Cave and Karst Science

The Transactions of the British Cave Research Association

BCRA

Volume 23 Number 1 June 1996

SEM analysis of sediments from the Lhasa karst, Tibet
Gypsum karsts and caves of the Canadian Maritimes
Famous caves: Wookey Hole, England
The Pure Karst Model
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.

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

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.

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

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

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

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

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

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

Cave and Karst Science

TRANSACTIONS OF THE BRITISH CAVE RESEARCH ASSOCIATION

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Cover photo:
Cerknisko polje, Slovenia.
Photo by John Gunn (see article by F. Šušteršič).
Cerknisko polje is one of several large, alluviated, flat-floored depressions that are distinctive features within the Slovenian karst landscape. Classified as a boder/overflow polje under the scheme of Gams (1978; Zeitschrift fur Geomorphologie, Vol.22, 170-81), it supports a permanent water body that expands considerably after heavy rain, as a result both of direct precipitation and a rise in the local water table. The photograph was taken during May 1996, when the expanded water body was draining steadily following heavy rain the previous week. In his article in this issue, France Šušteršič implies that, despite their dramatic visual appearance, such features are not fundamental karst landforms, but that they reflect later interaction between the ongoing effects responsible for primary karstification, and the local geological structure.

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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

One of the purposes of an editorial is to set out our policies concerning *Cave and Karst Science* and this seems to be an opportune moment to do so, as there is clearly still some confusion and misunderstanding in the British caving community. *Cave and Karst Science*, like its predecessors (*Cave Science* and *The Transactions of the Cave Research Group of Great Britain*), provides an outlet for the results of scientific study of caves and the karst environments in which they are formed. Naturally this leads to a strong "earth science" bias, as caves are almost all developed in rock. However, aspects such as biology, chemistry, physics and archaeology have never been ignored nor barred from publication. Similarly, it is important to consider aspects of the history of cave exploration and karst science, as demonstrated by two contributions from Trevor Shaw in this issue.

Though not intended as a medium for dissemination of expedition reports, a number of these, which included a scientific as well as an exploratory aspect, have been published over the years, most recently in Vol. 22, No. 2. These have been both popular and informative, and a policy of considering expedition reports on their merits continues to be applied.

A similar policy applies to articles or papers that deal with subjects that might best be described as Cave Technology rather than Cave Science. This title does not belittle the importance or the quality of the work described as technology - its proponents are necessarily highly skilled and knowledgeable and their work is no less deserving of publication than work usually described as science. As editors of *Cave and Karst Science* we recognise, as many others do, that the BCRA lacks a purpose-designed and suitably funded outlet for the results of such technical studies. Thus, we are happy to receive technical manuscripts for potential publication. However, we do believe that such contributions should be written to the same standards as other articles published in the journal and that they should likewise be subject to external comment on their quality, content and suitability for publication.

The process of peer review is ubiquitous in the world of scientific (and technical) publication. Papers that are fairly refereed are improved, to the advantage of the author and of the journal, as well as benefiting the readership. We know of cases where referees have abused the trust placed in them, to prevent the publication of new or different ideas, but we have built up contacts with a network of individuals who have a wide spectrum of expertise and whose assessments we believe to be objective, fair and, most importantly, constructive. With each manuscript that we receive we assess the need for peer review and try to locate a referee (or referees) fitted and prepared to do the job. Generally a refereed manuscript will be returned to the author together with the comments and suggestions received, and the author is requested to make appropriate amendments, or defend not doing so. Most authors agree that the process improves their output; small imperfections are corrected, confusing statements are clarified and omissions are rectified. Relatively rarely the thoughts and suggestions of the referee will prompt the author to "think again", and a more extensive revision is carried out. Finally, there will be papers that the referees and editors feel are unworthy of publication, as is the case with all serious journals.

In the context of peer review it is also worth reiterating our stated policy regarding the types of paper we hope to receive. Although we most certainly do wish to receive manuscripts from respected and already well-known authors, we are equally keen to encourage and receive manuscripts both from younger cavers and from authors operating outside of academic establishments. On a personal level, the first publication by JG appeared in Volume 1, Number 3 of the *Transactions of the BCRA* and, being based on an undergraduate dissertation, cannot be claimed to be a polished piece of high-powered scientific writing!

On a positive note we are grateful for the comments from BCRA members in the UK and overseas who see *Cave and Karst Science* as a reputable outlet for scientific results. We believe that if the quality of the content is maintained by application of an editorial policy that includes objective peer review, the journal's influence will increase. It has to be admitted and accepted that *Cave and Karst Science* cannot hope to appeal to all BCRA members, but lowering its standards or widening its remit will not improve this situation. So long as it continues to exist it must attempt to fulfil the function that was originally envisaged for it - to provide a means to disseminate reliable information concerning aspects of cave and karst science.

Currently we are slightly concerned that the majority of manuscripts we are receiving are biassed towards the broad study of karst rather than towards more specialised cave related aspects. We are happy that a fuller understanding of karst as a whole is desirable, and advantageous in the long term to all those with an interest in caves, and we have no compunction about publishing these papers. However, we would like to see more submissions dealing specifically with cave-related matters.

Among several karst-related papers in this issue is a philosophical examination of karst by the Slovene karstologist France Šušteršič, who will be well known to anybody who has visited the Classical Karst and caves of Slovenia. The paper is included as a historical document and as a pre-cursor of an updated review of karst that may appear later. The paper was originally written, in Slovene, during the Nineteen-eighties, but attempted publication of an English translation was blocked by its referees. Perhaps it is a sign of a greater willingness to consider new ideas that the present manuscript has been accepted as providing a variety of new and valuable viewpoints. In presenting his "Pure Karst Model" Šušteršič casts doubt upon a number of traditionally accepted cornerstones of karst studies, and introduces novel ideas that could help to direct future karst and cave research. One of us (DJL) regrets that the paper was not published 10 years ago, at which time it would have influenced his own thinking and obviated the need to "re-invent the wheel". The master of the "thought experiment", Albert Einstein, stated (as is re-iterated in the current Petzl product catalogue), *"Imagination is more important than knowledge"*. Off hand we are not sure whether publication of Einstein's visionary ideas was ever blocked by the reactionary referees of the day!

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The gypsum karsts and caves of the Canadian Maritimes

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Abstract: The karst which has developed on the widespread Mississippian gypsum-anhydrite deposits of the Canadian Maritime provinces is described. Nova Scotia and New Brunswick have large areas displaying all stages of erosion from drift covered through to cockpit karst. Caves are common, but small. Their morphological features, including certain forms that have not been reported before, are catalogued and described, and the nature of gypsum speleogenesis in the region is discussed. Cave passages are dominated by laughöhlen ("leaching caves"), defined in the classic German South Harz gypsum region. These forms are probably atypical and relatively rare elsewhere. It is emphasised that laughöhlen are the horizontal component of cave systems: it is here shown how they relate structurally and speleogenetically to (sub)vertical features that form between the karst surface and the water table. Dissolution of both karst surfaces and caves can be rapid. Speleogenesis here appears to be a hyperkarstic phenomenon.

INTRODUCTION

The three Canadian Maritime Provinces - Nova Scotia, New Brunswick and Prince Edward Island - are situated on the eastern seaboard between the estuary of the St. Lawrence River and the State of Maine (Fig. 1). They are a relatively low-lying region representing the northern extension of the Appalachian mountain chain, and were extensively glaciated during the Pleistocene.

Prince Edward Island is composed almost wholly of red sandstones and has no karst, but Nova Scotia and New Brunswick have limestones (Mississippian and Precambrian) and Mississippian gypsum ($CaSO_4.2H_2O$) and anhydrite ($CaSO_4$) (Fig. 2). Where exposed on the surface the limestone beds show karst features but the beds are restricted in areal extent and contain only a few small caves (McAlpine, 1983; Moseley, 1988a). However, there are large areas of gypsum-anhydrite, usually highly karstified, and caves are more common in here. Internationally, sulphate karsts are much rarer than those formed on carbonate (limestone) rocks, and thus the glaciated gypsum karsts of the Maritime Provinces, Nova Scotia in particular, are of considerable speleological importance. Descriptions and surveys of most of these caves have been published elsewhere (Moseley, 1973, 1974, 1976a, 1976b, 1976c; Sawatzky, 1986; Moseley, 1988a, 1988b). The history of cave exploration in the region was discussed in Moseley (1976a). The present paper describes the morphological and speleogenetic features that have been observed in the gypsum karst and caves of the region.

THE GYPSUM KARST SURFACES

Beds of Mississippian (Windsor Group) evaporites underlie a large part of central and northern Nova Scotia, including Cape Breton Island, and parts of New Brunswick. The dominant components are massive gypsum-anhydrite deposits but the evaporite sequences also include halite (NaCl) and secondary minerals and they are interbedded with shales, calcareous shales, and some lenticular limestone beds. The gypsum is secondary after anhydrite.

The gypsum-anhydrite strata outcrop over extensive areas in Hants and Colchester Counties in Nova Scotia. There are also significant surface exposures in Halifax, Cumberland, Antigonish, Victoria and Inverness Counties (Nova Scotia) and - in New Brunswick - Albert, Kings and Victoria Counties. All of these areas are low lying with little topographical relief. Due to the fact that the whole of Maritime Canada was subjected to widespread multiple glaciations during the Pleistocene, large areas of the beds are covered by thick deposits of glacial drift, but in the places where they have become exposed at the surface they have weathered into a distinctive highly karstified landscape. This rugged landform is referred to locally as "plaster rock", a reference to the commercial use of gypsum to make plaster.

The modern karst surfaces typically consist of non-arable wooded country with numerous dolines. Soil cover is almost invariably present, exposed rock being visible only in cliff sections, riverbanks, and in places such as the sides of dolines. The karsts have sizable areas of closely spaced dolines of up to 20m in depth commonly separated only by narrow ridges, or even, in the most extreme form merely small residual hills at the intersections of the dolines. This latter landform appears to be morphologically identical to tropical limestone 'cockpit' karsts, meeting the definition of such karsts given by Jennings (1985, p.106).

Solution dolines, collapse dolines and subsidence dolines all occur. Vertical or subvertical channels extend from the bottom of the solution dolines, connecting with the underground drainage systems below. The integration of the drainage can result in the formation of large open channels and cavities, and some of these caves can be entered and explored. Collapse dolines are usually created in places where there is no or little overburden by the collapse of relatively shallow underground cavities. The entrances of Frenchman's Cave and Frenchman's II (St. Croix, Hants County, Nova Scotia) are in a magnificent example of such a collapsed cave (Fig. 6). Subsidence dolines are normally the result of the upwards propagation of a cavity through thick soil or surficial deposits overlying karst rocks (Jennings, 1985), creating a vertical pipe that eventually reaches the surface, but in soft gypsum they may propagate by collapse through the rock itself. Once the collapse breccia fill has gone such features are difficult to distinguish from the dissolution pipes that

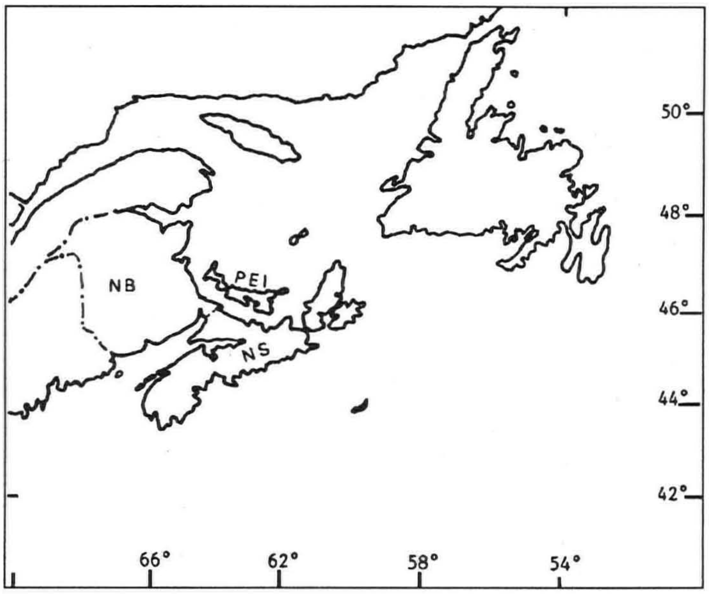
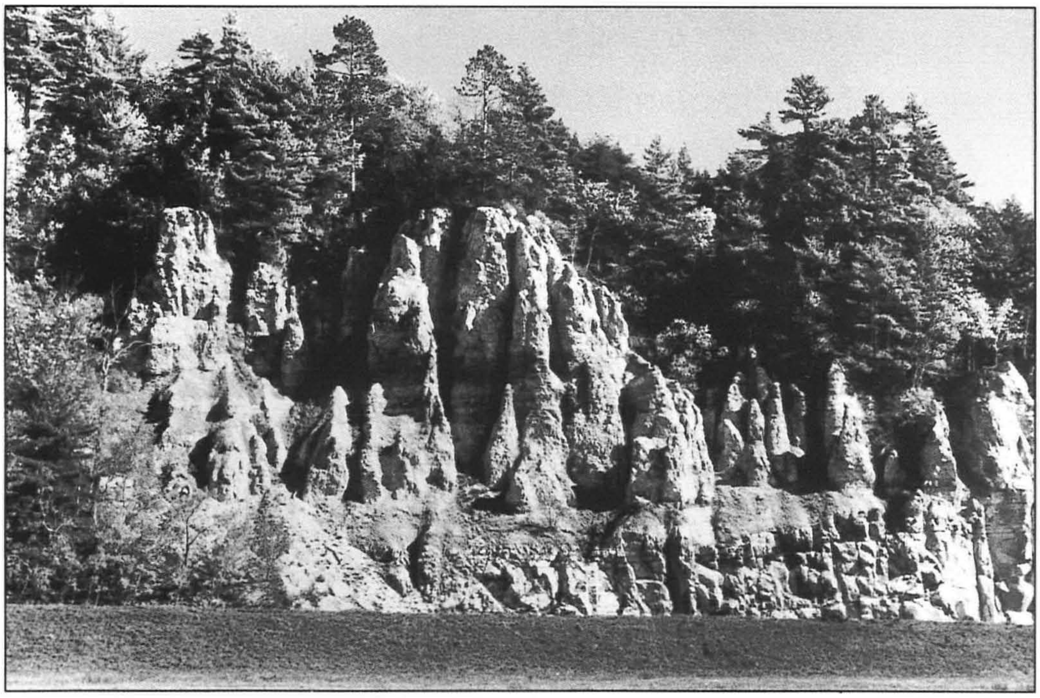


Figure 1. Area Map of Atlantic Canada (excepting Labrador). To show location of the Maritime Provinces: New Brunswick (NB), Nova Scotia (NS) and Prince Edward Island (PEI).



Highly karstified gypsum exposed in section in cliffs along the St. Croix River, Hants County, Nova Scotia.

extend from the bottom of solution dolines. There is a vertical pipe near the end of Cave of the Bats (Dutch Settlement, Halifax County, Nova Scotia) filled with glacial pebbles and boulders that appears to be the result of upward propagation - a rare example that can be examined directly (Fig. 4).

The sulphate karsts are formed on gypsum, most of the original anhydrite having been hydrated except at depth. However some anhydrite does remain and can be exposed within a cave by breakdown: palette-shaped structures, attached at one end and curving away from the roof, that are found in Frenchman's Cave are clearly the result of the expansion that occurs as calcium sulphate becomes hydrated.

Former karst surfaces buried and infilled by glacial deposits also exist and are sometimes exposed when the overburden is removed during the preparatory stages prior to blasting in gypsum quarrying operations. For example such palaeokarst features are routinely exposed by the ongoing quarrying operations in the Fundy Gypsum Company Ltd. quarry at Millers Creek (Hants County, Nova Scotia) and at Milford Gypsum Quarry (National Gypsum Ltd, Halifax County, Nova Scotia). Whilst these surfaces have been smoothed to a greater or lesser degree by glacial action (Stevenson, 1959, p.31) it is surprising that anything remains of the former karst topography considering the softness of the gypsum and the severe glaciation in the region. Nevertheless sedimentary fill and organic remains excavated from remnant dolines and former stream sinks show this to be the case, and demonstrate that the features observed are not due to dissolution taking place beneath the glacial drift. Finds at Milford Gypsum Quarry for example include a fossilised stream sinkhole with mastodon skeletons, pine cones and other organic remains, infilled during the early Wisconsinan (89,000 years B.P.). At this site the fossil karst surface was buried by 30m of glacial tills and interbedded sands (Grantham, pers. comm., 1996). At Millers Creek Quarry, a sample from under 20m of glacial drift overlying the gypsum surface was dated at 33,200 years B.P. (Roland, 1982, p.62), which suggests that this karst surface was formed during the interstadial known to have lasted for perhaps 15,000 years between the two major Wisconsinan ice advances. It may be assumed that most of these buried karsts date from this interstadial, but with some remnants also surviving from the last (Sangamon) Interglacial, which lasted for perhaps 100,000 years prior to the onset of the Wisconsinan nearly 100,000 years B.P. However, sedimentary fill at one site has been dated as Early Cretaceous (Grantham, pers. comm., 1996).

MORPHOLOGY OF THE CAVES

Twenty-seven caves have been reported in Nova Scotia gypsum (Moseley, 1988b), and three in New Brunswick (McAlpine, 1983). With a few exceptions, they are all active water courses and are thus undergoing the normal processes of erosion and enlargement: abandoned ("fossil") cave passages are rarer. None of the explored caves are very large. The longest is Hayes Cave (South Maitland, Hants County, Nova Scotia) which is approximately 400 metres in length.

There is no monograph that gives a comprehensive description of the morphology of caves in gypsum. Descriptions of individual caves or the caves of a particular geographical region are scattered throughout the literature and have never been collated in print. The terminology that has been used can be vague or imprecise, and sometimes special terms have been coined for gypsum caves whilst other terms have simply been adopted from those used for limestone caves. Accordingly, I shall attempt here to systematically describe the morphological features of Maritime Canadian caves based on original field observations; where appropriate referring to and comparing these with those reported and described in other parts of the world by various previous authors.

Caves are common in the gypsum karsts, in fact a day spent searching around any area will usually reveal some previously unreported cave development, but they can rarely be explored for any great distance. This is not necessarily a characteristic of gypsum caves. In the western Ukraine for example, the Miocene gypsum strata contain numerous caves of which the five longest together total 412km of mapped passage. One (Ozernaya Cave) alone has 107km of mapped passages (Klimchouk, 1992). Extensive well integrated underground drainage systems certainly exist within the Maritimes gypsum karsts, but extensive systems of open passages which can be entered and investigated have never been found despite considerable efforts, and probably do not exist. The caves can rarely be penetrated for more than a few tens of metres. Also, they do not contain multiple levels of superimposed fossil passages or the infill deposits that are often found in limestone caves and which, in areas that were glaciated, commonly reflect a long speleogenetic history extending through one or more glacial-interglacial cycles.

All the known caves in the Maritimes are dissolution ("solution") caves. Quellungshöhlen ("Bulge Caves"), a rare type of cave described by Biese (1931), have not been found. Quellungshöhlen are formed under

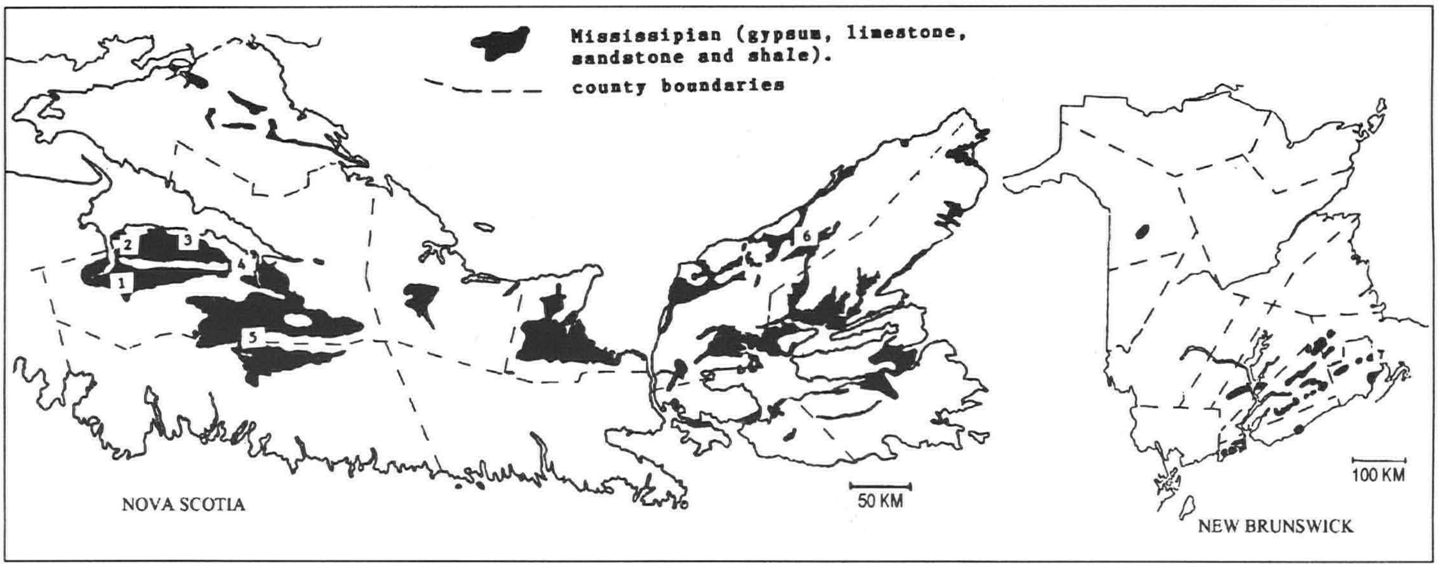


Figure 2. Outline maps of Nova Scotia and New Brunswick. To show the main areas underlain by Mississippian beds (gypsum, limestone, sandstone, shale), and cave locations mentioned in the text (1- St. Croix, 2 - Mantua, 3 - Minasville, 4 - South Maitland, 5 - Dutch Settlement, 6 - Frizzelton, 7 - Albert Mines).

the special circumstances where horizontal or subhorizontal beds of anhydrite are exposed at the surface. Expansion as the anhydrite hydrates to gypsum causes the upper layers to heave up forming a hollow dome somewhat like a rather flat igloo.

The dissolution caves display both horizontal and vertical or subvertical conduits and passages. Morphologically (and speleogenetically) the horizontal and vertical components each have their own distinct characteristics, and this thus forms a useful primary classification which is used here for the description of the morphological features that have been observed in Maritime caves.

Horizontal Passages

Biese (1931), describing the karst formed on the Upper Permian Zechstein evaporites of Germany, distinguished two types of dissolution cave (a) Joint Caves, and (b) Leaching Caves. This classification has been followed by subsequent authors, for example Pfeiffer and Hahn (1972). The two types may grade into each other. Both are recognisable in the horizontal elements of Maritime caves.

Leaching Caves were first reported by Gripp (1912) and more fully described by Biese (1931). In the original German they were called "laughöhlen". In conformity with the common practice in karst geomorphology of using as formal terminology the name of a feature in the language of the country where that feature is classically developed and/or was first described in the scientific literature, "laughöhlen" is recommended in preference to "leaching cave", and is used in this paper. The term is somewhat ambiguous though, and strictly should be applied only to a particular *passage* form that is the horizontal part of a cave system which normally will also contain vertical or subvertical features that display a quite different morphology and result from different speleogenetic processes.

Laughöhlen

The first scientific descriptions (Gripp, 1912; Biese, 1931) of laughöhlen were based on investigations in the Zechstein evaporites where these outcrop in a strip on the southern and western margins of the South Harz Mountains in Germany. They are characterised by their particular passage cross-section (Fig. 3) with a flat laugdecke ("Leaching Roof") and facetten ("facettes"): oblique lateral walls that meet the roof at an acute angle.

Although laughöhlen are common in the classic South Harz cave region, a review of published surveys of gypsum caves suggests that, worldwide, they may be relatively rare (the only map of a gypsum cave - other than those in the South Harz and in Maritime Canada - I have found which shows cross sections which are unambiguously of laughöhlen passages is Labyrinth Cave, Manitoba [Wright, 1991, p.38]). Though this observation must be treated with caution because survey cross-sections may not show the characteristic features of these caves due to cavern breakdown or because they have not been recorded by survey crews unfamiliar with what to look for, I believe that the majority of gypsum cave passages known around the world do not have the features diagnostic of laughöhlen. The huge caves of the Western Ukraine for example are all complex joint-guided three-dimensional networks (see maps in Klimchouk, 1992).

However, this is not the case in the Maritimes, where classic laughöhlen or intermediate forms are the norm and joint caves are very unusual.

Biese and several subsequent authors assumed that laughöhlen are restricted to gypsum, but a few examples have subsequently been reported in limestone (Kempe et al., 1975). They appear thus to be unusual in both types of rock, though relatively more frequently occurring in gypsum than in limestone.

Cave passages in gypsum tend to break down readily and hence the laugdecke and facetten are destroyed relatively rapidly. Vestiges of them can usually be found however, and passages retaining the original form sometimes survive. In some caves the remnants of several facetten and laugdecken can be identified one above the other : such "multiple facettes" have been found both in the South Harz and Maritime Canada.

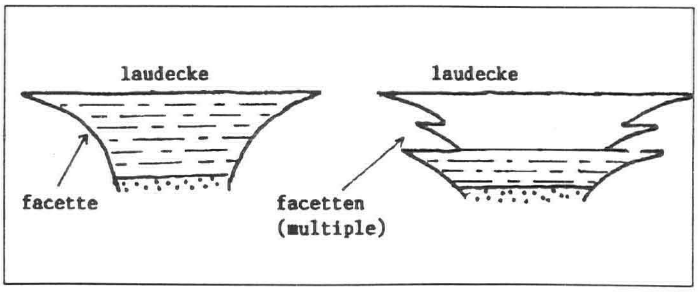


Figure 3. Idealised cross sections of laughöhlen cave passages.

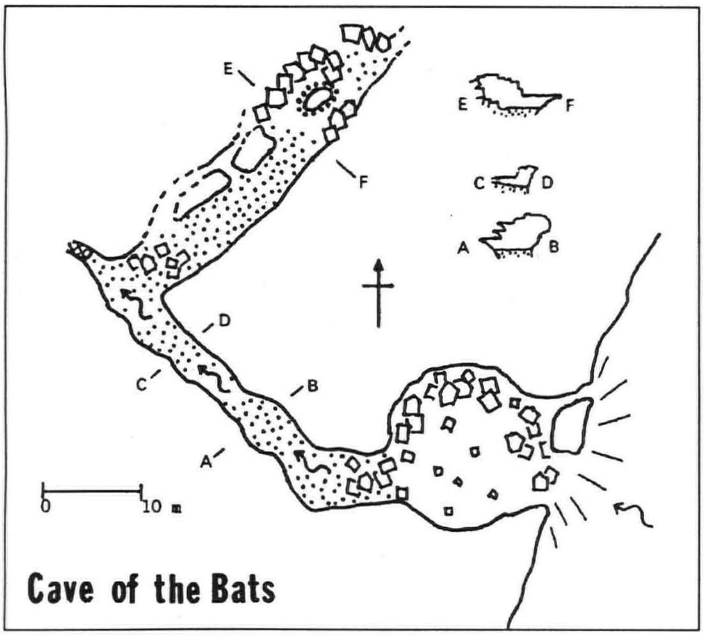


Figure 4. Cave of the Bats, Dutch Settlement, Halifax County, Nova Scotia. Note the facetten and laudecken shown on the cross sections. These are remnants that have survived the breakdown that has taken place throughout the cave.

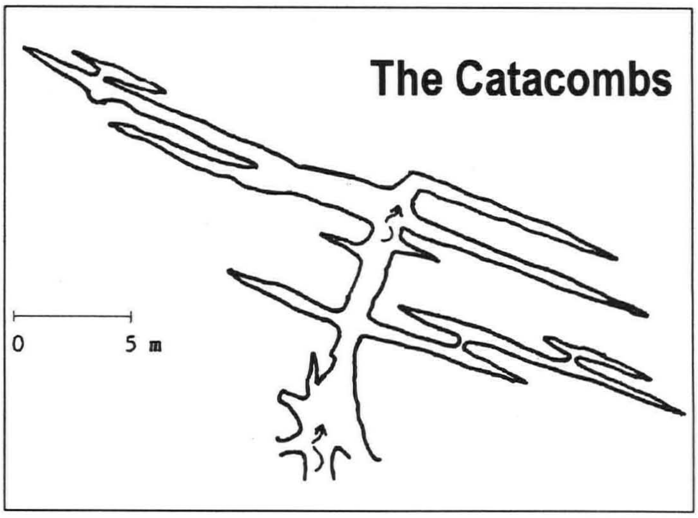


Figure 5. The Catacombs, Mantua, Hants County, Nova Scotia. A small rift cave formed in gypsum (quarried away).

In the Maritimes these dissolution conduits may extend over fairly large distances underground and have tributaries as well as (sub)vertical feeders, but the existence of most of such passages in the present geographical area is only inferred from the presence of sinks and risings. They are too small to explore and are full of water. Those that can be explored have been drained due to a falling water table. Some of these are now dry, whilst others have become vadose with active streams. Stream action is highly seasonal in this part of the world, with heavy spates occurring during the annual Spring thaw. The laughöhlen usually do not survive long after they have ceased forming and examples unmodified by breakdown are rare. There are none now known in the Maritimes. There were superb examples in the Honeycombs (Mantua, Hants County, Nova Scotia) (Fig. 11) before this important cave was destroyed in the early 1980s. Vestigial laugdecken and facetten are to be found here and there in some caves however, proving the original form of the passage. There are small remnants in Frenchman's Cave (Fig. 6, Section K-L) and others in Hayes Cave; better preserved examples are present in Cave of the Bats (Fig. 4, Sections C-D and E-F). Multiple remnants indicating staged falls in water level also exist. The best examples again were in The Honeycombs (Fig. 11); fortunately there are still some surviving examples, showing up to three remnant laugdecken, in Cave of the Bats (Fig. 4, Section A-B).

Joint Caves

Only one known cave, The Catacombs (Mantua, Hants County, Nova Scotia), contained an area of passages with narrow rift-shaped cross-sections and an unambiguous joint-guided network in plan view (Fig. 5). This cave no longer exists, having been quarried away in the early 1980s.

Passage forms with intermediate characteristics were somewhat more frequent, but, here again most examples have been destroyed by gypsum quarrying operations since 1980. Laugdecken sometimes have a small rift running centrally along them. There are no known surviving examples, but such features existed in Millers Creek Cave (Mantua, Hants County, Nova Scotia) and in The Honeycombs (Fig. 9; Fig. 11, Sections E-F to K-L). These caves were close to The Catacombs, and it would thus appear likely that all three were guided in their plan directions by a system of joints within the gypsum beds in the area. In these caves also, laugdecke may be flat as described by Biese, or, in some cases, gently convex: both types are shown in the cross sections in Figs. 9 and 11. Frenchman's II is a small cave developed at two horizontal levels connected by a joint-guided rift (Fig. 6, sections A-B to E-F).

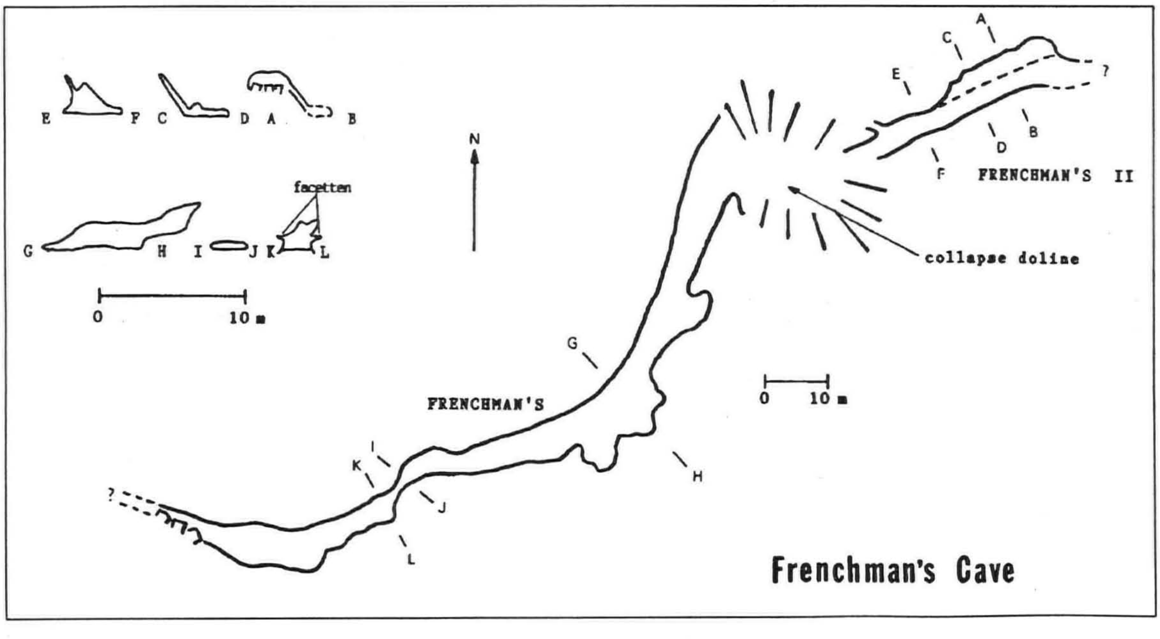


Figure 6. Frenchman's Cave and Frenchman's II, St. Croix, Hants County, Nova Scotia. Note particularly the girlandengang form of Frenchman's Cave.

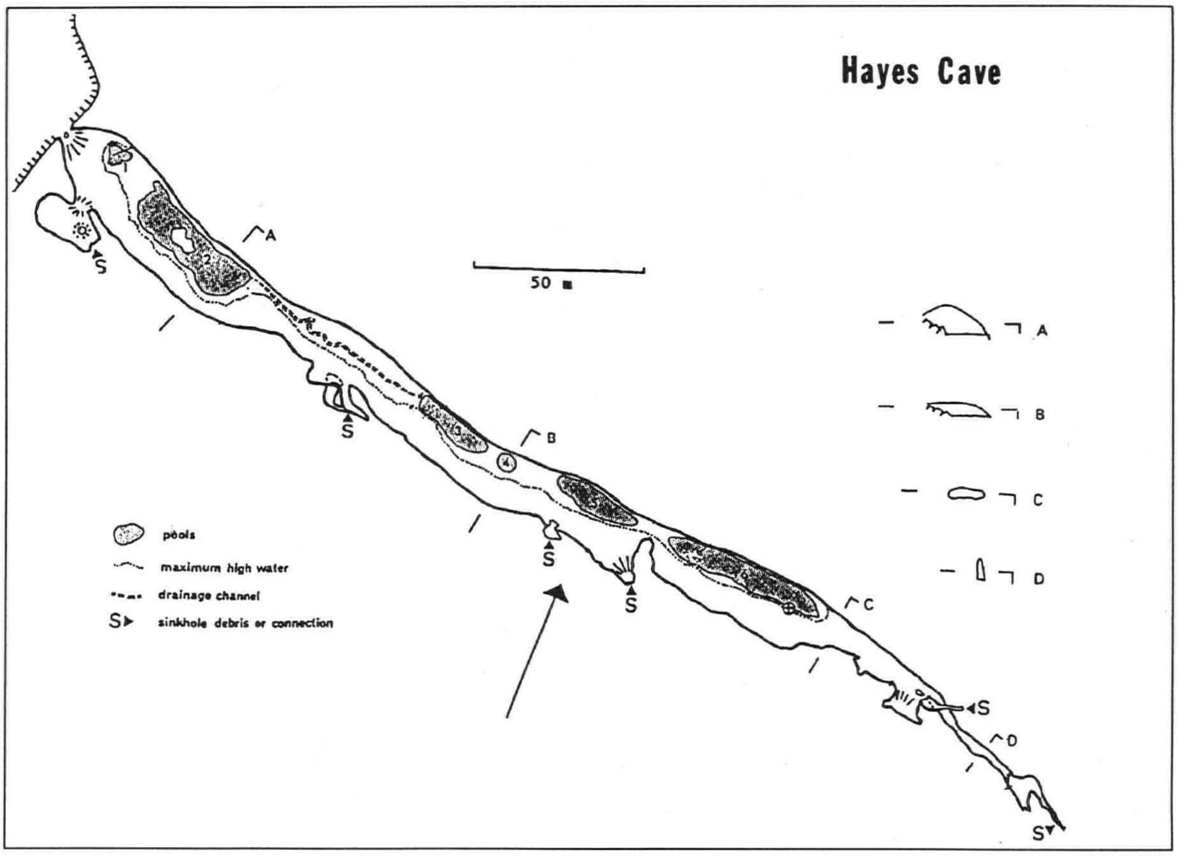


Figure 7. Hayes Cave, South Maitland, Hants County, Nova Scotia. The largest cave known in the Maritimes, it is extensively affected by cavern breakdown and shows few features of geological interest.

Girlandengang

It is not uncommon for horizontal cave passages in gypsum to display a sawtooth pattern in plan view. In limestone caves, Bögli (1971) coined the name "girlandengang" ("garland-gallery") for such features. Frenchman's Cave (Fig.6) and Hayes Cave (Fig.7) both show this type of passage.

Dissolution Cells

These are an unusual morphological form that appear to be unique to gypsum. I have not seen them specifically described elsewhere as a distinguishable features, but the distinctive morphology is considered to warrant a specific term and the name "dissolution cell" is here proposed.

Dissolution cells are large, isolated underground chambers (Figs. 8 and 9). Except where modified by breakdown they have the same cross section form as laughöhlen passages with a flat, or gently concave, horizontal laugdecke and facetten but differ in that they are chambers rather than passages and are truncated at each end by small and narrow inlets and outlets for water flow. In the known examples these inlet/outlet passages are too small to explore so it is inferred that the existence of a dissolution cell will almost always be unknown except where entry has been made possible from the surface by fortuitous circumstances, such as a partial collapse. Thus how common they are is entirely unknown; though it is reasonable to suspect that they are responsible for many collapse dolines, and at least some of the sudden collapses of the surface that occasionally take place in gypsum karst. I suspect that they are a characteristic feature of cave development in gypsum, but have received no attention because they are so infrequently detectable. Published maps of gypsum caves in the South Hartz Region (e.g. Hensler, 1968) show morphological similarities. Also Warwick (1962, p.178) described water-filled voids up to fifty feet in diameter that were broken into the course of underground mining operations in a Permian age gypsum bed, twenty-one feet thick, in the Vale of Eden (Cumbria, England) which may have been similar forms.

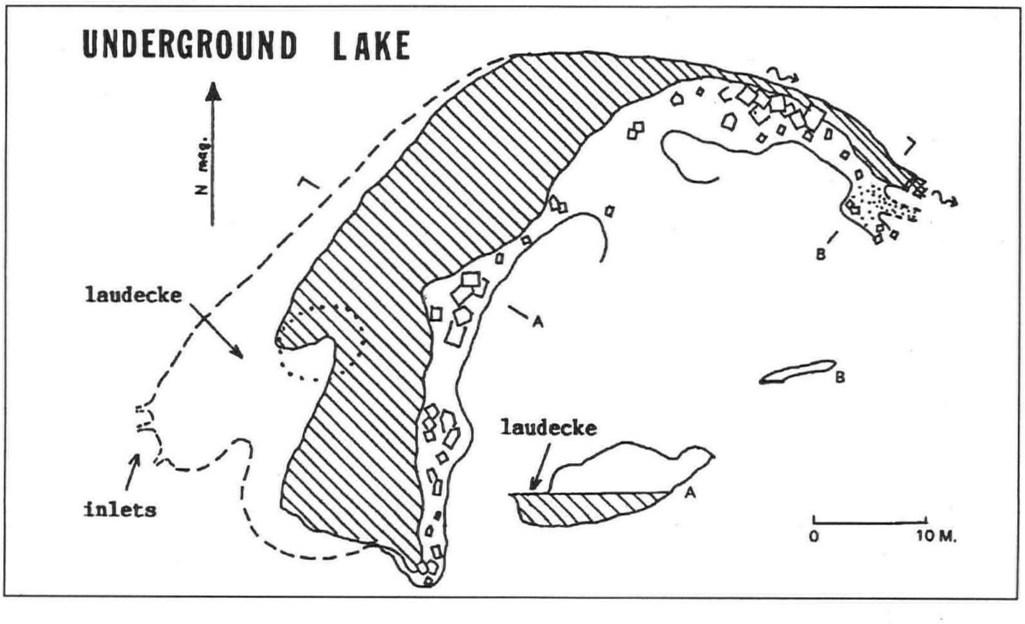


Figure 8. Underground Lake, Albert Mines, Albert County, New Brunswick. The type site for dissolution cells. The cave is still actively forming.

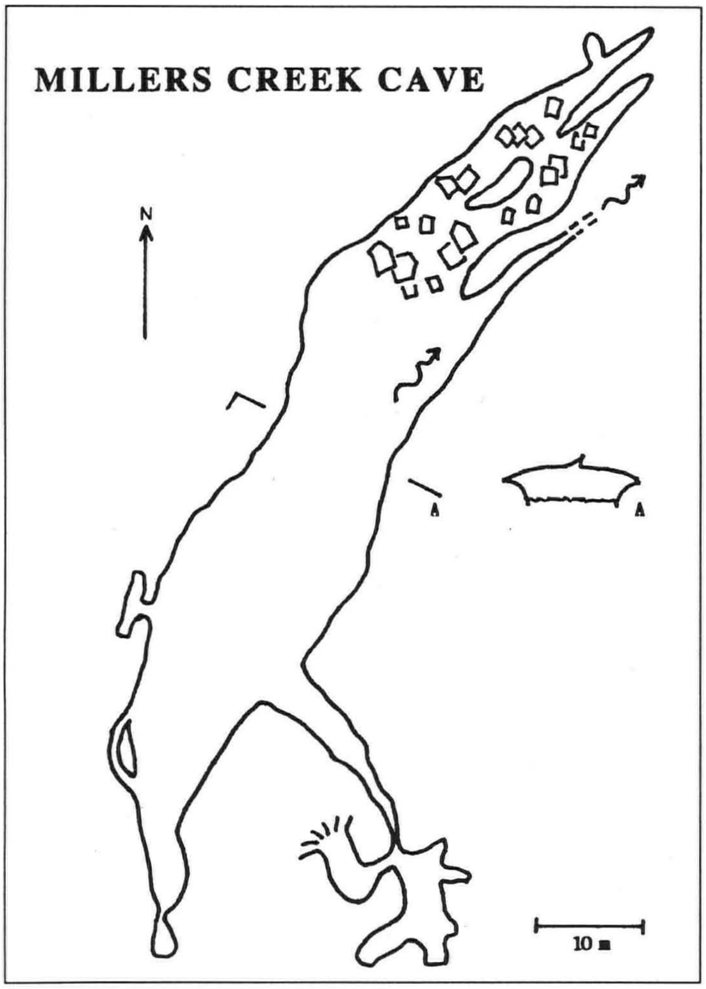


Figure 9. Millers Creek Cave, Mantua, Hants County, Nova Scotia. A dissolution cell that could be entered via a tight passage from the small cave on the south-east (quarried away).

Underground Lake (Albert Mines, Albert County, New Brunswick) is here proposed as the type example of this feature. It is an active, water-filled dissolution cell which is accessible due to a partial collapse of the overlying rock. Its features can be examined by S.C.U.B.A. diving: the narrow inlets are indicated on the map (Fig.8) as is the extremely flat roof. In this example the outlet stream can be explored for a short distance but is much more restricted than the cell itself. The surviving area of flat laugdecke is within a few centimetres of the water surface over its entire area.

One dissolution cell was known in Nova Scotia: Millers Creek Cave (Fig. 9). This cave was close to the surface and it was possible to enter via a narrow side passage from another smaller chamber formed beneath an adjacent doline. It was the only known dissolution cell in the Province. It was drained and thus readily accessible for study, though still partly active because it contained a seasonal lake that was up to 5m in depth at maximum. It was a chamber 75m in length, up to 17m in width and 6m in height. The laugdecke was extensively modified by blockfall, but otherwise retained the characteristic morphology. Millers Creek Cave was unfortunately completely destroyed by quarrying operations in 1981.

Vadose Passages

Cave passages with active streams are common. The stream beds are commonly composed of pebbles and gravel derived from the glacial drift outside the cave, but sometimes the stream flows on a dark brown coloured sediment as in Cave of the Bats (Fig. 4), Frenchman's Cave (from Section K-L to end of the cave, Fig. 6) and the northern side of the main passage of Hayes Cave (Fig. 7). In other cases the stream flows beneath breakdown, as in Minasville Cave (Minasville, Hants County, Nova Scotia) which is a dry except for a tiny stream which appears at one point from beneath the extensive breakdown that everywhere forms the floor, disappearing again within 2m. Vadose stream passages containing free-flowing streams with no, or little, sediment or breakdown exist but are unusual. The Stream Sink entrance of Munro Brook Cave (Frizzelton, Inverness County, Nova Scotia) (Moseley, 1976a, Fig. 3) is an example of this type.

Scarp Caves

On Weir Brook (St. Croix, Hants County, Nova Scotia) a small stream which emerges from a gypsum cliff 5m from the brook can be traced for 210m running just behind and parallel to the face of the scarp/cliff, back to where it emerges from scree before immediately sinking again into the base of the low scarp. The underground course of the stream is marked by a series of collapse features, one of which gives access to a 25m section of active stream cave (Weir Brook Cave, Fig. 10). The cave is obviously closely associated with a structural feature (the scarp itself), and the fact that the horizontal passage in The Honeycombs (Fig. 11) was also oriented behind, and more or less parallel to, a cliff face, is suggestive of some general association.

Vertical Features

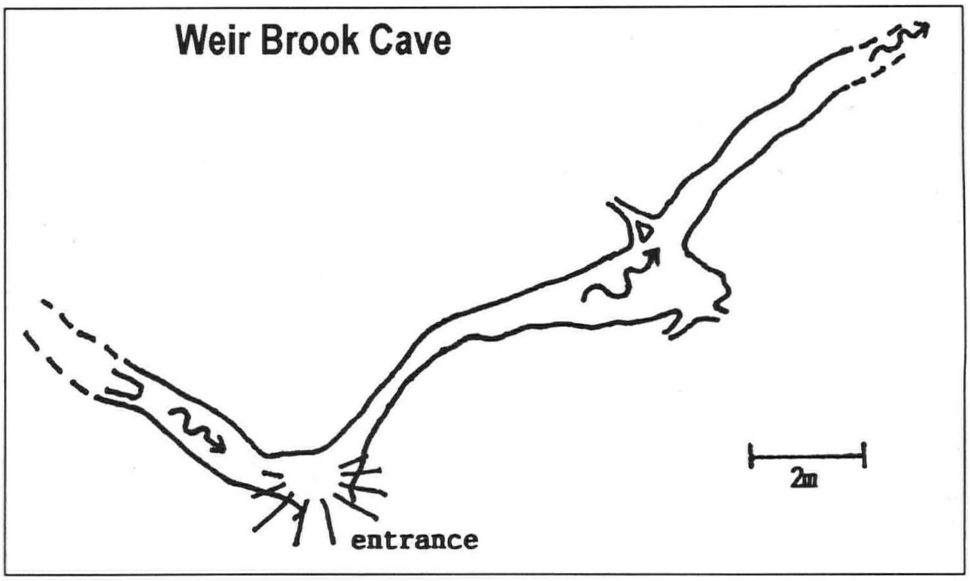
Turning now to vertical and subvertical features, one example of an early dissolution feature has been observed. In one of the vertical shafts of The Honeycombs, a structural plane was clearly visible cutting across one wall of the shaft. The plane contained several apparent dip tubes, visible in cross section as small lenticular openings. No other examples have been found in either Nova Scotia or New Brunswick. "Dip Tubes" (straight or slightly sinuous phreatic features propagated down the true dip of the strata or within approximately 15° of it) have been frequently and convincingly described in limestone caves, spaced in subparallel array across a given bedding plane during earliest cave development, but I am not aware of any previous reports of such features from gypsum caves.

The most characteristic vertical dissolution features are drainage conduits extending from the bottom of a doline and connecting to horizontal cave passage below. Initially, such features are structurally, not water table guided.

The most remarkable vertical morphological features in any of the caves were the group of interconnected shafts known as The Honeycombs (Fig. 11). This was a group of six shafts, oriented in a line a few metres behind a cliff face, oval in cross-section with the long axis perpendicular to the cliff face, and interconnected at the bottom. From the plan, it is apparent that the shafts were oriented on structural features (joints?) trending approximately East-West. Each had a uniform cross-section shape and diameter from top to bottom (except for some weathering effects near the top, and breakdown at the bottom), and were perfectly vertical. (Moseley 1974). The Honeycombs were a dry inactive (fossil) cave. There was one similar, but isolated, shaft nearby, and the area behind them had a number of comparably-sized and shaped, but shallow, doline-like features that appeared to be shafts infilled by subsequent deposits (leaf mould, etc.), though their depth was never ascertained. There is a small group of similar shafts at Minasville (Hants County, Nova Scotia), though these are only 2m-4m in depth and it cannot be known if they have interconnections below or are much deeper without excavating the infill. They are, however, like The Honeycombs, situated close to a gypsum cliff.

Another type of vertical feature are the upwardly propagating vertical 'pipes' described above: these are essentially mechanical features but are difficult to distinguish from mature vertical dissolution shafts unless they still contain the collapse breccia formed as they developed. The possible example in Cave of the Bats, mentioned above, is the only one that can be directly examined.

Figure 10. Weir Brook Cave, St. Croix, Hants County, Nova Scotia.



KARSTIFICATION AND SPELEOGENESIS

Karstification

Karstification begins as soon as the gypsum surface is uncovered by erosion of the overlying glacial drift. The erosion of the drift cover adjacent to river valleys for example results in progressive karstification showing all stages from drift-covered through well-developed "plaster rock" and cockpit karst and ending in residual karst features. Due to the high solubility of the rock (see Appendix), these sulphate karsts develop and evolve rapidly in geological terms. The sequence just described may take only a few thousand years. As a result, the active gypsum karsts in Maritime Canada are mostly post-glacial features. However, open shafts up to perhaps 12m depth have recently been found associated with the fossil karst (probably Wisconsinan) at Millers Creek Quarry (Laska, pers. comm., 1995) and this suggests that some active existing caves may be exhumed features of the interglacial or interstadial palaeokarsts, reinvaded by streams sometime following the final retreat of the glaciers.

Speleogenesis

Initiation of Horizontal Passages

Almost nothing is known in the Maritimes about the nature of the primitive dissolution features that initiate horizontal cave passage development.

The rift remnants breaking the otherwise uniformly featureless flat or gently concave laugdecken in The Honeycombs and Millers Creek Cave suggest that here the modern passages were preceded by small rift caves formed along joints. Kempe observed similar features in a number of South Harz caves and proposed (Kempe, 1972) a general model of gypsum cave development in which dissolution of such rifts is the first stage. This may however be a special rather than a general case, presupposing as it does that cave initiation in gypsum is always within joints, never in bedding planes or other horizontal planes of weakness. Certainly no features similar to the spongework described in limestone have been reported in the Maritimes gypsum, but this negative evidence carries little weight here: the rapidity of dissolution and breakdown easily explaining the absence of such features. They apparently do exist elsewhere: Waltham (1971) reported anastomosing bedding-plane channels in gypsum in the Zara region of Turkey.

Whatever the earliest stage consists of, there is subsequent coalescence, capture of flow, and creation of a main channel.

Joint Caves

Joint caves are the result of dissolution along joints. Network plan views and passage cross-sections are characteristic of phreatic conditions. The huge maze caves of the Ukraine were formed at depth within primary gypsum interbedded with porous limestone (Cooper, 1996, pers. comm.); the smaller joint caves of both the South Harz and the Maritimes exist within near-surface secondary gypsum and may be presumed to have developed in the shallow phreatic within, at most, a few tens of metres of the water table.

Laughöhlen

Most of the literature relating to gypsum cave speleogenesis is concerned with the mechanism of the formation of laughöhlen. There is general agreement that they form under 'shallow phreatic' conditions, at, or only a few meters below, the surface of the water table, and under conditions of very slow water flow. There is nothing in the Maritimes caves that conflicts with this view. As will be apparent from the following, most of the features of the horizontal conduits and passages indicate water-table guidance rather than guidance by structural elements within the beds: in addition to the features of passage cross-sections the passages also typically have horizontal or very gently graded longitudinal sections. (However it is also apparent from the example of the Mantua caves that the *direction* of the passage may relate to joints.)

The actual mechanism responsible for the formation of laugdecke and facetten remains disputed however, and several theories have been proposed.

Gripp (1912) conducted laboratory dissolution experiments with salt blocks and was able to make miniature laugdecken and sloping walls very similar to those observed in gypsum caves. He explained the shapes of these models as due to a dissolved salt concentration gradient, and extrapolated this to the natural process in gypsum. Biese (1931) concurred. In this theory water saturated with calcium sulphate sinks towards the bottom and the more concentrated solution is less aggressive thus resulting in an increased rate of dissolution towards the roof. Goodman (1964, 1969) and Reinboth (1968, 1974) both proposed as an alternative that the insoluble residues of gypsum sediment onto the facetten, protecting them from further dissolution. Enlargement of the passage is thus by continued dissolution of the laugdecke. This theory implies that these passages are formed below the water table surface, otherwise upwards dissolution would not be possible (a point which was also made by Kempe, 1972, p. 2). Kempe (1972) suggested that both processes are involved.

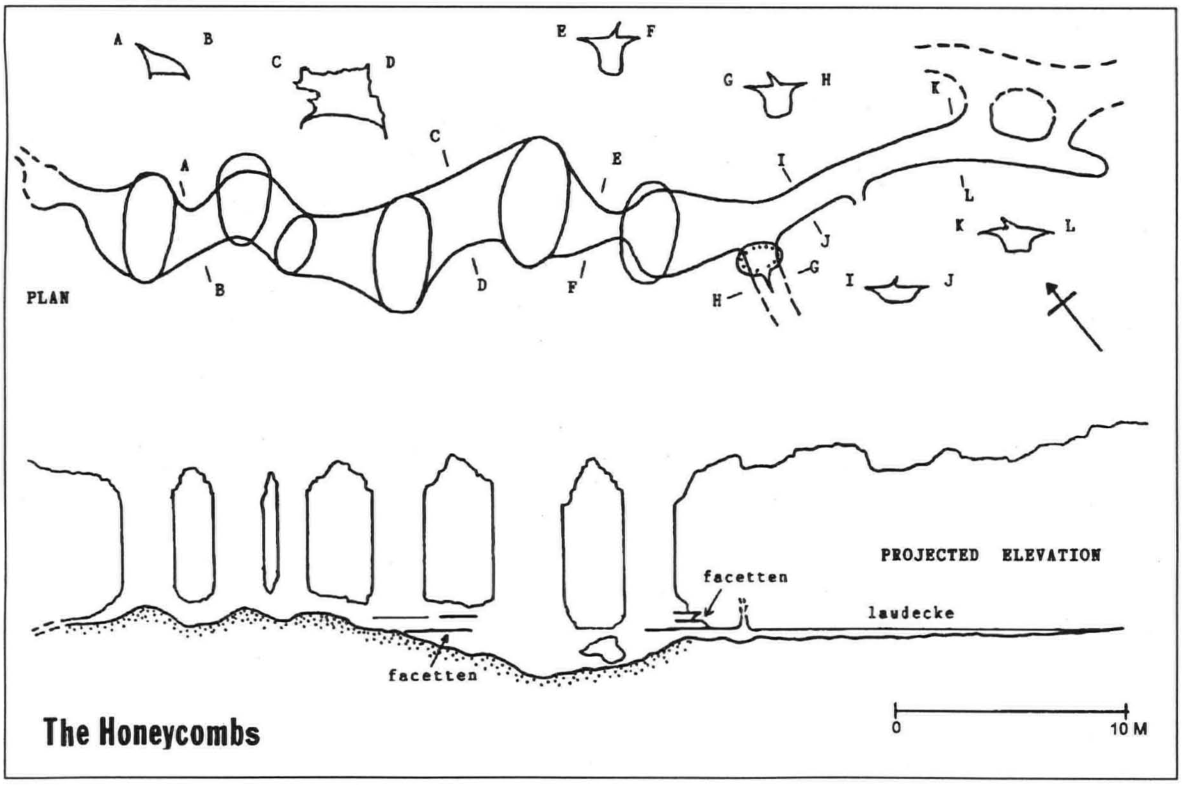


Figure 11. The Honeycombs, Mantua, Hants County, Nova Scotia. A unique cave showing both vertical and horizontal dissolution features largely unmodified by breakdown (quarried away).

Kempe et al. (1975) made conductivity measurements in several water-filled passages in South Harz gypsum caves and found the expected regular density gradient in some cases, and several homogeneous layers separated by steep density gradients in other cases. (However, in some sites there was no density gradient discernible. This has not been explained.) Also actual field experiments using fluorescein dye showed the existence of a 1-2mm thick film of water flowing down the surface of the facetten with a velocity of 3-30 cm. min^{-1}. Based on calculations, the authors show that this downwelling layer will develop turbulent flow and hence will dissolve the rock surface more rapidly than would simple diffusion. The existence of this downwelling layer implies a corresponding upwelling, thus a dynamic recirculating model, and the roughly triangular cross-section and (typically) 45° slope of the facetten was suggested by these authors to correspond to the minimum energy configuration. This is a convincing model that appears to fit the observed facts better than any other proposed to date for the formation of facetten.

Published attempts to explain laugdecke are less convincing. None of the above models appears to directly address the peculiar flatness and uniformity of many of these ceilings: they address mainly the sloping walls. The "salt-finger" model of Kempe et al. (1975) does address the nature of the solution processes at the ceiling itself but apparently assumes that the cave passage is forming below the water-table. This, in my opinion, is an unnecessary assumption. In the absence of any unambiguous field evidence to the contrary, the best way to explain laugdecken is simply that they form at the water table surface itself.

Field evidence in the Maritimes strongly supports formation at the water table. The laugdecke in the large chamber of Underground Lake is at the same level as the open water surface where the lake extends into the area where the roof has collapsed (Fig. 8, Section A). The main laugdecke in The Honeycombs was perfectly horizontal throughout its entire length of 35m, (Fig. 11) a fact very difficult to explain except as due to dissolution at a gravitationally-controlled water table surface. And finally in no case where multiple facetten have been observed has there been any evidence that any has been subjected to secondary dissolution. The only reasonable explanatory mechanism is that the multiple facetten reflect a series of sequential, standing water tables, each at a lower level than the previous.

The only contrary field evidence is the gently concave roofs in some of the caves that used to exist at Mantua, but it is possible to postulate a similar film of water as reported by Kempe et al as flowing outwards along the roof from a central upwell, and becoming more saturated and less aggressive as it approaches the walls. If this is the case, then the highest point of the curve of the concave roof may be inferred as the former water table surface.

Water Table Control Mechanisms

Many of the caves are close to rivers, and are obviously related to present (e.g. Cave of the Bats, Hayes Cave) or former (e.g. Minasville Cave) local water tables.

The Mantua caves (The Honeycombs, The Catacombs and Millers Creek Cave) and a group of shafts at Minasville, morphologically similar to though shallower than The Honeycombs, were associated with higher ground and cliffs that faced flat areas of land that are probably the sites of former post-glacial lakes. I hypothesise that the laugdecken in The Honeycombs corresponded with sequential standing lake levels, and were left dry and abandoned as the lake disappeared. There are three distinct levels: levels I and II survived only as remnant facetten on the walls, whilst the lowest, level III also created a 20m long laughöhlen-type passage and could also be traced along the walls beneath the shafts for another 15m until it disappeared beneath the sandy floor.

Girlandengang

Girlandengang are features of the junction between horizontal and vertical cave components, and are a reflection of the different characteristics of the two. Dipping gypsum beds statistically have to be much more common than horizontal or vertical beds: consequently in view of the fact that the "vertical" feeder conduits are normally structurally guided, i.e. will flow down dip in bedding planes or joints, they intersect the water-table guided horizontal passage from one direction.

It is here suggested that differential dissolution by mixing waters ("mixing corrosion") at the point of intersection, comparable with that proposed by Bögli (1971) for limestone caves, accounts for the creation

Passage in The Honeycombs, looking southeast from below the easternmost shaft into the crawlway. Illustrates the multiple facetten at this point (see Figure 11).

of dissolution pockets at the point of intersection and thus for the girlandengang passages encountered in gypsum caves. The chemistry of such mixing corrosion in gypsum is addressed below.

Dissolution Cells

In the absence of any specific evidence to the contrary, the most sensible explanation of dissolution cells is that they are the result of aggressive, rapid mixing corrosion at the point where two or more phreatic conduits intersect .

Evolution of Horizontal Passages

Open air-filled cave passages are formed when the water table lowers, as at Mantua, or by cavern breakdown creating open cavities above the water table surface. The chamber of Underground Lake is a good example of the latter process.

Cave passages in the Maritime gypsum tend to break down quickly and most of the caves are extensively affected by blockfall. Remnants of laugdecke and facetten sometimes survive. The caves often become vadose and continued evolution may be then mainly by dissolution of breakdown. Thick mud deposits often restrict further dissolution of the cave proper, except during spate conditions. Some caves consist of little more than crumbling, featureless passages or chambers, with floors of broken rock. Minasville Cave is an example. It is somewhat ironic that, as pointed out by Kempe (1972), this may often be the most stable stage in the life cycle of a gypsum cave.

Rapid breakdown is due to several factors. The most important are rapid dissolution and the mechanical weakness of the gypsum here (the greatest unsupported roofspan known is 20m [Hayes Cave], but this is atypical). Also all the known caves are in gypsum beds that outcrop at the surface and thus there are no overlying insoluble rocks to give structural strength. Finally, it is possible that in some places, anhydrite may remain which, upon being exposed by cave formation, hydrates and expands, spalling off blocks of rock. This may have occurred in Frenchman's Cave.

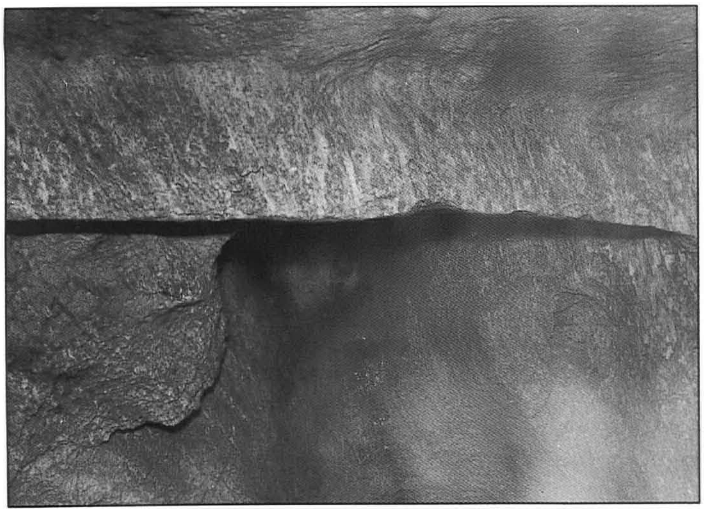
The cave entrances are also subjected to many freeze-thaw cycles. Boyd (1973) calculated the average annual number of cycles (-6°C to 2°C) at Dartmouth, Nova Scotia as 30. As a result entrances are often almost filled in by breakdown (Hayes Cave, Cave of the Bats, Frenchman's Cave). This reduces temperature fluctuations inside the entrance. The temperature in the zone extending for perhaps 20m (depending upon the topography of the specific cave) is below freezing for a large part of the year, normally from late November until perhaps April, but snow and ice accumulations can persist in some caves until late June. These so-called "Ice Caves" were often used for cold storage and as a source of ice for making ice cream prior to the widespread availability of modern refrigerators. There are no year round ice caves in the Maritimes. It is evident however that the 'smoothing' of temperature fluctuations results in fewer, perhaps only one, freeze-thaw cycle per annum in this zone. The mean cave temperature in central Nova Scotia is approximately 5°C (unpublished).

Scarp Caves

I am indebted to Dr. Anthony Cooper for the suggestion that the caves associated with scarps may be formed in fractures due to cambering of the scarp face. This is a very likely possibility.

Initiation and Development of Vertical Features

In contrast to the importance of the water table in the genesis of horizontal features, vertical features are mainly guided by the joints or other structural weaknesses such as, in dipping beds, bedding planes. Due to the rapid dissolution and erosion of gypsum, dip tubes are less likely than in limestones to survive beyond the early development stage, but unlike the situation with regard to the features that initiate horizontal water-table guided passages, apparent dip tubes have actually been observed at one site. As mentioned above, primitive dissolution conduits appearing similar to those in limestone caves were present in The Honeycombs. It is believed that vertical shafts evolve from these primitive dissolution tubes by capture of the flow by dominant conduits which consequently enlarge more rapidly relative to the others. In due course, the dominant tubes become large enough for a free air surface to be created and subsequently differential dissolution will tend towards the formation of vertical shafts in which the final form is gravitationally rather than structurally guided. A small vertical shaft visible in the roof of a small chamber just inside the entrance to Hayes Cave is an example (Fig.7).



Details of crawlway in The Honeycombs (in vicinity of Sections I-J to K-L, Fig. 11). This is a well-developed laughöhlen passage, with flat laugdecke ("solution roof") and facetten. Note the central rift remnant.

Physico-chemical aspects

In his classification of karstic phenomena based on phase equilibria, Cigna (1978) gave gypsum speleogenesis as one example of what he called a 'parakarstic' phenomenon, i.e. two components in equilibrium: in this case calcium sulphate and water. This clearly would make it different from the three component (calcium carbonate, carbon dioxide and water) phase equilibrium system of carbonate rocks ('karstic' in Cigna's classification), and there would be significant physico-chemical effects that differ from those in limestone and which would be expected to be reflected in the process of cave formation. As pointed out by Cigna, mixing dissolution cannot occur in a two component system (because the equilibrium curve is a straight line), so this important phenomenon cannot contribute to cave formation in parakarst.

Under actual field conditions, however, gypsum speleogenesis is almost certainly never such a simple two-component system because other dissolved substances present in underground waters have a significant effect. The phase equilibrium effects in multi-component mineral solutions have been studied for some time. As early as 1969 Runnells (1969a, 1969b) was considering the mixing of different mineral solutions. Using several two-mineral systems as examples, he showed that the addition of a second mineral may either increase or decrease the solubility of the first mineral. Since the change in solubility rarely shows a linear relationship to the amount of the second mineral added, mixing of two different chemical (or physical) components, assuming that one is initially saturated, results in either precipitation or further solution of that component. In the specific case of gypsum, calcite from associated rocks is frequently present in solution and the system calcite-gypsum-water was determined theoretically by Wigley (1973). According to his calculations, whilst the addition of gypsum to the system will diminish (or reverse) the Bögli mixing corrosion effect on the solubility of the calcite component, but the gypsum saturation curves are linear. However, in direct observations of the gypsum caves around Bologna, Italy, Forti and Rabbi (1981) discovered deposition of calcite sinter in the absence of any direct source of calcite. This implies that under field conditions, at least in these particular caves, there are four components in equilibrium: gypsum, water, calcite and carbon dioxide. These author's calculations imply that mixing of two waters with different carbon dioxide content (or pH) may increase the total solubility of gypsum (their Fig. 8, p.11). This is apparently in disagreement with Wigley who calculated that the solubility of gypsum is essentially independent of the carbon dioxide partial pressure. If they are correct, mixing corrosion is possible in gypsiferous rocks, and, because gypsum is so soluble in water anyway, the total effect in terms of actual amount of rock dissolved may be large. It should be noted that Forti and Rabbi's calculations apply to the general case where calcite is present in solution, whatever its source, so their belief that there was no direct source of calcite in their study area need not be correct for mixing corrosion effects to be present.

Limestone beds and calcareous shales are present in the Maritimes gypsum, and accordingly it is assumed that dissolved calcite will usually, if not always, be present. The pH of standing or slowly moving water within a number of Nova Scotia caves has been measured by the author and is in the range pH 7.3-7.8, with one anomalous sample of pH 6.5 in a standing pool containing decomposing vegetation from flooding. The norm appears to be pH 7.6. From Forti and Rabbi's Figure 8, it will be apparent that this range is sufficient to create substantial increases in gypsum solubility by mixing corrosion.

Phase equilibrium systems with more than the three components of carbonate karsts were termed 'hyperkarstic' in Cigna's classification.

No evidence of the calcite deposition reported by Forti and Rabbi has been found in any gypsum cave here. Forti and Rabbi distinguished two major types of physico-chemical conditions in their study area: in only one there is deposition of calcite sinter. The pH of the water in this type was found to be in the range 7.8-8.2. Where the pH was 7.0-7.4, it was unsaturated with respect to calcite and no sinter deposits were formed. The pH of water within Nova Scotia caves (see above) places the caves in the non-calcite depositing environment, and thus agrees with the observed absence of calcite sinter deposition.

CONCLUSION

The traditional view is that gypsum caves are essentially similar to limestone caves. This view is exemplified by Ford and Ewers (1978) who state "*There are extensive karst caves in other soluble rocks such as gypsum but these tend only to reproduce some of the morphological features of limestone caves with few additional significant features peculiar to themselves.*"

In contrast Forti and Rabbi concluded that if gypsum speleogenesis is indeed a hyperkarstic phenomenon then the genetic mechanisms could be quite complicated and they stated that in gypsum caves it is still possible to see morphologies and formations not well known or not yet completely explained.

It is apparent that whether gypsum speleogenesis is a parakarstic (unlikely) or a hyperkarstic phenomenon, it cannot be a three component 'karstic' phenomenon, and hence involves physico-chemical processes which differ in type from those taking place in limestone karsts. Whilst we yet know little about what such processes may be, extraordinary caves such as The Honeycombs lend support to the belief that something unusual is involved.

Almost all of the literature relevant to the dissolution of gypsum and speleogenesis of gypsum caves is essentially theoretical, and there is a serious lack of direct field data. It is somewhat surprising how few measurements have been made of the actual rate of gypsum dissolution in nature (see Appendix). I believe that progress towards the understanding of gypsum karst processes now depends upon fieldwork: basic studies of dissolution rates and chemical analyses of karst waters being the most obvious.

Great care will however be required in future research aimed at identifying and understanding which are the unique phenomena in the process of gypsum speleogenesis. A clear minded look at the morphological features in the Maritimes gypsum caves can only result in an admission that most of them differ merely in degree, not in kind, from those of limestone caves and, in the absence of detailed studies of the actual physico-chemical processes involved, the most reasonable causal explanation of those differences that have been observed is the much greater solubility of gypsum. Laughöhlen, long thought to be restricted to gypsum, are now recognised in limestone caves, and cockpit karst, previously considered to be a feature of tropical limestones, develops on gypsum in the cold-temperate conditions of Maritime Canada. Gypsum girlandengang suggest that mixing corrosion, similar to that in limestones, is also important in sulphates.

Gypsum karst processes are important not only from a purely scientific point of view but also practically because subsidence is a serious engineering problem where gypsum-anhydrite underlies built-up areas (see Cooper, 1995, for a discussion and review of this problem).

Despite the small size of the caves in the region, the extent, accessibility and variety of both surface and underground karstic phenomena in the Maritimes makes the region one of the most important areas for the investigation of gypsum karsts, and it must be considered to be of international importance. Unfortunately, there is a conservation crisis with the most scientifically unique and important caves having been destroyed by gypsum quarrying during the last twenty years. Whilst there are many sites where surface karst features can be studied, the importance of protecting the remaining caves cannot be overemphasised.

ACKNOWLEDGEMENTS

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APPENDIX: GYPSUM DISSOLUTION RATES

Gypsum is much more soluble than limestone in water. In distilled water under laboratory conditions at 10°C the solubility of $CaSO_4.2H_2O$ is 2.438 $g.l^{-1}$ compared with 13 $mg.l^{-1}$ for limestone (James, 1992). Solubility is affected by the presence of other ions that are frequently present in groundwaters which have passed through evaporite sequences. Sodium chloride is present in many gypsiferous groundwaters (James, 1992, p. 48) and the solubility of gypsum is much higher in saline water than freshwater (Pfeiffer and Hahn, 1972, p.197 report that a 3.5% solution of sodium chloride will dissolve 6.4 $g.l^{-1}$ of gypsum at 21°C). This may be particularly important in Nova Scotia where gypsum beds are exposed along several tidal rivers discharging into the Bay of Fundy. The literature on the effect of chloride and other common ions on the solubility of gypsum was recently reviewed by James (1992, Chapter 2) who also (Chapter 3) reviews dissolution rates and kinetics. Literature on the system gypsum-calcite-water has been discussed in the body of the present paper.

Several measurements of the actual dissolution rate of gypsum under natural conditions have been made in surface waters. Gypsum stones weighing 4 to 7 kg. on the beds of water courses in Colorado, USA, lost 0.10-0.15% per hour of their weight on exposure to flowing water (Haider et al., 1974). A gypsum block approximating a 3m square cube was dissolved in 18 months in the River Ure, Ripon, England (James et al, 1981). In Spain, rocks machined into spheres approximately 5kg in weight lost 0.10-0.50% per hour when suspended in flowing water courses (Navas, 1990). Cooper (1995) points out that these rates are in agreement both with laboratory determinations and with observations of the rate of undercutting of a gypsum cliff face on the River Ure. They imply gypsum dissolution rates of perhaps 0.5 to 1m of rock per annum where gypsum faces are exposed to freely flowing water under favourable conditions. No measurements have been made of dissolution rates of gypsum in Maritime Canada.

Information on gypsum dissolution rates within the cave environment is almost non-existent. Kempe et al (1975) published calculated dissolution rates of gypsum under phreatic conditions in South Harz caves that correspond to a retreat of rock surfaces of 5-6cm per annum. They commented that this value seemed too large for real conditions, but in comparison with the surface measurements given above, the figure is not unreasonable, and it shows the potential for very rapid cave formation in gypsum. There are no data on the actual rate of dissolution in gypsum caves.

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Why some caves become famous - Wookey Hole, England

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Abstract: When a visit to Wookey Hole took place in 1480, it was already known. Almost certainly this was the cave regarded, about 1135 AD, as one of the wonders of Britain. Influential descriptions of Britain, such as Camden's book of 1586, made more people aware of it. There were visits by scientists from the mainland of Europe as well as the English, and theories for the formation of speleothems were developed from observations made there. How was it that this relatively small and unspectacular cave became so well known so early? It is argued that this arose because of its closeness to the ancient road through the city of Wells.

INTRODUCTION

In the 20th century, with modern communications and easy travel, the caves that become famous are those that are specially attractive, reasonably accessible and well publicised. In earlier times several caves with less intrinsic interest or attraction became well known throughout the world. The small cave in the Aegean island of Antiparos was one of these from the 17th century onwards, and Wookey Hole was another, from a much earlier period. How did this come about?

Wookey Hole, 25km south of Bristol in south-west England, was only about 210m long until new extensions were found in recent years. The main chambers are quite spacious (up to 24m high) and the underground River Axe (789 l/sec) flows through the cave.

The strange thing is that it is not a visually exciting cave and apparently never has been. It contains few speleothems but the modern visitor appreciates it because of its prehistory and folklore and the way in which passages discovered by cave divers are skilfully presented. In earlier times the cave was a 'curiosity' and limited opportunities to see other caves made it seem perhaps more curious than it was. Even now the silence, the stillness and the underground river give it an air of mystery. Certainly it has been described regularly by visitors for many centuries, people from mainland Europe came to see it, and its speleothems were discussed in learned journals.

This paper explores the pattern of these visits and discusses some of the more significant descriptions. It then suggests possible reasons for the cave's long-lasting popularity.

Wookey Hole has been known under many variant names - Wokey, Ookey, Okey, Ochy and Ochie Hole - all derived from the Celtic word 'ogo' meaning a hole, still current in Wales as the Welsh word 'ogof' for cave.

PREHISTORIC OCCUPATION

The entrance passage was inhabited in the Iron Age and the Roman period, from about 100 BC up to the 4th century AD. Coins of Valentinian (364 - 373 AD) are the latest found there. Burials took place deep in the cave for some time before about 275 AD (Balch, 1914; Hawkes et al, 1979). Items from the excavations are in the museum at Wells.

PROBABLY WOOKEY HOLE

A Latin manuscript of about 1135 AD, translated below, describes a cave with an underground river, which it calls Chedder-hole:

> *"There are four things in England which are very remarkable ... The third is at Chedder-hole, where there is a cavern which many persons have entered, and have traversed a great distance under ground, crossing subterraneous streams, without finding any end of the cavern."*
> (Henry of Huntingdon, edition of 1853)

As the nearby town of Cheddar does have some caves and there are karst springs there, it is commonly assumed that Chedder-hole was there and has since become lost. The problem is that no cave even remotely resembling the one described was ever recorded at Cheddar, and where cave divers have reached the underground river there they have found it running only in narrow fissures.

However, in documents between about 1120 and 1260 the names 'Chederhol' and 'Ceddre Hole' apply to the town itself, which is close to the deep steep-sided valley now called Cheddar Gorge. The word 'hol' or 'hole' used to mean "a hollow, a valley" or "running in a deep hollow" (Smith, 1956) so the name Chedder-hole was just as applicable to the Gorge as to a cave. The index in the 1495 edition of Higden's *Policronicon* gives Wokihole as a synonym for Chedderhole.

The cave of Wookey Hole contains the requisite river and is only 8km away from Cheddar. It is most likely that the two names were confused in the manuscript, all too easy to do if the information came from hearsay and travellers' tales (Shaw, 1972, p.107).

To justify mention in Henry of Huntingdon's *Chronicle*, this grouping of four remarkable things or Wonders must have already existed before his time, either recounted verbally or in an earlier manuscript now lost. Chedder-hole remained one of the group of up to 37 Mirabilia or Wonders of Britain (Fig. 1) listed in many mediaeval manuscripts (Shaw, 1972, 207-209). It was again the third of four wonders in Higden's *Policronicon*. The English translation of this made in 1387 by John Trevisa was

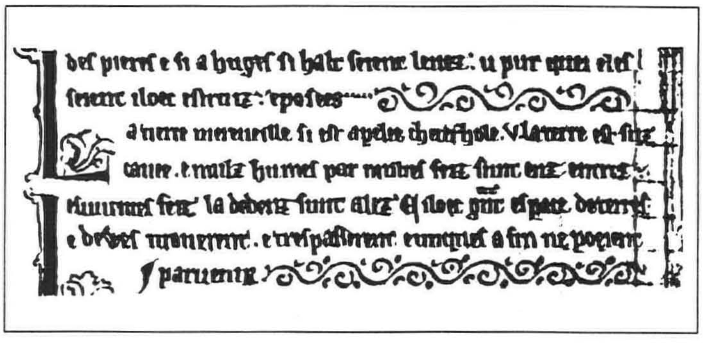


Figure 1. Chederhole listed as the third Wonder of Britain in a Norman French manuscript from the time of King John (1199-1216). British Library Additional MS.14252, f.103b, reproduced by courtesy of the Trustees.

published in 1480 by Caxton and was one of the first books to be printed in England. Later it appeared, still as the third wonder, in Holinshed's *Chronicles* in 1577 and subsequent editions. So the presence of this cave in Somerset was continuously publicised for some 500 years.

It has been supposed also, by Balch (1914) and Boon (1976), that a reference by Clement of Alexandria about 200 AD to a cave in Britain *"lying below a mountain, ... [where] the sound of cymbals clashing ... is heard"* is about Wookey Hole. This is argued on the grounds that similar noises have been heard there, but there is no evidence to support the identification.

WOOKEY HOLE IN 1480

William of Worcester, born in 1415, made journeys totalling 1300km on horseback in 1478, 1479 and 1480. He visited Wookey Hole in 1480 and wrote quite a detailed description of it:

> *"Wokey hole is half a mile from Wells and within the parish, it is a certain narrow entry where to begin with is the image of a man called the Porter. One must ask leave from the Porter, to enter the hall of Wookey, and the people carry with them sheaves of reed sedge to light the hall. It is as big as Westminster Hall and stalactites hang from the vault which is wondrously arched over with stone.*
>
> *The passage through which one enters the hall from the gate is about half a furlong in length, by [my] reckoning, and arched over, with stalactites hanging from a smooth surface above. Between the passage and the hall is a broad lake crossed by 500 stone steps; each step is about 4 feet, and if a man goes off the steps he falls into the water which is 5 or 6 feet deep on every side.*
>
> *The Kitchin before the entry to the hall is covered with a vault of stones whose span is beyond estimation; and there is an office called in English an oast, for drying barley corn to make ale and other things, and in it the figure of a woman clothed and spinning with a distaff held beneath her girdle.*
>
> *Thence they cross another alleyway about a hundred paces long, and a man may cross dryshod quite easily upon stepping-stones.*
>
> *Next comes the room called the Parlour, a round house built of great rocks, about 20 paces across; on the north side of the said parlour is what is called in English a (?holy) hole. This well, which is beautifully arched over, is full of water, and none can tell how deep this water is."*
>
> (William of Worcester, edition of 1969)

The "figure of a woman" will be referred to again in connection with the legend of the witch.

1577 - 1612

As William of Worcester's manuscript diary remained unpublished until 1778, it did not contribute to knowledge at the time.

About a hundred years after his visit, however, a series of printed books made people aware of the cave's existence. Harrison (1577) in a contribution to the widely read Holinshed's *Chronicles*, states that *"the second [river] Axe issueth out of Owky hole ..."*.

Then came William Camden whose *Britannia*, first published in 1586, was a detailed topographical survey of the British Isles:

> *"Among these [Mendippe] hills there is a cave or denne farre within the ground, wherein are to be seene certaine pits and riverets, the place they call* Ochie-hole, *whereof the Inhabitants feine no fewer tales, nor devise less dotages, than the Italians did of the Sibyl's Cave ... The name (no doubt) grew of* Ogo, *a British word, that betokeneth a* Den.*"*
>
> (Camden, 1610)

Seven Latin editions had appeared by the time the first English translation was published in 1610, and by 1700 there had been 14 editions in all. As this implies, the book was popular and the Latin editions made it widely read in Europe where information from it appeared in many descriptive books such as Becmann's *Historia orbis terrarum* of 1673.

Whilst Camden's book served principally to spread knowledge of Wookey Hole more widely, its inclusion is an indication that it was already well known. In the same way that in 1135 'Chedder-hole' was regarded as one of the four Wonders of Britain, it seems to have had its own moderate fame before the printed accounts. Once *Britannia* had appeared, knowledge of the cave could never again be dependent only on word of mouth and the book was undoubtedly the direct or indirect cause of many people learning of its existence. And, as will be seen from the number of travellers' reports in the next hundred years, a great many did come to see it.

Not long after Camden's book was first issued, and only two years after it appeared in English, the cave was the subject of a poetical description in Drayton's long topographical poem *Poly-Olbion* (1612). Again, it seems the cave was notable enough, or 'curious' enough, to attract such treatment.

Maps too, then as now, not only provided information but they showed only the information considered to be important or interesting enough. The entrance of Wookey Hole was marked on the county map of Christopher Saxton, first published in 1577 but prepared and engraved two years earlier. This was reproduced at a smaller scale in the 1607 and later editions of *Britannia*. John Speed's popular map of 1610 also showed the cave.

TOURIST VISITORS 1634 TO 1698

Camden's *Britannia* was in effect the first guide book for tourists. Later editions were updated and major revisions were made for more than 100 years. Other such 'guides', such as that by Leigh (1659), appeared throughout the century. Of less importance than *Britannia*, they nevertheless demonstrated that there was a demand for such books. It was the printed books and maps that enabled those at a distance to hear about the cave.

A visit by three Englishmen from Norwich in 1634 was described in detail, but the account remained in manuscript (Hammond, 1634) until 1834. Again, Celia Fiennes's visit in 1698 was not published until 1888.

Of more significance is the fact that foreign visitors came to see the cave. Lodewijck Huygens, the younger brother of Christiaan Huygens the Dutch physicist and astronomer, visited it on 9 May 1652, saying that it was considered one of the seven wonders of England (Huygens, 1982). Then in April 1691 two Danish men at Oxford, Seerup and Hemmer, *"had a great desire to see Ochie hole ..."* and went into it with the naturalist Edward Lhwyd (Gunther, 1945).

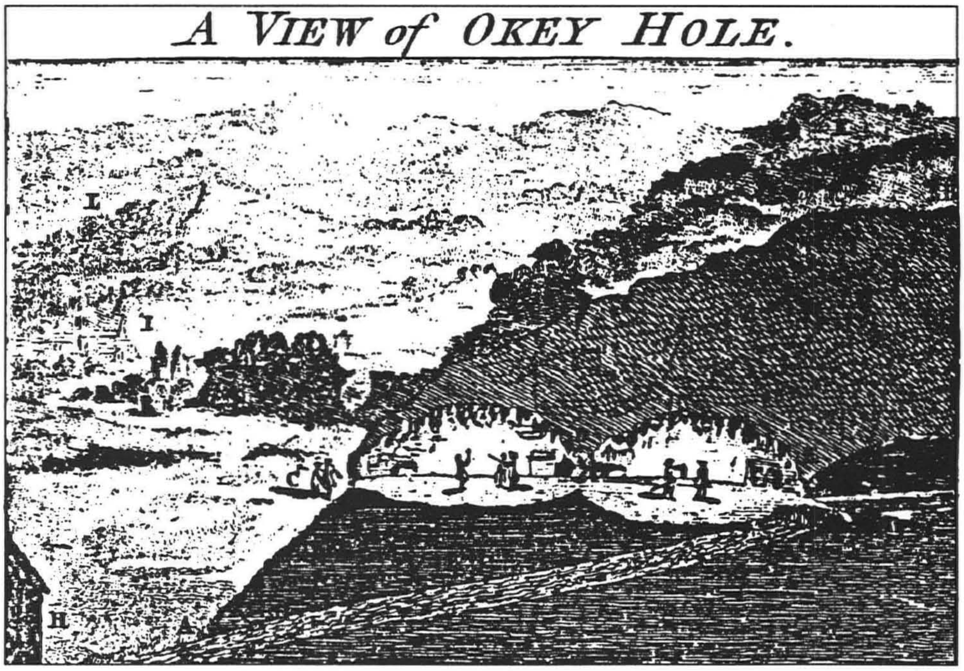


Figure 2. The first published picture of Wookey Hole, from Martin (1759).

OLUF BORCH AND SPELEOTHEM FORMATION IN 1663

Already, in 1635, Archdeacon Hakewill had used the fact that Wookey Hole contained growing flowstone as evidence that the world was not universally decaying as it grew older, as some theologians argued from the fact that weathering destroyed stone.

Oluf Borch (1626-1690) was a distinguished Danish scholar, physician and scientist. He came to England in 1663 and on 21 July he went into Wookey Hole. The speleothems, formed from dripping water, interested him particularly when he found that local villagers, drinking the same water, did not suffer from gall stones more than other people. He developed his ideas (Borch, 1667,1680) and concluded that speleothems were formed, not from impurities in the cave water, but from the fact that it remained still for so long that the water particles combined together and so became solid (Shaw, 1987).

THE ROYAL SOCIETY 1681

Once the Royal Society of London and similar learned societies in Germany, Italy and France had been founded in the 1650s and 60s and started publishing their papers from 1665, scientific information spread more easily over Europe. Thus the *Philosophical Transactions* of the Royal Society appeared in Latin, French, German, Italian and Dutch, as well as English, for many years, and were also summarised in several abridgements.

In 1681 the Royal Society published a description of Wookey Hole by John Beaumont, who discussed three alternative explanations of speleothem growth. Thus knowledge of the cave was spread abroad in another way, reaching those who might not read regional descriptions and travel diaries.

THE LEGEND OF THE WITCH

The Witch of Wookey, or rather the stalagmite whose silhouette resembles an old woman, is still pointed out to tourists today. According to legend, a witch living in the cave used to harm local people and their crops, and was finally turned to stone by a priest.

Celia Fiennes (1947) visiting the cave in 1698, said that this stalagmite was already called the witch then. Brome's (1694) account refers to an "old witch" of alabaster, and the Huygens (1982) diary of 1652 states that the cave is called "hole of the Witch of Oky". Earlier still, William of Worcester in 1480 had referred to "figura mulieris" (the figure of a woman).

So the supposed resemblance of a conspicuous stalagmite to a witch, or at least a woman, was recognised more than 500 years ago. The legend of the old woman living in the cave may have grown up to explain the image.

But there is another explanation. Excavations between 1908 and 1912 (Balch, 1914) revealed the remains of a human skeleton, an earthenware bowl, knives, a coarse comb, a rough calcite sphere and the bones of two goats. The human skeleton is almost certainly female, and it and the associated objects are early mediaeval, perhaps 10th or 11th century. Thus a woman evidently lived in the cave with the goats and it would not be strange if the local people regarded her as a witch.

It is tempting, and reasonable, to think that folk memory of this solitary goatherd, or rather of a supposed witch living in such a mysterious place, may have persisted for the four or five centuries until William of Worcester saw "the figure of a woman". But there is no evidence that this was so.

1700 - 1800

Individual travellers continued to visit Wookey Hole throughout the 18th century, adding nothing to our knowledge of the cave but showing that it was still an object of interest.

It was notable that two Swedes went there. The first of these was Angerstein (1753-54) on January 31 or early in February 1754. Then in 1760 Bengt Ferner (1987), who came to the area to study mining, visited the cave on February 2, noting that *"there are salmon in the water in the cave"*.

One of the many books to mention Wookey Hole about this time was that of Benjamin Martin (1759), noted for containing a pictorial sectional view through the cave (Fig. 2), the first picture of it to be published. The cave was, he said, *"much resorted to by Strangers"*.

Towards the end of the century several lengthy accounts of the cave were written, including those by Shaw (1789) and Maton (1797) in their descriptions of their travels. This kind of book being popular at the time

Figure 3. Just inside the entrance of Wookey Hole. Drawn by Bernard Lens III in 1719. Reproduced by courtesy of Mr. Andrew Clayton-Payne.

it would have brought knowledge of the cave to more people in the next century. The earlier classics such as Camden were no longer read so the more recent books of tours, supplemented, and in some cases provided information for, regional or national reference books such as the six-volume one by Cruttwell (1801).

By the middle of the following century organised tourism was beginning and consequently guide books as we know them started to appear. Before dealing with all that, though, another aspect of Wookey Hole in the 18th century needs to be addressed - pictures.

PAINTINGS AND DRAWINGS, 1719, 1786 AND 1794

At least 14 drawings and paintings were made of Wookey Hole, the interior as well as the entrance, during the 18th century. It might be supposed that they helped to make the cave well known, but in fact all of them remained in private hands for a long while. Consequently, with one exception, they are little known and have never been described in the karst literature.

First come ten ink and wash drawings made in 1719 by Bernard Lens III (1682 - 1740). The artist's dates are important as he was one of four of the same names, all of whom made topographical drawings in similar style. This series of pictures includes eight of the interior and two of these are printed here (Figs. 3 and 4). One of the two pictures of the entrance was reproduced by Williams (1952) and the other by Mallalieu (1979).

Samuel Heronymus Grimm (1734-1794) produced two ink and wash drawings of the cave entrance on 9 May 1786.

Better known, because it is in the Victoria and Albert Museum in London and has been frequently reproduced in books, is Michael Angelo Rooker's 1794 watercolour. This shows the stream emerging from the cave at the foot of an ivy-covered cliff. A good colour reproduction occurs in some of the cave guide books and leaflets, and in Conner (1984). What is probably the original pencil sketch for it, dated 25 October 1794, is in a private collection.

THE BEGINNING OF TOURISM

If tourism is defined as organised touring, or touring by more than a small number of individuals, it started in the 19th century when easier means of travelling, and particularly the railway, enabled more people to visit more places of interest. This, in turn, brought about advertising and guide books.

Perhaps an earlier version of popular, though local, visits by groups of people was the practice reported by Brome (1694) of men and women dancing and drinking in the cave - precursor of the Grottenfest that took place every year in Postojnska jama from 1830 or before.

Wookey Hole was prominent in the guide books published for Wells (Green 1849 and later editions) and Cheddar (Stevens, 1869). It is noticeable, too, that the Swan Hotel in Wells issued a guide book in 1875, with several pages on the cave. It ran to three editions.

The earliest advertisement traced is a printed one of 1868 (Fig. 5) which stated that visitors should apply to a Mr. Richard Bricknell at the nearby Bubwith's Farm, *"from whence a Guide with the necessary Lights will*

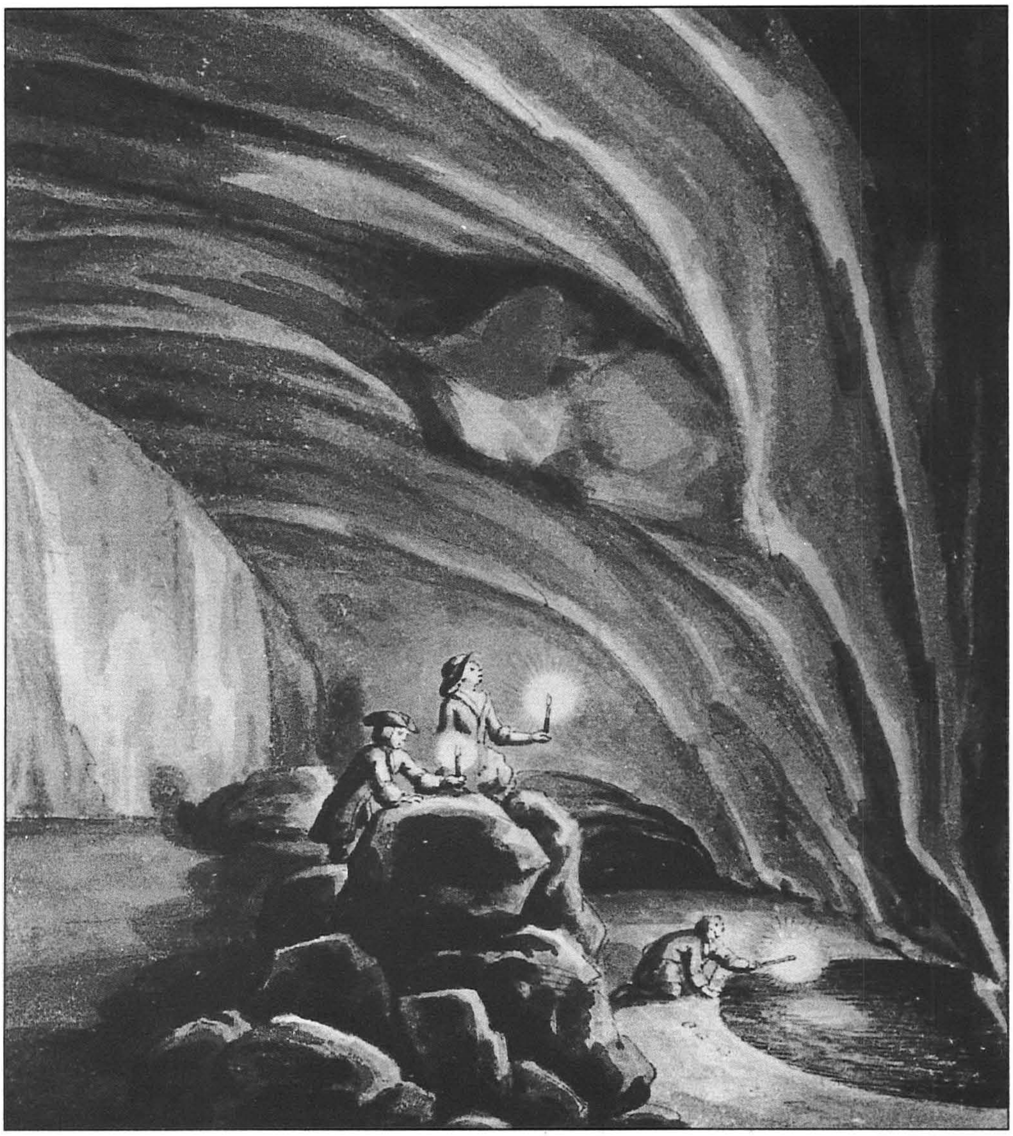


Figure 4. "The furthermost view within Ochie hole. To show the moving of the water they drop y^e Candle in it". Drawn by Bernard Lens III in 1719 and reproduced by courtesy of Mr. Andrew Clayton-Payne.

accompany visitors through the Cavern". A later advertisement (Fig. 6) appeared in the *Wells Journal* newspaper from 1895 to about 1910 and a similar one was issued as a small poster. By this time the farm offered refreshments as well as providing a guide, and there were "Special Terms for large Parties". Candles were carried and the large chambers were illuminated by pouring kerosene on the walls and the water and setting fire to it.

RECENT TOURISM AND CAVE DIVING

For many years the owners had not wished to develop the cave commercially and risk spoiling the quiet village with tourism. In 1925 Gerard Hodgkinson inherited the cave and had other ideas. He had paths constructed in the cave, laid out the grounds and built a restaurant. In 1927 the cave was reopened, still with emphasis on preserving the natural surroundings, and one advertisement reads *"This resort is not vulgarised by blatant modern buildings or spoiled by touts or other annoyances"* (Anon., 1935) - a clear reference to the tourist caves at Cheddar 8km away.

Cave diving, begun with copper helmets in the spacious underground river in 1935, has by now discovered 21 upstream chambers beyond those naturally accessible. Tunnelling in the 1970s brought several of these new chambers into the tourist route.

This tunnelling, and the creation of a separate exit for tours, was one of the first actions of the new owners (Madame Tussaud's, of waxworks fame) in 1972. A cave museum of high quality was also set up.

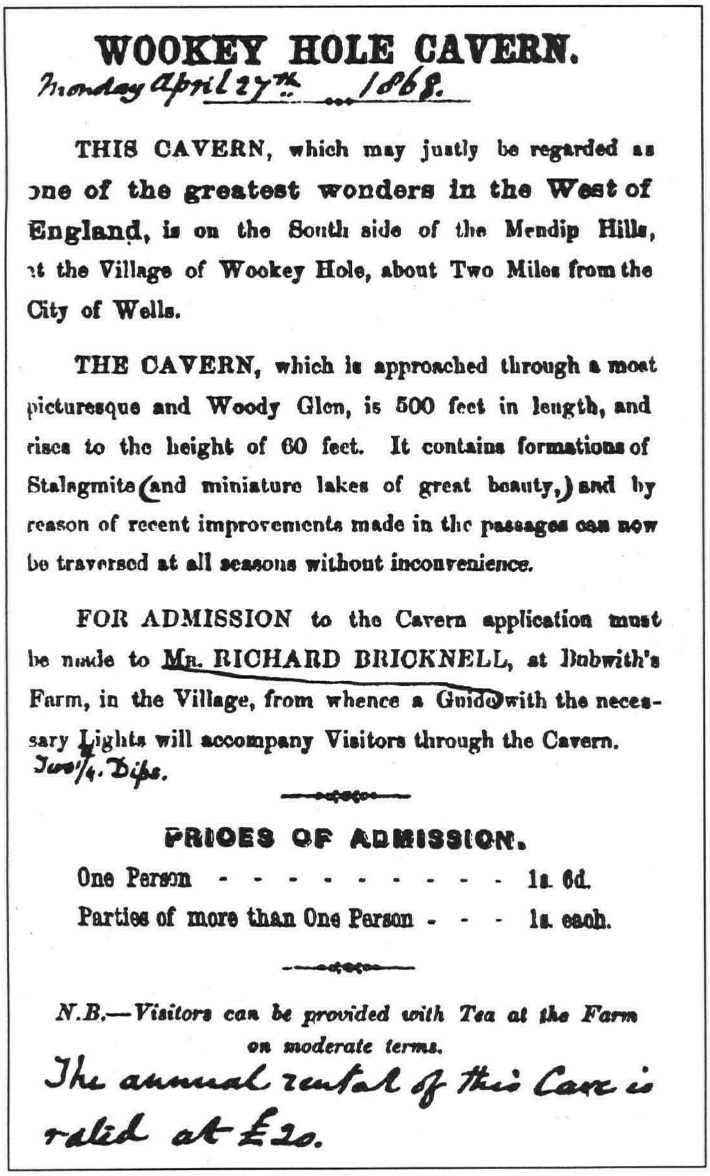
In 1989 the cave was sold by Tussaud's to their own managers, who have continued successfully to develop the place while retaining the mystery and dignity of the cave.

HOW DID WOOKEY HOLE BECOME FAMOUS?

Whenever Wookey Hole was described it seemed to be already well known. Brome (1700) wrote *"as Italy has Virgil's Grotto, and the Sybil's cave by Puteoli, so England hath Ochy-Hole by Wells"*. At that time its fame could be traced to reports from the previous century, to internationally read scientific papers, and to national descriptions or gazetteers such as Camden's *Britannia.*

But how is it that it was already considered important enough to be included in Camden's first edition of 1586 and named on Saxton's 1577 map? No doubt much of the data for these publications was derived locally, but even then it must have been recognised as worth recording. If the Chedder-hole of Henry of Huntingdon is accepted as being Wookey Hole, the question remains the same; how was it that the cave was already well enough known to be regarded as one of the Wonders of Britain?

In the early centuries, before printed books existed and with a small population, the existence of the cave as a wonder would have been spread verbally between travellers. The fact that Wookey Hole is only 3km from the city of Wells, itself at a junction of old roads, makes this all the more feasible. Wells was already old in 704 AD when a collegiate church was built there, and in 905 or 909 it became a cathedral city. The road to the even more ancient town of Glastonbury passed through it. Roads were


WOOKEY HOLE CAVERN.

Monday April 27th 1868.

THIS CAVERN, which may justly be regarded as one of the greatest wonders in the West of England, is on the South side of the Mendip Hills, at the Village of Wookey Hole, about Two Miles from the City of Wells.

THE CAVERN, which is approached through a most picturesque and Woody Glen, is 500 feet in length, and rises to the height of 60 feet. It contains formations of Stalagmite (and miniature lakes of great beauty,) and by reason of recent improvements made in the passages can now be traversed at all seasons without inconvenience.

FOR ADMISSION to the Cavern application must be made to MR. RICHARD BRICKNELL, at Dubwith's Farm, in the Village, from whence a Guide with the necessary Lights will accompany Visitors through the Cavern.

Two/4. Dips.

PRICES OF ADMISSION.

One Person - - - - - - - - - - -	1s. 6d.
Parties of more than One Person - - -	1s. each.

N.B.—Visitors can be provided with Tea at the Farm on moderate terms.

The annual rental of this Cave is rated at £20.

Figure 5. The earliest known advertisement for Wookey Hole, in use in 1868.

not shown on maps before the 17th century so it is not easy to confirm that the road through Wells was used much.

But Aston (1985) has shown that King John (who reigned from 1199 to 1216) passed through Wells more than five times on his journeyings through his kingdom. King Edward I (1272-1307) also came there. William of Worcester passed through Wells twice in 1478 and twice in 1480, and the city was on the route of John Leland the antiquary twice about 1540 (Bates, 1888). So the route clearly was important from early times; it would have been the cause of many people passing quite close to Wookey Hole and often stopping for the night at Wells where they might hear of the cave as a local wonder.

Thus there are many parallels between Wookey Hole near the route through Wells and the seasonal karst lake at Cerknica in Slovenia, which became known to travellers on the ancient trade route from the Adriatic to Central Europe.

Indeed the parallel between the two is quite close. Both were known to travellers, mentioned in printed books before 1600 and shown on maps at the same time; both were described in poems (in the 75 years from 1537); and both attracted scientific attention and were discussed in the publications of the Royal Society. Neither was spectacular but both were sufficiently remarkable to excite wonder.

When fewer caves were known and even fewer were conveniently close to cities and main roads it is perhaps not surprising, after all, that a cave with large chambers, some stalagmites and a mysterious river was sufficient to impress those who went there. The legend of the witch, too, which was already flourishing by the 1650s, would have added to the sense of mystery.

ACKNOWLEDGEMENTS

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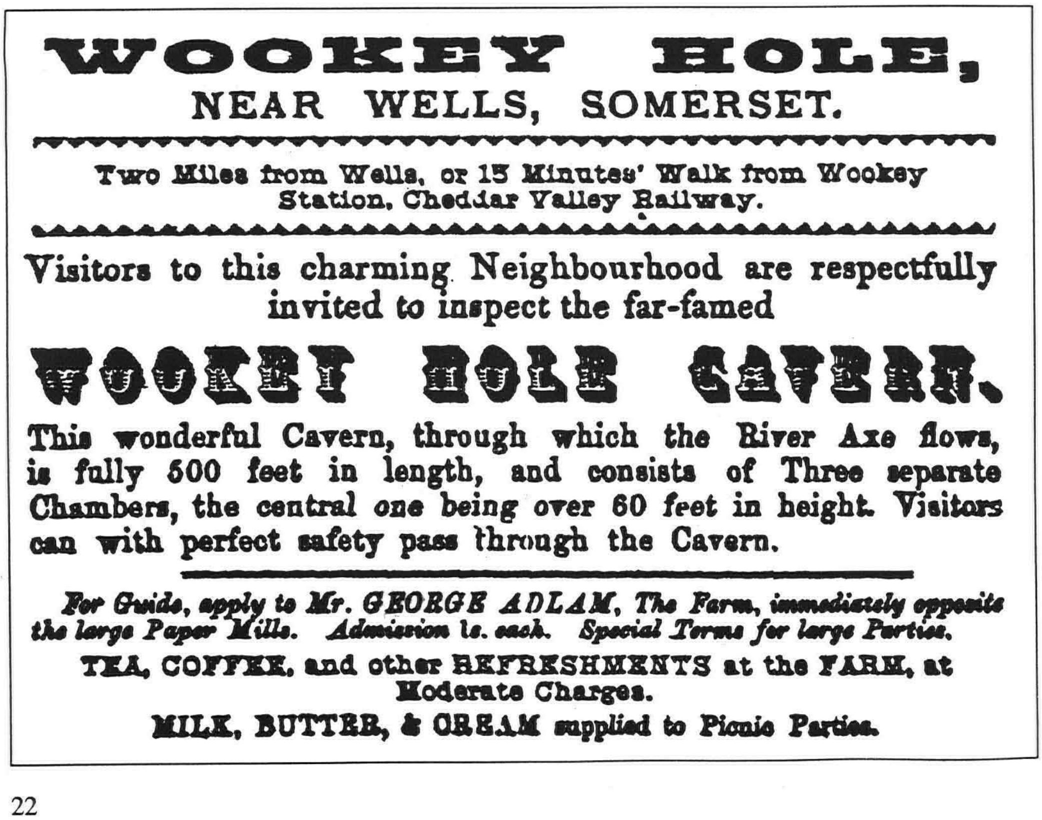
WOOKEY HOLE,

NEAR WELLS, SOMERSET.

Two Miles from Wells, or 15 Minutes' Walk from Wookey Station, Cheddar Valley Railway.

Visitors to this charming Neighbourhood are respectfully invited to inspect the far-famed

WOOKEY HOLE CAVERN.

This wonderful Cavern, through which the River Axe flows, is fully 500 feet in length, and consists of Three separate Chambers, the central one being over 60 feet in height. Visitors can with perfect safety pass through the Cavern.

For Guide, apply to Mr. GEORGE ADLAM, The Farm, immediately opposite the large Paper Mills. Admission 1s. each. Special Terms for large Parties.

TEA, COFFEE, and other REFRESHMENTS at the FARM, at Moderate Charges.

MILK, BUTTER, & CREAM supplied to Picnic Parties.

Figure 6. The advertisement used from 1890 to about 1910.

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The Pure Karst Model

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Abstract: The view is presented that karst is a self-contained geomorphic system, its origin relying primarily upon general physical laws, and that only those properties that would be realizable on a completely limestone globe are acceptable. The model is described in terms of eight basic axiomatic statements. True karst relief, conditioned by a completely developed and fully functioning unsaturated zone, appears only when all eight conditions are fulfilled. The conditions are, to a large extent, hierarchical and, from the viewpoint of the model, lack of fulfilment of some lower conditions mitigates against fulfilment of some higher ones. The fundamental elements of the karst surface are centrically organized depressions and elevations. Climatic variations may bring about different superficial appearances, but the inherent centricity remains.

STARTING IDEAS AND PROBLEMS

Few natural phenomena are as widespread, so well studied and yet so poorly understood as karst. The level of current understanding is indicated clearly by a quote from Renault (1977, p. 34):

> *"The karst concept reflects an intuitive idea that has been the driving force behind the first explorations and qualitative theories. It now only provides support, of essentially historical interest, for another, far larger and dynamic concept. There are still many obstacles to its development, ... , but the normal progress of research must produce a unified concept of karst phenomena"* [1].

Renault (1977) also points out that several types of definition - geomorphological, speleological, geological, sedimentological, hydrological and so on - are in use. Each of these is adequate within its own context. Confusion becomes unavoidable if trying to consider several definitions at once, either due to the complexity of the karst itself or simply due to historical inertia.

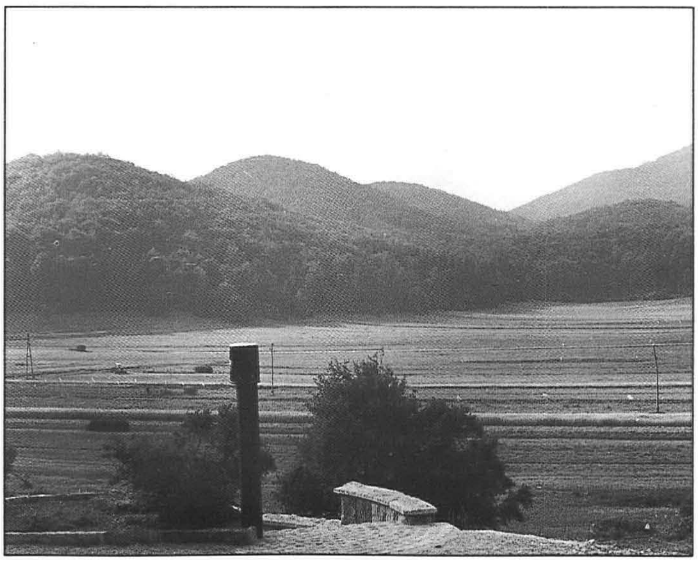
Different interpretations of karst morphology probably reflect projections of ideas from different geomorphological schools into the informational space relating to the karst. Among a half dozen main streams of geomorphological thinking, only ideas related to cycles and to climate seem to have been grasped readily by karstologists. The former view interprets karst relief as a specific set of degenerate fluvial landforms. The latter view is of a specific set of climate-related landforms. The view presented here is that karst is a typical landform assemblage, within which individual landforms are also typical. Karst is regarded as a self-contained geomorphic system, its origin relying primarily upon general physical laws.

In creating ideas about karst geomorphology the backgrounds and opinions of outward looking observers have prevailed. For instance, preconceptions about the norms of relief were inevitable. Applying existing knowledge to the karst, observers intuitively measured the degree of karstification against their existing standards acquired in areas of fluvio-denudational relief. Many modern studies concentrated upon the most spectacular or most readily observable landforms. Phenomena possibly essential to the self-sufficient geomorphic category of karst relief were neglected, or even ignored (Renault, 1977).

A typical example is the relatively great interest paid to karst depressions. Great effort has been invested in their study but disproportionately little noteworthy information has been acquired. In areas of normal fluvial relief a closed depression is exceptional and worthy of separate study, but there is no reason to believe that this is also true in karst areas. More importantly, until relationships between depressions and upstanding facets of karst relief are clarified, the position *"in a karst depression"* is just a topographical qualifier, without geomorphological significance. In contrast to the many studies of karst depressions, karst hills in areas of temperate climate have been neglected, or interpreted in non-karstic ways.

An observer whose work is inwardly directed and totally involved in studying karst is not interested in differences between karst and other relief types. Ideally such differences are not even recognised, and there is no preconception or awareness of possible external *"norms"*. The inward looking worker's intention is simply to explain the geomorphic system on the basis of its own internal logic and, by using general physical laws, treat it as an autonomous and self-sufficient natural mechanism. At the logical limit of this approach, such a worker would be concerned with the relief that would evolve if the entire surface of the globe was made of limestone. Different combinations of physical effects do not prove to be specific (karstic in this case) until they are compared with geomorphic categories lying outside the immediate sphere of interest.

What follows is an attempt to deduce the nature of the theoretical model of karst that would be deduced by such an inward looking worker, without reliance upon any knowledge of other geomorphic systems, and regardless of whether its entire physical realisation could occur anywhere on earth. All of the theoretical model's properties derive from ideas within present knowledge of the geomorphic processes involved, but only properties realisable on a completely limestone globe are acceptable. Perhaps more realistically, an ideal set of karst relief properties, which would form under optimum circumstances, may be deduced. Much of this work



Karst hills or "cones" in the area of Krizna jama. The "cockpit" in the foreground is filled with periglacial solifluction material.

[1] Translated by P J Molineaux and D J Lowe.

already exists, though achieved from a different direction, by progressive establishment of the means to discriminate karst areas from other types of landscape. Any schoolbook or monograph presents those principles in similar fashion (eg. Sweeting, 1972).

In applying this model to natural karst surfaces, the intention is not to find differences between them and non-karstic geomorphic systems, but to ascertain the degree of agreement between reality and the model. In this situation agreements are as important as disagreements. Practical application of the model Šušteršič,1987) has shown its potential power, particularly for organising several different phenomena, which may intuitively be called karstic but which display incompatible appearances, into a unique system. If other landforms (such as those accommodating to external non-karstic factors) appear, they may be defined specifically as distortions of karst relief. These hybrid forms are not grouped within a special set of non-pure karst phenomena (commonly termed merokarst), but they are related directly to pure karst landforms and, having crossed this bridge, one to another.

It is anticipated that karst is a self-dependent geomorphic system, as is confirmed almost daily in practice in large complexes such as the Dinaric Karst. The theoretical model obtained is an idealised concept, in the same sense that the concept of free fall in an absolute vacuum is idealised. It is referred to as the Pure Karst Model[2] (PKM).

HISTORICAL REMARKS

The Dinaric Karst of the former Yugoslavia has been studied scientifically since the mid seventeenth century, but until the end of the nineteenth century, when Cvijić (1893) published *"Das Karstphänomen"*, the work involved little more than collecting facts. The late nineteenth century was also the time of the first geomorphological syntheses by W M Davis. Since then an underlying conflict has existed between the practical experience of Dinaric Karst researchers and the fundamental geomorphological theories.

When studying the karst of the former Yugoslavia, Cvijić collected much detailed information, but apparently found no key to explaining the general disposition of the karst masses. At this time the new general erosional cycle theories of W M Davis provided a master key, that seemed equally applicable to karst areas. The basic concepts inevitably entered Cvijić's ideas. Apparently he recognised the illogicality of using Davis's theories in this way, and all his later work was an ongoing attempt to find out what was wrong. The widely known *"Cvijić -De Martonne karst cycle"* is just one example of the strenuous efforts made to overcome the illogicalities, invoking an impermeable basement situation that is totally unrealistic in the Dinaric context.

Without reiterating historical detail that was discussed by Roglić (1961), it remains interesting to recognise the underlying presence of cycle concepts in Cvijić's understanding of karst. The most evident indication has already been mentioned - the cycle theory presented an inviting new approach. In contrast the mechanical effects of regional tectonism were too poorly known to provide an alternative explanation of rock mass disposition. However, the ongoing nature of tectonics through time, now known as neotectonics, had been recognised. So, Cvijić was forced to seek an external explanation for the geomorphic phenomena that he observed at all scales, and adopted the only explanation that was available. His field experience did not support non-karstic explanations, but application of the cycle theory made the previous fluvial phase appear obvious. Once the cycle theory was applied many linear phenomena that are definitely not fluvial, but appear visually similar, were explained in this way, and the vicious circle was closed.

By the middle of this century, it became clear that karst is not simply degraded fluvial relief. Though not stated explicitly, it is evident from Roglić's works that he viewed karst primarily as reflecting a self-sufficient natural mechanism. His contact theory of karst planation surface origin is widely recognised as a benchmark work in climatic geomorphology. However, it also includes a valiant attempt to explain the origin of a fundamentally Davisian phenomenon (the fluvial peneplain) by essentially karstic processes, and this was achieved by developing contemporary ideas of climatic geomorphology.

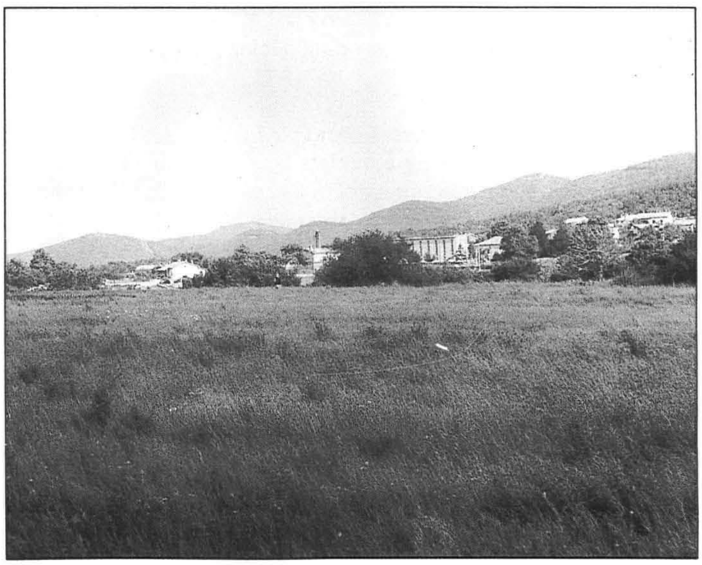
Between 1972 and 1979 staff at the Institute for Karst Research (Postojna, Slovenia) worked on a project to produce a fundamental speleological map of Slovenia. The whole of that part of Slovenia composed of karstic rocks (about 45%) was mapped systematically at the 1:50 000 scale (Habič, 1980). The main interest was in surface and underground karst phenomena.

The basic procedures reflected established rules of geomorphological mapping and made due reference to pre-existing literature about Slovenian karst. Thus, the final map reflects many different notions. The most important of these are the transparently hidden ideas that (a) the general lines of karst relief may be reduced to a few levels (cyclic predestination) and (b) medium-sized phenomena (closed depressions, dry valleys, hums, etc.) are scattered randomly across geomorphological space (climatic notion). Individual map sheets may reasonably be interpreted in this way, but unavoidable difficulties arise in trying to fuse them into a single map.

The interpretation of various smaller scale phenomena as different relics of some overall genetic process becomes suspect on questioning what would happen if the whole globe was limestone. The ideas presented below were developed initially as a purely theoretical attempt to put the experience acquired during the work on the speleological map of Slovenia into a logical frame, until their potential power became apparent. They were applied practically for the first time before the end of the nineteen-seventies, and developed later (Šušteršič, 1982, 1986, 1987b).

UNDERGROUND KARSTIFICATION

This paper considers the development of karst relief, and emphasises that the state of underground karstification is of paramount importance to its shaping. It will be shown that fulfilment of six basic conditions renders feasible the formation of underground karst, whilst eight conditions must be fulfilled to produce a surface karst landscape.



Subdued karst hills or "cones" near Lipica, in the Classical Karst of Trieste.

[2] It is stressed that the term "pure" indicates that the conditions claimed by the model suffice to define a total karst; it does not imply that the proposed conditions are actually completed anywhere in the world.

Underground karst may be viewed as a specialised type of underground water transfer system that evolves towards a tube system. A theoretical well-fractured rock (that includes bedding plane fissures) would start to conduct precipitation water at the instant of its emergence. Due to subsequent effects as water passes through, it would change from a porous to a karstic aquifer. Classically a fully developed underground karst is divided into aerated, vadose and phreatic zones. For the purposes of this paper a slightly different distinction, is more appropriate. Considering only unsaturated and saturated[3] underground karst zones, the former is equivalent to the aerated zone, the latter encompasses the vadose and phreatic zones.

The unsaturated zone transmits surface water to the saturated zone and its pores are water-filled for only part of the time. Water courses in the unsaturated zone range from capillaries to vertical free fall jets. Their main distinguishing property is that their activity relies upon the precipitation cycle, so that the whole water quantity is *"hanging"*. As the water descends it enlarges vertical shafts (Frumkin, 1986). The conduit system in the unsaturated zone ensures that water (and dissolved rock) migrate perpendicularly to the surface, or escape from the two dimensions of the surface to another dimension. Because of the included free fall element, activity at lower levels has no effect at higher levels.

The role of the saturated zone, lying below the unsaturated zone, is more complex. Due to interconnected vessel effects, flow is generally directed to the lowest hydraulic surface point, but in detail its direction is arbitrary, controlled only by hydraulic resistance. The first result of initial void enlargement is the creation of a maze that may subsequently develop into a cave system. According to local circumstances this cave system would be further organised into distinctly separated development levels, with the degree of separation reflecting the local effects of interference between karstic and non-karstic factors. The mere existence of the saturated zone affects the unsaturated zone in practically the same way as the presence of an insoluble basement.

The unsolved problem of erosional base level may be similarly clarified. It is evident that misunderstanding and a too straightforward application have slowed down the development of several segments of the karst science. In fluvial systems the notion of erosional base involves at least three approximately overlapping conceptions. In karst they are always separated. The notion for fluvial systems covers:

- base of denudation
- base of penetration
- base of negative mass transport (incision in subaerial circumstances).

If considering a river for instance, the first one is the level of the banks, the second is the lower limit of the groundwater body associated with the river and the third is the river bed bottom. Differences of these levels are negligible compared to the whole basin dimensions.

Denudation as a relief forming agent is inevitably a sub-aerial process. So, in karst the denudation base is the lower limit of the unsaturated zone. This is of no importance with regard to the other two bases. The transport base is the lowest point reached by active streams transporting dissolved mass. In karst it is usually below the piezometric surface. Even in other geomorphic systems the penetration base is only exceptionally in contact with this surface, but this is of no further importance. In karst, it may be defined as a limit, down to which fresh water has replaced sea water that was trapped in the rock after emergence. During the formation of the karst aquifer, the entire zone above the penetration base might have been involved. However, in accordance with the first Kirchhoff rule, active streams follow and further enlarge only the less resistant passages. All of the rest contain stagnant water, though remaining in contact with the former. If hydraulic conditions change, such passive passages may be instantly reactivated producing very undesirable effects when constructing dams on the karst. Thus, the separation of the denudational base from the other two bases is crucial to the development of karst relief, and to the definition of underground karst.

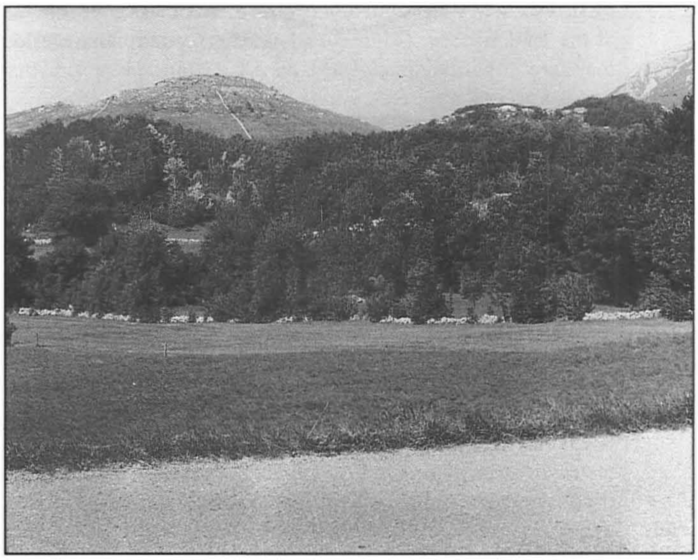
BASIC CONDITIONS FOR KARST RELIEF DEVELOPMENT

Definition of the karst surface

Geomorphology is intended to explain the geometry of a hypothetical surface, referred to as the earth surface, separating the solid mass of the planet from its atmosphere. When the processes that shape the earth surface are active inside the surface itself, geomorphological studies are confined to two topological dimensions. In the case of karst, which is topologically regarded as an essentially three-dimensional category, things become confused. In attempting to interpret the phenomenon of karst on the level of two topological dimensions, and to present the results in two dimensions as a geomorphological map, the abandonment of the third topological dimension brings about a fundamental devaluing of the information. Several karstologists, consciously or unconsciously, have put aside sharp definitions of the karst surface and so avoided this problem.

This discussion treats karst as a three-dimensional phenomenon. However, in principle the concern is with its topologically two-dimensional surface. The shaping of this surface is understood in terms of its roughness (its derivation) and not in terms of the disposition of masses. This understanding is not far from the general comprehension of the word *"relief"*.

Those topologically three-dimensional properties of the karst phenomenon that crucially influence its relief are considered only as their projections. Any components that do not affect the surface, are put aside as of secondary interest. The existence of the unsaturated zone facilitates vertical mass transport perpendicular to the effectively horizontal land surface, and the detailed properties of underground karst are irrelevant. The conditions discussed below are therefore the conditions of existence of the unsaturated zone, and the conditions of karst relief development.



Karst hills or "cones", intermediate relief and flat-floored depression near Otlica, western Slovenia.

[3] The terms "saturated"/ "non-saturated" are not taken in their more usual chemical sense, but taken as meaning that active pores in the parent rock are water-filled.

Basic conditions

The pure karst model is best described in terms of basic axiomatic statements. These depend upon the tenet that karst is a self-sufficient geomorphic system, and reflect the fundamental properties of karst in general, as established by karstologists during the last century of karst research:

a. A rock mass with an initial potential energy must exist;

b. The strength of the parent rock must support the formation of steep slopes and overhangs;

c. The persistence of rock characteristics must be sufficiently great that any lateral changes of properties are remote and hence negligible within the range of observations;

d. The parent rock's solubility must be uniform to the extent that transition of rock from solid to fluid state (dissolution) dominates over other types of weathering;

e. The initial permeability must be uniform throughout the parent rock;

f. Functioning of the system must not be reduced by climatic aridity;

g. The rock mass must be "open" on at least one side to allow development of an unsaturated drainage system;

h. Initial surface slopes must be gentle enough to minimise run-off and thus not prevent precipitation from leaving the surface.

Discussion of the basic conditions

a. Any elevated rock mass contains an amount of potential energy. This is a fundamental condition for any further geomorphic development. If a mass exists that is completely planed to base level, it is featureless and of no further interest to geomorphologists. This important statement has not been clarified well enough in the karst context. It holds true, indirectly, for the present model.

If the underlying rocks of an absolute plain are karstified, transport of material may continue below the surface, just as it would before total planation. However, because the plain is at base level (in its classical geomorphological sense), the saturated zone must be in contact with the surface, preventing the formation of karst relief. If a surface karst pre-exists, its typical forms disappear. The surface becomes featureless after erosion down to the base of denudation, though the erosional base (in the current sense) is not reached. In such conditions hydraulic resistivity in the fully inundated underground karst prevails over superficial resistivity, and water courses become more or less concentrated at the land surface. Consequently, underground karst erosion may slow down, tending towards zero, but it must be stressed that this is a secondary effect, not an inevitable outcome.

b. This condition is not meant to apply to sub-aerial situations, as any rock is strong enough to support some degree of relief. The mechanical strength needed for development of underground channels is much greater, regardless of the type of underground karstification.

A good example is provided by periglacial limestone gravel (Norian and Rhaetian limestone = Dachsteinkalk) in the Ljubljana Basin of west-central Slovenia. In the non-cemented sediment no karst effect has been detected, even though water flowing through it becomes saturated with carbonates. Portions of the same material, barely cemented to produce a relatively unresistant conglomerate, display underground features (shafts and caves), as well as surface karst landforms (sinks and dolines). The gravel's parent rock is nearly pure limestone, and is well known as one of the most karstifiable rocks in Europe.

In contrast, some strong rocks not normally considered karstic, support limited underground water movement. They display supposedly typical karst features (such as collapses and pocket valleys) if they are barely solid enough and do not produce debris that blocks underground channels. Several kinds of sapping, developed in very different rock types (eg. Navajo sandstones and various igneous trap rocks) are good examples.

Conditions a. and b. are general, and they are necessary for any relief to appear in any geomorphic situation.

c. The basic intention of this model is to predict the relief that would develop if the entire globe was composed of limestone, an ideal that is acknowledged as a geological impossibility. However, as no geomorphic system produces forms of infinite dimensions, and trans-environmental effects are limited spatially, it is sufficient to shift observations far enough from the borders to meet the limits of the primary axiom. The demand is three-dimensional, to encompass both the lateral and the vertical extents of the rock mass. There may be few limestone complexes in the world to satisfy these conditions, but some, such as the Dinaric Alps in the former Yugoslavia, Albania and Greece, do comply.

Past omission, or too loose a consideration, of this principle probably accounts for the bulk of the eclectic notions contributing to karst geomorphology. From one viewpoint many non-karstic effects in otherwise karstic areas have not been distinguished from purely karst effects. Thus karst was seen *"obviously"* as a special case, or derivative, of fluvial systems. On the other hand, in some areas limestone overlies a shallow impermeable basement, or it is confined between strata non-karstic rocks. In some such cases few karst relief features have developed at the surface, though the underground is heavily karstified.

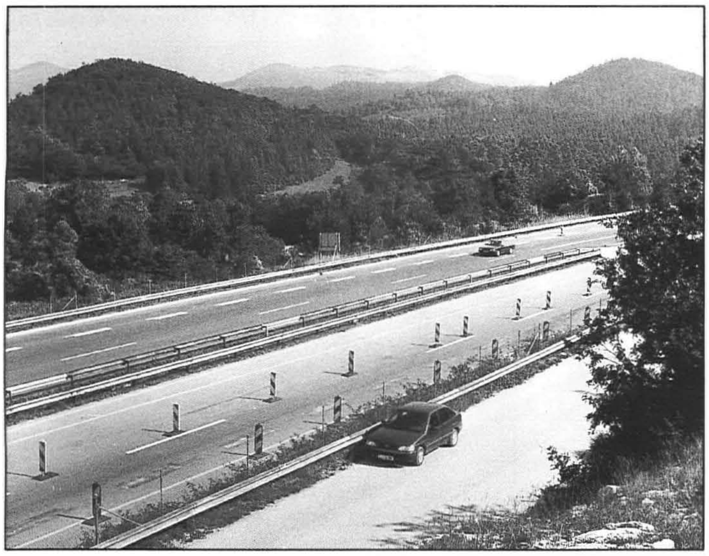
d. The solubility of bedrock is such a readily accepted element of karstification that it is frequently interpreted as the philosophers' stone of karstology. Yet the situation is not simple. All rocks are soluble to some extent, even those claimed to be insoluble. Thus, the term *"soluble"* must be interpreted in a relative way, such that rock dissolution must exceed the effects of all other weathering processes.

Several puzzling relationships displayed by the most significant karstic rocks (limestone, dolomite and gypsum) draw attention to another aspect of solubility, namely its uniformity. Karst features on dolomite either do not differ from those on limestone, or dolomite behaves like a semi-karstic or even non-karstic rock. In contrast, gypsum is several times more soluble than limestone, but its karst phenomena appear no more pronounced than those on limestone.

From the karst viewpoint, the crucial factor is the possibility of unconstrained vertical mass transport, so that voids always remain capable of transmitting water. Consequently, mass must leave the rock surface in solution, otherwise the process is impeded from the outset. The necessity for uniform solubility of the parent rock is thus dictated by the karst itself.

Dissolution of just some mineral components suffices to establish a limited weathering process on bare granitic rock surfaces, bringing about the formation of dissolution forms. This process is, however, insufficient to establish stable underground drainage and, hence, vertical mass transport. Some loosened grains, including the dominant quartz, are effectively insoluble, and these fill any initial pores in the parent rock. The amount of those components may be sufficiently small not to affect mass transport on the surface, but can block it completely underground.

This statement may be applied to relationships among the previously mentioned karstic rocks. Omitting any really insoluble impurities, which are negligible in the Dinaric Karst, all three rocks are completely soluble. Limestone and gypsum dissolve homogeneously. There is hardly any difference between the



Karst hills or "cones" and intervening depressions near Postojna, Slovenia.

solubility of crystal grains and cement, and no nests of exaggerated resistance to dissolution appear. Dolomite has a double role. In some situations it dissolves uniformly, like the other two rock types, and where this occurs there is no great difference between the three. In other situations a faster dissolution of some portions of cement brings about the formation of a sort of dolomitic silt. This is itself soluble, but at a slower rate than it is produced. It tends to block pores completely, and so inhibits karstification (Zogović, 1966). Dolomite's relatively poor mechanical resistance produces a similar effect on a different scale. Even temperate climatic conditions may reduce dolomites to gravel by freeze-thaw weathering, producing more or less the same effect as the non-uniform solubility. From the mass transport viewpoint it is irrelevant whether material blocking vertical mass transport is produced by dissolution or in another way, or whether the particles themselves are soluble or not, as there is no difference in effect. Thus the actual intensity of dissolution is of little importance (it merely controls the velocity of the processes), but its uniformity is critical.

Increased solubility of granitic rocks under tropical conditions establishes several similarities in relief formation between them and limestones. Some similarities are mentioned above, but another example is provided by rivers. On both rocks river beds are guided by geological structures, rather than other factors, as there is a lack of bed load that would cause abrasion or deposition at suitable points.

Increased rock solubility in some climates causes parallels with limestone surface shaping, but it has nothing to do with karst. Fulfilment of conditions a. to d. alone is insufficient to form a true karst but, if fulfilled, they render feasible the development of characteristic surface phenomena in any soluble rock.

e. Rock porosity is divisible into several types, according to its origin. Pores may form during early or late diagenesis and due to tectonism. Such a distinction has no relevance to this consideration, as water will penetrate accessible openings of any type, under gravity and obeying certain hydraulic laws. The expression *"initial porosity"* is much more useful, encompassing all possible voids, including bedding planes, before water started to enlarge them and create a karst aquifer.

The question of structural guidance is excluded from this discussion intentionally, and initial porosity is assumed to be more or less uniform, if not isotropic. This condition, which prevents relief features from being projected through a possibly highly anisotropic and generally linearly organized structural grain, is more or less fulfilled in the highly fractured Dinaric Alps. Sinking water generally has a choice of possible voids, and is able to pursue a preferred route when penetrating downwards.

If epeirogenesis were the most important energy inducing agent most fissures, except bedding, would form after uplift. This would necessitate an arbitrary long pre-karstic fluvial phase, and would provide a solid basis for the cyclic explanation of karst. On the other hand, if the embryonic Dinaric Karst formed before an active orogeny, no impediment exists to the idea that an initial porosity pre-dated uplift and the mass has been karstified since the moment of the carbonate rocks' emergence. Time orientated studies of the Dinaric Karst suggest that the latter possibility more closely fits the facts (Milovanović, 1965).

f. As water is the mass transport agent, little can be added to the initial statement. The steadier the precipitation, the more rapid is the progress of unsaturated zone karstification. Irregular stormy weather impedes downward penetration of water to establish a vertical drainage system, and the surface remains similar to any other semi-arid one, ignoring bedrock differences.

Fulfilment of conditions a. to f. can enable development of underground karst phenomena, while the surface develops in another way.

g. This condition is close to the first one in its effects and requires no further discussion. Any change in the impermeable border of a limestone mass, whether erosional or tectonic, affects the level of the saturated zone. This affects the vertical extent of the unsaturated zone, and hence may affect the superficial karstification.

h. Precipitation water gathered on the surface has no special affinity to either sub-aerial or underground percolation, but it must follow hydraulic rules. If the surface is relatively gentle, water may sink into the ground. When the surface is steeper, as for instance in pyramidal glacial mountains, water will run away on the surface, as it usually does in other high mountain geomorphic systems.

True karst relief, conditioned by a completely developed and properly functioning unsaturated zone, appears only when all eight conditions are fulfilled.

The conditions are, to a great extent, hierarchical and, from the PKM viewpoint, lack of fulfilment of some lower conditions mitigates against fulfilment of some higher one. Combinations violating this rule are relatively scarce. They include forms that are intuitively viewed as karstic, but which are totally unrelated one to another and may not easily be ranged into a unique system. Different imperfectly developed "karsts" (according to the PKM) become comparable and buildable into a unique system, by considering what they are missing. Using Cvijic's standard terminology, only one holokarst exists, but several merokarsts may appear, even if they lack mutual similarities.

REALISATION OF THE MODEL

Fundamental forms of the surface karstification

Karst relief shaping depends initially upon the spatial configuration of the active agents. The most important mass transport medium in the karst is precipitation water, as in most other temperate climate geomorphic systems. By assuming that drainage net organisation is crucial to the surface outlook, the fundamental difference between karst and non-karst relief may be established. In nearly all non-karstic situations mass transport is organised superficially and its pattern is an adsorptive linear

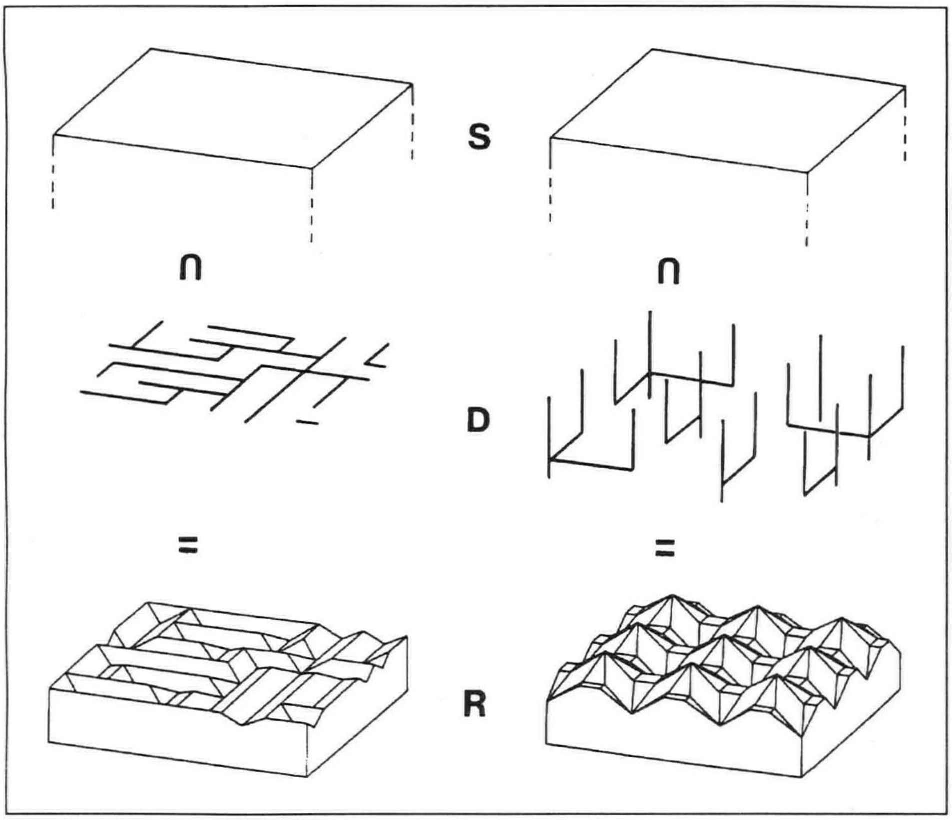


Figure 1. The Pure Karst Model presented in the terms of set theory. Fluvial relief is shown on the left side, karst relief on the right. S = initial surface; D = drainage system; R = the intersection of S and D. The symbol " ∩ " is the mathematical symbol for "intersection".

net. The dendritic drainage net and its complement, the mountain crest pattern, are clear examples. Expressed in set theory terminology, the intersection of the transport system and the surface is the transport system itself (Fig.1).

In completely karst circumstances surface rock is dissolved and (from the surface viewpoint) removed to some other dimension, nearly *in situ*. Such a surface is continuously lowering and denuded underground phenomena (caves) appear at the surface. The karst surface organisation reflects total karst mass drainage organisation rather than directly reflecting itself. In direct contrast to most geomorphic systems, it is not built into the surface but is perpendicular to it, forming a three-dimensional tree pattern. The intersection of the drainage system and the surface is a point array (Fig.1). Consequently, in the limiting situation, forms associated with pure karstification may be reduced to a point array, whereas those comprising a fluvial system always remain an array of linear elements (links).

The fundamental elements of the karst surface are thus centrically organised depressions and elevations. Climatic variations may bring about different superficial appearances, but the inherent centricity remains. This factor alone is the essence of the striking visual similarity between the Dinaric high plateaux and some tropical karsts. Surface landforms organized in other, non-centrical, ways reflect either a linearly imposed (anisotropic geological setting) or non-karstic interference in karst development. In both cases the basic conditions are not fully realised and the karst is incomplete in the PKM sense.

If such a comparison is reasonable, the parts of the karst drainage system that intercept the surface may be related to the area of influence of first order drainage links in fluvial systems. Positions described as *"in a depression"* or *"on an elevation"* differ little from ones such as *"a little bit upstream or downstream"* along a first order stream in a fluvial system. Fluvial system elements range from the dimensional order of rudimentary streamlets in areas of sheet flow, through to enormous streams (and antithetical mountain crests) of the highest orders. In contrast karst relief elements are scaled very strictly. Using the comparison introduced in the previous paragraph, the statement that the maximum dimension of a karst relief element may not exceed the dimensions of a vertical drainage element influence area becomes inevitable. Lacking comprehensive data, any attempt to estimate these dimensions in absolute units is intentionally avoided, but one certain constraint is apparent. Even if the concentration of vertical trickles was not limited areally, the very dimensions of the saturated zone streams impose rigid restrictions. The largest karst springs in the world are impressive, but compared to the surface flows, their discharge is very modest. No underground Amazon is to be expected!

The karst surface is not permeable down to its infinitesimal elements, but is a mosaic of blocks, each as impermeable internally as blocks of any igneous rock. It must be re-emphasised that the karst surface conducts water between these blocks. Precipitation water flows on the surface of the blocks just as it does on the surface of any non-karstic geomorphic element of the same dimensions. It appears that such blocks must be no smaller than several decimetres, otherwise the second basic condition is violated. So, karst relief landforms are constrained by two dimensional limits, spanning four size orders, imposed by the basic axioms of complete karstification.

True karst relief consists of centrical depressions and elevations, while fluvial relief is built up of valleys and crests. Regarding relief elements from this viewpoint, linear karst surface elements, such as dry valleys, must reflect either structural predispositions or non-karstic interferences. In the former case the relief may achieve maturity, but the ultimate landforms are not displayed because the initial porosity is highly anisotropic. In the latter case, maturity is either not achieved or the third basic condition is violated.

Pure karst versus tropical karst

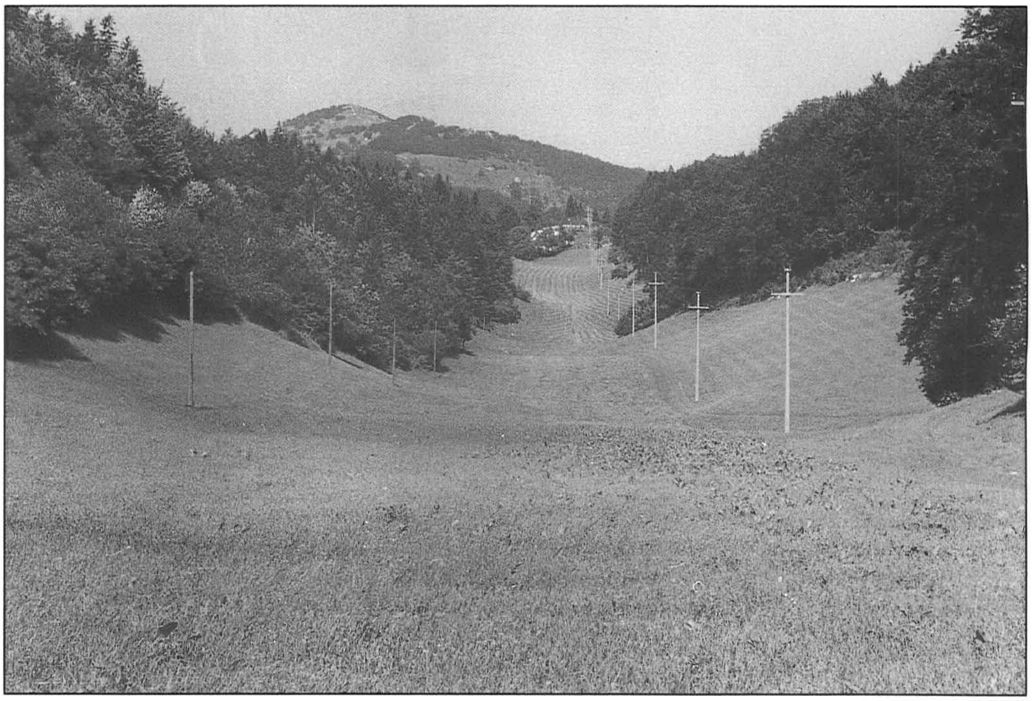
Decades before the climatic geomorphology era, when dealing with the karst of the south-central Slovenia, Rus (1925, p.105), wrote:

> *"On specific positions of the* [karst][4] *surface are ingrown depressions (Hohlformen[5]) while the territory around is occupied by elevations (Vollformen[5])".*

[4] Added by F. Šušteršič.

[5] German terms were added by J Rus, in order to make his evidently unusual, statement properly understandable.

False (apparent) dry valley: a linear depression formed along a fault. Near Kovk in the "High Karst" of western Slovenia.



This is an exact description of the pure karst surface, and, at the same time, many a tropical karst.

Today, the karst relief point pattern (deduced as the basic form of an ideal karst surface) is widely known as the dominant signature of tropical karst development. Consequently, similar karst surfaces outside the tropics have been explained by forced use of this principle. In the Dinaric Alps, large areas with scattered conical hills (hums) were explained as relics of Pliocene tropical shaping. This leap to the past is not needed in the PKM context, and the relationships between actual climates and relief geometry must be clarified.

Like all other geomorphic phenomena, karst generally displays adjustments made in response to final stage processes, related to the structural disposition, which is stable in terms of geomorphological time. Earlier landforms may leave traces, but these are obliterated over time. Field observation shows that the Dinaric Karst relief is just abandoning its Pleistocene forms and adapting them to present climatic conditions. This renders the tropical explanation of the surface much more questionable, compared with declaring the relief to be simply an active, well-developed complete karst. Under the Pleistocene periglacial climate, surface karst development apparently adapted to the prevailing conditions, and probably slowed down. Nevertheless, activity continued and hum development did not stop. The natural conditions in the Dinaric Alps are, however, very close to the ideal ones claimed by the PKM.

The relationship of some tropical karsts to the point pattern must still be explained. Williams (1972, p.135) wrote:

> *"One of the basic tenets of climatic geomorphology is that essentially similar landforms will result from comparable morphogenetic conditions. This view is widely held in Europe and particularly so amongst karst geomorphologists, for it is argued that karst processes are especially susceptible to climatic control."*

He then discussed the weak points of this concept. The idea of a close relationship between tropical climate and the karst relief point pattern organization remained valuable until present times, and the first sentence cited above provides a good explanation of why this is so. Williams and other researchers realised that something was wrong, but apparently could not identify exactly what. It is tacitly assumed that all the crucial morphogenetic conditions are climatic. Several different dissolutional landforms on totally non-karstic rocks develop under tropical climates and numerous isolated non-karstic hills (tors, kopjes, inselbergs) form on similar rocks under neighbouring savannah regimes. This seems to provide proof that climatic influences are crucial, but it does not hold true automatically.

All physical objects, not just geomorphic ones, are geometric bodies, and hence can be described by vector quantities. However, formative processes encompass both vector and scalar components. A vectorial outcome never results from a scalar operator, as the latter lacks directional information. In pure karst conditions there is no surface deposition and the only shaping process is mass removal, due to perpendicularly orientated mass transport through the unsaturated zone. Consequently, surface shaping is conditioned by only the vertical direction. Additional scalar components influence its absolute value, but introduce no new directional information.

Conditions governing isolated hill formation in non-karstic, savannah areas are essentially different, though in some ways strikingly similar, to those governing karst relief development. Tors and kopjes develop in two phases. During the first phase granites simply change to regolith, with the most fractured rock being most susceptible. Most of the derived material remains at its point of origin and tiny amounts are dissolved and washed away, in a way that is roughly comparable with the karst process. During the second phase regolith is swept away by a process that is incomparably faster than the preceding weathering. The process produces a pattern of isolated hills superficially reminiscent of conical karst. Accumulations of terra rossa may play a similar role to that of regolith in some circumstances, and the later development of some hum slopes may thus mirror that of inselberg slopes.

Because there is no deposition on the pure karst surface, its shaping means simply its decay. Mechanical disequilibrium is induced in the more affected areas. Feedback processes tend to restore equilibrium and, because they are mostly negative, they bring about steady state lowering. The mechanical instability is mostly governed by gravity (vertical vector), but positioning remote from the centre of disequilibrium adds concentric fields of horizontal vectors. Climatic conditions may accelerate or slow down the feedback processes, but their inherent vectorial components (insolation angle, direction of prevailing wind, etc.) are nearly negligible compared with the effects of vertical drainage.

Climatic conditions thus influence the dimensions of different relief elements but they cannot affect their areal distribution. So, case-hardening of mogote tops in Puerto Rico, orientated according to trade wind direction, is a climatic effect, but the isolated hills are present due to relatively pure karstification. The same rule applies to hums in the high

Karst hills or "cones" at Otlica in the "High Karst" of western Slovenia. The orientation of slopes is due to the effects of insolation and Pleistocene weathering processes being more effective on south-facing slopes.

Dinaric Karst. Their existence reflects the karstification stage, but their shape reflects recently (or sub-recently) active processes. Recognition of the term *"mogote"* as describing a typical member of the tropical relief feature suite is incorrect. However, if the term is understood as describing one result of an essentially karstic development under tropical conditions, it is correct. If supposition of the relatively steady state is valid, tropical and Dinaric (temperate) hums develop under different climatic conditions, and their intimate affinity is masked by their appearance. Different types of centrical depressions are similarly related.

The question of why conical hills appear widespread only in the Dinaric Alps and in many (but not all) tropical or subtropical regions, becomes inevitable. The answer was offered implicitly by Gams (1980, p.8), who stated:

> *"The best pronounced karsts in the world (not regarding caves, which appear in any climate) are in the areas of the highest precipitation and the highly elevated karst."* [translated by F S].
>
> In terms of the PKM this may be restated as:
>
> *"...where natural circumstances are closest to ideal conditions".*

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A SEM analysis of quartz grains in the sediments of the Lhasa karst areas, Tibet

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Abstract: The quartz grains from the sediments of the Lhasa karst areas have been examined by scanning electron microscopy. As the quartz grains were chosen from newly-discovered sediments in caves and relict karst doline, the results show some differences from the sediments sampled by the author in 1987, which were examined by Bull and others (1990). The grains from cave alluvial deposits and doline sediments show many features that are only produced in high chemical and water energy environments. These include solution grooves, holes and V pits. The cave sediments were deposited in the Pleistocene, according to the U-series dating. The analysis, however, shows that the grains might come from the sediments of the Tertiary surface of the plateau, which were brought into the caves by water, mixed with fresh weathering materials and then redeposited. The destruction of this Tertiary surface by intensive erosion was induced by the fast uplift in the Quaternary. Alternatively, many features had also been modified in the chemically active periods during the Quaternary.

INTRODUCTION

The Tibetan Plateau has an average elevation of 4000-5000m and its climate is cold and arid. Periglacial and aeolian processes dominate most of its area. Studies of karst solution processes, cave forms and limestone pinnacles show that present-day solution processes are very weak and the plateau lacks active karst landforms and karst sediments (Sweeting et al, 1991; Zhang, 1991, 1994, 1995 and 1996). In the early Tertiary, however, the climate here was hot and wet, since Tibet was at sea level and its position was close to the Equator (Molnar et al, 1993). About 50 million years ago, the collision between the Indian Subcontinent and the Eurasian Plate led to the uplift of the Plateau (Partriat and Achach, 1984; Powell, 1986/7; Coward et al, 1988; Windley, 1988) while accelerated uplift of the plateau began at the Pliocene (Ji et al, 1981; Xu, 1981; Zhao, 1986; Deway et al, 1988). As a result of this uplift, the physical conditions at height in the troposphere changed the climatic state of the plateau. Furthermore, the uplift of the plateau also altered the general circulation in this area thereby leading to climatic change in Tibet itself and the surrounding areas (Zhang, 1991). Recently Kutzbach et al (1989 and 1993), Ruddiman et al (1989), Raymo (1991) and Ruddiman and Kutzbach (1989, 1990 and 1991) suggested that the uplift may have induced the global climatic changes in the late Cenozoic. A cool and

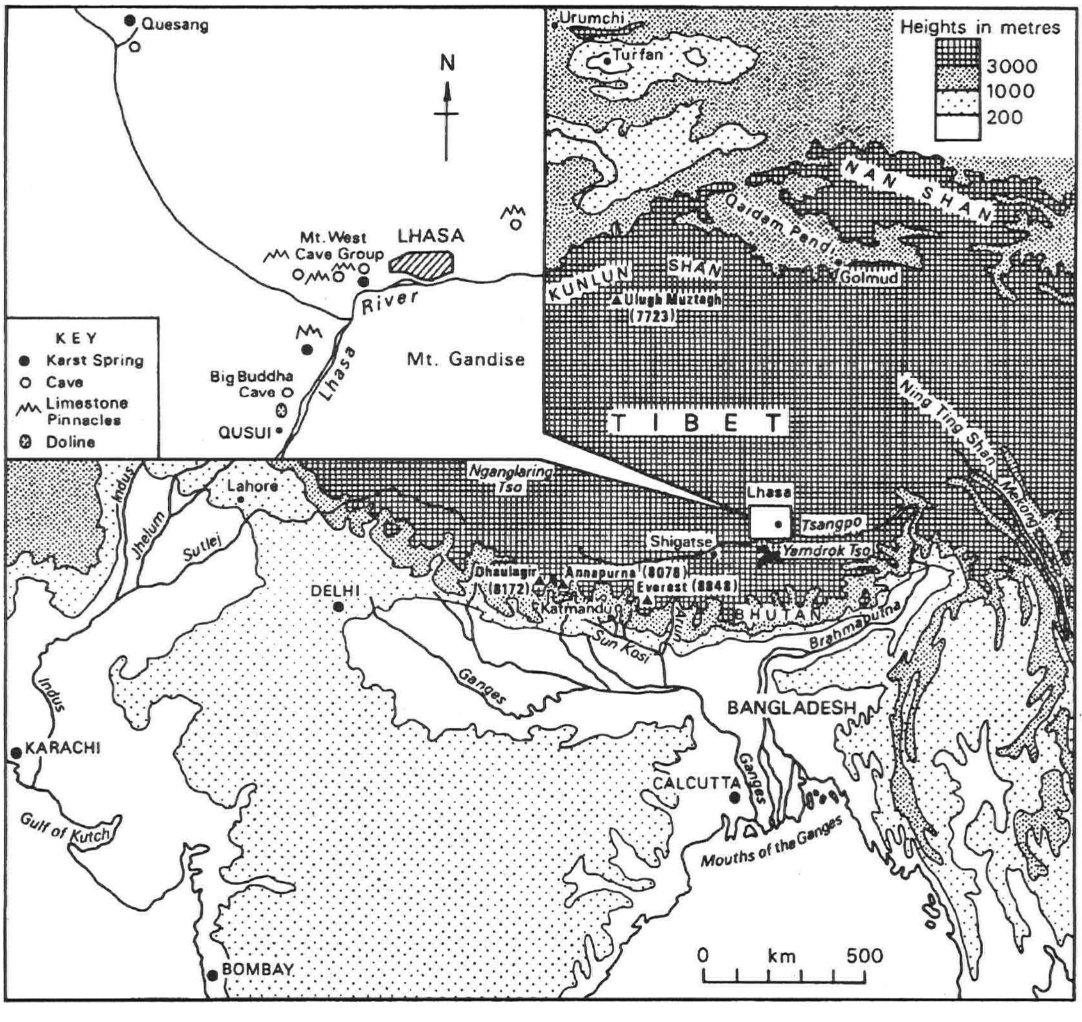

Figure 1. Karst landforms and sampling sites in the Lhasa area, Tibel.

moist climate was produced in the Pliocene due to a slight uplifted surface (about 1000m) and the northward movements of the plate (Windley, 1988). Fast uplift occurred at the end of the Tertiary and during the Quaternary, and eventually led to the present-day elevation and climate (Manaba and Terpstra, 1974; Haln and Manaba, 1975; Ji et al, 1981; Lin and Wu, 1981).

In a first field trip to Tibet in 1987, the author sampled some sediments from caves and limestone surfaces in Lhasa, north and south Tibet. The quartz grains of the samples were analysed by Bull and others (1990) and the results indicate that the majority of the samples studied from cave deposits in selected Tibetan caves and surface sediments areas are fresh, lacking significant environmental modification features. In a second expedition in 1988, a series of caves with old sediments, such as flowstones and cave alluvial sediments, and a relict doline were found near Lhasa, which cannot develop in present climates. These sediments are significantly older than those from the first expedition and are not like the former samples in terms of their physical and chemical appearances. Today, the plateau surface lacks modern cave water flows and chemical deposition. The main purpose of this scanning electron microscope (SEM) study is to examine whether the chemical and physical characteristics of these sediments are relict and produced in wetter and warmer conditions, and if they are, to explain how these sediments formed.

RESEARCH AREA AND SAMPLING SITES

The Lhasa karst area mainly extends west of Lhasa City (Fig. 1) and consists of Jurassic limestones. Limestone pinnacles, caves and karren can be found in this area. They are relict forms, except some small karren. In the research area, the average annual precipitation is about 400mm and its average annual temperature is near 5°C. The elevation of the sample sites range from 3,700m to 4,800m. Over 500 caves have been explored in north, central and south Tibet in three trips. The caves with relatively rich sediments are concentrated in the Lhasa area. All caves and sampling sites in this area are developed in pure Jurassic limestones.

A series of caves with interbedded layers of flowstones and alluvial sediments are located on Mount West, which lies to the west of Lhasa. They include the Cliff Cavern (Fig. 2, Cave No. 1, 2, 3 and 4) and Cave No. 5 (Fig. 3), which is 220m away from the cavern. In these caves, alluvial, flowstone, aeolian and diluvial sediments (Te 116, 117, 118, 119 and 120) have been sampled and examined.

A relict doline was discovered near the Big Buddha Cave near Lhasa (Fig. 4). Samples Te 156, 157, 158, 159 and 160 are doline deposits, Te 152 a palaeosol layer, Te 153 a debris layer and Te 155 a surface aeolian cover. The doline was exposed by quarry work of local people. The brownish red colour of the doline layers distinguish themselves from other sediments. The doline deposits are all kaolinite-rich. The palaeosol layer also contains some clay minerals.

A developing diluvial fan near Mount West, a massive limestone mountain by the Lhasa River Valley, was chosen for SEM comparison study. The fan deposits (Te 102, 103, 104, 105, 106 and 107, Fig. 5) were laid on a palaeosol layer (Te 101) which is 5m higher than the water level of the Lhasa River. The structure, chemical content, mineral compositions and colour of the palaeosol layer are very similar to Te 152. Half-decayed plant roots have been found in the layer suggesting that the deposit profile reflects recent to present-day weathering conditions on limestone terrain. This provides a useful basis for comparing the SEM features in modern deposits with those in cave and doline sediments.

An early Tertiary sandstone sample was also taken from a nearby location. This has also been used as a comparison sample because the hot and wet climatic conditions in the early Tertiary are already well-known.

RESEARCH METHODS

In recent years there has been a marked increase in the numbers of papers dealing with quartz grain surface texture utilizing the SEM. All this literature is concentrated on different aspects in the analysis of surface textures according to different sample sources (Krinsley and Doornkamp, 1973; Cater, 1984; Higgs, 1979; Bull, 1981; Wang and Deonarine, 1985). According to the characteristics of the Tibetan environments and samples, the following aspects have been considered in the SEM analysis:

1. Selection of grain size

The selection of grain size for SEM analysis is very complicated. Some workers pick grains at random while others specify sand size. Wang et al (1982) used 15-18 grains of 2.0-0.4mm diameter, but Wang and Deonarine (1985) considered that the 5mm range is best for the analysis of alluvium and glacial sands. Mazzullo and Ehrlich (1983) used the fine grains of 0.180-0.125mm and Manker and Ponder (1978) chose grains of approximately the same size (1 mm) and shape. Tovey and Wong (1978)

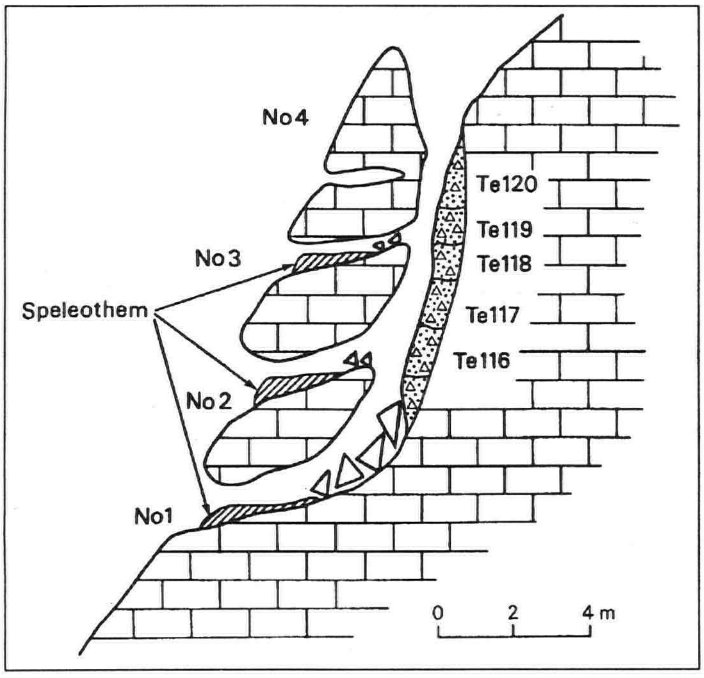

Figure 2. The profile of the Cliff Cavern on Mount West, near Lhasa.

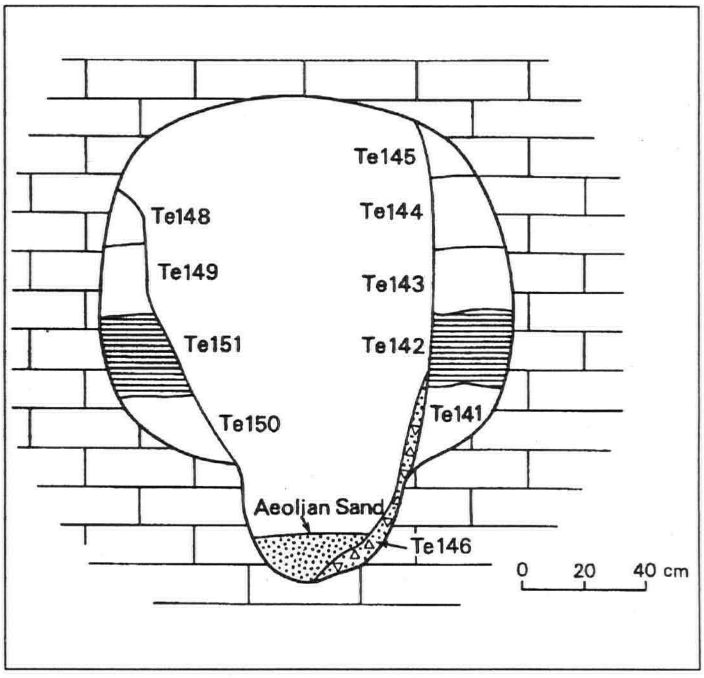

Figure 3. Sedimentary profile of the Cave No. 5.

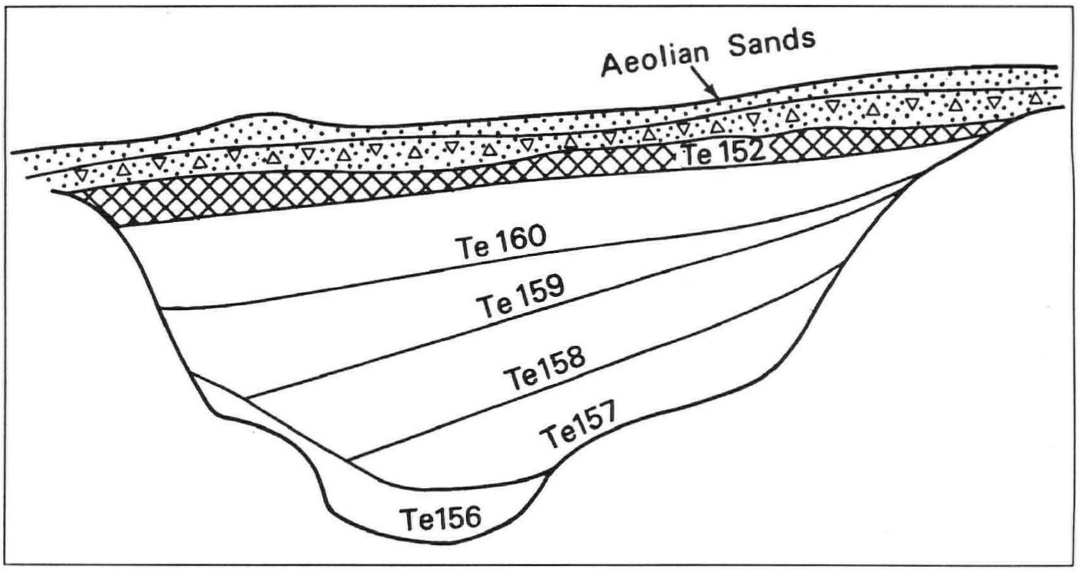

Figure 4. The profile of the relict doline near the Big Buddha Cave.

discussed the selection of grains advocating either a random selection or one based on size fractions of a sample. Krinsley and Doornkamp (1973) noted that features change with grain size and considered that 200 µm is a divide between small and large grains; this may in many cases reflect a generalized break between suspension and traction population of grains. Large grains (>400 µm) tend to show records of abrasion and grains <200 µm are biased towards showing chemical effects (Margolis and Krinsley, 1974). Hence Trewin (1988) suggested the need for the standardization of grain size in studies on surface textures. However, to date there is insufficient information on which to develop a standardized method in view of the complicated environmental factors involved and the different contributions of grain size. Consequently, in the SEM observation of Tibetan samples, the 0.1-0.8mm grains were selected based on the experience in Oxford because the wider range may reflect more surface textures.

2. Grain shape and edge

In observation of grain shapes the genesis of shapes should be noted, such as crystal control form and broken and reformed shapes during transportation. Crystal control, irregular, smooth and other shapes have been identified in this study.

The degree of rounding of grain edges is emphasized as well, being divided into very angular, angular, subangular, subrounded, rounded and very rounded based upon the classification of Powers (1953). The degree of roundness is one major key to environmental dynamics and in the same dynamic condition it implies the transport distance of the grains.

3. Surface marks

The identification of features on the grain surface is the major part of SEM observation. Various authors have given different names to the same features. Hence the standardization of terms is quite difficult. In this report, the surface mark terms are those of Higg (1979) and Krinsley and Doornkamp (1973). The surface marks found on the Tibetan sediments are V pit, impact pit, dish-shaped pits, parallel striation, imbricated grinding features, crescent-shaped pit, chemical V pit, solution hole, curved and straight groove, conchoidal fracture, cleavage plane, silica coating, silica crystal growth, silica scaling, adhering particle and scratch.

4. Characteristic combination and statistics

Interpretation of surface textures is quite difficult as the quartz grains from any environment have several different surface textures that might appear in quartz grains of other environments and only a few textures could be explained as a special feature of a particular environment. This problem was especially severe in the Tibetan samples, which may have experienced climatic extremes from tropical to glacial, together with redeposition and mixing.

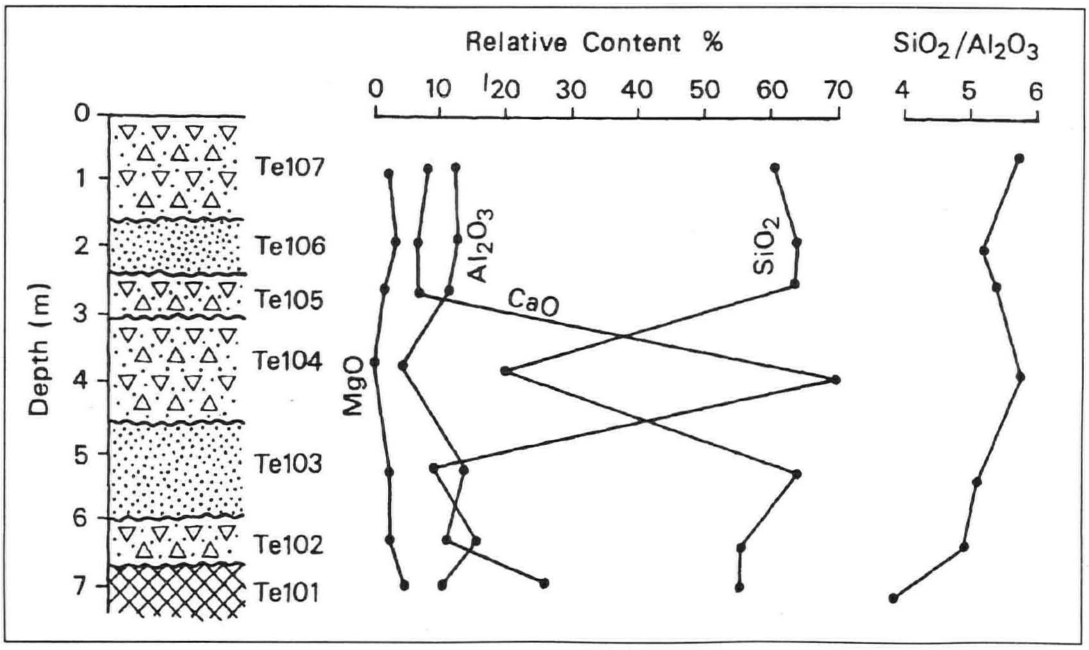

Figure 5. The sedimentary profile of the diluvial fan and sedimentary chemical composition.

The study by Culver and others (1983) shows that the correct determination of environment in SEM work does not depend on the recognition of single features but on the recognition of a combination of some features. The only way to arrive at a satisfactory conclusion in studies of surface textures, therefore, is to record all features and find their combined relationship in an environment from an adequate number of grains.

30-50 grains were selected from each Tibetan sample and every grain was observed from the screen of the SEM and all features of it were recorded in statistical tables. The frequency of appearance of every feature and the percentage of grain surface occupied by any surface mark was divided into four groups: a: >75%; b: 75-25%; c: 25-5%; and d: <5%. During observation, only typical features of each sample were photographed as the working time was limited. Based on these statistical results and referring to Higg's study (1979) in feature combination, an estimation of the depositional environment for every sample has been made. The final conclusion on sedimentary environments will, however, need the combination of SEM results with other evidence.

RESULTS

A total 22 samples have been selected and examined by SEM and the results are presented in Fig. 6. The samples can be divided into three categories. They are diluvial fan, cave and doline sediments.

1. Diluvial fan

These consist of 7 samples, from Te 101 to Te 107 (Fig. 5), and all are recent deposits. The fan deposits were derived directly from nearby source rocks, typically of limestone, granitic and/or metamorphic provenance. The fan profile demonstrates the changes of sedimentary materials (Fig. 5). The grains from these samples are mostly irregular in shape and few samples show any extensive chemical and physical modification; indeed many of the grains appear to reflect low level modification in a rather inert environment (Fig 6). The chemical and mineral compositions, the sedimentary structure and grain size distribution of the fan deposits and the phenomenon that aeolian sand is mixed into this profile all indicate that the deposits occurred in a cold and arid climate (Zhang, 1991). The chemical composition shows that the major source of fan materials came from the granitic and metamorphic rocks 150 m away from the fan, except for Te 104. In Te 104, limestone debris forms the majority of the chemical components and they are the product of frost weathering of local limestone. The other deposits were transported by temporary water flows and gravity to the fan site. Therefore, sample Te 104 might indicate a colder and drier period in recent times.

2. Cave sediments

The cave samples includes alluvial and flowstone group (Te 110. Te 112, Te 113, , Te 121, Te 122, Te 148 and Te 151), cave diluvial group (Te 117, Te 118, Te 119, Te 120) and a cave aeolian sample (Te 115).

SAMPLE NO	SHAPE										MECHANICAL											CHEMICAL					OTHER	
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28
Te101	□	○	•	•	•	○	●	○	•		○	•	•	○	○		□					○	•		●			
Te102	□	•			□	□	•	○	•	•	□		•	○	•	○		○				•			□			
Te104	●	•		•	•	□	□	•	•	•			•					○		•			○	○	○	•		
Te105	■	○	•	○	●	○	•				●	•					○	•				•			•			
Te106			•	•	•	○	□	○	•	○	□	•				□	□	○				□			○		□	
Te107	●	○	○	○	•						●						•	□			•			•	•			
Te110	●	○		○	□	○	•				●						○	○	○			□	○		○			
Te112	□	•	○	•	•	•	●	•	•		○	○	○									□	○		●		○	
Te113	●	○	○	•	○	○	□	•	•	•	□		○			□	○					■	○		□	○		
Tr113								•	■	□	•														■	■		■
Te115	□	○	•	□	•	•	•	○	□	•	□					□	○	○				•	•	○	○			
Te117	●			•	•	•	○	●	□		□				○	○	●					•		□	●			
Te118	□			•	•	○	□	○	○		□		•	○	□	○	○	○						○	●	•		
Te119	□		○	•	□	•	•				○					□	□								□			
Te120	□		○	•	□	□	□	•	•		○		○		•	□	□	□				○	□	○	□		○	
Te121	□	•	○	•	•	○	●	•	•	•	○	•			•	○	○	○	•			□	○	○	●			
Te122	○		○	•	•	•	○	□	□	•	•		•			□	●		○			●	□	•	•	□		
Te148	□		•	•	•	○	○	○	•	•	●				○		○	○						○	•			
Te151	□	□		•	□	□	○	•			□	•	•			•	○				•		○		□			
Te152	●	□		○	□	○	○	•			●					○	•								•	■		
Te156	●		■		•	○	□	□	•		○	○				○	○					●	■	○		●		
Te158	□		○		•	□	•	○	○		□		•			□	□	○				●	□	○		○		

Figure 6. SEM analysis results of the quartz grains in the sediments of the Lhasa karst area, Tibet.

1 irregular, 2 crystal control, 3 smooth, 4 angular, 5 angular-sub-angular 6 subangular, 7 subangular-subrounded, 8 subrounded, 9 subrounded-rounded, 10 rounded
11 conchoidal fracture, 12 parallel steps, 13 striae, 14 upturned plate, 15 dish-shaped concavities, 16 mechanical V depression, 17 mechanical V marks, 18 mechanical impact pits, 19 curved grooves, 20 scratched lines, 21 cracks or fissures, 22 surface solution features, 23 solution holes, 24 silica coating, 25 silica deposits, 26 solution grooves, 27 weathering features, 28 silica cracking

■ over 75%, ● 75% - 25%, □ 25% - 10%, ○ 10% - 5%, • rare.

The sedimentary profiles of the cave sediments (Fig. 7) represent certain similarity in deposition history and conditions between different caves, based on the analyses of other sedimentary characteristics (Zhang, 1991).

The flowstone deposits, consist mainly of calcite, initiated largely by the degassing of carbon dioxide from the cave water, although the actual deposition mechanism depends upon a supply of water which has a higher pCO_2 in comparison with the cave atmosphere. Whilst these wet conditions prevail in many temperate and tropical caves, evidence can be produced and be shown that in cold latitude caves, either the water supply is absent or the water has a low pCO_2 (Ford, 1971; Cogley, 1972; Smith, 1972). Some debates exist in this idea , such as Gascoyne (1977). However, many datings of speleothems worldwide show that most speleothems were deposited in warm periods of the Quaternary (Zhang, 1991). In higher altitude areas, the relationship between the speleothem development and warmer period is more clear (Hennig et al, 1983). The only sample which shows speleothems that are developing under present water-rich periglacial conditions was found in the Castleguard Cave of the Rocky Mountains. It is considered to result from suitable conditions of mixed gypsum-limestone or dolomite terrain or rock containing abundant pyrite (Atkinson, 1983). There is no dolomite in the sampling areas and all samples contain little SO_4^{-2}, less than 0.01%, while the speleothem in the Castleguard Cave is 0.9%. Therefore, the cave alluvial and flowstone samples most probably formed under a more water-rich and warmer environment than those of the present-day. Most of the cave alluvial and flowstone samples contain kaolinite and their grain size analysis shows that their mean sizes are finer than others. Compared with the recent diluvial fan sediments and diluvial deposits in the same caves, the quartz grains in the cave alluvial and flowstone are generally more rounded in shape, most of them being in the range of subangular to subrounded. They also have more advanced chemical modification, such as found in Te 110, Te 112, Te 113, Te 121 and Te 122. Their chemical solution features include solution holes, surface solution features and solution grooves. Mechanical features created by high velocity waterflows are mainly found in alluvial sediments. Some grain surfaces present high energy impact features (Plate 1).

The cave diluvial deposits mostly are half-cemented debris, mainly limestone debris, and have no clay mineral. The surface textures of quartz grains in them have a lot of mechanical features as well, but lack chemical solution features when compared with the flowstone and alluvial sediments. From the sedimentary profile, sedimentary structures and chemical and mineral compositions they were formed after the alluvial and flowstones and deposited in drier and colder conditions (Zhang, 1991).

The cave aeolian sand sample (Te 115) covers all cave sediments and its source was mainly from outside granite weathering materials. The shape of quartz grains from this sample is not well-modified, but with remarkable mechanical features, such as mechanical V depressions, V marks and impacts pits. It also lacks chemical solution features, but has some silica coating and deposits. It is a present-day deposit which is increasing in thickness today.

In this category, especially in the cave alluvial sediments, the surface texture of individual grains is very complicated, which is shown by the mixture of poorly modified grains and highly eroded grains in the same samples, plus some silica deposition. It implies the mixing of 'new' and 'old' sediments. The most interesting features are that the typical glacial and aeolian characteristics (parallel striaes and scratched lines, waterdrop-shaped grains) appear on some grains of the five samples (Te 118, Te 112, Te 120, Te 121 and Te 122).

3. Doline sediments

Three doline deposit samples were examined. Two of them are kaolinite-rich samples (Te 156 and Te 158) and the other one is from a palaeosol layer which contains some clay minerals (Fig. 4). The quartz grains of Te 156 and 158 are the most chemically modified samples in the Lhasa area and have very significant chemical features. Solutional holes, grooves and other features occurring in high energy chemical environments are the main textures found on the quartz grain surfaces (Plate 2). However, their edge shapes are irregular and subangular. The surfaces of the grains have been smoothed by chemical solution and they generally lack high energy mechanical features. This evidence fits with the doline's environment of deposition: short distance transport and intensive chemical weathering.

The quartz grains of the palaeosol have less chemical solution features and mechanical modification. Their shapes are more angular and they have few clay minerals. This may imply that the they formed in an environment which is drier and colder than that of the doline deposits.

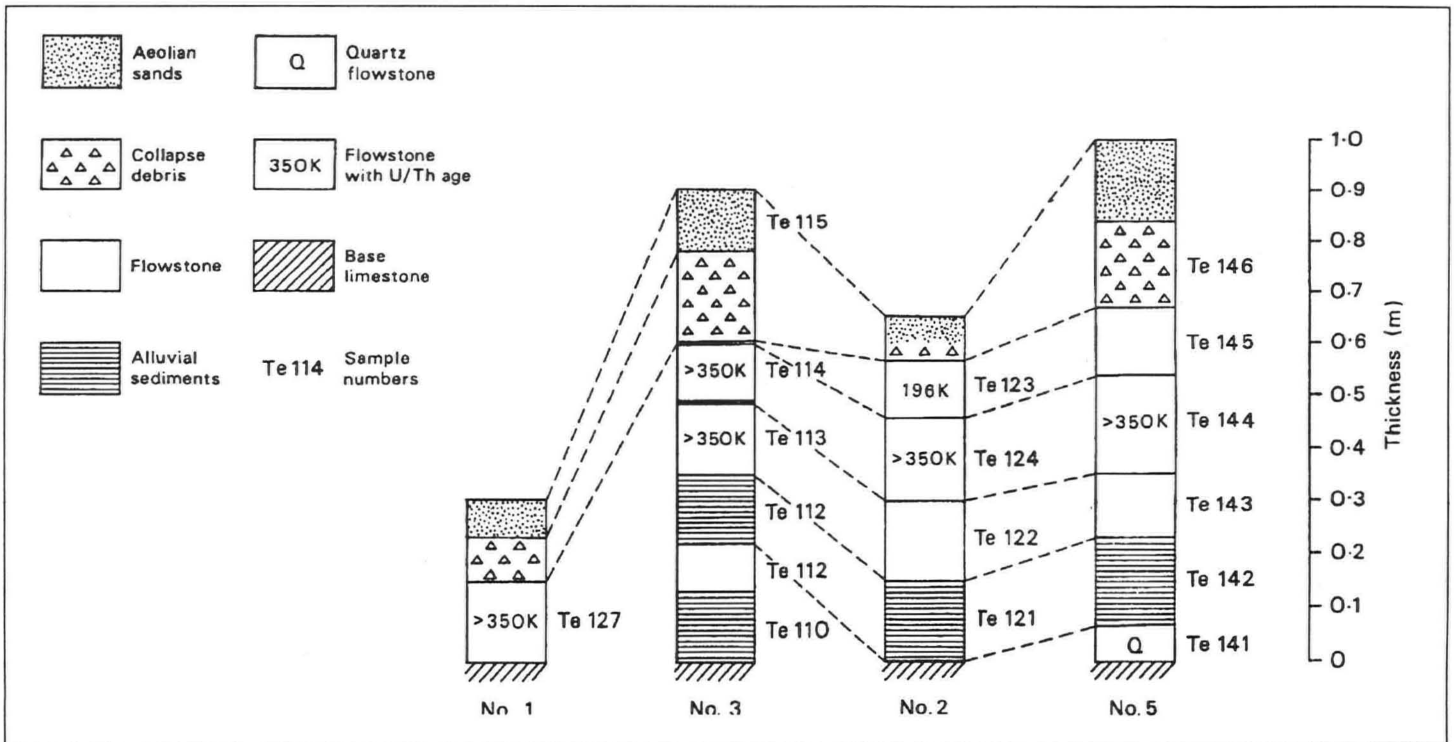

Figure 7. Sedimentary profiles and U/Th ages of the sediments in Cave Nos. 1-5.

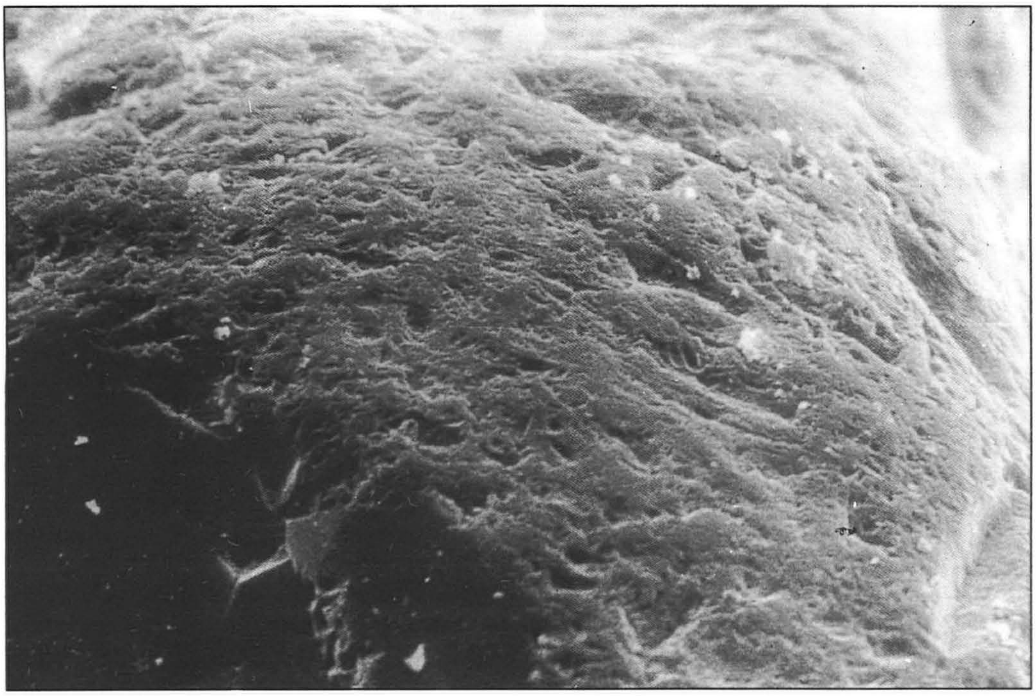

Plate 1. High energy impact features on a quartz grain of Te 148.

The aeolian sand cover is a present-day deposit. Like the cave sediment profiles, the superposition of the doline profile also indicates a tendency of changing climates from wet and warm to dry and cold.

DISCUSSION AND CONCLUSION

The analysis of the cave and doline sediments shows that there was at least one warmer and wetter period in the Quaternary in Tibet. Compared with the recent diluvial sediments and the results from Bull (1990), the quartz grains of the cave and doline sediments have relatively strong chemical and physical modification on their surface. Moreover, the cave sediments seem to reflect a mixing process, in which different origins of typical features in the samples were blended together during or after deposition. The problems that need addressing are (1) when this deposition occurred and (2) how to explain this mixing process. In order to solve these problems, the results from the mineral and U series dating analyses (Zhang, 1991) have to be used.

The major mineral components of the lower doline samples (Fig. 4) are calcite (about 70%), kaolinite, goethite and quartz, the last three (about 30%) being a typical laterite composition. It is not similar to the tropical doline deposits in which clay minerals are main part. The calcite consists of limestone debris that has smoothed edges and slight solution features. As the sediments were deposited in a doline which was filled up and is inactive at the present day, and because the location of the doline is much lower than the early Tertiary erosion surface, but near the wide valley floor, of probable Pliocene age, this deposition might occur some time between the late Tertiary and interglacial in the Pleistocene. Comparing the chemical features on the quartz grain surfaces with those of an early Tertiary sandstone (Tr 113 in Fig. 6), it seems that the chemical and mechanical modification of the doline samples is much weaker. Therefore, the doline samples were possibly a mixture of early Tertiary lateritic sediments and the weathered limestone debris of Pliocene age, when the climate was cooler and some frost weathering could occur. This period was also the beginning time of the fast uplifting and the broken period of the Tertiary peneplain of the plateau. The surface water flows could bring the laterite materials from the peneplain

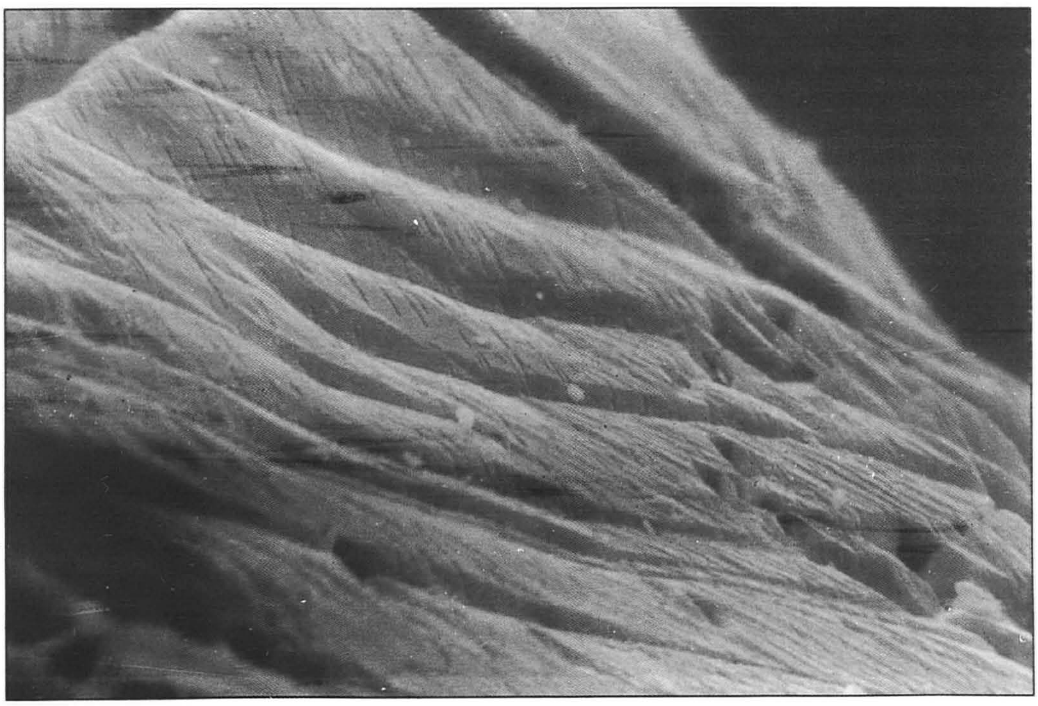

Plate 2. Solution grooves and holes on a quartz grain of Te 154.

and mix them with physical weathering debris of the limestone to fill up the doline. The formation of the palaeosol layer upon the doline deposits might indicate a mild climate in recent times based on the evidence of clay minerals and half-decayed plant roots in the soil. Soil in itself also implies that the climate then was wetter and warmer than the present-day, because there is little soil developed in the area under current conditions. After the palaeosol deposition, a limestone debris layer formed which is the product of frost and physical weathering, as indicated by the grains being all angular in shape and the lack of fine size of grains. The top aeolian sand cover is a typical current sediment in the area, where sand dunes are distributed in the valley and on the slopes.

Some of the cave sediments also contain laterite (Zhang, 1991). These sediments are mainly alluvial and allochthonous, and thus could be derived from surface sediments. The U/Th ages of most of the sediments are older than 350 ky, but the age of the top flowstone (Te 123) is about 200 ky (Fig. 7). The water marks and flowstone deposition show that the climate then was at times warmer and wetter than at present. However, the evidence of glacial features on grain surfaces in sediments between and/or below flowstones also indicates that significant karst solution and precipitation was still occurring after the plateau was uplifted sufficiently for glaciation to occur. The aeolian features on sand grains from cave alluvial sediments may imply that dry climates do not only occur at the present day, but also occurred in the past. The appearance of kaolinite and goethite in the samples does not indicate that the climate in the Quaternary was hot and wet, but shows that these minerals were recycled by cave waters from the eroded Tertiary peneplain, then deposited in the caves (Zhang, 1991).

The diluvial fan deposits, compared with the cave and doline deposits, present weakest modification in terms of the experienced chemical and physical processes. However, the whole sediment profiles of Lhasa karst areas certainly show a significant climatic change from Quaternary to the present-day.

ACKNOWLEDGMENTS

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SCIENTIFIC NOTES

CAVING FROM A HOLIDAY CAMP ABOUT 1908

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Abstract: Campers from the Bentham Holiday Camp (1908-1925) used to go through Upper Long Churn Cave on Ingleborough, as well as visiting the tourist cave at Clapham. Humorous postcards show two cave scenes, and a contemporary photograph is also reproduced.

Caving as part of organized adventure holidays is not new. It was one of the activities arranged at a holiday camp that existed at Bentham, close to the Lancashire border of Yorkshire in northern England, as early as 1908.

Evidence for this includes two potholing scenes in a set of humorous postcards, a photograph of a group from the camp at a cave entrance, and the reminiscences of Reginald Hainsworth, now aged 92, whose father ran the camp and who himself assisted there in its later years.

Figure 1. An advertising postcard for the Bentham Holiday Camp, published between 1808 and 1918.

The postcards with the two underground scenes are reproduced here as Figs. 1 and 2. The other cards in the set show life in the camp in the same vein, with captions such as *"Porridge Parade at Bentham Camp"* and *"The Dinner Procession at Bentham Camp"* (Fig. 3).

Nine different cards are known so it is likely that they were originally issued as a set of 10 or 12. The date of publication can be determined as not later than June 1918, for the postage rates printed on the back are *"Inland Postage ½d. Foreign Postage 1d."* and they were higher after that time. On this evidence alone the postcards could have been produced at any time before that, but it is most probable that they were printed before World War I started in 1914; certainly the number of young men in the drawings suggests pre-war days. The printer is not named and so cannot aid in dating publication.

As will be seen from Fig. 1, the secretary of the Bentham Holiday Camp was J. Hainsworth, and an illustrated booklet about it could be obtained from him, free. Unfortunately no copy of this has been traced. High and Low Bentham are two villages about one kilometre apart, and only some 8 km west of the nearest cave on Ingleborough.

More information about the Camp is given in a recent article in a local magazine, much of it based on information from Reginald Hainsworth who was well known from 1934 until the 1960s as secretary of the Cave Rescue Organisation in Yorkshire. In this article Johnson (1995) states that the Camp flourished from 1908 to 1925. Tents were erected each year on both banks of the Wenning between High Bentham and Low Bentham, just above a small waterfall. In 1912 a week's stay cost 19 shillings and 6 pence (97.5p) for men and 21 shillings (105p) for women and members of family parties because of the extra facilities required. The popularity of the Camp declined after the war, when tents had lost their attraction for returned soldiers, and the motor car was beginning to provide more personal freedom and flexibility for holidays.

The creator and organizer of the camp was Joe Hainsworth of Rose Bank, Robin Lane, Bentham, who later developed the local cinema there. Activities were held mainly in or near the camp and included cricket and football matches, concerts, fancy dress 'events', and local walks. There were also visits by train to Clapham, with a walk over Ingleborough. It was on these days that caves were visited.

Figure 2. More caving - another Bentham Camp postcard.

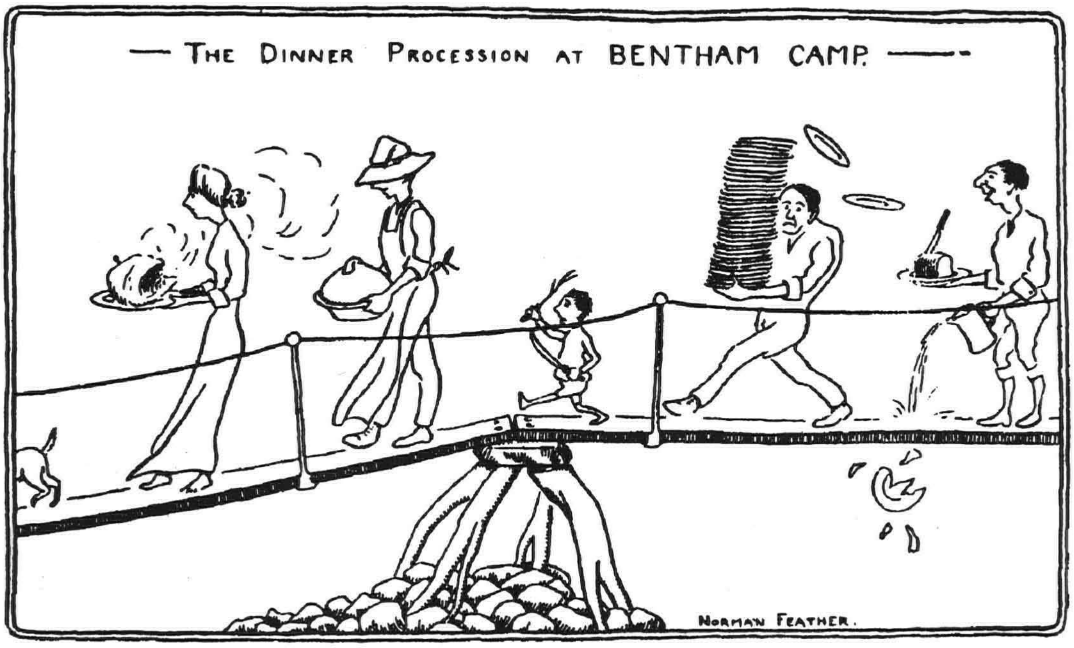

Figure 3. Life at the Bentham Holiday Camp - another of the postcards.

Reginald Hainsworth (1995) has provided a little more in a recent letter. He wrote:

> *"As far as I remember very little serious potholing was done from Bentham Camp. Visitors did not arrive equipped with necessary clothing or footwear. Visits were made to Clapham Cave on our way up Ingleborough. Also Alum Pot was viewed, and trips taken through upper Long Churn."*

Upper Long Churn Cave is an easy horizontal stream cave, then 250m long, accessible from both ends; Clapham Cave was shown to visitors by a guide, using candle light. A photographic postcard (Fig. 4) was produced after one of these excursions, titled *"Potholers [at] Bentham Camp"*.

Hainsworth (1995) also recalls that the artist who drew the cartoons for the postcards, Norman Feather:

> *"was a very good friend of my Father's, and a regular camper. I think he was on the staff of one of our Yorkshire papers."*

ACKNOWLEDGEMENTS

I am very grateful to Reginald Hainsworth for his reminiscences and for allowing the photograph to be reproduced; also to David St. Pierre of High Bentham who sent me a copy of Johnson's article.

REFERENCES

Hainsworth, R, (1955). Letter dated 28 October (1pp).

Johnson, D, (1995). Bentham Camp. *Bentham News*, Issue 107, September, p.4.

Figure 4. Bentham campers at the entrance of Long Churn Cave. The date of the picture is not known. Reproduced by permission of Reginald Hainsworth of Ingleton.

THESIS ABSTRACTS

HOLLINGWORTH, S., 1996

Copper tolerant mycoflora in the Alderley Edge Mine Complex

Unpublished BSc thesis, Manchester Metropolitan University, 97pp. [Available from S Hollingworth, 133 Wilton Rd, Manchester M8 4PD]

The Alderley Edge Mines are in an area of complex conglomerates containing a number of heavy metal ores, principally of copper and lead, with malachite and azurite being the principal sources of copper. Apart from known routes for conducted parties, the access to the mines is controlled and many areas have remained relatively undisturbed, thus creating an ideal environment for local adaptation. As copper derivatives form the basis of many anti-fungal preparations the evolution of tolerant fungi in the mines is of importance. Sites were selected in relatively undisturbed copper-bearing areas, to see if there was any development of copper tolerant mycoflora. As the rock is relatively soft, sites were sampled by removing small fragments into sterile containers for laboratory cultivation. Several species of fungi were isolated and initially identified through their fruiting bodies. Genus of *Penicillium spp., Cladosporium spp.,* and *Verticillium spp.* were isolated. Specific specie isolates included *Verticillium lecanii, Verticillium theobramae, Aureobasidium melangenum* and *Acremonium alternate.* Selected samples of the fungi were subjected to tests for tolerance to copper; they proved to be able to withstand higher concentration levels of copper than is normally expected. *Aureobasidium melanogenum* showed lesser tolerance than the other specimens. *Penicillium spp.* and *Cladosporium spp.* tolerated the higher copper concentration levels. All specimens though exhibited tolerance to copper. When observed under the microscope and with the naked eye the mycoflora appeared to have produced changes to its morphology, physiology and growth as copper concentrations increased. These results indicate that further research is necessary into heavy metal resistance in mycoflora.

ONAC, B P, 1996

Mineralogy of speleothems from caves in the Padurea Craiului Mountains and their palaeoclimatic significance.

Unpublished PhD thesis, University of Cluj, Cluj, Romania. [Available from the University and Speological Institute in Cluj; extended English abstracts are also available from the Libraries of UIS and BCRA.]

The thesis comprises an introductory section, which provides the reader with the basic geologic, tectonic and speleologic setting of the study area in the karst of Padurea Craiului Mountains and is then divided into a mineralogical/crystallographical study and a geochronological study. The mineralogical and crystallographical investigations were based on traditional and modern methods of laboratory techniques (X-ray, thermal, infra-red, scanning electron microscope and thermal ionisation mass-spectrometric analysis) and have given several new aspects concerning the morphology and origin of cave speleothems (for example, anthodites, oulopholites, fungites). Following detailed investigations on some moonmilk speleothems, a new classification system has been proposed. The results of this first part of the thesis lead into a discussion of the conditions of formations of the studied cave minerals and their morphology.

The second part (geochronology) is dedicated to speleothem dating and contains details of the 230Th/234U chronometer and its application. The various sampling sites (caves) are presented, as well as a list of uranium-series dates. Although there are relatively few data (65), a discussion of the distribution of the ages in time and with respect to Pleistocene climate has been undertaken. It is reported that the speleothems from the Padurea Craiului Mountains display less pronounced growth intervals than those from north-western Europe.

The thesis also examines the use of caves (via speleothem dating) to obtain rates of landscape evolution. The maximum average erosion rates for the Crisul Repede basin are in the range, 0.43-046 m/1000 years. These rates represent both glacial and interglacial conditions, and compare well with rates determined from other countries. A list of minerals which form cave speleothems is given in an Appendix. The list was compiled from the literature and updated with the author's investigations. It includes the mineral name, composition, crystal system and class, and frequency.

RUTHROF, K., 1996

Improving the Success of Limestone Quarry Revegetation

MSc (hons) thesis, Murdoch University, Western Australia [Available from the Department of Biological and Environmental Sciences, Murdoch University, W. Australia]

Several companies operate limestone quarries on the Swan coastal Plain of Western Australia, including Cockburn Cement which has quarries situated approximately 25km south-west of Perth. A post-mining rehabilitation programme is in use for its on-site quarries. Revegetation, one of the first major steps in the rehabilitation process, serves the purposes of reducing the risk of erosion and dust generation as well as minimising the unaesthetic nature of a quarry by using flora found in the surrounding bushland. Improving the success of revegetation is especially important when dealing with quarries in metropolitan regions, where public scrutiny and demand for space are more intense than in remote areas.

The objective of this study was to investigate the possibility of improving the success of revegetation of limestone quarries, using a diverse range of local flora, including species from the Tuart (*Eucalyptus gomphocephala)* forest and Banksia woodland. A systematic critical field analysis of a rehabilitated limestone quarry on Cockburn Cement's Russell Road Plant was completed. This, and a chemical analysis of the overburden topsoil mixture present in the quarry, provided information regarding plant growth constraints. It was shown that only 20% of species planted in the Cockburn Cement quarry were surviving. These included a number of Acacia species and *Eucalyptus gomphocephala.* The key growth constraints were shown to be very low levels of available nitrogen phosphorus.

Glasshouse trials were set up to test various soil amendments to increase the success and growth rate of local plants typically used in revegetation. Plant species were chosen from those which proved successful and those which had not performed very well in the Cockburn Cement quarry revegetation programme. Various nutrients required by the local plant species to increase their shoot dry weight in such a calcareous medium were identified by way of subtractive testing. Nitrogen and phosphorus proved important, especially if plants were grown on quarry floor material only. Iron, typically deficient in calcareous soils, did not negatively affect the dry shoot weight, though lime chlorosis was evident on *Eucalyptus gomphocephala* and *Acacia cyclops* when no iron fertiliser was added. In conjunction with the glasshouse trials, a field trial was set up in one of the Cockburn Cement quarries to test soil amendments on six local species. The trial suggested various practical methods of increasing survival and growth rates: the addition of organic matter in the form of sewerage sludge, adding topsoil from the surrounding bushland, and the addition of fertiliser as pellets and micronutrients. However, the sewerage sludge and off-site topsoil used in the field trial had the distinct disadvantage of importing weed species. Furthermore, success of these amendments was limited by the increase in grazing of planted species by rabbits.

Given these findings, the study concludes that improving the success of limestone quarry revegetation essentially requires the use of soil amendments such as topsoil and fertilisers. This improvement in success rate of local plant species has the potential for providing a more diverse floral composition in rehabilitated limestone quarries, allowing for the faster return of such areas to a near natural state.

BOOK REVIEWS

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

SLABE, T., 1995. *Cave Rocky Relief and its Speleogenetical Significance.* Karst Research Institute ZRC SAZU, Ljubljana. 128 pp, 138 illustrations, ISBN 961-6182-03-X, paperback.

Cave Rocky Relief comprises work by Dr. Tadej Slabe of the Karst Institute, Slovenia, into factors that shape underground karst. The study was carried out within the project Origin and Development of Karst Caves. Rocky relief is a term used to describe traces left by 'hydrological conditions and factors of cavernosity'. All examples of rocky relief are taken from caves in the Slovene karst. Although the names of the caves may be unfamiliar, they serve well in providing examples of specific rocky features.

Most of the book goes to describing the types of rocky features identified (Chapter 2); features formed by turbulent flow such as: scallops, flutes, ceiling pockets, potholes, columns, pendants, notches and channels. The role of cave passageway filled up by sediment is also considered, as is the influence of ice, condensation moisture, rock disintegration, guano, lichen and bears. The description of all these features, although suffering a little in translation, is comprehensive and combined with the use of clear and informative photographs. The origin and development of these features are also discussed. Here the author goes into some detail in discussing likely origins, tying in work by other authors. Plaster of Paris modelling was also used in an attempt to mimic conditions necessary for the formation of rocky features.

One of the objectives stated by the author is to use rocky relief studies as evidence of past hydrological conditions in the genesis of karst caves (Chapter 3). Rocky relief is used as an indicator of processes generated by the movement of water through conduit. Thus it is an indicator of processes occurring during the latter stages in cave development. Slabe considers the factors, conditions and processes of rocky relief discussed in Chapter 2 on a regional scale; implementing them to a number of case studies and building up a sequence of regional speleological history. The case studies take the form cross-sections of sites within Slovene caves. The rocky relief of each site was mapped in detail and considered with respect to present hydrological conditions. For each case the speleological history was then determined for the development of the selected caves within an aquifer.

Although the description and discussion of each form of rocky relief in Chapter 2 'The origin and development of cave rocky features' was thorough, Chapter 3 'Cave rocky relief - the evidence of formation and genesis' was less comprehensive. The relationship between geological setting and certain types of rocky relief, scallops in particular, discussed in Chapter 2 was not continued through to Chapter 3. When the case studies were considered it would have been useful for the reader to be aware of the geological setting in respect of tectonics and facies, as well as the horizons in which conduit development may have been initiated.

Reviewed by Leslie Brown, Limestone Research Group, Department of Geographical and Environmental Sciences, The University of Huddersfield, Huddersfield HD1 3DH.

SWEETING, M. M., 1995. *Karst in China - its geomorphology and environment.* Springer-Verlag, Berlin and Heidelberg, 1995, 263 pages. ISBN 3-540-58846-9. (No. 15 of Springer Series in Physical Environment). Price DM 198 (c.£90).

This slim book was Marjorie's "swansong". It was evidently in preparation for some years before her untimely death a year ago. She was one of a Royal Geographical Society group that visited China in 1976, opening up China to western scientific thought soon after their cultural revolution. With China containing the largest karst areas in the world there was scope for much interaction between western and Chinese scientific thought on karst processes. On her 15 or so visits to China Marjorie travelled widely and met most of the leading Chinese karstologists, notably Yuan Daxion of the Institute of Karst Studies at Guilin. This book is based on her co-operation with those Chinese scientists, and much of it is a summary of their literature - hitherto inaccessible to western scientists, even if they could read Chinese.

As a spin-off from Marjorie's visits, since the mid nineteen-eighties, there have been almost annual British speleological expeditions to various parts of China, during which the different approaches to speleological investigation have been obvious. Much of the western approach is concerned with pure exploration and with speleomorphological processes, whilst the Chinese approach is rather more practical, with an emphasis upon aspects of water supply, hydro-electric power and other engineering and economic projects. Surprisingly, Marjorie Sweeting refers only to the report of the first British expedition (Eavis and Waltham, 1986). One wonders why the post-1986 expedition reports were ignored?

Marjorie Sweeting's approach in this book has been to look at the whole geological history of each karst area in turn. Beginning with Palaeozoic sedimentation, virtually continuous carbonate sequences (with occasional palaeokarsts) suffered large scale tectonic stresses during Cainozoic times, as a result of the collision between the Indian and Asian plates. Broadly, as India moved northwards, central and eastern Asia were compressed and the Chinese structural blocks were squeezed sideways; the uplift of the Tibetan plateau is a geologically recent feature. Different areas experienced different amounts of uplift, faulting and folding. Couple the tectonic history with changing climates and there are marked contrasts in Chinese karst morphology. Little of China was glaciated, so the glacio-karst that is so familiar in the UK is unimportant there. However, there are vast areas and thicknesses of loess, and these blanket some karst. Much of the speleogenetic story is therefore very much longer than is normal in the UK, and disentangling tectonic and climatic effects is very much part of Marjorie's theme.

With this background the book should be essential reading for all karstologists, particularly those travelling to China. However, it has some shortcomings. For instance, it concentrates on the whole karst picture of each area so that caves receive a rather brief treatment. In spite of the vast areas and striking scenery of Chinese karst, the book includes only 36 photographs (and photograph 10 is upside-down). Many of the diagrams are reproduced from Chinese publications (with transliterated names etc.), and some of them are difficult to interpret - for instance, does Figure 39 demonstrate that there <u>is</u> or <u>is not</u> a relationship between depressions and structure?

All-in-all Marjorie Sweeting's book is a valuable and unique piece of karst literature that should be widely available. But - why such a ridiculously high price, which will put it way beyond the reach of most karstologists and many libraries?

Reviewed by Trevor D Ford, Department of Geology, University of Leicester, Leicester, LE1 7RH.

RESEARCH FUNDS AND GRANTS

THE JEFF JEFFERSON RESEARCH FUND

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

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

The award scheme will not support the salaries of the research worker(s) or assistants, attendance at conferences in Britain or abroad, nor the purchase of personal caving clothing, equipment or vehicles. The applicant 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.

Photography Group. This Group was launched with the publication, in December 1995, of *Underground Photographer*, 48pp A4 with black and white photos. The organisers plan to produce a regular newsletter covering photographic topics and featuring colour printing.

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, Jeff Jefferson Research Fund application forms, etc. are obtainable from the BCRA Administrator: B M Ellis, 20 Woodland Avenue, Westonzoyland, Bridgwater, Somerset, TA7 OLQ.