow slot at the upstream end of the gorge seen on the right, above the level of the cave.

Trow Gill differs in a number of ways from the other gorges whose origins are attributed to fluvial incision by glacial melt waters. Gorges such as Watlowes Valley, Gordale, Gurling Trough (Conistone Dib), Dib Scar and Jackdaw Nick (Trollers Gill) all have much more consistent cross sections (Watlowes Valley and Gordale are here considered as distinct from the amphitheatres of Malham Cove and Gordale Scar, whose origins (Waltham et al. 1997) are accepted as being unlike those of the gorges). Rapid changes in cross section are usually associated with dry waterfalls, as in Watlowes Valley and Dib Scar (and with still-active falls, though with a misfit stream in the case of Gordale). Downstream increase in width, as noted in Trow Gill, is not seen in any of the other gorges. This width variation, from 3m at the head of the gorge to 40m at the downstream limit, sets Trow Gill apart from the other gorges on the southern margins of the Askrigg Block.

At the downstream end of the narrowest section of Trow Gill there is a 3m-deep undercut in the true right wall. This is referred to as Trow Gill Cave by Brook et al. (1991), with a quoted length of 8m, described as an undercut ending all round against solid walls. This cave has featured widely in the literature on Trow Gill, in debating the possibility that cavern collapse played a role in gorge formation. Glover (1974) comments on low, shallow bedding caves on both sides of the gorge giving the impression that the gorge originated as a cave, though no undercut of equivalent size is seen elsewhere in the gorge. The cave is shown on plans of the gorge in Waltham (1990) and Waltham et al. (1997) (Fig. 1), and in Sweeting (1972), but neither author comments upon it specifically. Waltham and Davies (1987) comment on the occurrence of incised alcoves, notably along bedding planes, that are similar to the products of underground erosion, and note that these have led to the mistaken impression that Trow Gill is a collapsed cavern.

Undercuts along bedding planes on a scale greater than a few centimetres deep are not particularly common in the type of gorges being discussed here, despite comments in the literature that refer to such features. Where undercuts of such dimensions do occur, they are usually associated with tube-like cave entrances in cirque-like settings. An excellent example is seen only 100m south west of Trow Gill, in the small amphitheatre of Foxholes (Fig. 1). Foxholes has been interpreted as an abandoned resurgence for waters from the Gaping Gill cave system (J N Cordingley, personal communication) and a detailed description of the cave is given in Cordingley (*in press*). Another nearby example, though on a larger scale, is seen at the entrance to Ingleborough Cave at NGR SD 754712.

Figure 3. An interpretative sketch of Figure 2. The dashed lines indicate a possible position of the hypothesised cave entrance obscured by the scree and boulder slope.



Close examination of Trow Gill Cave shows that at the up-gorge end its roof and floor begin to move apart as it opens out into the gorge. The continuation of this widening trend is hidden by the scree and boulder slope that fills the narrow upper section of the gorge (Fig. 2). The shape of the undercut suggests the possibility that a true cave entrance could exist, obscured by the scree and boulder slope (Fig. 3).

The evidence of the gorge width variations and the possible existence of a cave entrance hidden beneath the scree and boulder slope at the start of its narrowest section, suggest a possible alternative origin for Trow Gill as a pocket valley. It is hypothesised here that the gorge originated as the headward, cirque-like cliff, commonly found in such settings, with a spring issuing from a cave passage (Trow Gill Cave) now obscured by scree and boulders at the foot of the headwall. The narrow upper section of the gorge is still interpreted as the product of fluvial incision, possibly related to capture of the waters of an older and much less incised dry valley that was beheaded by Trow Gill. This dry valley runs parallel to, and to the south west of, Trow Gill, and rejoins the Clapdale valley over the low scar containing Foxholes cave (Fig. 1). Various mechanisms, such as headward collapse, initiation via underground leakage through joints or flood pulse overflows, could be responsible for this capture. A model of Trow Gill's origin involving a fluvially modified pocket valley could account for the problem mentioned by Waltham et al. (1997) of there being no channel of significant size feeding into Trow Gill from higher on the slopes of Ingleborough. The stream that was responsible for excavating the narrow channel above Trow Gill Cave may not be the agent responsible for the large feature of the main gorge.

DISCUSSION

If the interpretation of Trow Gill given in this Forum item is valid, then a significant volume of water must have resurged from the proposed cave passage. On the basis of proximity and size, the most likely source for such waters is from within the Gaping Gill cave system. If so, this would add another past resurgence level to those that must be considered in any attempt to model the development history of the Gaping Gill cave system - a possibility that was speculated upon by Waltham et al. (1997).

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BUBBLING SPRINGS: A REQUEST FOR INFORMATION

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The Derbyshire Wye, which has its headwaters to the west and east and south-west of Buxton and flows eastwards to join the Derwent at Rowsley, is the only river that maintains a perennial flow across the centre of the Peak District karst. Although the river has no perennial tributaries, its discharge increases substantially as it flows across the limestone, as a result of inputs from springs (some of which enter the bed directly) and from lead mine soughs. Many of the springs are listed by Stephens (1929), and their chemistry has been studied by various authors, including Edmunds (1971), Christopher (1981) and Raper (1989). Recently, as part of an ongoing investigation of sulphur isotopes in karst waters, several springs have been re-examined. During the course of this study it was noted that Cowdale Spring, about 4km ESE of Buxton, was emitting a continual stream of gas bubbles, as a series of periodic bursts, with each burst comprising a few millilitres of gas. Subsequent visits to the site confirmed that this was not an isolated phenomenon, although it has not been possible to measure the total discharge of the gas and, hence, to determine whether this varies over time. As none of the other springs along the Wye Valley are known to emit bubbles, it was decided to sample the bubbles at Cowdale Spring, to determine their composition.

A sample was collected on Monday 14th July, 1997, using a methodology that will be described, together with the analytical results, in a subsequent, more detailed, paper. The gas in the bubbles is composed dominantly of nitrogen and oxygen, and has a normal atmospheric argon/nitrogen ratio. The oxygen content is close to half that of normal air, while the carbon dioxide content is about 7.5 times that of normal air. This composition resembles that of typical soil gases, where oxygen has been removed and carbon dioxide added by bacterial and plant root respiration. Comparison of the carbon isotope compositions within dissolved bicarbonate and in the gas bubbles shows that they are not in equilibrium with the springwater, suggesting that they have not had a long residence time in contact with the water.

An initial literature search has failed to locate any published accounts of this type of bubbling spring. As we intend to undertake further research into the phenomenon, we would be interested to hear from anyone who knows of any similar bubbling springs, or has details of any earlier investigations of them.

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STALAGMITE SHEETS SHATTERED BY EARTHQUAKES

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In a recent issue of *Cave and Karst Science,* Straw (1997) discussed the geomorphological development of Kent's Cavern at Torquay, Devon. In his discussion he drew attention to the highly disturbed and shattered sheet of Crystalline Stalagmite, the lower of two stalagmite sheets in that cave. He also quoted some observations made by Pengelly of his excavations 1860-1880 (in lengthy reports to the British Association 1864-1884). During Pengelly's excavations the Crystalline Stalagmite was found to occur as angular blocks variously within later Cave Earth and/or covered by Granular Stalagmite. Straw regarded the Crystalline Stalagmite as having accumulated up to around 100,000 years ago whilst the subsequent Cave Earth started to accumulate around 53,000 years ago and contains a typical Devensian cold mammalian fauna. Straw argued on the basis of as yet unpublished dating work by C Proctor that the shattering must have taken place between 100,000 and 75,000 years ago (early Devensian).

Pengelly regarded the shattering of this stalagmite layer as due to hydraulic heave by uprising waters but his contemporary Vivian (1868) thought that frost heave might have been the cause. Straw (1997) argued that Devon was sufficiently far south in Britain for such drastic frost action to have been unlikely as the climate was not cold enough. Hydraulic pressure strong enough the shatter a thick stalagmite layer in the context of Kent's Cavern is very unlikely. Instead Straw proposed that the stalagmite sheet had been broken up by a catastrophic event between 100,000 and 75,000 years ago and the only event which could have had the observed effects was a strong earthquake.

Other Devon caves also show shattered stalagmite sheets. In his paper on Joint Mitnor Cave (at Buckfastleigh, some 20km west of Torquay) Sutcliffe (1960) noted a locally fractured stalagmite floor overlying the fossiliferous pitfall deposit which contained a mammalian fauna dated as belonging to the "Last Interglacial". The stalagmite sheet was regarded as possibly of Devensian age. Like Pengelly, Sutcliffe (1960) regarded this shattering as possibly due to frost heave. Reed's Cave, situated in Higher Kiln Quarry, within 100m or so of Joint Mitnor Cave, also shows a shattered and apparently faulted stalagmite sheet, though no fossiliferous cave earth has been found either above or below it.

No U/Th dates are available for the stalagmite sheets in either Joint Mitnor and Reed's Caves, but the Joint Mitnor sheet could well be early Devensian, and thus correlate with the Crystalline Stalagmite of Kent's Cavern. The lack of fossiliferous deposits above the Reed's Cave sheet suggests that it might be younger, possibly Holocene. Stalactites on the end of a curtain on the adjacent wall have been broken off and there is recent growth on the stumps, whilst the broken fragments have been cemented to the floor by recent deposition.

Disruption by periglacial frost heave some 100km south of the ice margin in South Wales and close to the Atlantic maritime influences seems unlikely. Frost disturbance of the adjacent sediments might be expected, but none has been reported. Though the caves concerned are of no great depth, it seems unlikely that permafrost could be effective there. No evidence of earlier sediments suffering liquefaction or being washed out, with resultant collapse, has been brought forward. Hence the writer (and Dr Sutcliffe in correspondence) support Straw's proposal that earthquake shock was responsible. The question now arises - *"What sort of earthquake would be required to break a solid stalagmite layer up to 45cm thick?"*, and *"Is there any evidence of an earthquake of that magnitude in Devensian times elsewhere in Southern Britain?"* A strong shock, such as would be needed to fracture a 45cm-thick stalagmite sheet, may have been responsible for partial cave roof collapse in Kent's Cavern and at Buckfastleigh, though dating fallen boulders is virtually impossible.

Several compendiums of British seismicity have been compiled, but none is specific enough to indicate the magnitude of shocks in the Devensian. However, Shotton (1965) recorded faults affecting British Pleistocene deposits. For example, "Wolstonian" Lake Harrison deposits and underlying Triassic mudstones were faulted by as much as 16m in M1 road cuttings at Narborough, Leicestershire, impliying that substantial earthquake shocks occured in later Pleistocene, perhaps Devensian, times. Minor tremors are fairly common, and one was felt in Totnes, South Devon, in October 1997, but such shocks would be too weak to shatter stalagmite sheets or to dislodge cave roofs. Readers are asked to keep a look out for equivalent shattered stalagmite sheets as these may constitute evidence of the previously unrecognised phenomenon of earthquake effects in British caves.

Dr Sutcliffe (personal communication) has noted that shattered flowstone is not uncommon in southern caves. Two such are Eastern Torrs Quarry Cave, Yealmpton near Plymouth, and Banwell Bone Cave extension in the Mendips. These should be re-examined with the possibility of earthquake damage in mind. A possible northern example of earthquake

Broken and faulted stalagmite sheet in Reed's Cavern, Buckfastleigh (scale bar 12.5cm) (Photo by A.J.Sutcliffe).

damage is in Poole's Cavern at Buxton, Derbyshire. Here, near the Roman Chamber, an overhanging stalagmite bank has "rifted" away from the shelf behind over a length of some 7m, leaving a gap 30-40cm wide now full of miscellaneous sediments (at least partly derived from making the show cave pathway). Later stalagmite deposition has begun to heal the rift. The forward movement of this "rifted" stalagmite bank has generally been regarded as due to undermining by a long-vanished cave stream, but perhaps earthquake shock was responsible. No date can be proposed, but a Devensian event is not impossible. A somewhat unlikely example is G.B. Cavern on Mendip, where a stalagmite sheet has partly collapsed, leaving behind the well known Bridge. While undermining by the cave stream is usually regarded as the cause, an earthquake shock could have been as effective.

Earthquake damage to speleothems has been reported from various locations outside Britain. Schillat (1969, 1976 and 1977) noted broken stalactites and fractures healed by later growth in stalagmites in several caves in Germany. In Colorado's Groaning Cave, similar fractured stalactites were attributed to earthquakes by Davis (1986). The possibility of studying ancient earthquakes using broken stalagmites in Trieste and Central Italy was proposed by Forti and Postpischl (1988). There are doubtless many other examples in areas where earthquakes are more common. Massive fallen stalagmite columns in some Pyrenean caves (e.g. Sabart, near Foix, France) might indicate earthquake damage. Apart from damage to speleothems, many rift caves have been attributed to earthquakes (Sjoberg, 1989; Forti and Postpischl, 1988), but few have been studied in detail in this context. Damage to saltpetre deposits in Mammoth Cave, Kentucky, has been attributed to the New Madrid earthquake of 1811.

Strong earthquakes are rare in Britain today but how many cave collapses or chokes might have been caused by earthquake shocks? Also, what would present day cave explorers see or feel if an earthquake were to occur while they were underground?

ACKNOWLEDGMENTS

Thanks to Drs A.J.Sutcliffe and A.C.Waltham for their critical reading of the first draft, and to Roy Paulson for calling my attention to references (in *Current Titles in Speleology*) to seismic effects in karst environments .

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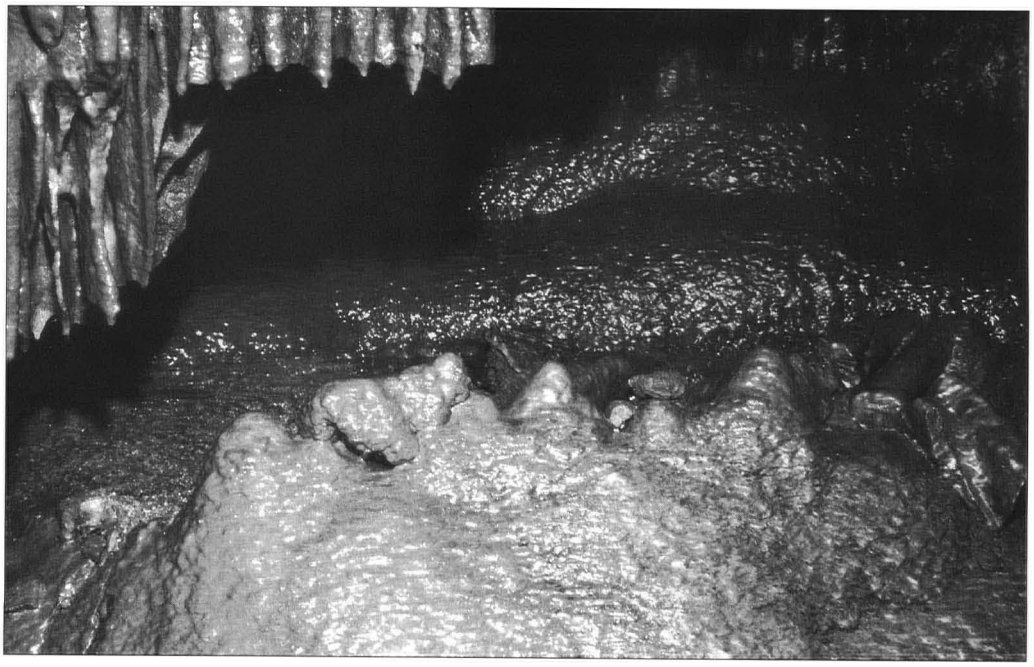
Stalagmite flowstone in Reed's Cave with fragments of fallen stalactites partly covered by more recent stalagmite in the foreground. Note broken stalactites, partly healed, on the roof above (photo by A.J.Sutcliffe).



BOOK REVIEWS

HILL, C and FORTI, P, 1997. *Cave Minerals of the World.* NSS, Huntsville, Alabama, 463pp, 270 colour and 3 b/w pictures, 60 diagrams and 14 tables. Recommended price: (US)$70 plus postage and packing. Enquiries to: National Speleological Society Bookstore, 2813 Cave Avenue, Huntsville, Alabama, 35810-4431, USA. Telephone (international code)(205)-852-1300, or access the relevant NSS Web site on http://www.caves.org.nssbook/order.html.

This book, the 2nd edition of *"Cave Minerals of the World"*, is unique in its approach, as it provides a world-wide coverage and discusses the most important aspects both of speleothems and of cave minerals. The content of this edition has benefited greatly from the results of field work and research performed during the last 11 years (since the first edition was issued). It includes details of recent advances in cave mineralogy studies and shows a greater understanding of the crystallogenesis of speleothems, as well as describing the usefulness of cave minerals in interpreting growth environments, cave system evolution and palaeoclimates.

The book's contents are organized along methodological lines. An *Historical Introduction* provides the reader with descriptions of all the theories that were proposed before the middle of the 19th century to explain speleothem growth. The first chapter, *Speleothems*, presents clear explanations of the genesis and morphology of 38 speleothem types and sub-types. Following this, the *Cave Minerals* section provides details of 255 mineral species ascribed to 13 different chemical groups, including native elements, sulphides, oxides and hydroxides, carbonates, sulphates and phosphates. A discussion of depositional conditions and mineral stability is provided for each chemical group. The book is fully referenced throughout (with more than 4,000 entries), and the text is complemented by many useful illustrations. A *Glossary* provides descriptions of about 400 terms, with some entries including details of corresponding terminology in up to 13 languages.

The objective of this new edition of an already invaluable cave mineralogy text are the same as those of the first edition., but the scope of the subject has been widened. In particular this widening is achieved by the inclusion of contributions, covering *"Special Topics"*, provided by a number of world experts. Within this chapter the following subjects are analysed: *Crystallography of speleothems; Minor, trace and ultra trace constituents of speleothems; The calcite-aragonite problem; Monocrystalline and macrocrystalline speleo-thems; Hydrothermal cave minerals; Aerosols: are they a mechanism of speleothem growth?; Cave microclimate and speleothems; Micro-organisms and speleothems; Archaeology and speleothems; Dating and Paleo-environmental studies of speleothems; Speleothems and earthquakes; Speleothem old age; Field observations; Laboratory techniques; Colour of speleothems; Luminescence of cave minerals; Speleothem growth rate; Protection of speleothems; Speleothems: preservation, display and restoration.*

For the first time the book includes a *"Top Ten Caves"* section that describes the richest cave systems in the world from a mineralogical point of view. These systems are: *The Blue Cave* (France), *Alum Cave* (Sicily), *Liquid Crystal Cave* (Israel), *Cupp-Coutunn Cave* (Turkmen-istan), *Kyusen-do Cave* (Japan), *Skipton Cave* (Australia), *Mbobo Mkulu Cave* (South Africa), *Caverna Santana* (Brazil), *Lechuguilla Cave* and *Kartchner Caverns* (USA).

By its general character the book appears first and foremost to be intended to appeal to cavers and young geologists but, at the same time, it is an ideal handbook for everyone eager to know about the major problems of cave mineralogy.

Reviewed by Bogdan Petroniu Onac, Department of Mineralogy, "Babes Bolyai" University, Kogalniceanu, 1, 3400 Cluj, Romania.

KLIMCHOUK, A, LOWE, D, COOPER, A and SAURO, U (editors), 1996. *Gypsum Karst of the World.* International Journal of Speleology, Vol. 25, Nos. 3-4 (theme issue), 307pp. ISSN 0392-6672; published by the Society Speleologica Italiana; price (US)$20 (£13).

Much more than just a mere thematic issue of an obscure journal, this volume is a splendid review of gypsum karst. It was compiled largely by the first-named editor, who also wrote most of the chapters in the first section, dealing with processes of gypsum karst evolution. A wider range of authors provided the second half, reviewing the world's major gypsum karst regions. Klimchouk argues that gypsum karst is a genuine karst, though it is not excluded by its best definition (as in the BCRA Dictionary of Caves and Karst) - as a landscape formed on soluble rock with efficient underground drainage. Indeed, gypsum karst is all the more exciting because its dissolution rates are an order of magnitude faster than those of carbonate.

A key chapter is Klimchouk's own, on speleogenesis, backed up by another, that he co-authors, on the important aspect of intrastratal karst in gypsum. There are some very impressive caves in gypsum, and 46 caves (half being maze caves) with more than 2km of passages are listed. Some of the quoted statistics are outdated (lacking data on caves in Russia's Pinega gypsum, where Olimpijskaja is now more than 9km long) and do not match some figures cited in later chapters. Perhaps more interesting are the contrasts with limestone caves. Gypsum's rapid dissolution rate can account for the many blind passages in the huge interstratal maze caves, and passages with inverted triangular profiles are a feature of the increased density of gypsum-saturated water. Low rock strength and rapid dissolution encourage roof breakdown in gypsiferous sequences, accounting for an abundance of vertical breccia pipes and associated dolines. There is, however, no mention of subglacial or proglacial development of gypsum caves, which may be of great importance in areas once covered by Pleistocene ice.

Sauro's view of surface karst landforms is rather brief, with a bias to Italian examples. This does reflect the limitations of gypsum karst, whose landforms can survive for long periods only in the more arid climatic regions. Major tower or cone karsts cannot develop, though doline karsts on gypsum can be very spectacular. Sauro notes a significant difference between limestone and gypsum karsts: fissures at the surface or at rockhead are generally sealed in gypsum, unlike the abundance of dissolutionally opened fissures in pavements or pinnacled rockheads in limestone.

The volume's first half also has chapters on the hydrogeology, chemistry, speleothems, karren and environmental problems (water resources, pollution, subsidence etc) of gypsum karst. The second half contains nation-based chapters reviewing gypsum karst in the USA, Britain, France, Germany, Spain, Italy and China, along with three chapters on parts of Russia, another on the Baltic Republics and then the inevitable chapter dealing with the Ukraine. There is also a concise summary of gypsum karst in the rest of the world.

The regional chapters, with impressively long reference lists, include some excellent material. Britain's gypsum karst is limited in extent, but the problems of living on Ripon's gypsum are worthy of wider attention. Spain appears to have some fine caves in the Sorbas region, and China has very young gypsum karst in the lake basins of Qinghai. Notable data shortfalls are on the vast gypsum area in Canada, and on the remarkable gypsum caves of Pinega in Russia (see *International Caver*, No. 10, 1994). The highlight has to be the chapter describing the huge caves of the Ukraine, where perhaps a map covering the surface karst and underlying caves of Optimistichesckaja and Ozernaja (lying close to each other) would have been a useful addition. The statistics on the Ukraine caves are indeed spectacular, but the coefficients of karstification by area are peculiarly high, and their method of calculation should have been defined for the benefit of Western readers.

Viewed as a whole, the criticisms are minor; the volume will long remain an essential item on karst and caves in gypsum. Its price is surprisingly low, and it goes a long way towards abrogating the tragic shortage of literature in other than the Russian language on this fascinating subject.

Reviewed by Tony Waltham, Trent University, Nottingham, UK.

CORRESPONDENCE

From: William R Halliday
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Date: 14 December 1997

Subject: Discussion of karst and pseudokarst

Dear Editors,

How quickly we forget!

In 1849 James Dana wrote:

"Wherever showers fall on this portion of [the island of] Hawaii they are at once absorbed by the cavernous rocks; and consequently through its whole extent, south and east, there are not two permanent streamlets. Water is to be found only in caverns, and often a journey of several miles must be taken by the villager to supply himself for his daily consumption." (Dana, 1849).

The volcanic area of which Dana wrote is almost half the size of Wales. Present are the 60.2km-long Kazumura Cave and dozens of other lava tube caves, cenote-like pits up to 263m deep, innumerable sinkholes and sinking ephemeral streams (some of which enter caves), and at least two water caves. Many other examples of such terrains can be cited: volcanic, glacial and otherwise. To exclude these from discussion of definitions of pseudokarst is to ignore the reality of much of the surface of the earth.

Similarly, to exclude the work of Commissions of the International Union of Speleology is to limit international acceptance of the discussion in these pages. The IUS now has three commissions working in areas that many speleologists consider pseudokarstic. The Commission on Volcanic Caves relates to syngenetic caves and pits. Another deals with glacier caves and pits (and also periglacial karst). Still another covers other forms of pseudokarst. At the 1997 XIIth International Congress of Speleology, a full day's session was on "Vulcanospeleology and Pseudokarst", with 12 papers and a lengthy group discussion that produced a consensus on the definitions debated here. It will be published in the final Congress volume.

Unfortunately, of those writing in these pages, I recall only Charlie Self attending and participating in the face-to-face discussion. No matter how valid the reasons for non-attendance of the others, this en masse absence decreased both the value of the consensus and of the discussion published here. It should be remedied as soon as possible. Neither karstographers nor those working in the field of pseudokarst can, nor should, define the other's field independently.

At the discretion of the organizers, an excellent opportunity for broad face-to-face discussion may occur in September 1999, at the 9th International Symposium on Vulcanospeleology (Catania, Italy). Another may occur in Iceland in 2000. I propose that the BCRA take the leadership in bringing concerned British karstographers face to face with their counterparts in studies of pseudokarst at one or both of these meetings. Attendance of the others is assured.

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A COMMENT ON "AN OCCURRENCE OF MIRABILITE ($Na_2SO_4.10H_2O$)/THENARDITE (Na_2SO_4) IN A COOL TEMPERATE CAVE: POLLARAFTRA, COUNTY FERMANAGH, NORTHERN IRELAND"

Dear Editors,

These comments relate to the article by John G. Kelly and Tim Fogg in *Cave and Karst Science*, Vol. 24, No. 1, (April 1997), entitled "An occurrence of mirabilite ($Na_2SO_4.10H_2O$)/thenardite (Na_2SO_4) in a cool temperate cave: Pollaraftra, County Fermanagh, Northern Ireland", in which it is stated that: *"Mirabilite and/or thenardite are previously unrecorded within a temperate cave, ..."* (Kelly and Fogg, 1997, p. 42). This statement is misleading, because mirabilite and/or thenardite have both been reported previously from many caves around the world (including Canada, Norway, Spain, France, Romania, Bulgaria and Japan) that do not lie in tropical and semi-arid regions, but in temperate to alpine, or even sub-arctic, areas (Yonge, 1986; Calandri, 1987; Seeman, 1987, Silvestru, 1990; Onac and Lauritzen, 1995).

The authors' method of mineral identification is rather empirical, as they appear only to have looked at the crystal habit, performed flame tests and checked the mineral taste, stating that: *"Flame tests give a strong yellow colour, distinctive of sodium, and this, the crystal habit and distinctive taste confirm that the crystalline mineral is mirabilite..."* (Kelly and Fogg, 1997, p. 42). It is known that many sulphate minerals present an apparently acicular to fibrous habit (producing mineral flowers or mineral cotton) and a slightly bitter and/or salty taste. Also, such analysis of crystal habit, if carried out only "by eye", can result in mis-diagnosis, as many minerals display pseudomorphs or/and paramorphs. Furthermore, other cave minerals, such as aphthitalite, blödite, burkeite, glauberite, hydro-glauberite, natroalunite and tamarugite, also have the Na^+ anion as an essential component (Hill and Forti, 1997). When performing flame tests, the presence of this anion will always result in a strong yellow flame colouration. Also, if Ca^{2+} appears alongside Na^+ in the mineral composition the flame colour will be yellow-orange. Because of this it is difficult to distinguish "by eye" between minerals that have only Na^+ and those that have both Ca^{2+} and Na^+ on the basis of a simple flame test.

Taking into account the controversial problem of deposition and stability of both mirabilite and thenardite in the cave environment, and the possibility for some confusion (as discussed above), it is suggested here that at least an X-ray analysis should have been carried out to confirm the supposed identification. When describing cave minerals, especially those with an apparently unusual occurrence, identifications should be based not only upon macroscopic observations, but also upon the results of appropriate laboratory tests (such as X-ray, chemical, thermal, IR and microscopic analyses).

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Dear Editors,

We refer to the note from Bogdan Onac [see above], in which he discusses various aspects of our earlier paper describing an occurrence of mirabilite/thenardite in Pollaraftra, Northern Ireland (*Cave and Karst Science*, Vol.24, No. 1, 41-44), and we thank Bogdan for the information provided.

When attempting to identify the mineral from Pollaraftra, we were acutely aware that an X-ray diffraction or other form of laboratory analysis was essential for a 100% definitive identification of the samples' chemical composition and hence of the mineral being examined. However, we did not have easy access to X-ray diffraction equipment and therefore had to rely upon purely observational techniques. In view of this, we felt it was essential to describe our identification criteria. When conducting the flame test, we did not have access to a spectrophotometer, so sodium chloride (NaCl) was also "flamed" as a control. The flame colours from the study mineral and from the NaCl were identical, and we considered this to indicate the presence of sodium alone. However, even if the Pollaraftra material is a mixed calcium/sodium sulphate mineral, its occurrence and recognition remain significant, in that sulphate minerals in general are rare in the caves of County Fermanagh.

We are interested to learn of the wider than supposed distribution of mirabilite/thenardite in temperate caves. This previously recorded distribution was not apparent from our literature search, which was conducted prior to the recent publication of the revised edition of *Cave Minerals of the World* [See review in this issue].

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THESIS ABSTRACT

WALKER, D. C., 1997

The use of Geophysical Techniques in the Detection of Shallow Cavities in Limestone.

Unpublished MSc thesis, Department of Earth Sciences, University of Leeds, United Kingdom. 95pp.

Electromagnetic, resistivity and microgravity techniques were compared for their ability to delineate and resolve shallow natural cavity systems in limestone. Geophysical work was carried out at two field sites. Electromagnetic and resistivity constant-depth profiling surveys were carried out at Kitley Caves in Yealmpton, South Devon, with the purpose of determining the lateral extent of the already partially mapped system. Lower Long Churn Cave in Ribblesdale, North Yorkshire, was used as a control site for the testing of resistivity tomography and microgravity techniques. Several cavities had already been mapped at this site, and were known to be approximately cylindrical passages, with radii of 2-4m within a depth range of 5-20m, in the area to be surveyed.

At Kitley Caves, both the EM31 and resistivity surveys were carried out over a 20x30m grid, approximately 50m west of Western Torrs Quarry. The station interval for the EM31 survey was 2.5m, whereas resistivity readings were taken at 1m intervals. Both techniques identified a linear, low resistivity, anomaly orientated close to the primary joint direction. This feature is interpreted as a sediment-filled fissure, but excavation of the site would be required for verification.

The main Lower Long Churn Cave passage was also identified using EM mapping at 2.5m intervals. Four 155m lines were surveyed using resistivity tomography technique, with 32 electrodes at 5m spacing selected in a Wenner configuration. This survey successfully delineated Diccan Pot and Lower Long Churn caves in the locations and depth ranges expected, and also identified a previously unmapped feature that was interpreted as an air-filled cave or fissure 40m to the south of the main passage. The inversion process caused the features to be horizontally smeared to approximately twice their true dimensions, and in some cases anomalies from separate features were combined.

Lower Long Churn Cave was also successfully delineated using microgravity. Analysis of the residual Bouguer anomaly, combined with two dimensional forward modelling, implied a density contrast of 2.0g/cc, a radius of 2.1m and a depth of 5m. This agreed to within 2.5m with the depth given by resistivity. The position of the tunnel axis found using the two techniques differed by a maximum of 4m.

Resistivity tomography and microgravity were thus concluded to be techniques accurate in the delineation of shallow subsurface cavities. Future improvements in the latter method depend on the development of instruments that are sensitive enough to detect small changes in gravitational acceleration, whilst remaining relatively insensitive to background noise. Resistivity tomography is becoming an increasingly more valuable technique as refinements in the inversion process reduce smearing of anomalous features and improve the accuracy of the subsurface images produced.

RESEARCH FUNDS AND GRANTS

THE BCRA RESEARCH FUND

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

a) To assist in the purchase of consumable items such as water-tracing dyes, sample holders or chemical reagents without which it would be impossible to carry out or complete a research project.

b) To provide funds for travel in association with fieldwork or to visit laboratories which could provide essential facilities.

c) To provide financial support for the preparation of scientific reports. This could cover, for example, the costs of photographic processing, cartographic materials or computing time.

d) To stimulate new research which the BCRA Research Committee considers could contribute significantly to emerging areas of speleology.

The award scheme will not support the salaries of the research worker(s) or assistants, attendance at conferences in Britain or abroad, nor the purchase of personal caving clothing, equipment or vehicles. The applicant must be the principal investigator, and must be a member of the BCRA in order to qualify. Grants may be made to individuals or groups (including BCRA Special Interest Groups), who need not be employed in universities or research establishments. Information about the Fund and application forms Research Awards are available from The BCRA Administrator (address at foot of page).

GHAR PARAU FOUNDATION EXPEDITION AWARDS

An award, or awards, with a minimum of around £1000 available annually, to overseas caving expeditions originating from within the United Kingdom. Grants are normally given to those expeditions with an emphasis on a scientific approach and/or exploration in remote or little known areas. Application forms are available from the GPF Secretary, David Judson, Hurst Farm Barn, Cutler's Lane, Castlemorton Common, Malvern, Worcs., WR13 6LF. Closing date 1st February.

THE E.K.TRATMAN AWARD

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

BRITISH CAVE RESEARCH ASSOCIATION PUBLICATIONS

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

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

CAVE STUDIES SERIES - occasional series of booklets on various speleological or karst subjects.

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

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

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

BCRA SPECIAL INTEREST GROUPS

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

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

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

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

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

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

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