Cave and Karst Science

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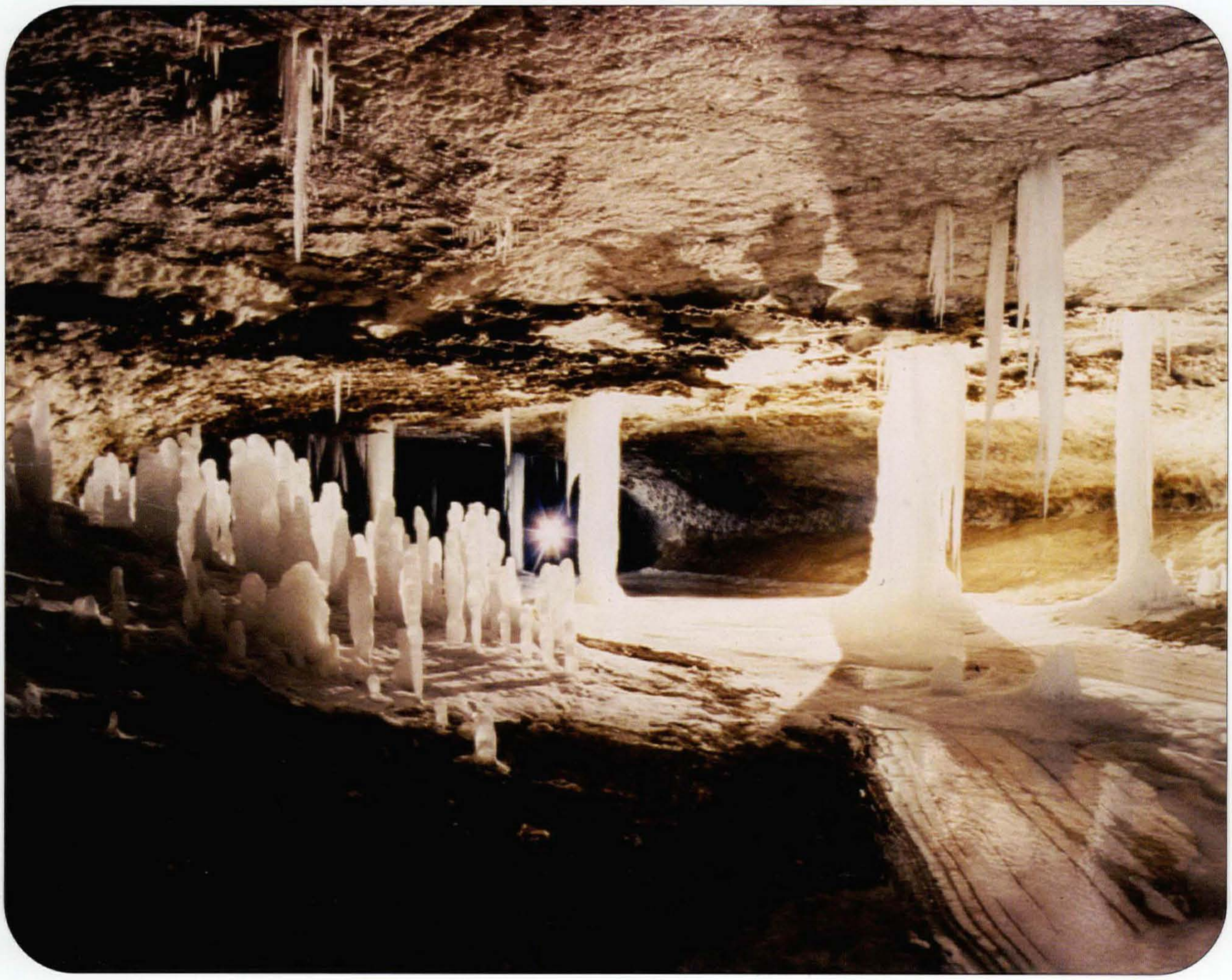

BRITISH CAVE RESEARCH ASSOCIATION

1973 - 1998

Cave and Karst Science

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

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

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Cave and Karst Science

TRANSACTIONS OF THE BRITISH CAVE RESEARCH ASSOCIATION

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Cover photo:
Lomonosovskaya, Pinega, Russia.
Photo by Tony Waltham (see article by Waltham and Cooper)
The main passage of Lomonosovskaya is an elliptical phreatic tube 3m high and over 12m wide cut in the massive gypsum. Pinega is close to the Arctic Circle, and each winter the gypsum caves are decorated by beautiful ice formations.

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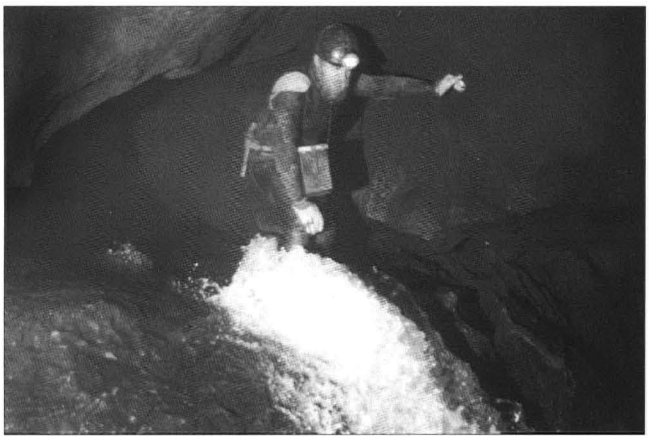
EDITORIAL

Dave Lowe and John Gunn

It was with some relief that we finally witnessed the birth of *Cave and Karst Science* Volume 25(2). This latter issue, dealing with various aspects of research in the Bahamas, was conceived to provide a tribute to the achievements and inspiration of the late Rob Palmer. Being essentially thematic, its pool of source material was simultaneously rich but restricted, and the need for liaison between a disparate team of busy contributors, a collating author, numerous academic referees and the normal editorial and publishing team ensured a longer than average gestation for the issue. It is somehow ironical that during the period between our agreement to publish a thematic issue celebrating the contributions of one particularly gifted personality and its eventual arrival, at least two more, equally memorable, characters have been lost to the world of cave and karst science.

Of the two, Alfred Bögli was the more widely known and scientifically respected in the international karst arena. Soon after hearing the sad news of his death in mid-1998 we approached a spectrum of contemporary scientists around the world, inviting them to produce short, personal memories or tributes, describing the man himself and his impact upon their own work and cave and karst science in general. A selection of these contributions, together with some of our own words, is presented between this Editorial and the first paper of this issue.

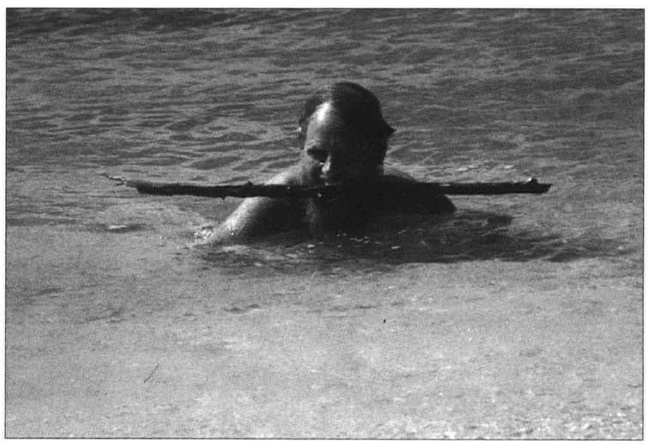
More recently, the British cave and karst community was shocked by the news of the premature death of Pete (PB) Smith, in mid-November 1998. PB was not an international cave scientist in the mould of Alfred Bögli, but for many years he has been an almost legendary character in British caving. Many of those who knew him as an outspoken and dedicated cave explorer and digger may be surprised to learn of his long-standing contribution to cave science in the United Kingdom and, to a lesser extent, overseas. For this, and because PB was well known to both of us, we make no apology for including the following photographs and personal thoughts overleaf, to close this Editorial.



PB in the Lower Bung Series, Speedwell Cavern, 1984 (Photo John Gunn).

The Tonga '86 team, with PB second from the left (Photo Dave Lowe).

PB (right) surveying in Third Cave, 'Eua Island, 1986 (Photo Dave Lowe).



PB, retrieving a stick from the Pacific Ocean, 1986 (Photo John Gunn).

P B SMITH – "MASTER CAVER"

(1938-1998)

In common with others who had the 'pleasure' of caving with PB over a number of years, I have many memories of an inimitable character and greatly regret that I will never again pick up the 'phone to hear the immortal words: *"Master Caver here!"*. I could tell many entertaining stories about caving trips in Derbyshire, our 1986 expedition to Tonga and his later attempts to teach me to ski. Instead I will say a few words about what is probably the least known aspect of PB's contribution to caving - his involvement in our scientific work at Castleton and elsewhere in the Peak District.

As I have commented frequently to colleagues who have never ventured underground, caving is unique amongst sports in the contribution that its participants make to science. It is, of course, a truism that without cavers there would be no cave science, but I know that my research has benefited enormously from the help of many cavers and, particularly, from PB. Whenever there was a need for a weir to be constructed, a stilling well to be installed, or some other piece of underground engineering, it was to him that I turned, and he was always helpful. My team were quickly introduced to PB's unique way of working, and specifically to 'gobbo' and the wonderful things that it could do to cement. As is so often the way with cave science, things did not always go according to plan, and there is no doubt that without PB's efforts various instruments would never have been installed. Following on from the early hydrological research PB played an important role in supporting cave radon research. Characteristically in the latter context, he also took the opportunity to explore areas that are normally off limits, while helping with the installation of ventilation systems in various show caves!

PB was a great guy to cave with and to work with, and he will be greatly missed.

John Gunn

To me PB was always a mystery. He'd simply always been there and it felt that he always would be. Before we went to Tonga in 1986 I asked him why he had never joined a distant expedition. He replied simply and without bitterness – *"Nobody ever invited me"*. Among my many memories of PB from before, during and after the Tonga expedition, that one statement stands out as especially significant, because it speaks of a paradox, and a side of PB that was not always obvious. On the one hand PB seemed to have been everywhere and done everything. He knew everybody that mattered and they knew him. He had an appropriate story for every situation and occasion. Yet, he had waited, goodness knows for how many years, to be invited to join an expedition outside Europe. His activities were famous, or perhaps infamous, among his chosen circle, but seemingly he could not have been accused of being too "pushy".

From the standing-room-only area at the back of Sheffield Crematorium chapel on 1st December 1998, I looked around at the throng assembled to pay their respects to PB. The spectrum of ages and backgrounds represented was astonishing. Though few can have needed to be reminded, we were reminded during the address that all of us must have our own memories of PB, and know a wealth of "PB stories". I couldn't even begin to estimate just how many such memories and stories must have been reactivated during those brief and inadequate moments. These days the word "unique" is commonly overworked, but to me PB was, and remains, a unique and irreplaceable character. With him I was privileged to spend time that was sometimes exciting, sometimes exhausting, sometimes hilarious, sometimes frustrating but never dull. All of it was time well spent.

Dave Lowe

†

ALFRED BÖGLI

(1912-1998)

Alfred Bögli was born in Bern and studied geography, geology, petrology and mineralogy from 1931 to 1937, qualifying as a teacher in a secondary school in Bern in 1935 and in Luzern in 1937. In 1939 he took a geography degree in Friburg. During that time he studied the glacial morphology of the Alps, as well as morphogenesis, hydrography and karst morphology. In 1945 he joined the Group for geomorphological research of the Swiss Alps, and in 1962 started to compile geomorphological maps for the Swiss Atlas. In 1965 he took charge of geography, karst geomorphology and hydrography courses at the University of Frankfurt, becoming an honorary professor in 1967. From 1969 he delivered physical geography courses at the University of Zürich.

Just after the 2nd World War he began research in the Hölloch, where he devoted much of his time. In 1949 he co-operated as a geologist with the Research Group of the Swiss Alpine Club. After being appointed scientific director of the Speleological Group of the Hölloch in 1951, he became general director of the cave in 1959. The explorations that he led covered and mapped much more than 100km of cave. Astonishingly, in 1969 he spent more than 5,400 hours in the cave, about two thirds of the hours in a year!

Bögli became an internationally recognised expert on karst phenomena, and was entrusted with various related tasks. He was, for example, a member of the International Geographical Union Commission for Karst Phenomena, the first foreign member of the Cave Research Foundation (USA), and a member of the Union Internationale de Speleologie Commission for Karst Terminology. He also carried out research in Jamaica and the USA. Nevertheless, the contribution that placed Bögli among the Greats of speleology, was his elaboration of the theory of mixture corrosion, with his first publication on the subject in 1964.

In 1969, at the 5th International Congress of Speleology in Stuttgart, I reported my regret that the theory seemed unappreciated and held in poor regard. In particular, I compared the importance of the mixture corrosion theory in speleology with that of Einstein's relativity theories in physics. Though gratified by the comparison, Bögli requested its removal from the text for publication in the proceedings, because he thought it was exaggerated and would attract criticism from other colleagues. To his regret it was too late to modify the text, and the original version, including the rich appreciation of the theory's importance, was published in the proceedings. To my knowledge, no censure of him resulted from my words and therefore, while regretting any embarrassment it caused him, I now rejoice at what happened.

I have long been convinced that investigation and development of the mixture corrosion concept was the first example of how a fundamental theoretical idea can help explain natural phenomena, such as many aspects of the karst. The lack of immediate acknowledgement of its potential significance reflects a formerly widespread mentality among those whose thinking tended to rely exclusively upon observations of nature, excluding any quantitative check involving mathematical formulae. Only later, as the older generation disappeared, did younger workers appear, who were more open to accept formulae and symbols. Consequently, the ideas that Bögli developed finally received the recognition that they deserved.

All the community of cavers and those with an interest in karst regret the loss of a great colleague and a good friend, who gave us new views with his teaching. We express our sympathy to the Bögli family.

Arrigo A Cigna
Cocconato
Italy

"A new scientific truth does not triumph by convincing its opponents and making them see the light, but rather because its opponents eventually die, and a new generation grows up that is familiar with it."

[Max Planck]

✝

To become involved in the science of speleology one needs two prerequisites. First is a passion for the underground world and its fascination and adventure. The second is a desire, to achieve an understanding of this wonderful world, by gaining insight into how it is shaped by the natural laws of physics and chemistry. Alfred Bögli was a most important example to me, when I started to make my way into speleology. His book *"Im Banne der grossen Höhle"* ["Under the spell of the great cave"] presented an inspiring journey into the emotional world of caving, which in turn motivates sober scientific thinking and brings knowledge. That was exactly how Alfred Bögli progressed. The outcome was publication of his textbook *"Karst hydrology and physical speleology"*, which provided a scientific milestone by introducing quantitative physical chemistry to the understanding of karst and its morphology.

I met him only twice. The first time he guided an excursion through his Hölloch, in Switzerland. His vivid personality and his inspiring explanations impressed me. Of course we discussed mixing corrosion. I had just published an article confirming that this mechanism can form cavities. Later, with advances in the knowledge of dissolution kinetics, it turned out that caves can also form without mixing corrosion. We discussed this later, when we met at a party in the Dechenhohle in Germany. Although by then he had reached the great age of 80, his mind was open to these new ideas, but he was also a little bit disappointed! I owe him a great deal; his pioneering work laid the stable foundations that supported my first steps into the science of speleology.

Wolfgang Dreybrodt
Bremen
Germany

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During the 20 years after the Second World War, when Alfred Bögli was already known as one of the world's leading karst scientists, some influential Slovenian geomorphologists still considered dissolution to be a marginal process in karst development. Bögli's contributions to the systematic recording of knowledge about dissolution, and his own additions to this knowledge, gained great support when systematic field measurement of dissolution in different environments began in Slovenia. Interest was attracted particularly to Bögli's interpretation of dissolution by rainwater on the rock surface as a process of establishing pCO_2 equilibria between free air and water. His classification of Karren was generally adopted in Slovenia, where attempts were later made to use the depth of Rillenkarren as an index of their age. Bögli's development of the Mischungskorrosion concept was also adopted widely in Slovenia, as it provided a much-needed explanation of some previously unexplained speleological features.

During this phase Alfred Bögli's ideas were among the most advanced in karst geomorphology. His monograph *"Karsthydrographie und physische Speläologie"* (1978) included a main chapter *"Speläometeorologie – Speläoklimatologie"* and at that time most participants at the Yugoslav speleological meeting saw no need to introduce this "new" classification of climatology. Here again, with his international reputation and numerous publications, Alfred Bögli helped us, by paving the way in advancing modern karst research methodology.

Alfred Bögli visited the more important karst features in Slovenia several times, and discussed ideas with researchers at the University in Ljubljana. As the co-ordinator of a planned karst monograph he invited me to contribute a section on poljes and other surface forms. Unfortunately the publisher abandoned the plan, and although Bögli did not collect any royalties, he intervened to ensure that due payment was made for my work.

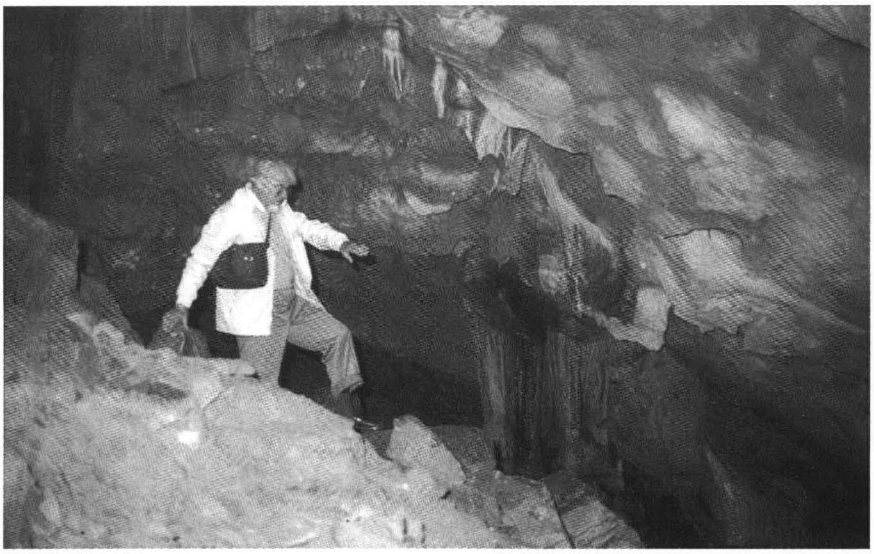
Ivan Gams
Ljubljana
Slovenia

✝

There is no doubt that Alfred Bögli achieved "legendary" status amongst karst scientists, for his work on karren and on mixture corrosion, and amongst cavers for his exploits in the Hölloch. I have memories of both aspects of his character, but not for the reasons that one might think. I remember, as a fledgling lecturer, the feeling of pleasure when receiving the first offer from an international publisher to review a new book – the English version of *"Karst Hydrology and Physical Speleology"*. I also remember my horror as I began the first reading and realised that my "O-Level" 'Physics with Chemistry' was going to be stretched beyond its limits! Bögli was certainly a physical geographer who saw the need to apply the laws of physics and chemistry, long before the majority of his peers. He never seems to have received full recognition for this, but he was surely one of the first 'Process Geomorphologists'.

My second memory is of meeting the man for the first time in 1984, at a seminar organised by Camille Ek in Liege. The details of the seminar itself have become hazy, but I well remember a sprightly 72-year-old striding through Remouchamps Cave and wandering off the path to investigate an area of breakdown (see photo). I also remember him taking a grandfatherly interest in the two youngest participants on the trip, my daughter (aged 2) and son (aged 4 months)! Bögli loved his caves, his karst and his science, and it is appropriate that this journal honours him as an exemplary cave and karst scientist.

John Gunn
Huddersfield
UK



Alfred Bogli investigating breakdown in Remouchamps Cave, Belgium, in 1984.

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Few in the world of speleology and karst research are unaware of the extensive and varied contributions made by Alfred Bögli. To many though, he remains best remembered for his descriptions of the theoretical background of, and physical evidence for, carbonate corrosion by mixing waters. We now recognise that Soviet authors had previously discussed mixture corrosion, but their Russian language publications apparently went unnoticed by "western" researchers. There is no doubt that Bögli's work was, to all intents and purposes, original.

My personal memories of Bögli are limited. In 1971 the caving club at Birmingham University was invited (by Gordon Warwick) to attend a potentially interesting guest lecture in the Geography Department. The caving club had no geographer members, and a few cavers sat isolated and clannish at the back of the room, spellbound and fascinated, as Dr Bögli raised and answered questions about cave development that they had never even considered. Perhaps the fundamental importance was lost on some attendees, but seeds were sown in other minds, and his words and pictures fired imaginations. That the impression he made that day was profound is reinforced when I remember that, when he presented essentially the same talk at a Cave Research Group seminar soon afterwards, I sat through it again, with undiminished interest, and greater understanding both of the topic and its potential magnitude. The seeds he sowed in 1971 undoubtedly led to the start of my own transformation from a caver to a cave scientist.

Bögli's mixture corrosion ideas were first published widely in "the West" in 1964, and no doubt their significance was obvious immediately to some readers. However, my recollection is that mixture corrosion "arrived" in Britain with those talks in 1971. Thenceforward, and no less today, no cave development discussion was complete without reference to its potential role.

Dave Lowe
Nottingham
UK

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When a great person passes on, we find ourselves trying to assess the meaning of greatness. "Fred" Bögli has certainly achieved that status, but what is his most enduring legacy? Surely the concept of Mischungskorrosion (mixing-solution), his classification of karren forms, and his book on physical speleology are his greatest scientific achievements? A pragmatist could, however, point out that he was not the first to recognize the importance of mixing-solution, and that much of his other work has been superseded by more recent research. What, then, does endure?

My thoughts drift back to the late 1950s, when I first read Dr Bögli's riveting article *"The Hell Hole in the Muota Valley"* in the NSS Bulletin. He had begun his karst studies relatively late in his career, while I was only an impressionable teenager. But I'll never lose the thrill that he was able to convey in his spare, understated words about the cave that dominated so much of his life. In later years it was clear from his several popular and well-illustrated books that, for him, exploration was as important as science. And finally, his painstaking methods, deep immersion in field work, and drive to explore and understand his enormous cave show a passion that is all too rare in science. To me, that is Alfred Bögli's legacy - a deep love of caves and karst, passed from one generation to the next.

Arthur N Palmer
Oneonta
USA

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The geo-ecology of three Hungarian karsts

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Abstract: The sensitivity of karst systems to human activities has become increasingly apparent as a result of research during the 1980s and 1990s. Environmental processes are very rapid on karst, and non-karstic materials integrate quickly into the karst system, modifying and damaging the natural processes and forms. This paper presents some results of research into karst geo-ecological systems in three Hungarian karst areas.

(Received 26 May 1998; Accepted 10 December 1998)

INTRODUCTION

The environmental impacts on karst regions have to be analysed, since these processes are very rapid. Non-karstic materials can integrate quickly into the karst water system, modifying or damaging the natural forms that have been developing for millions of years. Karsts are therefore especially sensitive geo-ecological systems and research on different aspect has been encouraged since the 1980s (Jakucs, 1980, 1987; Bárány-Kevei, 1976, 1985a,b, 1987; Pfeffer, 1990; Hardwick and Gunn, 1966; Tranter, Gunn, Hunter and Perkins, 1997).

The first sphere of the karst-ecological system is the air just above the surface, where there is a karst microclimate. While macroclimate is responsible for the quantity and intensity of precipitation, the microclimate modifies the quantity of water infiltrating into the rocks. Microclimate also affects the development of vegetation, influencing in turn the quantity of CO_2 produced during root respiration. The microclimate of the air just above the surface influences soil temperature and humidity. Millions of micro-organisms live in the soil, changing the components of the soil-air through the decomposition of organic materials and through their own metabolism. They also indirectly influence soil physical and chemical soil properties, which influence the quality of seepage water, leading to corrosion processes of different intensities. The inner dynamism of soil can prevent extreme changes occurring in the system (through buffer ability and redox potential), though it cannot compensate for the long duration of the processes. The inner dynamism of soil can change on the long term, possibly leading to a malfunction in the whole system. The changes due to external forces are reversible down to the rock boundary. However, when they have entered the rock layer become irreversible. Water in the rock layer (the aquifer) is the primary transporting agent of materials and energy. This water reaches the surface again in karst springs and if polluted, its value of exploitation economic and ecology is decreased. Another irreversible process, the degradation of dripstone can also occur due to polluted water entering the cave (Jakucs, 1987).

On the basis of the above, the karst-ecological system may be defined as: a structured and dynamic system in which rock, soil, microclimate and macroclimate represent the abiogenic elements, while microflora, macroflora and -fauna represent the biogenic ones. The inter-relationship of the biogenic and abiogenic elements, along with the material and energy flux occurring in this interrelationship maintain the development and movement of the system. Its structure is defined by the vertical and horizontal distributions of its elements. Its specific features include its sensitivity, the rapidity of its processes and its three-dimensional surface of effects (Fig.1).

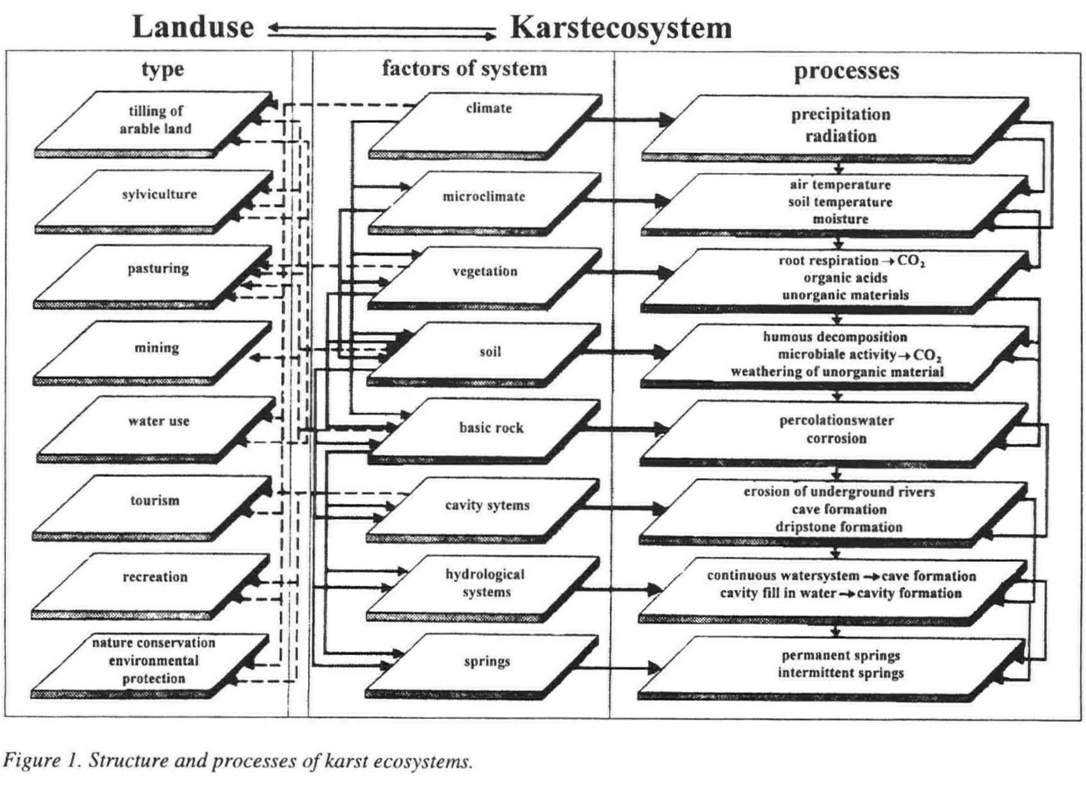

Figure 1. Structure and processes of karst ecosystems.

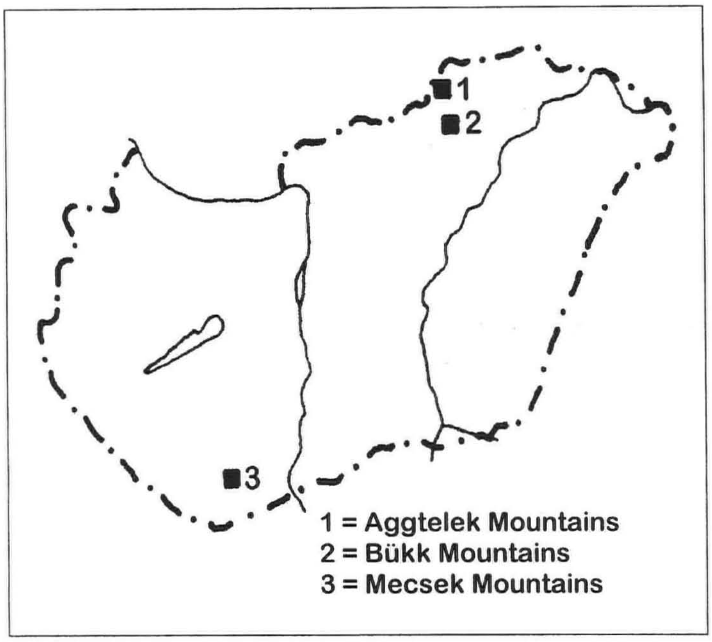

Figure 2. Outline sketch map of Hungary, to show approximate relative locations of the three karst areas discussed in the text.

Karst dolines provide an excellent basis for the study of these interrelated processes. The ecological survey of karst dolines is especially important, as these depressions are the most endangered points in many karst systems, where they provide concentrated recharge.

The present study compares the geo-ecology of three areas in Hungary: the Aggtelek Hills, the Bükk Mountains and the Mecsek Mountains (Fig.2). Most of the Mecsek and Villanyi karst areas have been changed by human activity (coal mining and quarrying). In contrast the karst region of the Bükk Mountains has retained most of its original character, owing to the protective impact of the Bükk National Park. This has been a conservation area much longer (23 years) than any other karst region. The Aggtelek National Park has existed for 13 years and thus human impacts are relatively small. However, due to, grazing, other agricultural activity and forestry prior to the conservation act, some traces of human impact can still be perceived. Now that Baradla Cave, with its Domica Branch on the Slovakian side of the national border has became a World Heritage Area (1996), geo-ecological investigation of the karst cannot be neglected in considering landscape protection issues.

METHODS

The general research methodology adopted is applicable to all kinds of karst regions. When investigating the individual components of the geo-ecosystem (soil, microclimate, vegetation and microbial activity) the methodology developed in each scientific field can be applied. Various parameters of soil samples from outcrops were analysed in laboratory: grain composition (aerometrical analysis), carbonate content (Scheibler's calcium-meter), pH value (digital pH meter), hydrolic acidity (titration), heavy metal content (Perkin - Elmer atomic adsorption spectrophotometer). Nutrient analysis and the definition of the water-soluble ions were carried out at the MÉM NAK Institute at Hódmezõvásárhely according to Hungarian standards.

Microclimate monitoring was also undertaken at each site. The following parameters were measured: soil temperature at 5 and 30cm (electric resistance thermometers), sunshine hours (Campbell-Stokes radiation meters), wind velocity (anemometer), air temperature (Assmann's psychrometers).

In each doline vegetation was surveyed using five quadrats, one on each of the north, east, south and west slopes and one on the bottom. Species present and percentage cover were both recorded. The karst vegetation was evaluated using the ecological indicators (water budget, heat budget, soil reaction and nitrogen demand) given by Zólyomi (1966) based on the known community composition. A survey of the microflora (defining the number of aerobic and anaerobic bacteria on agar nutritive soil) was carried out at the Microbiological Department of the Attila József University, Szeged.

DISCUSSION

The relationship between soil, microclimate and vegetation was investigated, as these elements influence the entire karst system.

The ***physical and chemical characteristics of karst soils*** are of importance from the viewpoint of karst ecosystem changeability. Soils can buffer extreme impacts, though in the case of very strong influences they may intensify the impacts, because enzymes entering the soil stay there for a long time. The inner dynamism of the soil is independent (Szabó, 1995). Dynamism is expressed first in the soil chemistry, which influences the development of soil aggregates (structural soil elements). The structure and texture of soil define its air, water and heat budgets. However the chemical and physical features change in relation to biological activity.In Hungary as a whole there is little variation in the *physical quality* of the karst soils, which are unconsolidated, immature soils developed primarily on solution residue or on loess-like sediments. Their dominant fraction is loam (50-60%), whereas the sand fraction is poorly represented in the Bükk dolines. The soils at Aggtelek are poorly sorted, too and their clay content is 20%, higher than that of the soils in the Mecsek karst region. This considerable clay content is due to the dolines at Aggtelek being older than those in the Mecsek Mountains. These soils have a large capacity for water storage. The thick clay-rich sediments can eventually become impermeable and in karst depressions clay sedimentation makes the effects of karst corrosion move towards the edges, so that dolines become wider rather than deeper.

The pH, acidity, alkalinity and $CaCO_3$ content describe the ***chemical state of soils***. Water-soluble anions and cations, which are important in karst corrosion, are also chemical properties of soils.

Soils in the Mecsek and Aggtelek mountains. are mildly acidic (average pH 6.0 - 6.5) with those at Aggtelek slightly more acidic (0.3 - 0.4) (Bárány-Kevei, 1992). At several sites values of 5.0 were recorded, indicating that acidification was occurring (in the summer of 1995 *Calluna vulgaris* was found on the karst surface at Aggtelek). At the same time it is known that soils formed on limestone are generally non-acid. To investigate occasionally low pH values the difference between the pH of solutions of soil mixed with (a) water and (b) potassium chloride were measured. An increase in the difference between the two pH values indicates acidification of the soil (Stefanovits, 1981). The difference between the two pH values in soils from dolines in the Bükk, Aggtelek and Mecsek mountains indicates that they have been acidified. Since there is a tendency for acidification to occur at sites where direct human impact is low (e.g. in the Bükk National Park), it is most probably the result of acid deposition.

Analysis of ***water-soluble cations and anions*** can be used to describe the chemical state of the soil. As would be expected, Ca^{2+} cation content is high in karst soils, but K^+, Na^+ and Mg^{2+} are also abundant. SO_4^{2-} anions are abundant, together with significant quantities of Cl^- (Bárány-Kevei, 1987). There is a general tendency for cations and anions both to be found on the slopes near the edges of the dolines, rather than in their floors. The minimal quantity of ions deposited in doline floors indicates the intensity of leaching at this level.

The large volume of ***heavy metals*** present in the soils may indicate ecological change. For example, analysis of heavy metal concentrations in soils on a karst area in the English Peak District, carried out by Colbourn and Thorton (1978) and by Xiandong and Thorton (1993), *Heavy metal content at Aggtelek:*

	Al (ppm)	Zn (ppm)	Mn (ppm)	Fe (ppm)	Co (ppm)	Ni (ppm)	Pb (ppm)	Cu (ppm)
N slope	23575.0	148.75	2125.0	27150.0	17.5	37.75	54.75	57.4
E slope	34055.0	96.250	1225.0	32115.0	24.35	36.45	38.25	18.5
W slope	29695.0	100.0	1587.5	3028.75	23.4625	33.6125	27.75	18.75
Lake Vörös Depression	35462.5	76.25	1400.0	75873.75	35.0	33.25	162.5	28.25
SW slope	26912.5	126.25	1487.5	29670.0	20.25	32.225	78.75	32.5

Heavy metal content in the Bükk Mountains:

	Al (ppm)	Zn (ppm)	Mn (ppm)	Fe (ppm)	Co (ppm)	Ni (ppm)	Pb (ppm)	Cu (ppm)
E slope	30767.5	105.0	1250.0	28882.5	19.4874	31.425	55.5	28.25
Doline floor (20cm)	21115.0	118.75	1450.0	19413.75	12.1125	20.9125	46.25	19.25
Doline floor (80cm)	25572.5	123.75	2000.0	26917.50	23.325	24.275	52.5	22.25
pinewood	23687.5	75.0	837.5	21243.75	21.5625	21.44375	52.875	12.0
NE slope	28082.5	211.25	2087.5	31175.25	16.575	35.325	58.25	50.0

Heavy metal content in the Mecsek Mountains:

	Al (ppm)	Zn (ppm)	Mn (ppm)	Fe (ppm)	Co (ppm)	Ni (ppm)	Pb (ppm)	Cu (ppm)
S slope	18865.0	67.5	737.5	22132.5	15.425	22.725	18.25	14.25
N slope	18470.0	65.0	787.5	22547.5	15.4	24.425	37.5	15.0
W slope	24045.0	76.25	400.0	32727.5	14.45	23.2	7.75	10.25
E slope	18990.0	70.0	662.5	22216.25	15.425	24.3	26.25	11.25

Table 1. Heavy metal analysis of the three dolines.

suggested that metal enrichment levels within the soil are affected by the nature of underlying mineralised rock, past mining activities and smelter pollution. In the present study, heavy metal analyses were performed on soil samples collected from three dolines, one in each of the Aggtelek, Bükk and Mecsek mountains (Table 1).

Heavy metal concentrations are higher in all three karst samples than they should be if originating from the parent rock alone. The limestone is relatively pure, so the heavy metal content of karst soils can come only partially from the rocks, and contamination must originate from dry and wet deposition.

The intensity of ***microbial activity*** is affected by the pH and ion content of the soil. There are millions of soil microbes (bacteria, ray fungi and microbial fungi) in 1g of soil. More than two thirds of the CO_2 emitted in soil comes from the decomposition of organic material, and only one third comes from root respiration. The most intensive CO_2 production takes place in the upper 20 to 30cm soil layer, as a result of aerobic bacterial activity. This is dependent upon the temperature and humidity of the soil. If the temperature is low (e.g. lower than 20°C) bacterial activity decreases. Low soil humidity (e.g. less than 20 to 30 volume percent) also reduces microbial activity. The soil is thus a very complicated, dynamic system and a small change in any factor may result in larger changes due to positive feedback mechanisms.

Soils from Bükk and Aggtelek (in both of mountain ranges 16 to 20 samples were collected from each doline) were not found to be advantageous for microbial activity (Kevei-Bárány and Zámbó, 1988.). In soil beneath forest cover (brown-earth-like soil) there are typically 15 to 20 million bacteria in 1g, with much fewer in grassy eco-systems (in rendzina-like soil). There is a significant relationship between the number of bacteria and soil temperature in the upper layers of doline soils. In deeper layers, however, the number of bacteria correlates more closely with humidity than with temperature.

Research in the Aggtelek Karst in the summer of 1995 demonstrated that the number of microbes is greater near the surface of the soil, and that microbial activity is more intense in forest associations than elsewhere (Fig. 3). The quantity of CO_2 emitted by microbes is an important ecological parameter. The three soil profiles investigated (1/1 = near-surface, 1/2 = middle level of the profile, 1/3 = lower level of the profile) are situated in the upper 60 to 70cm of the soil.

Vegetation cover exercises a strong influence on the processes in karst soils. Karst shrub woods (Orno-Cotinion) are characteristic of Hungarian karst areas. An adaptation of the Central European mountainous beech wood (***Fagion medio-europaeum***) covers the karst surface above 700m elevation in the Bükk Mountains. It has a Central Range-type vegetation that passes down into the oak belt. There was extensive clearing of the forests in the Central Range during the early part of this century. Barren karst surfaces, which appeared after deforestation, can still be recognised in some areas, but they are not common in Hungary. Only traces of the deforestation can be recognised in the very slow natural re-forestation of the dolines. In most of the dry valleys juniper took over following deforestation, and this demonstrates the low nutrient availability within the soil. The originally diverse doline vegetation is increasingly becoming more uniform. Grazing has contributed significantly to the decline of species diversity.

The species composition of the vegetation in the Bükk dolines reflects the common features of the karst. Mapped species include those characteristic of mountain and sub-montane beech wood as well as steppe meadow, rocky and pusta grassland slopes, tufted grass and montane hayfields. The average values of the ecological indicators (water and heat budgets, soil reaction and nitrogen demand) are presented in Fig. 5 on the basis of sampling dolines in the Bükk Mountains. There is no significant difference between the heat budget and the vegetation species found in the Bükk dolines, but as this area is a micro-region, even the 0.45 difference cannot be neglected. The higher heat budget value recorded on the N slopes demonstrates the

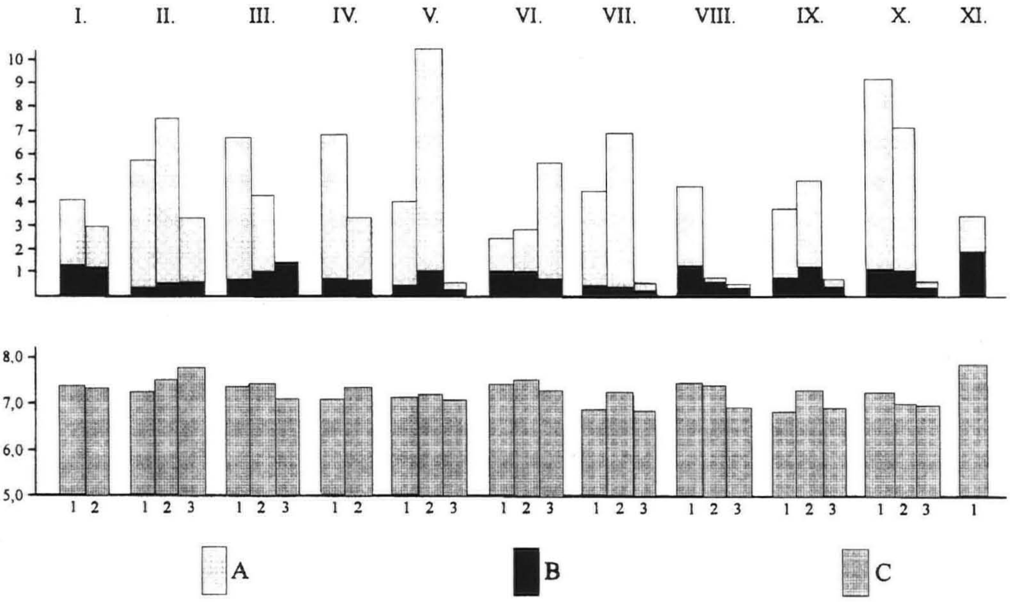

Figure 3. Number of bacterium and pH values in soils of Aggtelek doline (1995). I = Bottom of doline, II = N slope, III = E slope, IV = bottom of W slope, V = Middle of W slope, VI = top of W slope, VII = wood on upper part of W slope, VIII = top of S slope, IX = W slope of Szár Mountains, X = bottom of E slope, XI = middle of E slope. A = number of aerobic bacteria (10^6/g), B = number of anaerobic bacteria (10^4/g), C = pH value.

relative aridity of these slopes and this influences all other ecological factors. The effect of exposure is also clear in the analysis of the water budget indicator. Its average value is 6.62 in the northern and 2.82 in the southern halves of the dolines, showing the slope-dependent distribution of soil humidity. Like heat and water budgets, the differences in soil reactions are also significant (Bárány-Kevei, 1985).

The ecological values measured at Aggtelek differ from those measured in the Bükk Mountains. Species requiring less nitrogen are more abundant at Aggtelek, due to intensive grazing having increased the nitrogen content of the soil in the former area. Many species present were not members of the original species association. Average indicators of the water budget show temperate-fresh and temperate-dry characters.

The dominant factor of karst formation and development is ***climate***, but the ecological factors are influenced to a greater extent by ***microclimate***. In the Hungarian karsts microclimatic systems influence trough-specific orographic and morphological conditions. The independent microclimatic areas of karst dolines are most characteristic where the microclimate modifying effect of exposure prevails side by side with the effect of enclosure of the depression (Bárány, 1976; Bárány-Kevei, 1985). The differential warming of the various slopes according to aspect results in important differences in the energy input and temperature of the soil. Fig. 4 shows the change in Aggtelek doline soil temperature during August 1996. Differences in temperature affect both the microbial activity and the composition of the macroflora. Temperature conditions of the west and northwest slopes are found to meet the demands of bacterial activity the best. The high humidity and low temperature of the south slope, and the strong radiation input of the north slope prevent the bacterial population from increasing significantly. If the whole ecological system is considered, this results in a slower decomposition and transport of organic materials on the south slope than on the others.

CONCLUSIONS

The physical and chemical characteristics of karst soils exert an important influence on change in karst ecosystems. Soils can buffer extreme impacts, though in cases of very strong influences they themselves serve as agents that may intensify impacts, in ways that may be either advantageous or deleterious. Because enzymes from micro-organisms enter the soil and remain there for long periods, the inner dynamism of soil is independent.

The difference between the pH values of soils mixed with water and with potassium chloride indicates acidification in dolines in the Bükk, Aggtelek and Mecsek mountains. The higher the clay and organic material content, the more heavy metals are bound to the colloids. Neutral soils usually absorb heavy metals, whereas in strongly acidic soils most of the metals enter solution.

Biological processes have a feedback effect on the chemical properties of the soil through the decomposition of humic materials, so

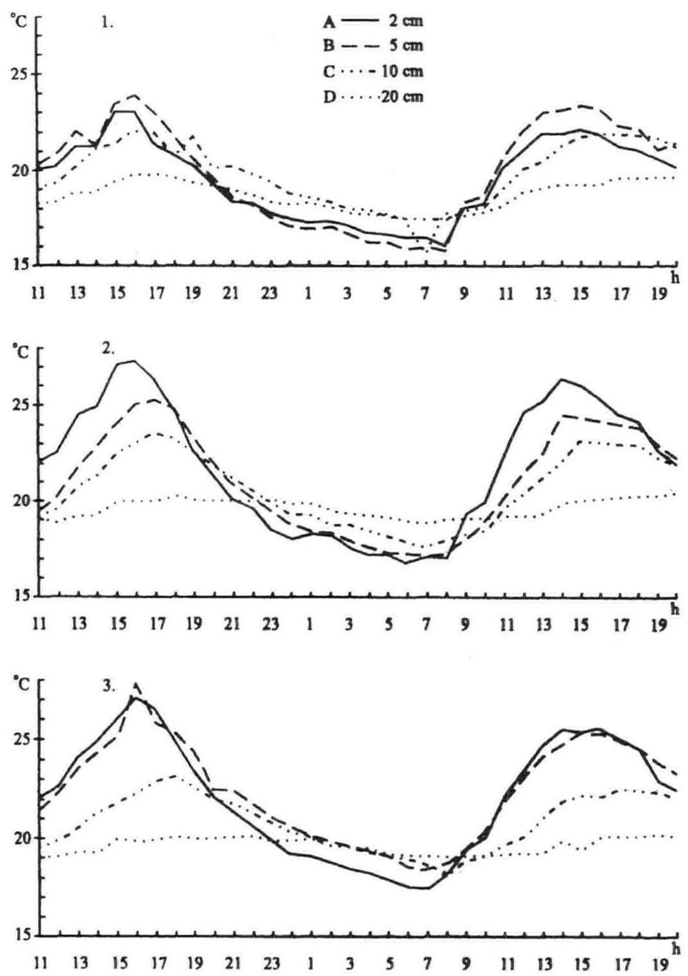

Figure 4. Change of temperature in the soil of an Aggtelek doline (August 1996)
1 = bottom of doline, 2 = middle of E slope, 3 = top of E slope.

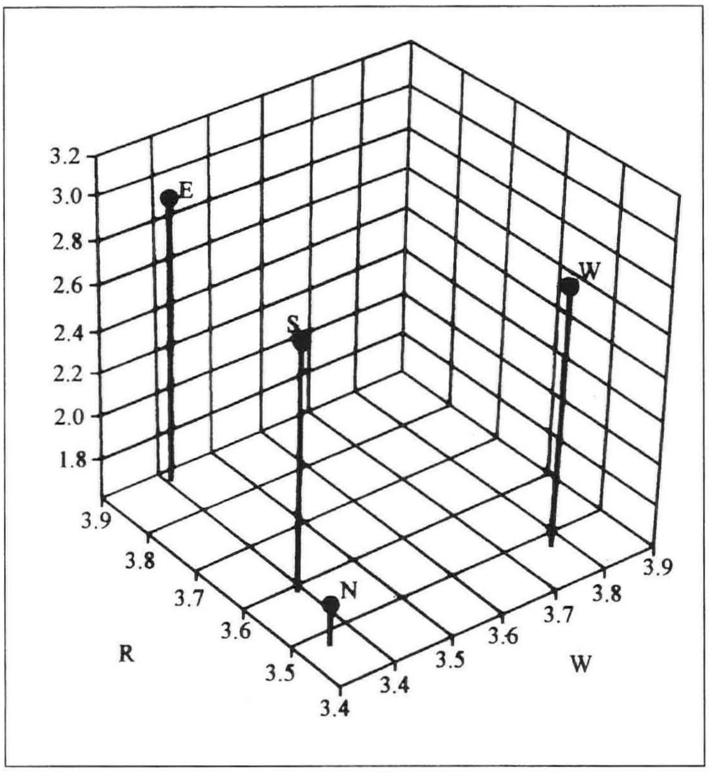

Figure 5. Ecological indicators of vegetation in Aggtelek doline.
W = water budget, R = soil reaction, N = nitrogen demand.
N = northern slope, E = eastern slope, S = southern slope, W = western slope.

upkeep of the natural bacterial populations and conditions is desirable. There is a significant relationship between numbers of bacteria and soil temperature in the near-surface layers of doline soils. In deeper layers, however, the number of bacteria correlates with humidity rather than temperature.

The vegetation has developed on karstic rocks with rendzina and clayey soils. The species have developed associations that can adapt to the extreme water budget of the soil. If the vegetation changes, as at Aggtelek, both the intensity of karst corrosion and the further functioning of the karst ecosystem are subject to change. The degradation of vegetation acts against natural processes, as shown in the appearance of a few heather species along the edges of the dolines. Their cover is small, but they are indicators of environmental change.

Microclimatic systems that modify the radiation input are formed in the karsts within the local mountainous and valley climates under specific orographic and morphological conditions. The differences in daytime radiation input according to slope aspect are not compensated for by the night-time heat emission, as the flow of the cold air causes cooler air to collect in the dolines (thermal inversion). This microclimatic feature results in a specific inverse distribution of vegetation, which is more sparse in the doline floor than along its edges.

The future exploitation and management of the karst areas has to rely on knowledge of the function of karst-ecological systems. This knowledge can only be acquired within the methodological framework of landscape ecology.

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Morphometric studies of bell hole development on Cayman Brac

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Abstract: Bell holes are cylindrical cavities that extend vertically upwards into ceilings of caves. They have been reported only in the humid tropics. The processes responsible for their formation are not fully identified; different hypotheses have suggested mechanical, chemical or biological action but none of these appears to explain the holes satisfactorily. On the Caribbean island of Cayman Brac bell holes appear to be distributed at random in the entrance zones of certain caves. The environment in which these holes formed and developed is subaerial rather than subaqueous. Fifty-five bell holes from five sample caves were measured in detail with a graduated gauge; profiles were drawn and volumes calculated for each. Bell holes in four of the caves displayed similar morphometry, whereas the holes in the fifth cave were significantly different in size but not shape. All appear to be dissolutional rather than erosional features. Dissolution, enhanced or not by microbiological activity, is thought to take place in a thin film of condensation water.

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INTRODUCTION

Bell holes are cylindrical or saucer-shaped cavities occurring in the ceilings of certain caves (Fig. 1). Their long axes are always vertical. Diameter and depth are variable but, in general, are less than one metre and two metres respectively (Table 1). Bell holes appear to be developed with complete disregard for any bedrock controls such as stratal dip or the ceiling geometry (horizontal or inclined, planar or curving, etc; Fig. 2). They may form in rock without fractures or any other apparent feedwater inputs at their apex. In some instances two or more holes have merged to create a compound form.

As far as we are aware bell holes have been reported only from caves located in humid tropical settings, e.g. Trinidad (King-Webster and Kenny, 1958), Sarawak (Wilford, 1966), Trobriand Islands (Ollier, 1975), Netherlands Antilles (Wagenaar Hummelinck, 1979), Belize (Miller, 1981), Cayman Islands, BWI (Lips, 1993), Isla de Mona, Puerto Rico, and Bahamas (Lauritzen *et al*, 1997), Yucatan, Mexico (Beddows, pers. comm., 1998) and in most of the circum-Caribbean lowland cave areas (Miller, pers. comm., 1997). Six of these locations are islands and one a peninsula (Yucatan), where the caves are at or close to the coast, but the Sarawak and Belizean examples are far inland. Table 1 presents the range of bell hole depths and diameters reported by these authors.

Bell holes differ from the most common type of ceiling solution pockets, observed in caves in all environments (tropical, temperate and arctic/alpine) because of their more limited form, cylindrical and strictly vertical. Conventional ceiling pockets are, in general, associated with fissures, joints or bedding planes in the ceiling (Slabe, 1995; Dreybrodt and Franke, 1994; Ford and Williams, 1989; Quinif, 1973; Bretz, 1942). Several different explanations have been offered for their origin and development. Bretz (1942) suggested that wall and ceiling pockets are formed in a phreatic environment with *"...an absence of definite current..."* (p.711). He also discussed ceiling tubes and half-tubes, which he believed to be phreatic features formed when a slow hydraulic circulation utilises the intersection of a bedding plane and a joint. Quinif (1973) and Ford and Williams (1989) also consider that the majority of conventional ceiling pockets develop under phreatic conditions and suggest that their preferential dissolution may be initiated by enhanced chemical aggressivity where groundwater flow in the principal conduit mixes with infiltration water descending along joints.

In contrast, Dreybrodt and Franke (1994) contend that ceiling solution pockets form in a vadose environment when infiltration water entering a cave through a fracture is undersaturated with respect to calcite, resulting in bedrock dissolution. If surface water with a $pCO_2 < 5 \cdot 10^{-3}$ atm enters a joint and dissolves limestone on its way down under closed system conditions it will have a lower pCO_2 than the cave air and it will absorb CO_2 from the cave air, thus increasing its aggressiveness and dissolving more limestone. Following Lange (1968), these authors describe ceiling solution pockets as *"...negative copies of stalagmites..."* (p.241), because the principles of the formation of both features are the same except that stalagmites are formed by net precipitation and ceiling pockets by net dissolution of material.

Figure 1. Natural cross-section through a bell hole as a result of ceiling collapse in Rebecca's Cave.

Location	Author	Depth (m)	Diameter (m)
Trinidad	King-Webster and Kenny (1958)	0.91 - 1.82	0.45 - 0.76
Sarawak	Wilford (1966)	up to 1.82	0.15 - 0.76
Trobriand Islands	Ollier (1975)	-	up to 1
Belize	Miller (1981)	0.5 - 2	-
Bahamas	Lauritzen *et al* (1997)	up to several metres	-
Isla de Mona	Dogwiler (1997, pers. comm.)	average: 0.31	average: 0.26
Cayman Brac	This study	0.17 - 5.68	0.25 - 1.30
	Lauritzen and Lundberg (in press)	typical: 0.40 - 0.80; but may be up to several metres	typical: 0.20 - 0.30
ceiling pockets; group 1: independent, without fissures	Slabe (1995)	small: 0.08 - 0.15 large: 0.15 - 0.75	0.08 - 0.15 0.30 - 1.50

Table 1. Bell hole sizes reported in the literature.

A distinctive feature of bell holes that must be emphasised is that they appear to lack any point of entry for infiltration waters from above. This would indicate that the process or processes responsible act from within the cave environment and that they are formed from the base upwards; simple dissolution or mixing corrosion involving drainage from overhead fissures is not an option. This was also stressed by Wilford (1966) for the bell holes of Sarawak.

HYPOTHESES OF BELL HOLE FORMATION

The origin and development of bell holes remains poorly understood. Previous authors have invoked a variety of mechanical, chemical and biological processes to explain their development.

Action of roosting bats

An early suggestion was that the actions of bats might be central to the process. King-Webster and Kenny (1958) proposed that bell holes were excavated by the claws of generations of roosting bats jostling for the centre position in a chance indentation in the cave ceiling. Over time this caused erosion of the soft granular rock. The slight widening that causes upwards taper in most examples was attributed to bats climbing the sides to get to the apex when the cavity becomes too deep to fly into directly. Miller (1981) also observed bell holes only where there were bats, and suggested that their urine might be an active agent, because its acidity will increase limestone dissolution.

A common association of bats and bell holes does not necessarily mean that the bats are responsible for the holes. The explanation may be as straightforward as the fact that bats look for protected places to roost, and bell holes are ideal for this purpose. Moreover, the nearly perfectly cylindrical forms and the absence of any claw-marks on the walls of the bell holes that we have observed cast doubt on this hypothesis. A major role for urine also seems problematical, as it would require that bats urinate upwards at the top. Such an effect could more likely contribute to the widening, but the bell holes we have observed have very smooth and regular walls, rather than walls streaked, channelled or fluted by acidic trickles. Black spots have been observed in some bell holes occupied by bats, but these marks could equally well be explained by dirty claws or body fat.

Simple aqueous dissolution

Wilford (1966) suggested that bell holes are aqueous dissolution features formed in the same manner as potholes, being *"...produced by eddies in fairly fast flowing water, the turbulence locally increasing the potential aggressiveness of the water..."* (p.180). However, bell holes are commonly observed in parts of caves where such rapid flow is very unlikely or impossible, which even led Wilford to question his own hypothesis. In addition, potholes are generated, at least in part, by one or more grinding rocks that are trapped inside them and spun by the force of the water, thus eroding mechanically down and outwards. This is clearly infeasible in the case of bell holes, where rocks could never be trapped or spun around to erode the ceiling. Furthermore, the precise verticality of the bell holes, despite the frequent occurrence of inclined structures, militates against this hypothesis.

Ollier (1975) suggested that bell holes might be formed by slowly flowing waters in the phreatic zone, where dissolution can occur equally well in all directions. But, if so, they would also be expected to occur in the cave walls. This was not found to be the case on Cayman Brac and is not reported from the other sites described in the literature. Once again, the strictly vertical long axes are difficult to explain in any simple phreatic situation. In addition, Miller (1981) observed bell holes in Belize *"...above relatively recent collapse in old phreatic chambers, where it is obvious they postdate the phreatic activity..."* (p.77). Lauritzen *et al* (1997) and Lauritzen and Lundberg (in press) also argue for a vadose rather than a phreatic origin for bell holes on San Salvador Island, Bahamas, because of the association of bell holes with

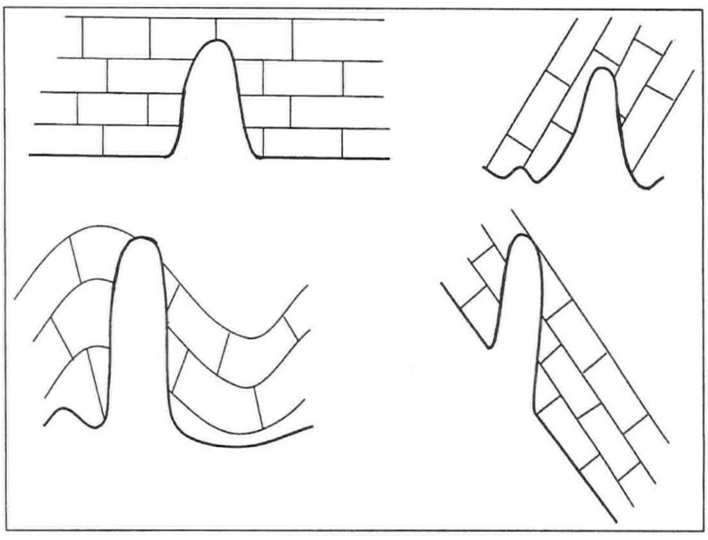

Figure 2. Schematic representation of bell holes. Note the strictly vertical long axis and the complete disregard for any bedrock controls such as stratal dip or for the ceiling geometry.

depressions on the floor directly underneath them and the fact that both appear to intersect vadose speleothems such as stalagmites at some locations.

Other biogenic or biogenic plus flood origin

In addition to bats, cyanobacteria, algae and the decay of larger plant material might, in theory, play a role in bell hole development through increase of limestone dissolution as a consequence of CO_2 liberation and production of other acidic compounds, etc. There have been no field studies or modelling of any effects, as yet.

Plant material is usually introduced into caves by rivers, but none of the caves on Cayman Brac has, or has had, a flowing river. Occasionally, hurricanes might have been able to flood some of them, thus introducing organic material. The development of bell holes probably takes much time, however, and this mechanism would require that plant material always be deposited at the same few locations and that there be no equivalent dissolution of the remainder of the ceiling. This seems unlikely.

All of the genetic proposals summarised above seem incomplete or otherwise unsatisfactory at present. Despite the simple, striking form of bell holes there have been no previous attempts to measure them in detail. Therefore, the objectives of the field study reported below were to measure bell hole morphology and distribution by precise techniques, in the hope that this might reveal quantitative relationships more strongly indicative of the genetic mechanism(s).

CAYMAN BRAC

Cayman Brac (19°43'N 79°47'W) is the most eastern of the three Cayman Islands in the Caribbean Sea (Fig. 3). The islands lie on isolated volcanic blocks forming part of the Cayman Ridge, the northern margin of the Cayman Trench. They have cores of Tertiary strata - the Bluff Group (Jones *et al*, 1994a), which are fringed by a Pleistocene limestone - the Ironshore Formation.

Cayman Brac is a tilted island 19km long and 1.5 to 3km wide. The Bluff Group forms an inclined plateau descending from +45m at the eastern end to sea level in the west, where it is overlain by the Ironshore Formation. The dip or tilt is due to differential tectonic movements of the island. The Bluff strata form cliffs around most of the island, with the Ironshore limestone forming a coastal platform at the cliff foot. The principal shoreline erosional feature is a very strong bio-erosion notch in the cliff at +6m above modern sea level. This does not show any evidence of tilting, which indicates that there has been tectonic stability since at least the last sea level high stand (stage 5e or Sangamonian, 125,000 years BP; Woodroffe *et al*, 1983).

The Bluff Group consists of the Brac, Cayman and Pedro Castle formations (Fig. 3). The Brac Formation is exposed only in lower parts of cliffs at the eastern end of the island. On the north side it consists of wackestone to grainstone limestones. There are dolostones with pods of skeletal wackestones at various levels on the south side. Foraminiferal fauna and $^{87}Sr/^{86}Sr$ ratios from the limestones indicate a late Early Oligocene (about 28 Ma) age (Jones *et al*, 1994b).

Most of the island is composed of fabric-retentive dolostones of the Cayman Formation. These are dominated by mudstones and wackestones but beds and lenses of rhodolites, rudstone, packstone and grainstone are also present. Bedding planes are difficult to trace from one end of the island to the other and marker beds are absent. Leaching of fossils has occurred and fossil-moulded vugs are visible. Due to the absence of age-determining fossils and disruption of initial $^{87}Sr/^{86}Sr$ ratios by dolomitisation it is not possible to assign a definite age to the formation; an Early to Mid Miocene age is suspected (Jones *et al*, 1994b).

The Pedro Castle Formation (Jones *et al*, 1994a) is found only over a small area at the west end of the island where the Bluff Group is overlain by the Ironshore Formation. It consists of dolostones and partially dolomitised limestones. The presence of *Stylophora*, a branching coral that became extinct in the Caribbean region towards the end of the Pliocene, and an average $^{87}Sr/^{86}Sr$ ratio of 0.70912 from the limestones, suggesting a minimum age of approximately 2 million years, are good indicators of the Pliocene age of this formation (Jones *et al*, 1994b).

The known caves on the island are between 5 and 450m in length and are situated in the cliff all around the island and on the plateau. The caves in the cliff have entrances between one and 23m above the Sangamon +6m Notch and may be divided into two groups: "Notch"

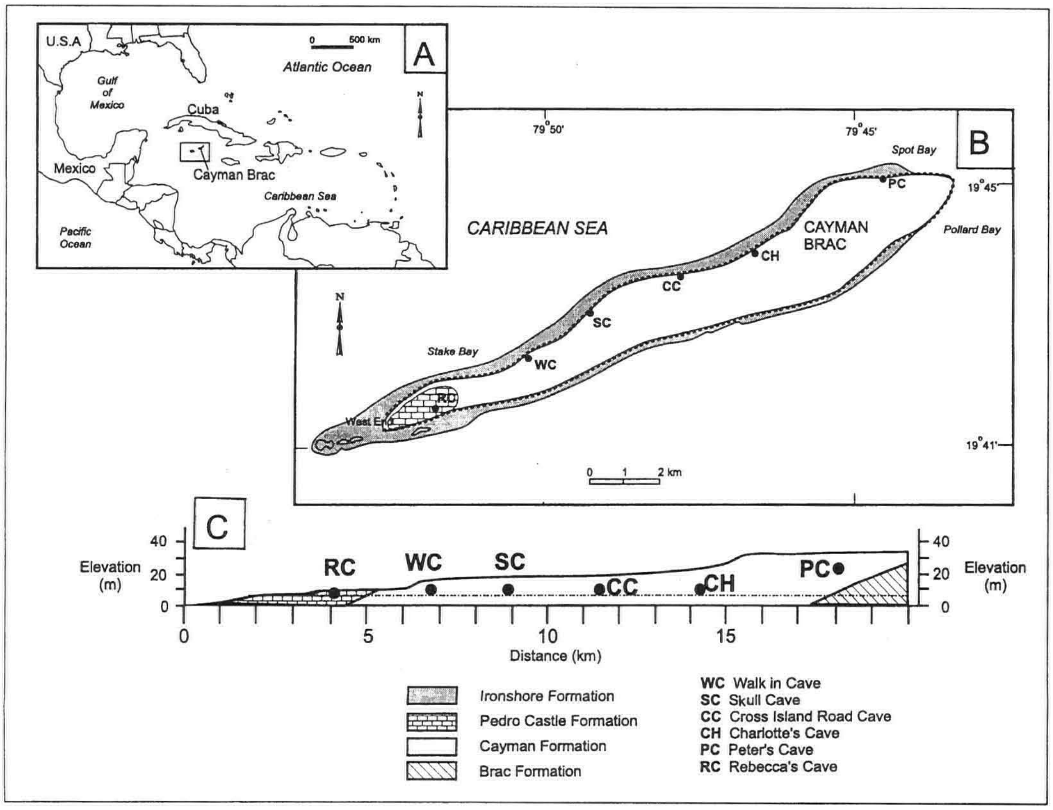

Figure 3.
A) Location of Cayman Brac.
B) Geology of Cayman Brac and location of caves; caves discussed in this paper are indicated by letters.
C) Profile of Cayman Brac with elevation of the caves.

caves, which have their entrances only one to two metres above the Sangamon level, and "Upper" caves with entrances at irregular intervals more than two metres above the Notch. Although the former are close to the Notch this does not necessarily imply that the two features are genetically linked and have the same age. Four of the five sample caves used for this study are located in dolostones of the Cayman Formation (Charlotte's Cave, Skull Cave, Cross Island Road Cave and Walk-in Cave). Rebecca's Cave is formed in partially dolomitised limestone of the Pedro Castle Formation.

The morphologies of the two types of caves differ substantially. The "Notch" caves are good examples of the flank margin or coastal water mixing zone caves described by Mylroie and Carew (1990): horizontal cavities with rounded walls, characterised by large rooms close to the cliff that are backed by blind passages radiating inwards, and with few speleothems. They are relatively short on Cayman Brac, being less than 100m in aggregate passage length, even when small lateral tubes or niches are measured separately. The "Upper" caves do not display such common features. They have multiple passages, are longer (>100m) and their formation has been influenced by structural features such as joints and bedding planes.

The bell holes are limited almost entirely to the entrance zones of the Notch caves. Circular skylights observed in certain caves (e.g. Rebecca's Cave and Bats Cave) are believed to have originated as bell holes, but subsequently have been intersected by dissolutional lowering of the land surface overhead.

Cayman Brac is an ideal site in which to study bell holes because of its physical simplicity. The island is small ($44km^2$), contains (to the authors' knowledge) only one short stream and has a relatively simple hydrological system: infiltrating rain water forms a freshwater lens that floats on top of the heavier saline water. The bedrock is very pure, with less than 3% insoluble residue, because the island is located far from any mainland or shelves where rivers might bring clays and sands into the sea. The climate is of a tropical marine type. The mean annual temperature is 26ºC with very small seasonal temperature variations. Average precipitation is 1025mm, concentrated mainly in the summer months and reflecting the NE-SW direction of the rain-bearing trade winds. The proximity of the sea maintains a moderately high relative humidity at all times.

METHODS OF MEASUREMENT

The caves were mapped at BCRA Grade 5 by standard procedures, and the locations of all bell holes were plotted precisely upon the surveys.

The depth and diameter of 55 sample bell holes in five caves were measured using graduated wooden dowels (Figs. 1 and 4A). The horizontal bars of the T-shaped device were of known lengths in 5cm intervals. The vertical section consisted of dowels with adjustable linkage, graduated in 1cm intervals. Standard procedure was to measure the height of the ceiling and the diameter of the bell hole at ceiling level (basal diameter), then to measure diameter up the hole in steps of 5 or 10cm, reading off the distance to the floor at each step. Bell hole profiles were drawn by subtracting the floor-ceiling distance from these measurements. Bell hole volumes were calculated as series of stacked cylinders because not all the diameters decrease gradually from base to apex (Fig.4B).

RESULTS AND ANALYSIS

For this study ten bell holes in Skull Cave, four in Walk-in Cave, six in Rebecca's Cave, eleven in Cross Island Road Cave and 24 in Charlotte's Cave were used (Fig.5). All bell holes extend vertically into the ceiling regardless of its angle and display smooth walls without any vertical fluting or other kinds of grooves. Locally, two or more bell holes intersect each other (e.g. in Skull Cave) to form a compound bell hole.

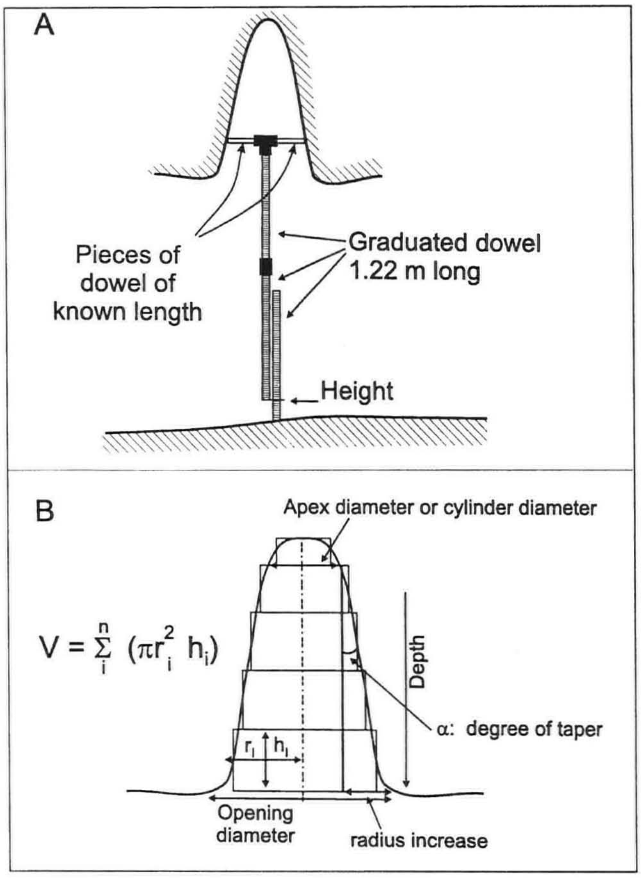

Figure 4.
A) Bell hole depth and diameter were measured with graduated wooden dowels. The ceiling height was measured to a precision of 1cm and was subtracted from the measured height, thus giving the bell hole depth. The diameter was measured with dowels of known length that varied, allowing diameter measurements between 5 and 150cm to be measured with a precision of 5cm.
B) Bell hole volume was calculated as a series of stacked cylinders.

Location

Bell holes on Cayman Brac appear to be limited to the entrance zones of the Notch caves. In most instances these contain the largest and highest rooms in these caves and receive some measure of daylight. Bell hole distribution within the entrance zones appears to be random, however, although in some cases they are found in clusters. Also, within this zone, there is no relationship between the distance from the entrance and the depth, basal diameter or volume of the bell holes (Fig.6). It can be concluded that whatever process(es) are responsible for the formation of the holes, they operate rather uniformly over the areas in which they are found.

Charlotte's Cave is an exception because 8 of its 24 bell holes follow two lines intersecting at an angle of 90º, one line being parallel to the cliff and the other perpendicular to it (Fig. 6E). There does not appear to be any lithological or structural reason for this alignment. However, at the same place there is an abrupt step of about 2m in the floor that is roughly parallel to the cliff, while the ceiling slopes upwards, into the cave and normal to it. Thus, the alignment might be due to some, as yet unknown, topographical influence on bell hole formation.

Morphometry of individual bell holes

Fig. 7 depicts the measured sections of all sample bell holes, drawn at the same scale to emphasise the variety of their depth and diameter in the different caves. The bell holes of Charlotte's Cave look like miniature versions of the range of shapes and proportions measured in the other four caves. This might be an indication that the developmental process in this cave is slower or working under less than

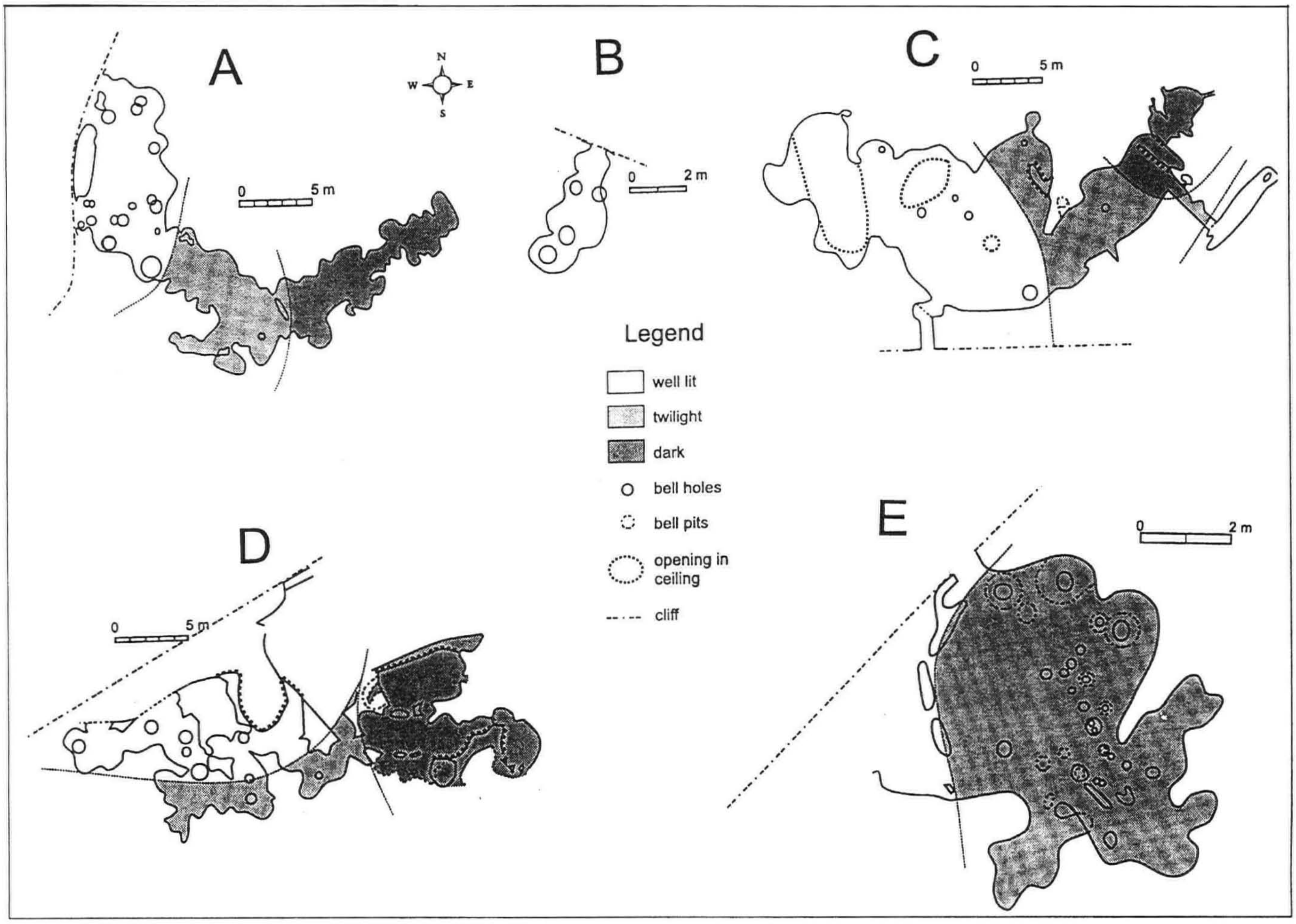

Figure 5. Location of bell holes (and bell pits) in A) Skull Cave, B) Walk-In Cave, C) Rebecca's Cave, D) Cross Island Road Cave and E) Charlotte's Cave.

ideal situations. It might also be that the bedrock at this particular location is more resistant to the process because of its composition, e.g. more coral-rich.

Bell holes RC1, RC2 and CH3 are examples of the perfect vertical long axis occurring where the ceiling is steeply inclined. Some holes have a broad, nearly flat apex (e.g. SC10 and CC7) whereas others are more pointed (e.g. CC9, WC1 and CH5). Several holes display drastic reduction in diameter near the apex (e.g. CC6 , CH11 and CH20). Others show a more stepped taper (e.g. SC4, CC8 and CH2). WC2 is exceptional in that it first widens and then narrows again along its mid-section. These changes in diameter are most likely indicative of changes in the parameters governing the development process, e.g. change in environmental conditions. SC5 has the most atypical bell hole shape; it is narrow at the bottom and widens towards the apex. It is one of three bell holes that have merged to form a compound feature, and this might have caused its unusual form.

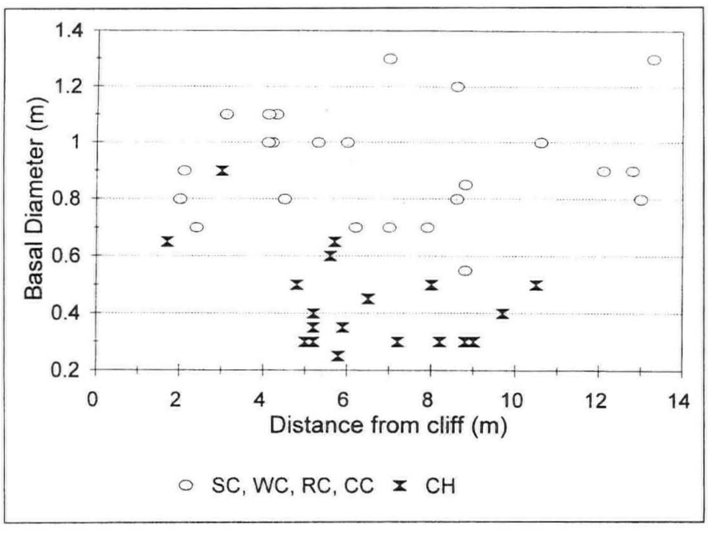

Figure 6. Basal diameter of bell holes in five caves on Cayman Brac versus their straight-line distance from the cliff.

The depth of bell holes varies from as shallow as 0.2m to as deep as 5.7m, but the majority do not exceed 3m (Fig.8A). The deepest bell holes are limited to Skull Cave and Cross Island Road Cave. Bell holes in Walk-in Cave and Rebecca's Cave, plus four from Skull Cave, are very similar in depth, between 1.0m and 1.5m. The majority of the holes found in Charlotte's Cave are much shallower and narrower.

Diameters measured at the base of individual bell holes range from 0.25m to 1.3m (Fig. 8B). In spite of this range the basic shape of the holes is very similar, with a depth to diameter ratio ≥1 for the vast majority. Almost all of them display upwards taper: the taper angle ranges from 2.5° to 30.5°, with an average of 10°. The apex diameter can be taken to represent the bell hole as a perfect cylinder, whereas the basal diameter indicates its widening away from the perfect form. The apex diameter (indicated by a dash near the apex of bell holes on Fig.7) never exceeds 0.7m and is generally between 0.3m and 0.5m. (Fig. 8C). Plotting the two diameters against each other produces a very poor relationship, especially if the Charlotte's Cave data are not drawn (Fig.9). This suggests that any subsequent widening is not related to the initial diameter alone. Relationships between depth and either apex or basal diameter are very poor as well (Fig.10). Instead there does seem to be a relationship between depth and taper angle; the latter appears to decrease exponentially with increasing depth, suggesting that widening of the bell holes slows as they become deeper (Fig.11).

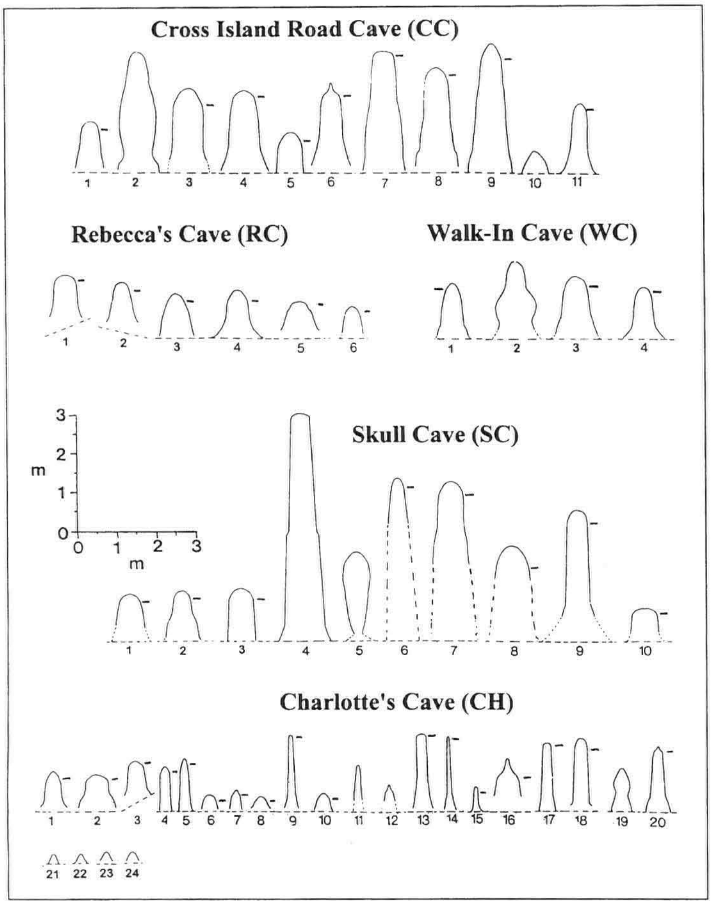

Figure 7. Cross-sectional profiles of all sample bell holes. The horizontal check marks near the apex of each bell hole indicate where the apex diameter was measured. Bell holes that formed compound bell holes could not be measured where they were joined to another bell hole and their lower limits are indicated with dotted lines to show the approximate shape.

The volume of bell holes is very varied, ranging from $0.002m^3$ to $2.55m^3$. The smaller volumes were found in Charlotte's Cave and the largest ones in Skull Cave and Cross Island Road Cave (Fig.8D).

In general, the bell holes in Charlotte's Cave differ from those in the other caves because of their smaller size and high depth to diameter ratio (Fig.8). Mean diameters, depths and volumes form a class of their own on the lower side of the scale, differing at a 95% probability level (Student t-test) from the other four caves. Volume of the bell holes in Charlotte's Cave is more strongly correlated with the basal diameter (r^2= 0.80; Fig. 12) than in the other four caves. Charlotte's Cave is in the same dolostone formation as three of the other caves, suggesting that these pronounced differences are not related to the bedrock composition or texture in any very simple manner. The entrance of Charlotte's Cave is much smaller than any of the other entrances, however, resulting in a darker environment with fewer hours of light per day. If photosynthetic biological activity is (partly) responsible for the initiation and development of bell holes (as discussed below) then this might result in a less ideal growth situation for the organisms and, consequently, smaller bell hole sizes.

Compound bell holes

At some localities, two or more bell holes merge to form a more complex feature, referred to as a compound bell hole. The majority of bell holes noted in caves on Trinidad by King-Webster and Kenny (1958) were compound. On Cayman Brac there are four pairs and one triplet in Skull Cave and two pairs in Charlotte's Cave.

Even in these compound features it is possible to identify the individual bell holes quite clearly. This suggests that there is simultaneous expansion outwards and upwards of individual bell holes after connection has been established. This could occur either in a water-filled passage or when there is dissolution from a thin water film on the walls, as might be expected if condensation corrosion played a role.

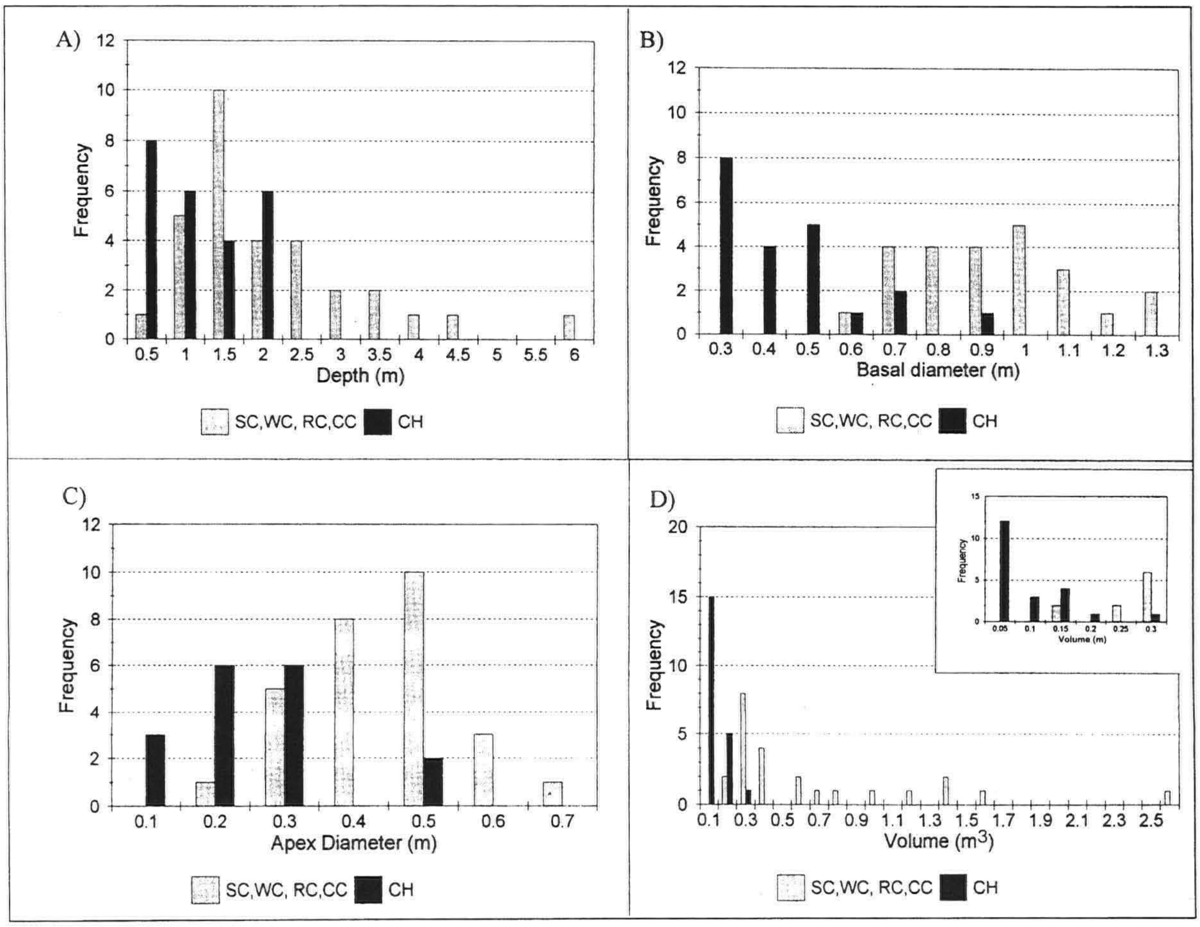

Figure 8. Frequency distribution of: A) depth, B) basal diameter, C) apex diameter and D) volume of bell holes in five caves on Cayman Brac. Note the distinct distribution of Charlotte's Cave when compared with the other four caves.

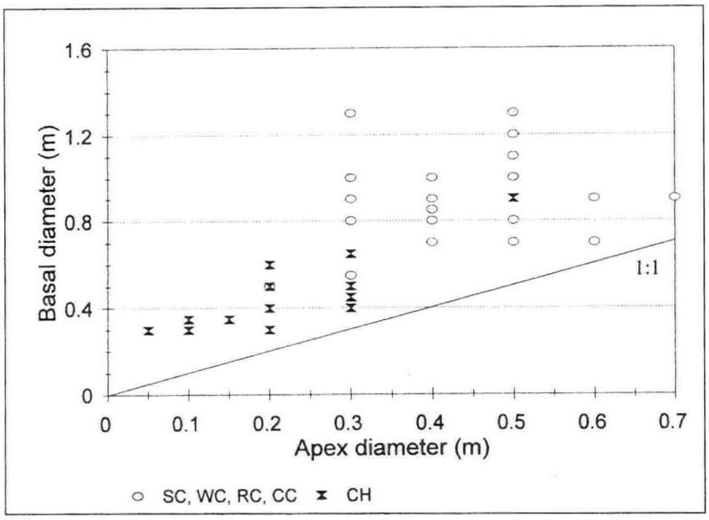

Figure 9. Apex diameter versus basal diameter of bell holes. The solid line indicates a one-to-one relationship between the two parameters.

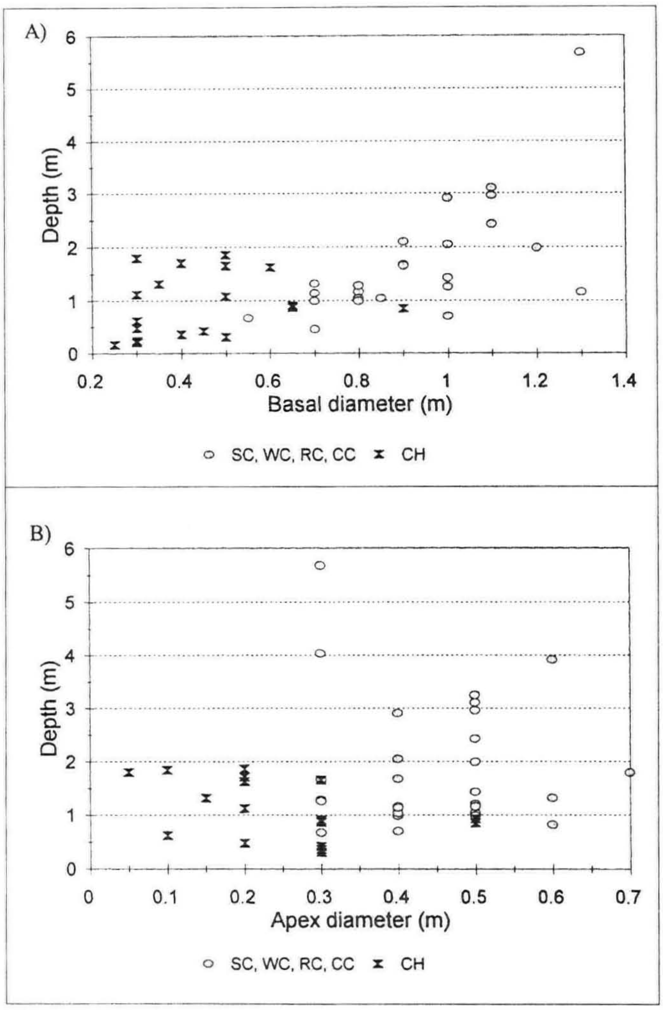

Figure 10. A) Basal diameter and B) apex diameter versus depth of sample bell holes.

Bell pits

Bell pits (Lauritzen *et al*, 1997; Lauritzen and Lundberg, in press) are circular to oval floor depressions that are commonly found directly underneath bell holes or may occur on their own. On Cayman Brac they were observed only in Charlotte's Cave.

Although in Lighthouse Cave, San Salvador Island, Bahamas, *"...almost every bell hole is associated with a paired bell pit in the floor..."* (Lauritzen and Lundberg, in press) only nine of the 24 measured bell holes in Charlotte's Cave had such a relationship (Figs. 5 and 13). There were also four bell pits that did not have a bell hole in the ceiling above them. Each bell pit in Lighthouse Cave had a slightly larger diameter than its associated bell hole and none were quite as deep as the hole (Lauritzen *et al*, 1997; Lauritzen and Lundberg, in press). In Charlotte's Cave two pits had slightly greater diameters than the bell holes above them, another two were about the same and five were smaller (Fig.14A); two bell pits were deeper even than the holes above them (Fig.14B). Of the 13 bell pits in the cave, seven had a circular cross section and six were oval. This is distinctly different from bell holes, which are almost always circular in cross section.

DISCUSSION

There are three alternative environments in which bell holes might have formed: a) subaqueous, b) sporadic flooding and c) subaerial. In the subaqueous environment bell hole development would most likely take place according to the mechanisms proposed by Ollier (1975). The Notch caves were formed in phreatic zones at the margins of a freshwater lens in conditions of slow water flow. As noted, the bell holes appear to have formed from the base upward and outward. In the case of dissolution in a water-filled passage, bell hole-like shapes should also occur in the walls and floors of the passages. Further, the sharp rims between individual bell holes in compound examples should gradually round out and then disappear as dissolution enlarges the voids. The rims in all compound cases on Cayman Brac are still clearly visible and sharply inflected, strongly suggesting a subaerial rather than a subaqueous environment.

As no rivers or evidence of past rivers are observed inside the caves, sporadic flooding could only have occurred when sea level was higher than at present or, perhaps, during hurricanes. The islanders use the caves for shelter during hurricanes today, suggesting that, if it occurs at all under modern conditions, flooding is extremely rare. The last period when sea level was close to the entrances of the caves was when the Notch formed during the last (Sangamon) interglacial, 125,000 years ago. If complete flooding of each bell hole cave occurred during the Sangamon, then the caves were older and open to the outside at that time. Sea level must have risen a further 6m or more above the +6m notch on occasion (2m to the typical entrance and another 4+m to reach the ceilings). Flooding might also have been the result of very high and intensive wave action during this period of high sea level. However, the entrances to Skull Cave, Rebecca's Cave and Charlotte's Cave are (very) small, implying that wave action will have been drastically dampened inside the caves. As with phreatic submergence of the caves, a periodic flooding mechanism does not appear to offer a satisfactory explanation for the development of the bell holes.

All bell holes on Cayman Brac are in the entrance zones of the caves, as are those studied by Lauritzen and Lundberg (1997) on San Salvador Island. In Belize, Miller (pers. comm., 1997) observed a few bell holes far inside one river cave, but most examples were also near to the entrances. This apparent preference for entrance zones would suggest that certain conditions exist here that favour their formation. On Cayman Brac, all are found in areas that receive some amount of natural light, and where significant aqueous condensation occurs (Tarhule-Lips and Ford, 1998). Condensation is prevalent in the entrance areas and decreases sharply inwards from the cliff (Fig.15). Water condenses as thin films on walls and ceilings when warmer, humid air flows along cooler surfaces. Heat released by condensation eventually warms the rock surface to the ambient air temperature, thereby inhibiting further condensation. For it to be renewed, cooling of the surface is thus required. This is achieved either when cooler air flows over the rock or when water evaporates from it. Both cases will occur during the night on Cayman Brac, when the outside dew point temperature falls below that in the caves. The process is thus sustained by a regular alternation of warmer and cooler (day and night) airflow, which can only take place when the cave is open to effective outside air circulation (Fig.15).

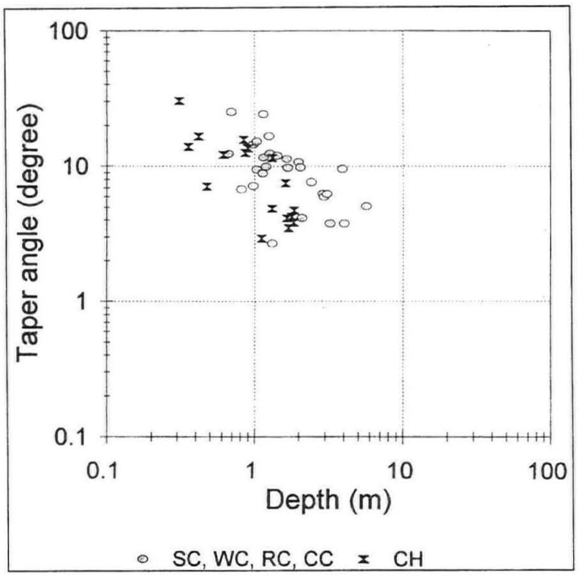

Figure 11. Taper angle versus depth of sample bell holes.

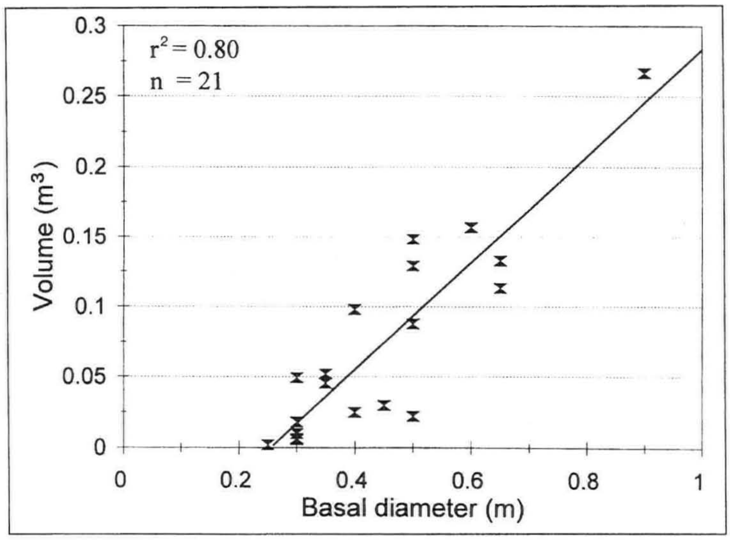

Figure 12. Volume versus basal diameter of sample bell holes in Charlotte's Cave; solid line is the line of best fit.

Condensation corrosion is the dissolution of soluble rock by condensation water. Condensation water that is undersaturated with respect to carbonate bedrock has been observed in many different karst areas of Eurasia (see Dublyansky and Dublyansky, 1998, for a review). It is believed to be active primarily in the cave entrance zones on Cayman Brac, (both at and above the Notch), where it can be seen to have dissolved both bedrock and speleothem (Tarhule-Lips and Ford, 1998).

Air exchange in the bell holes will probably be less dynamic than the general cave air exchange, but can still occur on a daily basis. M J Simms (review comment, 1998), suggests that *"When warm air flows into the cave during the day the air in the bell holes, which will have cooled gradually during the night, will sink to be replaced by rising warm humid air. The water in this humid air will then condense on the, by then slightly cooled, walls of the bell holes and so cause dissolution. The air in the bell holes will be fairly static and, being slightly warmer than the night-time air, will remain there during the night when cooler air flows into the cave below. Only when warmer air flows into the cave again during the day will the, by then slightly cooler and drier, air in the bell hole be replaced by more warm humid air. The static nature of the air in the bell hole may be the controlling factor in producing the remarkable symmetry of these dissolutional kàrst forms, while the regular daily replacement of cool dry air by warm humid air by the mechanism outlined above will ensure the continued upward growth of these features. The deeper bell holes will provide a more stable environment for static air and hence will favour their continued formation in a positive feedback mechanism"*.

The initiation of bell holes remains a stumbling block for this proposed mechanism, as it does in general terms for all of the alternatives reviewed above. For preferred condensation, it is necessary to have an initial indentation into the ceiling that is deep enough to prevent the general air circulation from exchanging the air inside the hole with great frequency. We suspect that favourable patches occur on the ceiling rock surface or within its skin. Wetting and drying on patches, and/or favourable illumination, attract micro-organisms capable of enhancing bedrock dissolution. Queen (1994) has concluded that the systematic redistribution of water, heat, atmospheric gases and solutes by thermal convection in a cave influences *"...the physical environments which control the nature and distribution of cave macro- and microbiota..."* (Queen, 1994, p.62).

Cunningham *et al* (1994, p.13) report heterotrophic bacteria and probably also autotrophic bacteria in *"...ceiling-bound deposits of supposedly abiogenic condensation-corrosion residues..."*. The ceiling deposits were commonly associated with floor deposits of *"...talc-like, porous, white to buff coloured material..."* that was derived from the surrounding bedrock. The autotrophic bacteria were believed to utilise trace elements (iron, manganese or sulphur) in the bedrock to *"...mechanically (and possibly biochemically) erode the limestone bedrock to produce the residual floor deposits..."*. Bedrock can also be

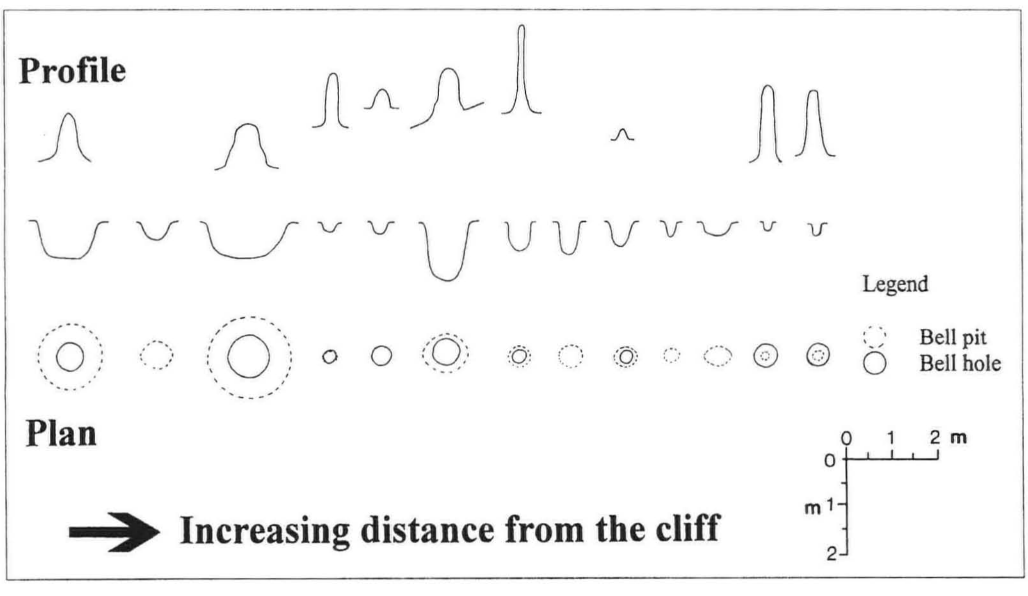

Figure 13. Bell pits and associated bell holes in Charlotte's Cave.

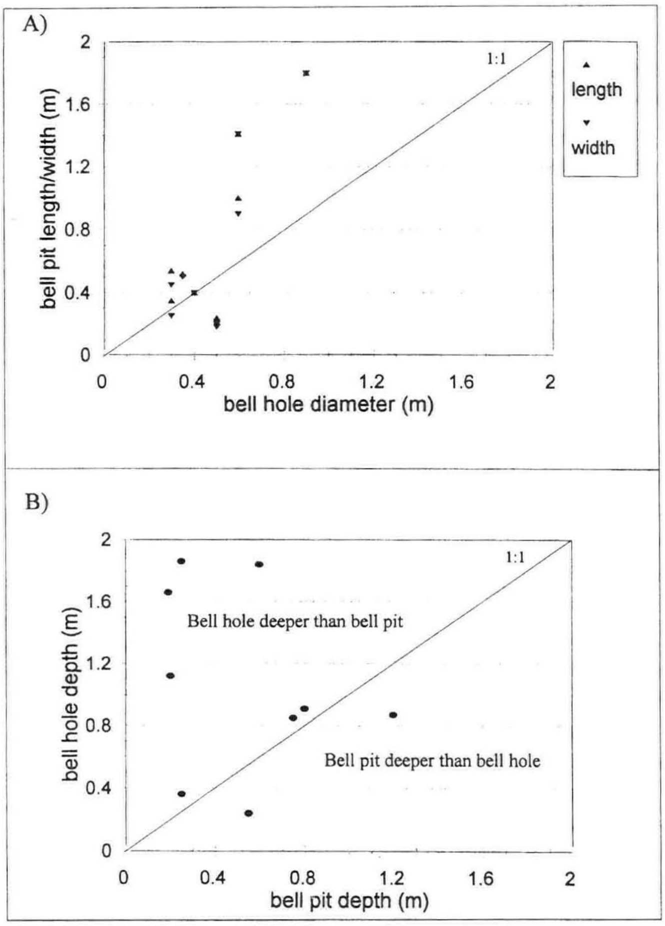

Figure 14. A) Relationship between bell hole diameter and bell pit length/ width measurements. B) Relationship between bell hole and bell pit depth.

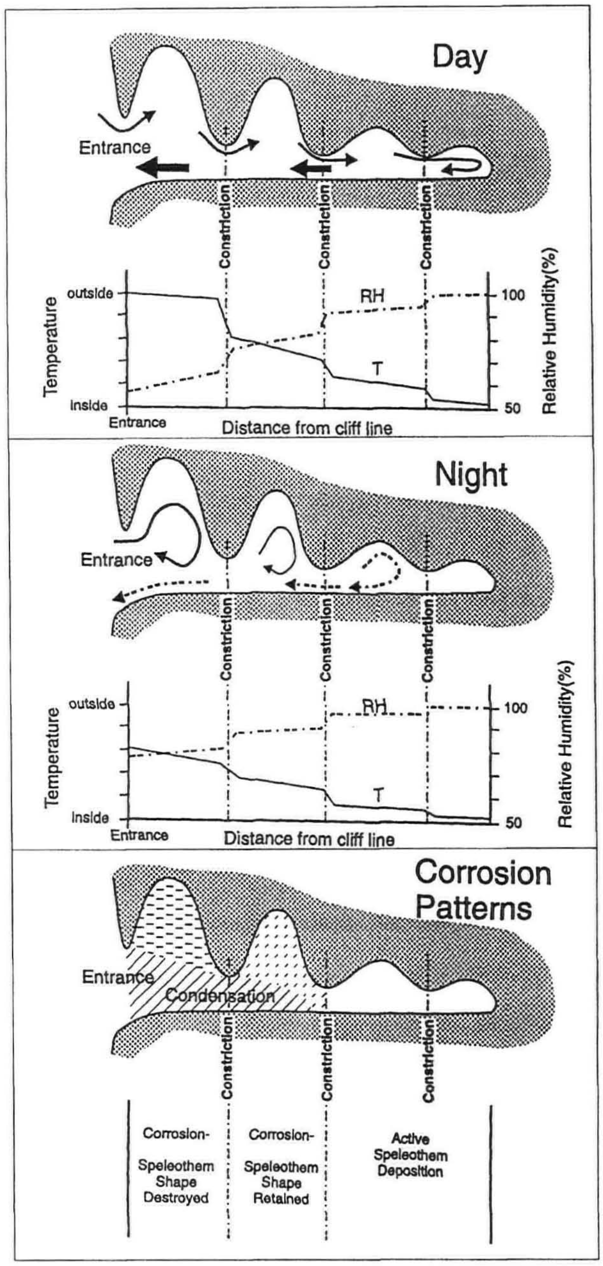

Figure 15. Proposed model of condensation corrosion in coastal caves on small holokarstic oceanic islands with young rocks (from Tarhule-Lips and Ford, 1998).

dissolved by liquid acidic compounds released by micro-organisms or by carbonic acid formed from water plus the CO_2 that they produce.

Jones (1995) investigated microbial biofilms on cave walls in the twilight zone in Skull Cave and Bats Cave on Cayman Brac and Old Man Village Cave on Grand Cayman. The bell holes in Bats Cave were not selected for this study. The cave has mainly circular skylights, believed to have been bell holes that were intersected by surface erosion (Lips, 1993). He concluded that all microbes had an epilithic life mode. The biofilms were 100-200µm thick and *"...incorporate an abundant, diverse community of microbes and mucus that mediate a wide array of destructive and constructive processes..."* (Jones, 1995, p.559), the destructive processes being more common than the constructive ones. Calcite and dolomite were attacked by irregular etching, leaving small (<4µm) residual particles of the two minerals. There was *"...relatively little evidence of detrital grains being trapped and bound..."* by the filamentous microbes (p.556), leading us to suppose that the solid particles are carried away from the local system. The dissolved calcite and dolomite can be reprecipitated (calcification) or can also leave the system. Calcification was found to be limited and to be controlled by environmental factors rather than by the microbes themselves. Merz (1992, cited in Jones, 1995, p.559) *"...noted that calcification takes place only if the associated waters are supersaturated with respect to calcite, if there is bicarbonate uptake by cyanobacteria, and if the sheath is suitable for precipitation..."*. If the water used by the micro-organisms derives from condensation (as we believe), lack of calcification is due to the fact that the condensation water on Cayman Brac is generally undersaturated, not supersaturated, with respect to calcite and/or dolomite (Tarhule-Lips and Ford, 1998).

To improve understanding of the role of fungi in carbonate diagenesis, Jones and Pemberton (1987a, b) placed 20 different species onto crystals of Iceland spar calcite in Pyrex vessels, where they were kept moist and at a constant temperature for 253 days. At the end of the period samples of the calcite crystals were examined with a scanning electron microscope and found to be extensively damaged by dissolution. Great care was taken not to put moisture directly onto the crystals and fungi. Even so, Jones and Pemberton (1987a) noted that some of the water condensing on the inside of the vessels had dripped onto the calcite, washing silt size particles from them, to form accumulations on the bottoms of the dishes.

From these findings, we suggest that bell holes may be initiated where colonies of micro-organisms are able to establish themselves within a cave at specific locations that are wetted by condensation water. Microbial activity is at its optimum in the well lit - twilight entrance zones of caves, although it is not precluded deeper inside. Enhanced dissolution beneath thicker biofilms on preferred patches of a ceiling causes these areas to recede faster than the surrounding rock, resulting in an indentation. The strict circularity of the bell holes and their characteristic maximum diameter at the apex suggest that regular microbial colonies with dominant species are at work. Daily cycles of condensation and evaporation are also at their optimum in the entrance zones, as shown above. During the condensation period there is wetting of the film plus simple (inorganic) dissolution, while desiccation

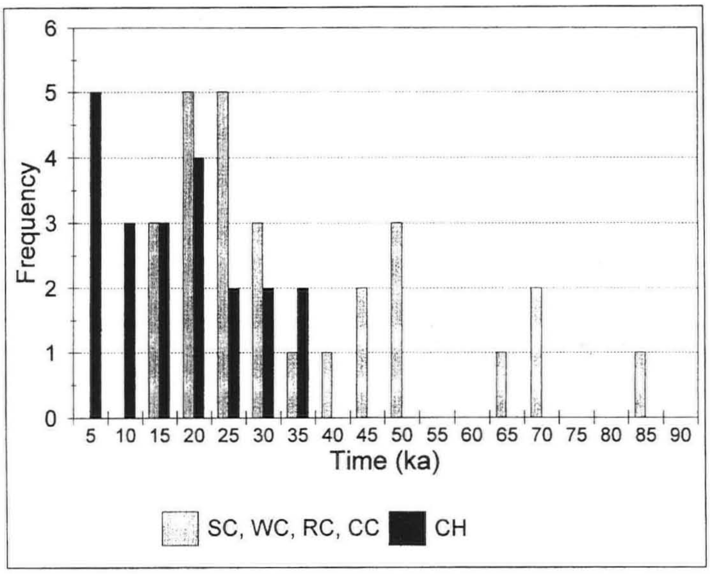

Figure 16. Frequency distribution of estimated time (not necessarily continuous) required for the development of bell holes.

during the evaporative phase permits any detrital particles that have been liberated to fall away.

The strict verticality of the bell holes strongly suggests to us that the formative process (initiating and maintaining the cylinder) is gravity-dependent. Removal of residual particulate matter (such as observed by Jones and Pemberton (1987a,b) in their experiments) is most effective where it can fall freely downwards. The particles released are likely to be very small (<4μm; Jones, 1995) and, because no heaps of sediments were noted directly below the Cayman bell holes, it may be supposed that they are dispersed as aerosols. Regulation of growth by the detachment and fall of micro-particles explains why bell holes become deeper more rapidly than they become wider, resulting in the typical bell shape. Once a cylinder is formed, water condensing on the walls will flow away as a very thin film, in which dissolution capacity is reduced progressively towards the base, because saturated water flowing from above dilutes any undersaturated water condensing on the lower parts. This may explain the exponential decrease in degree of taper with increasing depth in the Cayman bell holes (Fig.11). As they become deeper, film flow at the base is dominated increasingly by transfer of saturated water from above, reducing dissolution rates in these lower parts, whereas they remain the same near the apex.

Lauritzen *et al* (1997) ascribed the bell pits underneath bell holes in Lighthouse Cave, San Salvador Island, to chemically aggressive drip water from the bell holes. This implies that the film flow retains some dissolutional competence at the base of the bell hole, at least at certain times of the year. We would add that some of the bell pits observed in Charlotte's Cave, Cayman Brac, are cut into steeply inclined slopes, supporting the proposition that they must be formed by aggressive drip water. Miller (1981) also described bell pits underneath some bell holes in Belize and thought that they might have been formed by *"...films of aggressive water as suggested by re-solution of some nearby stalagmites..."* (p.77). Many of the bell pits in Belize were filled with bat guano, which might have enhanced dissolution through its acidity. None of the pits in Charlotte's Cave contains guano at present but it is possible that they did so in the past.

Rates of bell hole formation

From recession rates measured on gypsum tablets suspended in four caves on Cayman Brac, mean condensation corrosion rates of ~24mm per 1,000 years have been estimated for calcite (Tarhule-Lips and Ford,

Cave	Bell Hole * (see Fig. 7)	Area (m^2)	Volume (m^3)	Time ** (ka)
Skull Cave	1	0.38	0.20	22
	2	0.50	0.30	25
	3	0.38	0.39	42
	4	1.33	2.55	80
	5	0.38	0.45	48
	10	0.38	0.15	16
Walk-In Cave	1	0.50	0.28	23
	2	0.64	0.64	42
	3	0.79	0.52	28
	4	0.79	0.31	16
Rebecca's Cave	1	0.50	0.28	23
	2	0.50	0.22	18
	3	0.57	0.33	24
	4	1.33	0.39	12
	5	0.79	0.26	14
	6	0.24	0.11	19
Cross Island Road Cave	1	0.38	0.25	27
	2	0.79	1.32	70
	3	0.64	0.71	47
	4	1.13	0.97	36
	5	0.38	0.27	29
	6	0.79	0.58	31
	7	0.95	1.50	66
	8	0.95	1.13	49
	9	0.95	1.39	61
	10	0.38	0.10	11
	11	0.64	0.27	18
Charlotte's Cave	1	0.33	0.11	14
	2	0.64	0.27	17
	3	0.33	0.13	17
	4	0.07	0.05	29
	5	0.10	0.05	23
	6	0.13	0.03	8
	7	0.07	0.02	11
	8	0.20	0.02	5
	9	0.10	0.05	20
	10	0.16	0.03	8
	13	0.20	0.13	27
	14	0.07	0.02	11
	15	0.07	0.01	6
	17	0.13	0.10	33
	18	0.20	0.15	31
	19	0.20	0.09	19
	20	0.28	0.16	23
	21	0.05	0.00	2
	22	0.07	0.01	3
	23	0.07	0.01	3
	24	0.07	0.01	4
Maximum		1.33	2.55	80
Minimum		0.05	0.00	2
Average		0.45	0.36	25

* Compound bell holes for which the volume was estimated have been left out.
** Time = V/(RR*A), where RR = retreat rate = 24 mm/ka

Table 2. Maximum time required for bell hole development.

1998). If we consider only the vertical recession of the bell holes and attribute that to dissolution by condensation water alone (neglecting any microbial enhancement), the time required to form them can be calculated. This ranges from ~2,000 years for the smallest individuals to ~90,000 years for the deepest. Excepting the examples in Charlotte's Cave, the mean age is ~35,500 years (Fig. 16; Table 2). From the dated speleothem record on Cayman Brac (Tarhule-Lips and Ford, 1997) it is clear that vigorous dissolution by condensation corrosion in cave entrance zones has occurred during distinct periods in the past, but not continuously. If condensation corrosion and bell hole formation are linked, then it is most likely that bell hole formation has not been continuous either. Our estimates give a crude idea of the amount of corrosion time that may be required to form these bell holes, but do not necessarily indicate the age of their initiation. Discontinuous formation might also explain some of the more abrupt changes in the shapes of certain bell holes (e.g.CC6, CC8, WC2, SC2, SC4, CH2, CH16 and CH19 in Fig.7).

CONCLUSIONS

Bell holes are generated from the base upwards in the illuminated entrance zones of Notch caves on Cayman Brac. They have achieved their typical bell shape as a result of simultaneous upward and outward expansion, where the upward expansion is more rapid. From the degree of taper it is concluded that the outward expansion slows down as the bell hole grows deeper. The most likely environment for bell hole development is subaerial rather than subaqueous, because the perfect vertical long axis and the location are difficult to explain in fully flooded or intermittently flooded situations. We suspect that they develop as a result of a combination of microbiological activity and condensation corrosion. The most soluble particles are removed first, discharged in the film flow. Their loss permits the residual grains to fall away. We suggest that simple gravitational fall makes a most important contribution to bell hole deepening; it explains the precise verticality of the long axis.

Estimates of the time necessary to create the deepest examples range up to 90,000 years, but are probably overestimates because bio-corrosion is not included. However, in the deeper cases, bell hole growth was probably periodic rather than continuous.

We suggest that further research into the role of condensation and of microbiological activity is needed. The walls and apices of bell holes should be sampled for the presence of biofilms. Detailed micro-climatological studies inside the bell holes might help to establish the patterns of air exchange in them but will be difficult to carry out: computer modelling is probably an easier option. The amounts and chemical composition of their condensation water should also be looked at in detail.

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Features of gypsum caves and karst at Pinega (Russia) and Ripon (England)

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Abstract: A profusion of collapsed dolines and subsidence hollows characterises the gypsum karst around Ripon in Yorkshire; clearly there are caves beneath the area, but none is accessible. In arctic Russia, the Pinega karst has many gypsum caves, among which some of the larger passages appear to have been formed by subglacial meltwater. The environments of the two sites are comparable, and one possible implication is that the unseen caves at Ripon may also be of Pleistocene subglacial origin.

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INTRODUCTION

Gypsum supports a distinctive type of karst, which differs from limestone karst in ways that are largely related to the far greater dissolution rate of gypsum in water and its lower mechanical strength. Bare rock outcrops, exposed crags and very large cave chambers are rare in gypsum, but sinkholes, smaller cave systems and surface collapses are common. A recent review (Klimchouk *et al*, 1996) identifies the extensive distribution of gypsum karst around the world.

Gypsum (hydrated calcium sulphate) is soluble in water to a limit of around 2,500 ppm. This is four orders of magnitude greater than the solubility of limestone. However limestone solubility is enhanced by the presence of carbon dioxide, and gypsum dissolution is enhanced, to an even greater degree, by other dissolved salts. In natural waters, gypsum is about 30 times more soluble than limestone. Equally important to karst processes are the rates of dissolution; both field measurements and theoretical data indicate that gypsum is dissolved about 50 to 100 times more rapidly than limestone (Klimchouk *et al*, 1996). These comparisons are only approximations, but the implication is that gypsum is rapidly and extensively dissolved under normal natural conditions.

Anhydrite (anhydrous calcium sulphate) is also highly soluble, but it dissolves more slowly than, and in a different manner to, gypsum; it has to hydrate to gypsum before it can be dissolved. The conversion of gypsum to anhydrite occurs at around 42°C; this corresponds to a depth of about 1,200m in regions of normal geothermal gradient. The reverse process, hydrating anhydrite to gypsum, depends upon the presence of water and generally only occurs within about 100m of the ground surface. At temperatures below 42°C anhydrite is unstable in contact with water (Zanbak and Arthur, 1986). At lower temperatures it is furthest out of equilibrium, and therefore converts to gypsum more rapidly as temperatures approach 0°C. Additionally, anhydrite appears to have a higher solubility than gypsum at temperatures below 50°C (Zanbak and Arthur, 1986). However, this may be an effect of anhydrite's metastability, where its hydration to gypsum causes disaggregation of the rock and hence increases the rate of subsequent dissolution (Mossop and Shearman, 1973). The presence of dissolved salts in the water also accelerates the dissolution process (Klimchouk, 1996b).

Within Britain, gypsum is restricted almost totally to a few relatively thin formations in the Permian and Triassic sequences of central and northern England. Its dissolution has continued at rates that are extremely high in geological terms and also significant on a human time-scale. The only conspicuous active surface karst occurs on the Permian gypsum extending north and south from Ripon, though palaeokarst is more widespread and also occurs in Cumbria (Cooper, 1995, 1996). Caves are few in Britain's gypsum; over 100m of passages of about 2m in diameter were exposed in a Cumbrian gypsum quarry (Ryder and Cooper, 1993), and fragments of smaller caves have been observed in various gypsum mines in Cumbria and south of Nottingham and Derby.

The surface landforms typical of gypsum karst in Britain occur only in belts that are just a few kilometres wide and are parallel to the outcrops. The down-dip margins are marked by the transition from gypsum to anhydrite, and the up-dip margins are the limits of total dissolutional removal of the rock. Almost none of the British gypsum is exposed at the surface, the notable exception being the rapidly eroding cliff outcrops at Ripon Parks (James *et al*, 1981). At depth, the sulphate rock occurs as anhydrite with only limited jointing, but deep groundwater circulation has been possible, especially in Yorkshire, where there are adjacent beds of limestone. This slow groundwater movement has caused hydration of the anhydrite to gypsum, down to a depth of about 100m in Yorkshire. Close to outcrop stress relief following denudation further opens the rock joints, and increased flows of groundwater have reached the gypsum, mainly by transfer from the adjacent limestone aquifers. Once dissolution and cavity development have been initiated in the gypsum, caves continue to evolve through multiple phases until the entire gypsum bed has been locally removed. During and following this gypsum removal, cavities migrate upwards as their ceilings collapse, causing brecciation of the overlying insoluble rocks and eventual subsidence at the surface.

THE DOLINES OF RIPON

An almost complete cover of diverse drift deposits obscures the outcrops of gypsum beds in the broad and shallow valley of the River Ure, around the Yorkshire town of Ripon (Fig.1). Dissolution of the buried gypsum has created hundreds of doline depressions in the ground surface (Cooper, 1986, 1995, 1998; Powell *et al*, 1992; Cooper and Burgess, 1993; Thompson *et al*, 1998). Though there are no accessible caves at open sinks or risings, there are sulphate-rich springs that add to the flow of the River Ure, and this is a very active karst terrain.

The Ripon gypsum occurs as two beds within the Permian succession of dolomitic limestone (commonly known as the Magnesian Limestone). The lower bed is 25m to 40m thick, while the upper is just under 10m thick, though it is notable that the thicknesses of both beds are very variable and they are locally reduced due to their dissolutional removal by groundwater. Each bed of massive gypsum is underlain by dolomitic limestones and overlain by marls, and the two lie

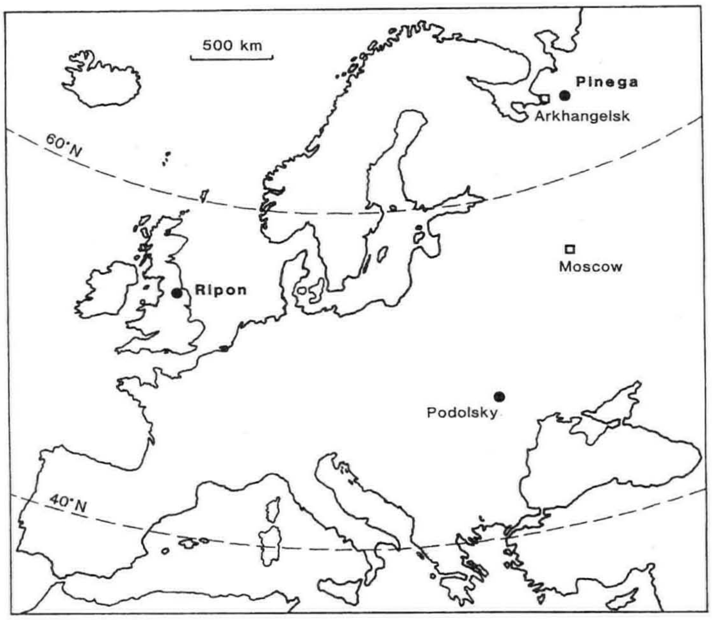


Figure 1. Location map of gypsum karst regions referred to in the text.

stratigraphically about 25m apart; some of the marls are gypsiferous immediately above the massive gypsum beds. The sequence dips very gently to the east; this creates a wide sub-drift outcrop, with continuation of the gypsum down-dip beneath a progressively thicker cover of marl and sandstone. Beneath the River Ure, the Permian sequence is cut into by a buried valley that is largely filled with permeable sands and gravels. At some places, including Ripon Parks, this provides access for river water to the gypsum beds. However, at Ripon itself most of the gypsum dissolution is caused by the escape of artesian water into the valley gravels from phreatic cave systems developed in the gypsum (Fig.2). Continuing subsurface dissolution of the gypsum is undeniable; high sulphate loads are normal in water abstraction boreholes and springs in the area (Cooper, 1988), and the River Ure gains a substantial sulphate content in its passage through the Ripon area.

Dissolution of the gypsum results in the formation of collapse dolines, which can have catastrophic consequences in the urban environment; these dolines belong to one of the two broad families of surface depressions that are widespread and continuing to evolve in the Ripon area (Fig.3).

Areal subsidences

Very slow and gentle subsidence has created broad and shallow closed depressions in the drift-covered surface. Some of these subsidence features exceed 100m in width, but there are many more smaller hollows (Cooper, 1986; Cooper and Burgess, 1993). These broad and shallow subsidence hollows occur in the west of the karst belt, where the gypsum lies at rockhead and is therefore exposed to circulating groundwater within the permeable drift. The dominant subsidence process may be widespread dissolution at the rockhead surface, with localised increases where drainage is concentrated. Slow subsidence of the drift cover continues without any intermittent and dramatic collapses, though a few small catastrophic collapses have occurred within these areal subsidences. The implication is that cave development and undermining occurs on a limited scale. The slow and gentle subsidence is analogous to the well documented areal and linear subsidences in the salt karst of Cheshire, where rockhead dissolution is the only possible mechanism of removal of the salt which is dry and watertight at depth (Waltham, 1989).

In the most active part of the Ripon subsidence belt, associated with the margins of the buried Ure valley, some of the large subsidence hollows are amalgamations of numerous smaller conical collapse depressions, which may have developed individually as subsidence dolines (see below). Subsequently, peat deposits have accumulated in these low-lying and water-logged depressions. Slow downward movement has affected buildings in these areas; this largely reflects settlement on the peat and clay, but active gypsum dissolution could also contribute to the failures. The subsidence effect is well demonstrated by terraced houses in Ripon's Princess Street, which have sagged steadily and progressively since their construction about 80 years ago (Plate 1).

A different style of areal subsidence is represented by the depression that extends to about $8km^2$ at Snape Mires near Bedale, 15km north of Ripon. Glacial lake deposits underlie a lacustrine flat that passes eastwards into a complex of ridges and troughs. Peat fills show that the troughs have evolved over the last 12,000 years since the lake deposits formed at the end of the Devensian Ice Age (Cooper, 1986). The Snape Mires depression has its western margin over the eroded feather edge of the gypsum, but its eastern floor is underlain by the complete Permian sequence and the Triassic Sherwood Sandstone. The subsidence zone contains numerous prolific artesian springs that have deposited calcareous tufa. It is likely that gypsum dissolution at this site is related to flows of artesian water from the underlying dolomitic limestone of the Cadeby Formation (Cooper, 1986).

Plate 1. Terraced houses in Ripon that have subsided into a gentle arc since their construction. They lie across a dissolutional hollow in the gypsum that lies buried beneath a drift cover, but much of their movement is due to drainage compaction of the peat that has infilled the hollow. (Plates 1 to 8 from photos by Tony Waltham).

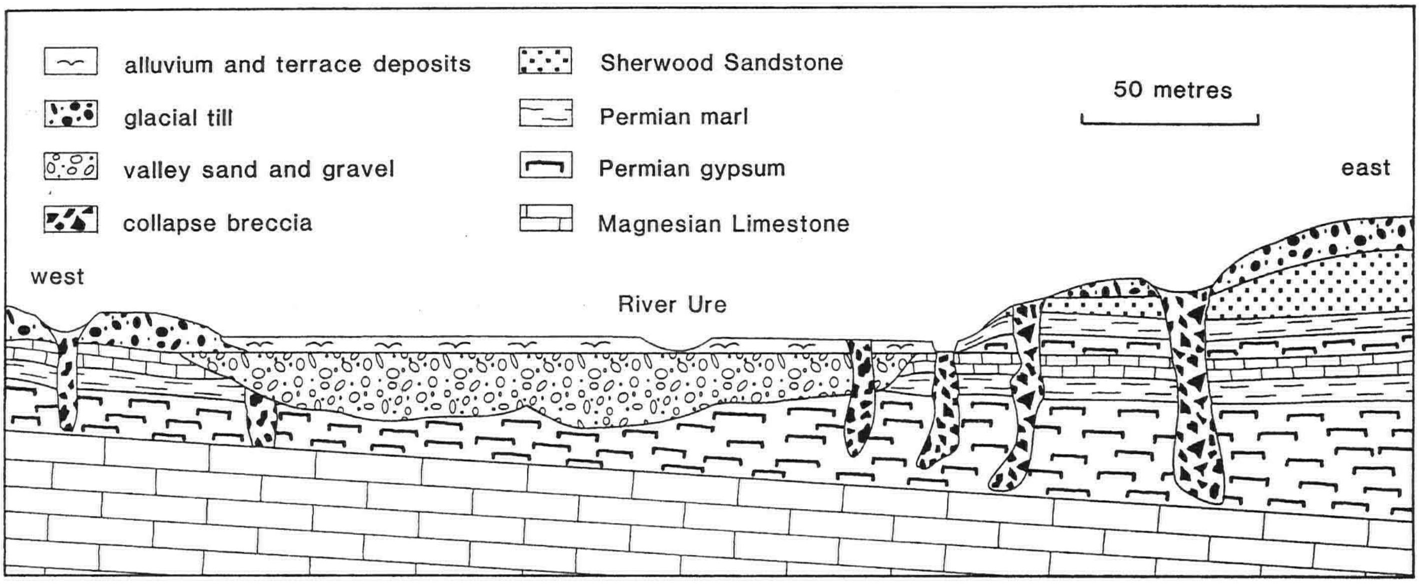


Figure 2. Cross section through the gypsum beds, the pipes of collapse breccia over and through them, and the buried valley beneath the River Ure, at Ripon. Groundwater flows freely between the gypsum and the valley sand and gravel where they are in contact in the floor of the buried valley. The gypsum is thinner to the west due to greater dissolutional loss where the cover thins up-dip.

Where the gypsum has been largely or totally removed by dissolution, the sequence of overlying beds has foundered. This produces a synclinal bowl of subsidence, so that the gentle easterly dip is reversed to the west, and the foundering also creates localised angular folding and brecciation. Large areas of foundered and brecciated strata lie concealed by drift, north of the Ripon karst and off the Durham coast (Smith, 1972, 1994).

Subsidence dolines

Brecciation of the strata above the gypsum is not restricted to the broad zones of foundering. It also occurs where roof rocks collapse over individual dissolution cavities within the gypsum, so that voids migrate upwards by roof stoping. This creates vertical breccia pipes, that are characteristically 3m to 25m in diameter. Pipes have been intersected by boreholes in the Ripon area, and some are exposed in cliff sections of the cover rocks on the Durham coast around Marsden Bay. Locations of the pipes are likely to have been guided by the jointing in the rocks and by the morphology of the present or former underlying cave systems. The breccia pipes now act as focal points for groundwater flow and ongoing dissolution.

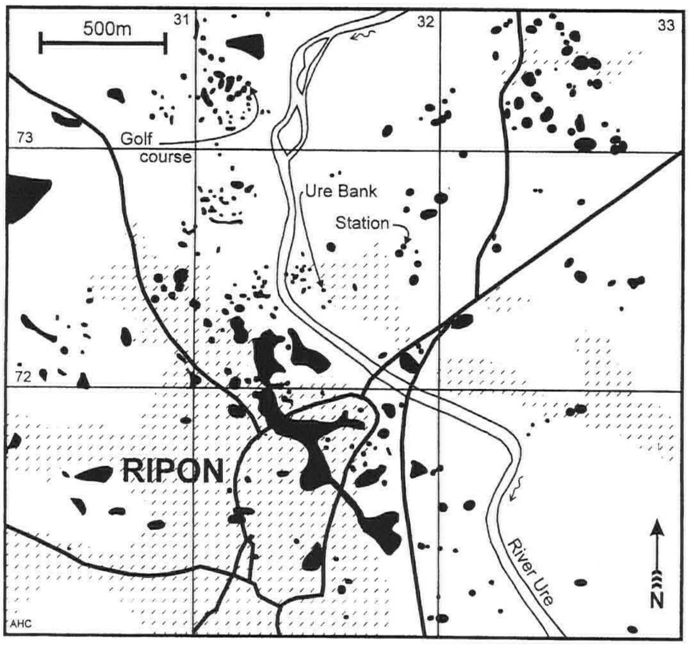


Figure 3. Map of karstic dolines and subsidence hollows in the immediate vicinity of Ripon. Both types of dissolution depression are marked in black; sites that are named are referred to in the text. Surface relief is low across the whole map area. Diagonal stippling marks built-up areas; heavy lines indicate the main roads.

Some breccia pipes propagate through to the surface to create dolines, of which there are many in the Ripon karst. As these features are formed by the failure of the insoluble cover of rock (and soil) over cavities that originated in the buried gypsum, they are subsidence dolines or subsidence sinkholes (Lowe and Waltham, 1995). Some of the Ripon dolines have steep collapsed walls in strong cover rocks, and appear like dropout failures of subsidence sinkholes (Culshaw and Waltham, 1987). These may be described as cover collapse dolines (but they are not classical collapse dolines or collapse sinkholes. These latter terms imply surface collapse of the soluble rock, which is generally concealed beneath younger rocks in the Ripon area).

Of the many subsidence dolines around Ripon, some have developed as dropout failures, where the surface has collapsed suddenly into cavities that have been growing underground and unseen for a long time beforehand. Others develop more slowly, where less cohesive soils and rocks sag or ravell steadily into caves beneath; subsequently, some of these are filled with peat and clay. The loss of many tens of cubic metres of soil and rock into the ground, either suddenly or over short periods of time, must involve the existence of caves of comparable size. Most of the Ripon dolines have diameters of 5m to 30m. For many of the dolines the visible parts are entirely within the drift deposits, but some do expose rock. A collapse near the site of Ripon railway station in 1834 (Plate 2) created a hole 11m across with vertical walls that descend through 15m of red sandstone, the Triassic rock that overlies the Permian sequence of gypsum, dolomitic limestone and marl. The 1860 collapse at what is now Ripon Golf Course, and the 1939 collapse near the hamlet of Nunwick (north of Ripon), are two of the dolines that still expose Permian dolomitic limestone in their walls.

More than 70 events of subsidence and collapse have been recorded and dated in the Ripon area, and there are many more undated features recognisable within the landscape (Cooper, 1986). The most notable recent event was the collapse in the front garden of a house on Ure Bank Terrace, just east of the river, in April 1997 (Plate 3). A hole 10m in diameter was created by the loss of about $300m^3$ of ground within less than 12 hours (Cooper and Waltham, 1998). The site of the new

Plate 2. The collapse shaft that developed through massive sandstone near the site of Ripon station in 1834.

ground failure had experienced at least six previous collapses, each of which had been subsequently refilled; it is the most dramatic expression of ongoing cave development in the gypsum beneath Ripon.

Cavities in the gypsum

Boreholes into the Permian gypsum sequence have intercepted clay-filled cavities up to 20m high, most of which are below the present water table. Many of the cavities in the gypsum are partially filled with sediment, notably laminated clays that are identical to the glacio-lacustrine clays that occur at the surface. Some of the cavities contain gravel, one yielded peat (beneath laminated clay) and one yielded housebricks in a cave fill beneath 25m of undisturbed rock and drift. The redeposited materials are evidence that erosion and movement of collapsed or fill materials is a continuing process in the caves. It appears that there are many caves beneath Ripon, and they are clearly related to the subsidence dolines above them. However, none of the caves is accessible, and there is consequently room for debate on their morphology and mode of genesis.

Gypsum caves are renowned for their joint-guided maze patterns - exemplified by the very long cave systems in the Podolsky region (Fig.1) of the Ukraine (Klimchouk, 1992, 1996a). The Ukraine and Ripon gypsum sequences form comparable interstratal karsts, both with the gypsum sandwiched between aquifers that carry artesian groundwater flow. By implication, maze caves comparable to those in the Ukraine could underlie Ripon. Any rectilinear distribution of dolines and depressions could correlate with a joint pattern, and hence with the supposed cave passages, where the optimum collapse locations lie at and above joint or passage intersections. This type of relationship has been demonstrated in the context of the Ukrainian cave systems (Klimchouk and Andrejchuk, 1996). Alignment analysis of the surface features at Ripon perhaps indicates such a pattern (Cooper, 1986), but the distribution of the most active subsidence prone locations (Fig.3) could also be related to cave passages of more irregular morphology.

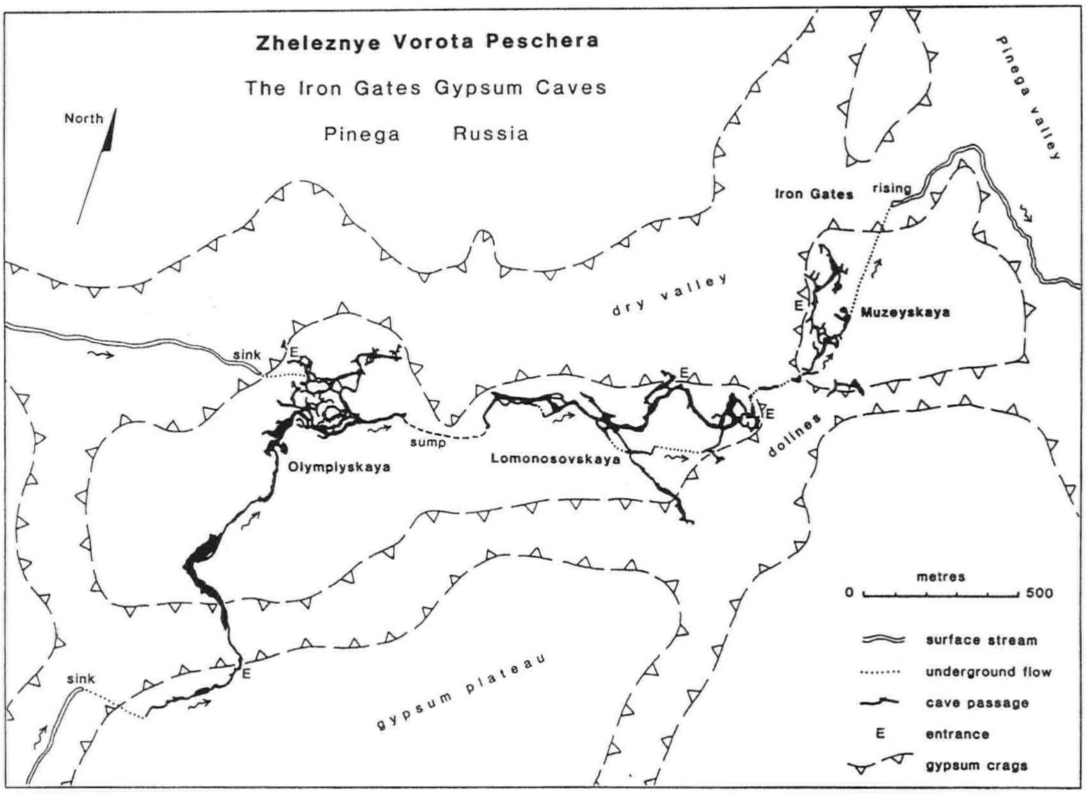
Large isolated dolines may occur over larger sections of cave passages, instead of merely over joint intersections. High flow rates concentrated in large passages could enable rapid dissolution of the gypsum walls. Piles of inwashed collapse debris within large caves would deflect water flows to enhance dissolution of the immediately adjacent gypsum, thereby causing repeat collapses at the same site, as is common at Ripon. It is reasonable to hypothesise that large caves exist under Ripon, if a mechanism for their genesis can be conceived.

THE CAVES OF PINEGA

The Pinega karst is located 100km east of Arkhangelsk, in the arctic north of Russia, almost due north of Moscow (Fig.1). Its landscape is developed in a sequence of Permian evaporites about 50m thick. These consist of bands of blue anhydrite and white gypsum containing thin beds of brown dolomite and red clay. Local relief is low, with forested plateaux rising only about 50m above the Pinega River. The Iron Gates nature reserve lies on the gypsum plateau. It contains two small valleys that are largely dry; streams sink in the floor of each valley, and they

Plate 3. The collapse that occurred in alluvial sediments in front of a house on Ure Bank Terrace in 1997.

Figure 4. Outline map of the Iron Gates caves in the Pinega karst (after surveys by Arkhangelsk Geologia).



join in a fine system of caves that lies largely under the intervening ridge. Between the sinks, the dry valleys have their floor profiles broken into a chain of shallow depressions. Gypsum crags line the valleys, with faces 20m high providing the only conspicuous terrain features in a continuous cover of taiga forest. Relief is low - from sinks to resurgence the fall is only about 25m.

Cave morphology

The active caves at the Iron Gates have now been explored for most of the way between the main sinks and the rising, and the combined system of Olympiyskaya and Lomonosovskaya has just over 9,000m of passage (Fig.4). The main passage of Olympiyskaya carries the southern stream through chambers up to 30m wide, into a lower canyon, and downstream into a series of splendid wide elliptical tubes. In Lomonosovskaya, the main phreatic tube is still about 10m wide and elliptical in profile (Plate 4). Both modern entrances have formed where crag retreat has breached the old tube, much of which has now been abandoned by the main stream, which takes an immature route to the south. Old passages leading out under the dry valleys are blocked by sediment. East of Lomonosovskaya, the ridge narrows and lowers to a broad saddle that has breached the caves, and the stream is now seen in karst windows between fragments of surviving passage. Muzeyskaya contains largely relict passages (Plate 5), which are flooded towards the east. The hydrology is more complex than the cave map (Fig.4) reveals, and there appears to be a series of parallel flooded caves heading north. These feed the main rising and some flood outlets a little higher up the valley.

Outside the Iron Gates reserve there are more caves in the same gypsum, notably west of the river and south of the town of Pinega. Both Symphoniskaya and Golubinskaya have long straight tube passages formed on joints (Plate 6), and also sections of rectilinear joint maze. Pekhorovsky Provol has an 18m daylight shaft (Plate 7) giving access to over 2km of caves, with a trunk passage that is an elliptical tube 20m wide and 2.3m high. The longest single cave system is Kulogorskaya, with 14.5km of passages, lying just east of Pinega.

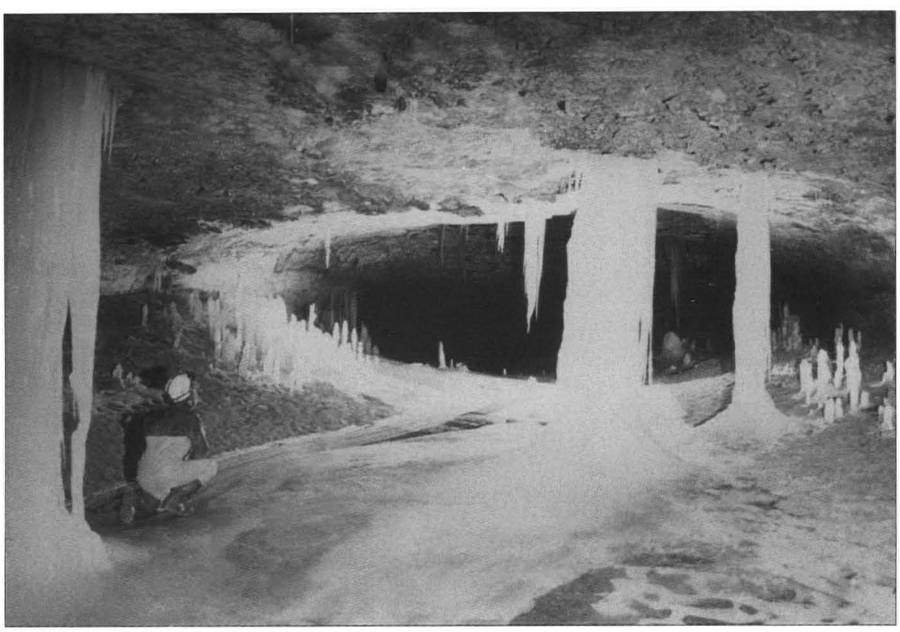


Plate 4. The elliptical phreatic tube that is the trunk passage in Lomonosovskaya, with a variety of winter ice decorations.

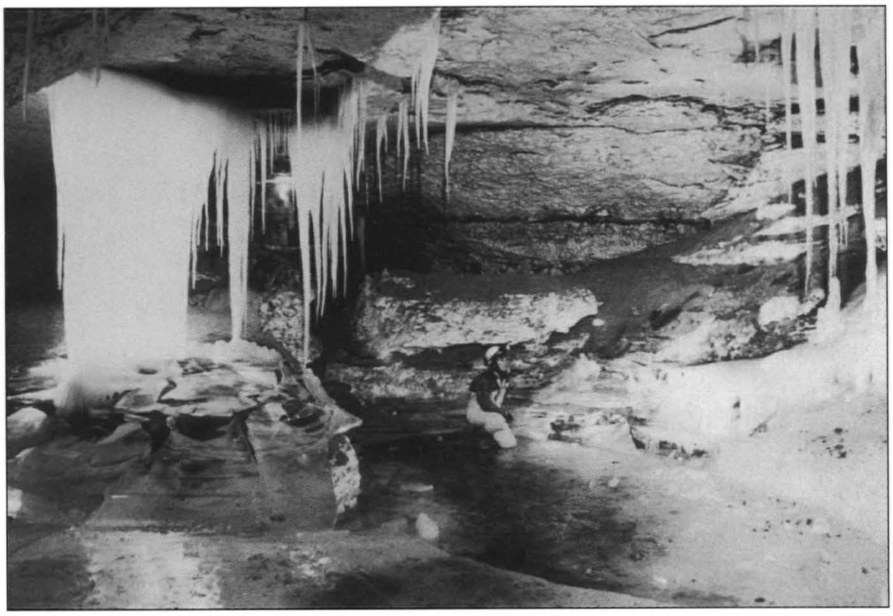


Plate 5. A spacious chamber in the main fossil trunk route through Muzeyskaya.

All the caves in the Pinega gypsum lie just south of the permafrost limit in sub-arctic Russia. Natural geothermal warming therefore ensures that the trunk stream through the caves maintains a flow throughout the year. In winter very cold air sinks into the caves, and induces freezing almost everywhere except along the trunk stream. Both water vapour and percolation water therefore freeze, and each winter the caves are decorated with incredibly beautiful snow crystals and ice formations (Waltham, 1994).

Cave development and collapse

The very high solubility of gypsum permits cave inception to take place along the slightest of structural weaknesses. At some sites in Pinega, the less permeable dolomite bands and the palaeokarst horizons with clay have clearly guided the initial caves. The largest phreatic tubes have then developed in, and with their roofs formed of, the most massive anhydrite beds; these occur just above the dolomite and clay horizons. Some of the flat cave ceilings in the strong blue anhydrite do appear to be on bedding planes. Other large areas of very clean, flat roof cut in the same rock appear to be dissolutional features created at past water levels. These may be analogous to the *laudecke* of the South Harz Mountains *laughohlen* caves (Kempe, 1972), but no associated facettes have been recognised, as the appropriately sloping cave walls could be parts of elliptical tube profiles. Erosion rates in the cave streamways have been measured at up to 20mm per year. Fine scallops have formed on passage walls, and the tubes are perfectly shaped. Roof joints are neatly etched out of the phreatic caves, but a steady level maintained in flowing water has cut perfectly flat roofs in the blue anhydrite or the white gypsum.

The joint-guided passages and rectilinear mazes within some of the Pinega caves are comparable to small versions of the well-known maze caves in the Ukrainian gypsum. It is reasonable to suppose that they have been formed by slowly moving groundwater, which is able to etch out every structural weakness to create maze caves of this type.

Distinctly different are the large phreatic tubes in so many of the Pinega caves. These were very efficient phreatic conduits, which appear to have developed under much higher hydraulic gradients than exist today. The Pinega caves are however young, and they evolved rapidly. Many of the phreatic trunk passages are now partially drained in the vadose environment, but they are still efficient flow routes that carry high summer flows; others are now permanently dry and fossilised.

The early development of the caves was under conditions very different from those of today. During the glacial maxima of the Pleistocene, the Pinega region lay beneath the piedmont glaciers that formed the eastern sector of the Scandinavian ice sheet. Under these conditions there was little meltwater flow within the ice, and the ground beneath was permanently frozen; this was not an environment for cave development. At the beginning and end of each cold phase, the

Plate 6. A long straight, phreatic passage on a joint/ bedding intersection in Golubinskaya.

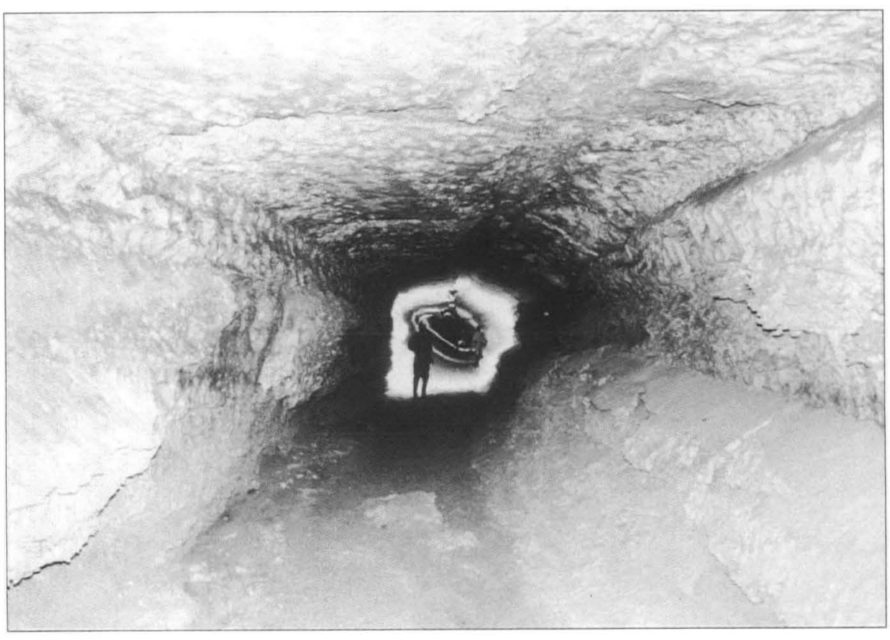


Plate 7. The entrance shaft of Pekhorovsky Provol, through beds of massive gypsum, draped with snow and ice in late winter.

marginal zone of the huge ice sheet lay across the Pinega karst, during the ice advance and retreat respectively. At these time there was a massive abundance of seasonal meltwater, on, within, beneath and in front of the glaciers. Meltwater cut many of the braided valleys through the low gypsum plateau; it also occupied and enlarged the broad trunk valley which crosses the region (but is only occupied by the Pinega River south of the town of Pinega).

Through their summer periods of temporary activity, glaciers are efficient aquifers, carrying meltwater down crevasses and moulins into caves within the ice, along the ice/rock contact and into any permeable underlying rock. When marginal glacier ice spreads over unfrozen ground, the glacier aquifer becomes contiguous with any aquifer systems in the ground. Groundwater flows may then cause renewed dissolution in a karst aquifer. It is significant that meltwater's ability to dissolve gypsum is not hindered by any dependence on biogenic carbon dioxide, and it is only slightly reduced by low water temperatures.

These are the conditions that prevailed at Pinega during parts of the Pleistocene, and that appear to have provided the environment in which much of the cave development took place. Under the thick cover of ice, steep hydraulic gradients were created temporarily within the combined aquifer of the glacier crevasses and the gypsum fissures; these gradients no longer exist in the low relief of the modern Pinega karst. The main phreatic tubes in the gypsum could have been formed by powerful flows of either subglacial or proglacial meltwater. Large phreatic tubes in the Iron Gates caves are already partially drained within the ridges where they survive, but these sites would have been phreatic when ice occupied the intervening valleys beneath its cover of the entire terrain.

Gypsum caves are notorious for their unstable roofs. Large phreatic, subglacial conduits become distinctly unstable when exposed to changing conditions and weathering in a shallow, vadose environment. The wide, old high-level chambers upstream in Olympiyskaya contain a spectacular and sobering amount of fresh collapse debris (Plate 8). In the smaller joint-guided passages, breakdown does occur on a smaller scale (Plate 9), but stable roof arches develop more easily across the narrow passages. Roof degradation is locally dominated by the surface layers of rock curling down, peeling off and ultimately falling away from the main cave roof span; most failing slabs are less than 200mm thick, but a few slabs up to 800mm thick are deformed into huge bent cantilevers. The bending of the roof slabs may be due to the expansive transformation of anhydrite to gypsum, or to gypsum recrystallisation, within the slab. Alternatively it could be due to creep under the influence of gravity. Locally this enforced breakdown has continued until the cave roof has collapsed up to a dolomite horizon. The overall instability of the rock means that collapses are not uncommon at Pinega, and have blocked some recorded entrances; new entrances are then found where doline floors collapse.

IMPLICATIONS FOR THE RIPON KARST

The concept that the large gypsum cave passages of Pinega could have been formed mainly by meltwater in subglacial environments may have implications for the Ripon karst. The large sizes of some of the doline collapses at Ripon indicate that the area is underlain by a mature karst, in which large individual cave passages may be a significant element. The concept that these caves were enlarged in the gypsum by subglacial meltwater can only be conjectural while none of the caves is accessible.

Plate 8. Ongoing roof breakdown in the high-level of the trunk route at the upstream end of Olympiyskaya.

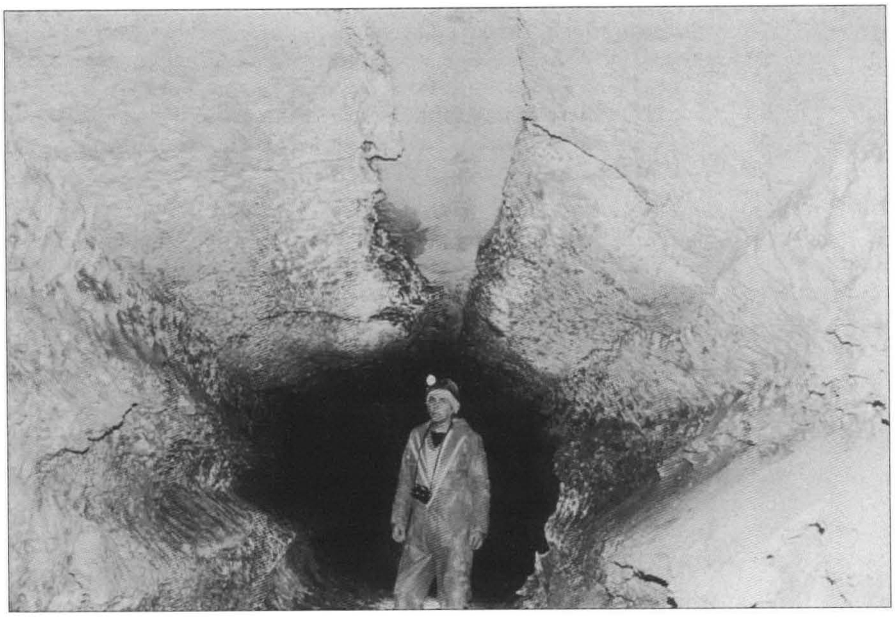


Plate 9. A modest amount of breakdown to a higher bedding plane in the roof arch of a joint-guided passage in Golubinskaya (photo: Vladimir Kisseljov).

There is considerable scope for debate on the environment of the cave genesis, and analogies with the Pinega karst may be considered as a contribution to an ongoing and as yet unresolved debate.

Dissolution by slowly moving water plays a major part in the enlargement of many maze caves (Palmer, 1975). Favourable environments exist where low hydraulic gradients develop in the areas of low relief that characterise gypsum karsts, because of the low mechanical strength both of the gypsum and of the associated rocks. Gently dipping units of gypsum, interbedded with other permeable rocks, are ideal hosts for interstratal karst, where again maze cave development is favoured (Klimchouk, 1996b). All these conditions apply to the Ukrainian karst of Podolsky, which contains the very extensive gypsum maze caves, and also to the Ripon karst. Cavity migration through the cover rocks does create subsidence dolines over the maze caves (Klimchouk and Andrejchuk, 1996). It is therefore possible that the caves beneath Ripon are extensive mazes with no distribution or pattern except the repetitive framework imposed by the joint systems. However, the small passages of such maze caves are barely compatible with the sizes of the observed dolines, and it is likely that larger trunk caves are present.

A number of factors may have contributed to the evolution of larger cave passages in the Ripon gypsum. Drainage through the gypsum into the Ure valley would have been greater before the valley was filled, but flow increases could only have been modest from the small up-dip catchments. Possibly also important was backflooding into any caves when the gypsum was at river level in the old valley; this would have introduced aggressive river water into the caves, but the process tends to generate larger maze cave instead of larger trunk passages (Palmer, 1975). More importantly, if larger cave passages do exist beneath Ripon, they are most likely to have formed in the environment of enhanced water flow that existed temporarily around and beneath the Devensian ice margins.

During the Devensian, the Ripon area lay beneath the western edge of the massive glacier that occupied the Vale of York (Fig. 5). The Vale of York glacier was fed by the Scottish-Scandinavian ice sheets in the north, and flowed to lower latitudes and altitudes in the Vale, where it was melted slowly in the warmer atmosphere and on the warmer ground. It was a wet-based ice mass, lying on unfrozen ground and associated with copious seasonal drainage. It spread across a deeply incised proto-Ure valley; this cut through the gypsum belt close to the course of the present River Ure (Powell *et al*, 1992), before turning east and drained into the Vale of York through a gorge at Boroughbridge, 10km downstream of Ripon (Cooper and Burgess, 1993). As the ice advanced, this deep proto-Ure valley was partly choked up with sand and gravel outwash in the Ripon area, passing distally into pro-glacial lake deposits of laminated clays. These deposits were then overridden by the ice-sheet (Cooper and Burgess, 1993).

At the glacial maximum, the main glacier in the Vale of York extended southwards to the east of Doncaster and had flows of Pennine ice converging onto it. However, this maximum advance was short-lived and left only thin deposits over the southern part of the Vale. For most of its life the Vale of York ice-sheet was more established with well-developed terminal moraines, first at Eskrick, and then at York (Cooper and Burgess, 1993). The foothills to its west were left largely unglaciated and a belt of lateral moraines extended from west of York, through Knaresborough and onwards to the northwest so that they now lie about 4km west of Ripon. West of these lateral moraines the Pennine drainage was diverted around the edge of the ice in a series of channels, including the Knaresborough Gorge, to drain southwards into the River Wharfe southwest of York.

The lateral moraines and western margin of the ice-sheet approximately follow the outcrop of the dolomitic limestone that lies below the gypsum sequence. The limestone escarpment is traversed by numerous deeply incised channels aligned to the west. The channel up the escarpment through Studley Royal (immediately west of Ripon) is just one of those that have bounding deposits of sand and gravel. The disposition of these channels and their associated deposits suggest water flow up the dip-slope of the escarpment westwards to the marginal drainage channels. There is also evidence of abundant long-lived water movement within the Vale of York glacier, which developed extensive eskers down its length. These ridges of glaciofluvial sediment may have accumulated in huge glacier caves at the base of the ice or within supraglacial drainage systems. At the margins of the ice-sheet some subglacial channels were entrenched into the bedrock before being filled with till from the wasting ice.

Especially in the summers, there was an abundance of meltwater around and beneath the Vale of York glacier. The hydrostatic head produced by the glacier would have induced large flows of water that were injected into any fissures in bedrock aquifers. The gypsum was ideally located in the walls of the pre-glacial channel, which was then full of water and gravel beneath the ice; now it is more fully choked with sediment and buried beneath later deposits in the modern valley (Fig. 2). Water could have been forced down through the gypsum beds into the underlying limestone to resurge from the subglacial outcrop a few kilometres to the west. This enhanced water flow could have excavated phreatic conduits very similar to those now accessible at Pinega. In the groundwater environment of the melting glacier, these conduits would have grown far more rapidly and far larger than any

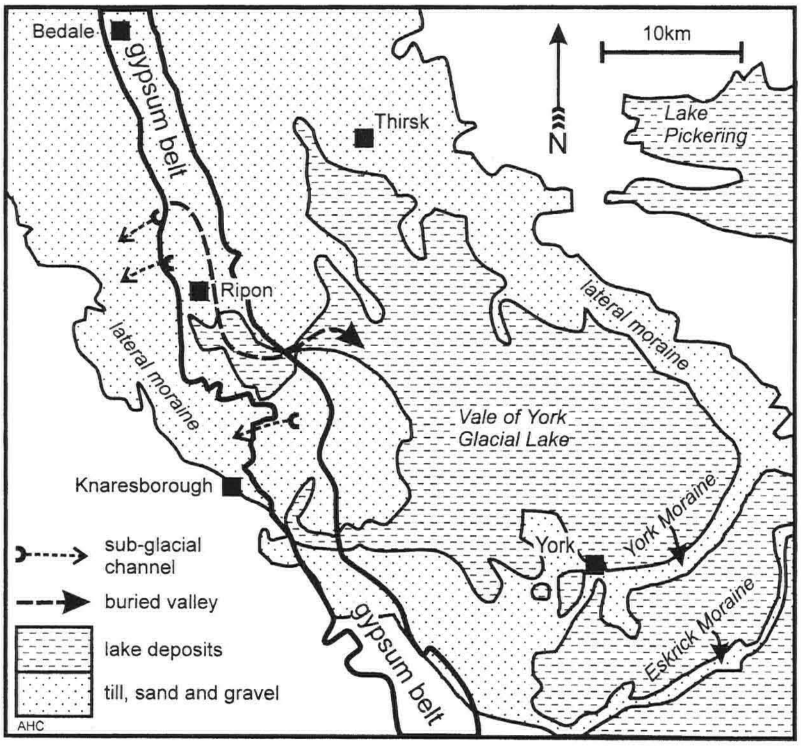


Figure 5. The relationship of the belt of gypsum karst to the drainage features and sediments of the Devensian glacier in the Vale of York. The gypsum belt is mapped as the zone between the gypsum's outcrop and its down-dip transition to anhydrite. Drift is absent or very thin in the unshaded areas.

passages in a maze cave that had formed without the massive throughputs of meltwater. There may well have been an earlier phase of maze cave development in an interstratal karst not exposed to such massive drainage input; however, whether maze cave elements are still recognisable is open to debate. Zones of roof collapse scattered along the largest sections of the new major conduits would subsequently propagate upwards, and so provide the roots of the modern doline collapses. The seasonal surge of glacial meltwater resulted in extensive pro-glacial lakes in which varved laminated clays and silts were deposited. Similar deposits have been proved in caves that have been penetrated by boreholes into the gypsum of the Ripon area.

At Ripon itself, no outline of dendritic conduits can be recognised in the pattern of dolines, as is normally the case over cavernous interstratal karst. However, the subsidence ridges of Snape Mires, which appear to be related to collapsing caves beneath (Cooper, 1986), do have a crudely dendritic pattern that could overlie winding trunk caves at shallow depth. At the glacial maximum, the western edge of the ice-sheet was about 10km west of Snape Mires, and subsequently it melted back across the main subsidence area. Here the subsidence ridges affect late glacial lake deposits and some of the collapse is syndepositional, indicating cave degradation during the late glacial interval. It is likely that cave enlargement took place not long previously, and that both processes evolved consecutively beneath the margin of the retreating ice sheet.

It is certainly possible that large cave conduits were dissolved out of the Ripon gypsum by subglacial meltwater. These could now provide routeways for the main lines of groundwater flow, and would therefore be the main zones of continuing dissolution activity. If this is the case, the patterns of Pleistocene glacier drainage may be the ultimate influence in the distribution of the modern dolines. It could just be that consideration of the palaeohydrology of the bygone glacier could contribute in some small way to the ongoing problems of the residents of Ripon, who wonder where their next ground collapse will be.

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Trollers Gill, Wharfedale, North Yorkshire: its geology, caves and hydrology

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Abstract: Part of a karst valley system on the southern edge of the Askrigg Block is described. Aspects of the present underground and surface hydrology, including the currently known sinks, risings and cave fragments, are considered in relation to the modern topography and the underlying geology. Possible mechanisms previously suggested for the evolution of the surface morphology are reviewed, and a development model based on rapid incision by glacial meltwater is presented.

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INTRODUCTION

Trollers Gill is a north-south orientated valley, east of Appletreewick in upper Wharfedale, Yorkshire. The valley, forming part of the course of Skyreholme Beck, contains a modestly spectacular gorge section (Figs 1 and 2). Some authors have used the name Trollers Gill for the gorge section only, but here it is applied to the Skyreholme Beck valley from an old mine dam west of Burhill (Fig.2), downstream to Parceval Hall Bridge. Upstream of the dam the name Dry Gill is used. The more specific name Jackdaw Nick is applied to the gorge section, as appears to be the most widespread usage.

In normal water conditions the stream sinks in several choked depressions in its bed to the north of Jackdaw Nick [around SE 069622], and the gorge itself is dry. The choice of main water sink depends upon the stream discharge, though on Fig. 2 the stream is shown sinking at its typical low discharge position. South of the gorge water resurges into the streambed from springs on the western valley side (here termed the West Side Springs) and from Nape Well on the eastern side of the valley. In times of flood the underground drainage routes are overwhelmed and the gorge again carries a stream.

Jackdaw Nick is approximately 200m long, up to 30m deep and 4m wide at its narrowest point. North of the gorge the valley is more gently incised, the stream originating from Blackhill Level and Timpony Joint, respectively the rising and flood rising for the Stump Cross Caverns system. South of the gorge, after gathering two tributary dry valleys, the valley takes on an imposing U-shaped profile with steep craggy sides, before losing its individual character and merging with the valley of Blands Beck. Beyond the confluence the combined waters flow towards the River Wharfe.

GEOLOGY

Skyreholme Beck cuts directly across the Skyreholme Anticline (Fig.3), a southwest-northeast orientated fold that forms part of the Ribblesdale Fold Belt (Phillips, 1836). These Variscan structures developed in late Chadian to Pendleian times in response to regional dextral shear (Arthurton, 1984). They lie roughly parallel to the Craven Fault zone, and plunge towards the northeast. Asbian carbonates of Great Scar Limestone facies exposed in the gorge form part of the Askrigg Block, in contrast to the rocks of deeper water facies deposited in the Craven Basin to the south. The southern margin of the Askrigg Block is generally related to the line of the Middle Craven Fault zone. In the Appletreewick district the fault zone appears discontinuous but, on the evidence of the facies exposed around Trollers Gill, it must lie to the south of the area covered by this study (Dunham and Wilson, 1985).

To the north, the east-west line of the North Craven Fault truncates the Skyreholme Anticline. A small outlier of Brigantian and Pendleian Bowland Shales and Grassington Grit is preserved against the fault on the northern limb of the fold; Black and Bond (1952) give a detailed account of the succession. Water sinking in Hell Hole gathers from the low lying ground underlain by the Bowland Shales, whereas the more resistant Grassington Grit forms the scarp of Farncarl Crag. A detailed geological map of the Skyreholme Anticline area is published in Anderson (1928). To the south the thin Bowland Shales horizon is not currently exposed, and the high ground of Simons Seat across the Fir Beck valley comprises younger Namurian rocks of Millstone Grit facies.

THE CAVES

A catalogue of caves in the Trollers Gill area is given by Brook *et al* (1988) and their locations are shown in Fig. 2. They can be divided into four groups:

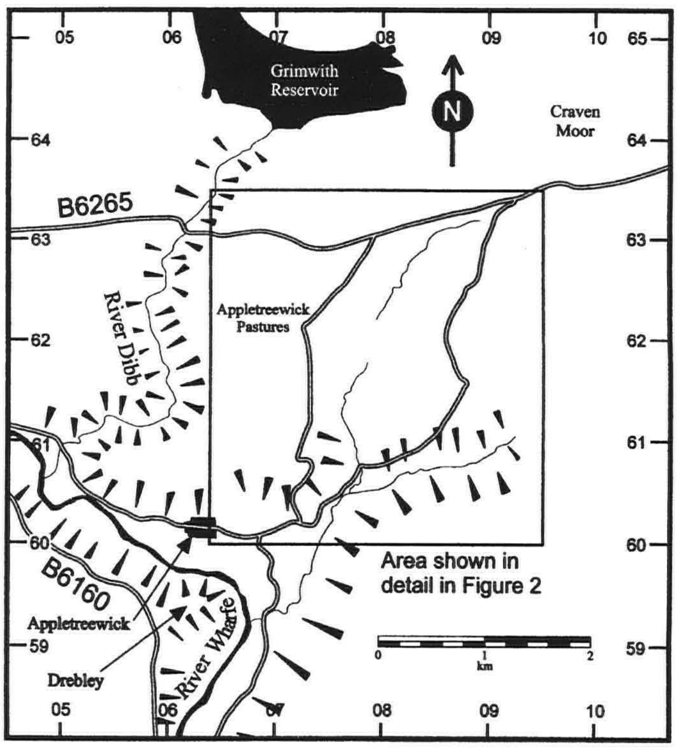

Figure 1. Location of the Trollers Gill area.

Swallet caves

Two swallet caves, Hell Hole and Spar Pot, are known. Hell Hole is the more extensive, containing 210m of passage and two 20m shafts. The cave ends in a choke, with the water being lost down an impenetrable slot (Brook *et al,* 1988).

Spar Pot, situated above the western side of the valley, swallows a small stream into a rift, at present filled with old tyres. The cave has been followed for 9m down boulder-filled rifts, to where the continuation is blocked by loose rocks (Marvel, 1994).

Resurgence caves

Nape Well is the only accessible resurgence cave known in the area. It consists of 20m of aqueous passage (including a squeeze opened up by the use of explosives) ending upstream to the northeast where the stream emerges from a wide bedding plane only 20cm high.

Cave fragments entered via old mine workings

On many occasions the area was the scene of various mining ventures for galena and fluorspar. It is crossed by several small west-east oriented veins, referred to as the Nape Well Strings by Dunham and Wilson (1985), as well as containing the Gill Heads Vein complex in a tributary dry valley to the east. These were a significant source of fluorspar, and were mined until the 1970s. Several mines intersected natural passages, the most extensive of which that may still be entered are in Trollers Gill Cave (Fig.4). About 60m of mined passage leads to a phreatic tube that trends north-south, following the c.30° dip of the beds towards the south on the southern limb of the anticline. Down-dip the passage is blocked by a sump that is choked by mud after 2m (Monico, 1995). Various dissolutional features visible in the roof of the mine workings suggest that the miners may originally have followed a natural passage. A 5m-high natural aven can be entered near the mine entrance.

Gill Heads Cave No.3 (Brook *et al,* 1988) consists of a 46m-long mine level entering a short section of passage. Workman (1977) describes 20m of cave passage entered via a 20m-long mine level called Warren Cave. However, investigation of the mine levels in the area when researching this paper revealed no natural passage. Gill Heads Cave No.2 (Brook *et al,* 1988) is described as a part-natural and part-mined shaft that can be descended to a choked floor at 20m depth.

Gemmel and Myers (1952) record an attempt to dig into what was described as a vast underground lake, found in the course of mining beneath Burhill, east of Trollers Gill. Burhill itself is shown on the Ordnance Survey map to be only about half a kilometre from Trollers Gill. However, the unsuccessful dig was undertaken nearly two kilometres to the east, and is recorded by Brook *et al* (1988) as Bruffs Swallet.

Other caves

A 3m-high by 1.5m-wide entrance 30m above the floor of the valley [SE 06956179] leads to only 4m of passage, aligned along a joint. On the eastern side of the gorge, directly above Nape Well Cave, what appears to be the top of a sediment-filled phreatic tube can be seen some 50m above the valley floor. This hints at the existence of some relict high-level cave development in the area, pre-dating the incision of Trollers Gill.

Up-valley of the stream sink above Jackdaw Nick a 12m-long fragment of crawling-size passage occurs in the west bank just above stream level. This cave (Bone Hole) consists of a small tube that becomes too low. Another small fragment of cave, recorded by Brook *et al* (1988) as Gill Heads Cave No.1, consists of a small square chamber entered from a doline close to Hell Hole. No trace of this cave could be found when researching this paper.

HYDROLOGY

The hydrology of the area has received little previous study. Gemmel and Myers (1952) comment that Nape Well ran discoloured when mines near the lost cavern under Burhill were active. In an area like that around Trollers Gill, where many different mining operations have operated over the years, it seems unlikely that only one mine would be working at a time. If the economic situation was such that one mine was being worked, it seems logical to assume that other mines in the

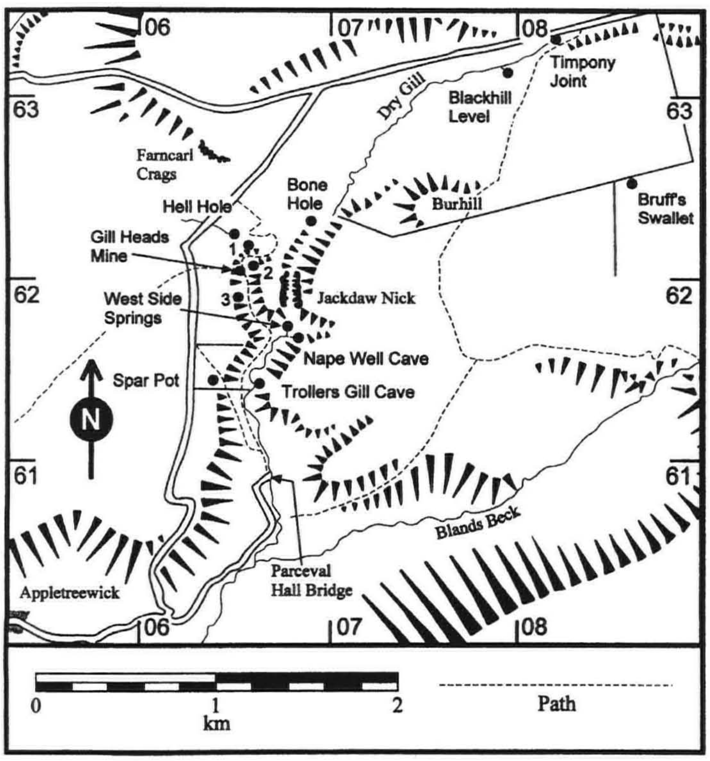

Figure 2. Map of the study area.
(Base map reproduced from Brook et al (1988) with permission.)

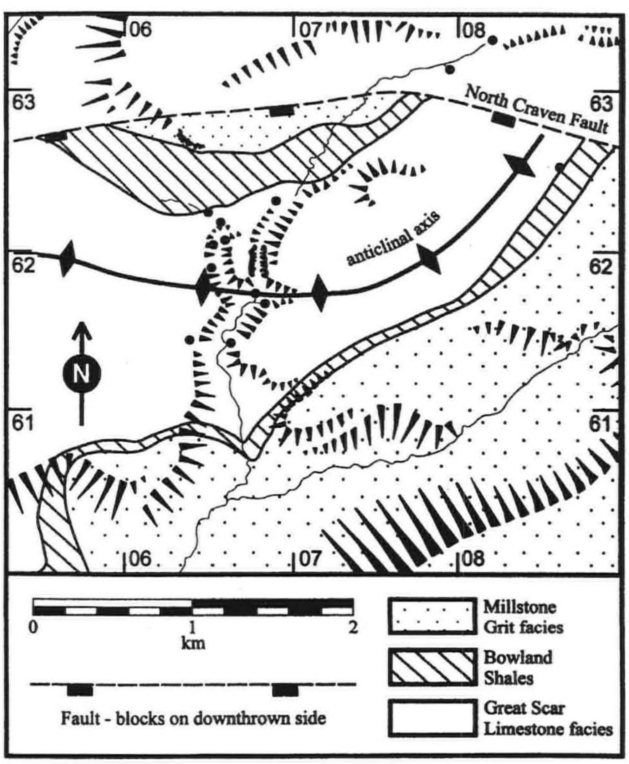

Figure 3. Geological map of the Trollers Gill area.
(Base map reproduced from Brook et al (1988) with permission.)

Date	West Side Springs	Stream Bed Rising	Nape Well
29/03/97	6.5	-	7.5
06/04/97	7.5	-	8.0
11/05/97	7.5	7.5	8.0
18/05/97	8.5	-	8.0
01/06/97	9.0	-	8.0
08/06/97	9.0	-	8.5
20/07/97	9.5	9.5	8.5
03/08/97	9.5	9.5	8.5

Table 1. Temperature of resurgent waters (°C.).

area would be active at the same time. If so, the discoloration could have originated from other sources than the lost cavern area.

An attempt to trace the water from Hell Hole is recorded by Griffiths (1981), who suggested the springs on the west side of the valley (the West Side Springs of this paper) as a likely resurgence. He also suggested that the valley-side springs are unrelated to any water that resurges directly into the streambed, as happens during high flow. The attempted visual trace using fluorescein dye was abandoned after six hours of observation. A flow-through time greater than six hours for a straight-line distance of only 550m was taken to indicate the presence of a substantial proportion of flooded passage between Hell Hole and its presumed resurgence.

O'Connor *et al* (1974) comment on Hell Hole feeding unspecified springs in Trollers Gill, but give no definitive information. They also refer to a lost connected to Nape Well encountered by miners - presumably the one discussed by Gemmel and Myers (1952) - though neither references nor supporting evidence are provided.

Regular recording of water temperatures at the risings in Trollers Gill (Table 1) showed that the springs on the western side of the valley are all at the same temperature. Whenever it could be measured the intermittently active rising in the streambed just downstream of Jackdaw Nick was the same temperature as the West Side Springs. This suggests that the springs have the same source and those on the valley side are not separate from the stream bed flood rising as Griffiths (1981) suggested. Nape Well always has a different temperature to the West Side Springs, suggesting it is fed by a different catchment.

Several dye traces using optical brightening agent (OBA) were undertaken at widely separated intervals. First detectors were placed at Nape Well, West Side Springs and Parceval Hall Bridge (Fig.2). They were removed after two weeks of variable weather and all were negative, indicating that no OBA was finding its way into Trollers Gill from other sources. Between each trace replacement control detectors were placed and removed; none of these showed any trace of OBA. OBA introduced into Hell Hole was detected at the two main West Side Springs, but not at Nape Well or at the main sink above Jackdaw Nick. OBA introduced into Spar Pot was not detected at the west springs nor at Nape Well. It was, however, detected at Parceval Hall Bridge. OBA introduced into the sink above Jackdaw Nick was detected at the West Side Springs and at Parceval Hall Bridge, but not at Nape Well.

The data from the OBA tests allow a number of conclusions to be drawn about the hydrology of the Trollers Gill area:

1. Water sinking at Hell Hole and at the stream sink upstream of Jackdaw Nick resurges at the West Side Springs;

2. No discrete resurgence is visible between the risings and Parceval Hall Bridge (which is beyond the limestone outcrop), so water from Spar Pot probably enters the stream through the alluvium flooring the valley. Much of the valley floor alluvium could be of recent origin, having been deposited in a lake formerly impounded behind the now breached Skyreholme Dam.

The origin of the water resurging at Nape Well is still unknown, but over $2km^2$ of the limestone outcrop east of the gill, along the axis of the anticline, appear to be the most likely source. Detectors recovered from Nape Well showed little contamination with organic debris, compared to those from other sites in the Gill. This suggests an autogenic, rather than allogenic, origin for the water.

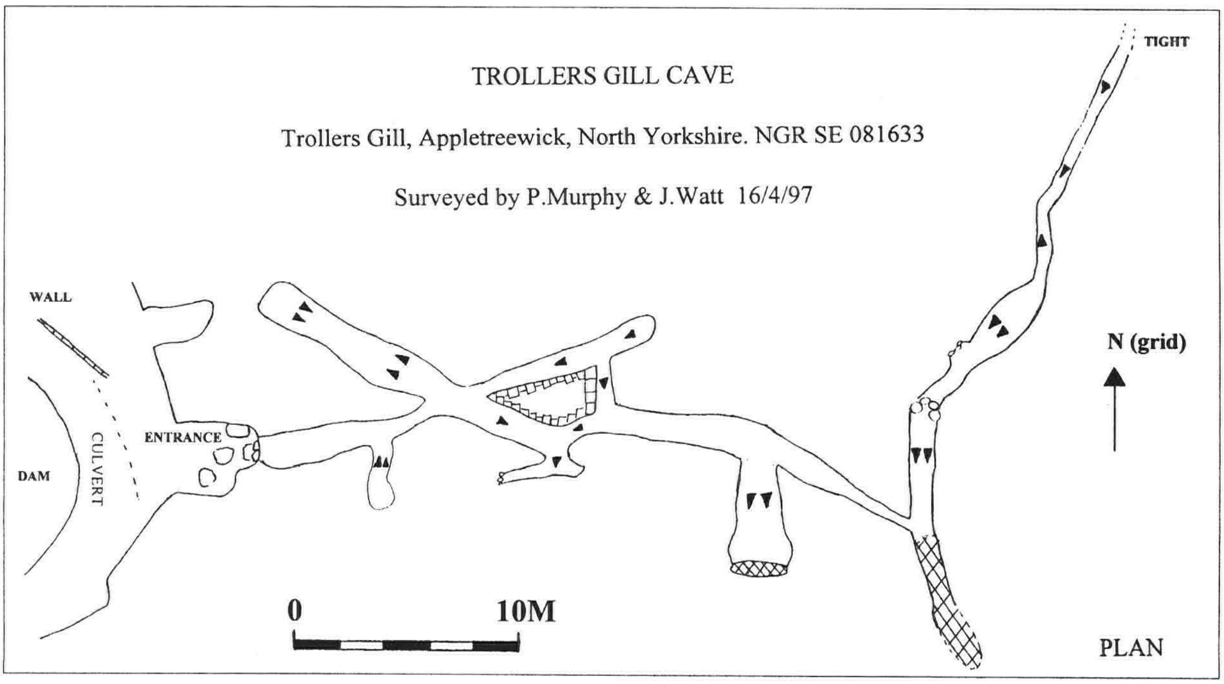

Figure 4. Trollers Gill Cave (surveyed by P. Murphy and J. Watt.)

GEOMORPHOLOGY OF JACKDAW NICK

The Jackdaw Nick gorge dissects the northern limb of the Skyreholme Anticline, the tributary dry valley from the east being incised into the fold's axial zone. The gorge is remarkably linear, cutting across the dip of the beds with very little sinuosity. Fluvial potholes and swirl pools have developed at the few bends in the gorge, and the gorge walls are smooth and in places overhanging.

The geology of Trollers Gill has been described (Phillips 1836; Wilmore 1910; Kendall and Wroot 1924; Versey 1946 and Varker 1994), but little has been written regarding possible origins for the Jackdaw Nick gorge. Varker (1994) advocated cavern collapse as the gorge formation mechanism. This appears unlikely, as no indications of cavern collapse, such as subsided blocks or surviving roof spans are present. Cavern collapse is extremely rare in the massively bedded and competent limestones of Great Scar Limestone facies.

Jackdaw Nick has many features in common with other gorges on the southern margin of the Askrigg Block, such as Gurling Trough (Conistone Dib), Dib Scar, Watlowes Valley and Gordale, all of which are interpreted as fluvial features incised by glacial melt waters under periglacial conditions (Waltham *et al*, 1997). Gorge formation can be remarkably rapid under such conditions. Raistrick (1931) interpreted Trollers Gill as belonging to a set of lateral drainage channels on the north side of Wharfedale. In this interpretation Trollers Gill had formed as an overflow channel for water from a glacially dammed lake at Grimwith to the north.

The tributary valley entering Trollers Gill from the west has no obvious feeder channels. Up-valley from Gill Heads Mine a col exists between this valley and the upstream end of Jackdaw Nick. The tributary valley may be an abandoned valley oxbow, possibly the route taken originally by the Dry Gill valley waters, before the incision of Jackdaw Nick provided a more direct route and captured the drainage.

Water overflowing from a lake would carry very little sediment, as most would have settled out into the ponded water. Sediment loading is generally acknowledged as a very important factor in gorge incision, as sediment acts as an abrasive agent, enhancing the efficiency of streambed erosion. An alternative origin to that proposed by Raistrick (1931) is that the Jackdaw Nick gorge was cut by water derived from ice melting on the interfluve between Wharfedale and Nidderdale, around Craven Moor, which flowed down the valley of Dry Gill. This source area is underlain in part by rocks of Millstone Grit facies, a potential provider of sediment to enhance abrasive scour.

CONCLUSIONS

The gorge of Jackdaw Nick formed as a result of fluvial incision by glacial melt waters, probably in the latter stages of the Devensian glaciation, and is one of several such features found on the southern margin of the Askrigg Block. The meltwater possibly originated from ice decaying on the interfluve between Wharfedale and Nidderdale. A tributary valley joining Trollers Gill from the east may be an abandoned oxbow pre-dating the incision of the Jackdaw Nick gorge.

Dye tracing results indicate non-integrated underground drainage in the area and direct observation suggests that the active conduits are impenetrable. Evidence of relict cave development is visible in the area. Perhaps large passages and vertical development visible in Hell Hole, and others suggested by the size of the entrance to Spar Pot, are elements of relict cave systems, now occupied by underfit streams. The development of these passages could pre-date the incision of the Trollers Gill valley.

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CAVE AND KARST SCIENCE Vol. 25, No. 3, December 1998
Transactions of the British Cave Research Association

Forum

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

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

CORRESPONDENCE

ERRATUM: THE USE OF REBREATHERS IN CAVE DIVING

Cave and Karst Science 25(2), the Bahamian blue holes theme issue, contains much of interest and is a fine tribute to the achievements of the late Rob Palmer. However, Fiona Whittaker's introductory overview contains a small but important error on page 54. The first use of mixed gas closed circuit diving apparatus in caves was almost certainly well before the Andros Project. The earliest records available (1, 2, 3) refer to the deployment of nitrox rebreathers at Wookey Hole (Somerset) in December 1956 and in Hurtle Pot (Yorkshire) in April 1957. On both occasions nitrogen was used as a diluent gas. This use allowed deeper explorations to be made, beyond the limits imposed by oxygen toxicity, than would have been possible if pure oxygen had been the supply gas (as with earlier apparatus).

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COMMENTS ON "GEOCHEMICAL AND DEPTH CONTROLS ON MICROPOROSITY AND CAVITY DEVELOPMENT IN THE MAYNARDVILLE LIMESTONE: IMPLICATIONS FOR GROUNDWATER"

Dear Editors,

These comments relate to the paper by Lisa Shevenell and Patrick M Goldstrand in *Cave and Karst Science*, Vol.24, No.3, (December, 1997). The paper presents some interesting hypotheses on the development of both macroporosity and microporosity in the Maynardville Limestone in Bear Creek Valley, and effectively summarizes information from a number of the many hydrogeological and geochemical studies performed at the Y-12 facility. However, we are confused by the use of a well hydrograph method for calculation of local storativity and transmissivity, and the use of these parameters to assess the heterogeneity within this carbonate aquifer. Although the method of using well hydrographs was described elsewhere by Shevenell (1996), and a similar technique was used by Moore (1992) for interpretation of stormflow hydrographs in the root zone on forested Oak Ridge hill slopes, the method goes against the grain of conventional thinking about carbonates.

Shevenell and Goldstrand compute storativity relying on the assertion that the recession constant of the well hydrograph is equal to that of the aquifer discharge (see equation 1 of the Shevenell, 1996 reference). The implication they make is that the recession constants of each hydrograph in a well are equal to the recession constants of some discharge component. However, discharge into surface streams or from significant springs draining Bear Creek Valley was not discussed. To what aquifer discharges are the authors referring? Are we to believe that ground water in wells such as GW-694 and GW-704, which are less than 30 metres apart, and are both completed in zone 4 of the Maynardville Limestone, actually drain to different discharges merely because they have different hydrograph recessions? We note that these wells share the same suite of contaminants, not only with each other but with the closest downgradient spring (Lockheed Martin Energy Systems, Inc., 1996).

A qualitative assignment of wells to groups that appear to have hydraulic characteristics consistent with the lesser and greater permeability elements of a karst aquifer seems useful, and might be augmented with chemograph analyses and ground water tracing to or from these wells. We support efforts such as this study which aim to characterise the multiple porosities and permeabilities of karst aquifers. However, we know of no evidence to support the equality of well hydrograph and discharge hydrograph recession in carbonate or karst aquifers, and Shevenell (1996) puts forth no data to support this claim. In our experience, ground water in wells completed inside and outside of conduits may display quite different responses to storms and yet drain to a single spring. Unfortunately, this problem would seem to be amenable to physically based theoretical analysis in only the simplest cases, as explored below.

During baseflow in a master conduit carrying the entire aquifer discharge the effects of transient head changes should be minimal and inertial head losses would typically dominate over viscous head losses, even under very low hydraulic gradients. If such a conduit were intercepted by a well directly upgradient of a spring, the following relationship should hold:

$$h_w - h_{sp} = \int_{s_w}^{s_{sp}} \left[f(s) v^2(s) \right] ds$$

The subscripts *sp* and *w* refer to the spring and the well, *v* is the average velocity of groundwater in the conduit, *f* is a lumped parameter friction factor, and *s* is the distance along the path of the conduit. If an interval of time is chosen such that it is large in comparison with the travel time from the well to the spring but is sufficiently small so that neither cross sectional areas nor Reynolds numbers in the conduit decline significantly,

$$h_w - h_{sp} = Q^2 \int_{s_w}^{s_{sp}} \frac{f(s)}{A^2(s)} ds$$

Here Q is the spring discharge and $A(s)$ is the cross-sectional area of the conduit. Recession of well and spring hydrographs should then be:

$$\frac{(h_w - h_{sp})_{t2}}{(h_w - h_{sp})_{t1}} = \frac{Q_{t2}^2}{Q_{t1}^2}$$

between times t1 and t2, providing this interval is chosen consistent with the assumptions given above. Consequently, if $Q \propto e^{-at}$ then h_w should be proportional to e^{-2at}, providing h_{sp} doesn't change significantly. In this case the well hydrograph recession constant would be twice that of the spring (aquifer) discharge.

In conclusion, we believe that a quantitative assignment of local aquifer parameters based on well hydrographs is confusing and misleading. We regret that the authors felt it necessary to include these data in their paper when it seems that a more qualitative comparison of recession constants and hydrograph characteristics would have sufficed.

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AUTHOR'S REPLY by Lisa Shevenell, Nevada Bureau of Mines and Geology, University of Nevada, MS 178, Reno, NV 89557-0088, USA.

We appreciate the attention and comments provided by Sidney Jones and Gareth Davies and I will attempt to clarify and emphasize some parts of the paper. Note that their comments mainly refer to a previous paper (Shevenell, 1996), which discusses a well hydrograph analysis method.

The presentation of the results of the well hydrograph method for estimation of aquifer parameters is only one of several types of information included in the *Cave and Karst Science* paper. The various data demonstrate differences in flow behavior in a highly heterogeneous karst aquifer where areas dominated by microporosity are markedly different than those dominated by macroporosity (conduits), as expected. Jones and Davies express concern over the locations of surface discharges that might be associated with the aquifer waters monitored by wells, and they question whether well and spring hydrographs are equal. In no paper have I stated that the two discharges are equal. Equation 1 from Shevenell (1996) relates flow and water levels at one point (the well), suggesting that measured water levels are directly related to the flow through the conduit at that well. There is no implied relationship between the well and a discharge spring. Regarding this possible relation between well and spring hydrographs, waters monitored in wells in the valley may or may not discharge locally to specific springs monitored within Bear Creek Valley. Without thorough, reliable, tracer tests from particular ells to known discharge locations, specific discharge locations from individual wells generally cannot be identified at present. Such tracer tests are generally lacking at the site, except some that have shown ambiguous results (Goldstrand and Haas, 1994). With regard to the assumption that recession slopes on a well hydrograph can be related (are equal) to those at a distant discharge site, very few data exist to evaluate this possibility (due to the general lack of the aforementioned tracer tests). Hence, I have made no such claim of equality.

The only data of which I am aware concerning hydrographs from a well and spring that are potentially connected indicate that the recession slopes will not be equal. Hydrograph data have been collected from one well (GW-684) and a nearby spring (SS-5) by Desmarais (1995). These two monitoring points are known to be directly connected to one another via a cavity, on the evidence of an observed increase in turbidity in SS-5 during drilling of GW-684 (Shevenell *et al*, 1992) and an increase in turbidity and water level in SS-5 during water injection into GW-684 (Shevenell *et al*, 1995). Again due to the lack of tracer tests under natural flow conditions, it is unknown if the water tapped by the 39m-deep well actually discharges at the spring located approximately 27m away. However, as can be observed from the Desmarais (1995) data (Fig.1), the rises and recessions of the spring mimic closely those in the nearby well, which is completed in a conduit that exhibits direct hydraulic communication with the spring. The slopes of the recessions from the spring and well are not equal, with the well recessions being 1.6 and 1.8 times those observed in the spring, depending upon the storm. The inequality of the two recessions is most likely a result of the two sites draining different areas, with the spring probably representing flow from a number of different conduits. The recessions of the spring or well represent drainage characteristics from areas up-gradient of them, which feasibly will not be the same for both the spring and well, and hence, they will have different recession constants

Jones and Davies ask if they are to believe that water in wells 30m apart (GW-694 and GW-704) drain to different discharge areas. No such statement or implication was made in the paper. The responses in these two wells demonstrate one of the major points in the paper. GW-704 necessarily exhibited different behavior than GW-694 because it is NOT completed in a conduit or fracture (as is GW-694), and hence, diffuse, slow flow dominates. The two wells share the same suite of contaminants (as Jones and Davies note) showing direct communication between conduits/fractures and matrix intervals, and hence that the two aquifer regimes are interconnected. However, as also stated in the paper, the flow regimes are indeed different as shown by (1) the hydrographs, which reveal quick versus diffuse flow conditions, and (2) geochemical characteristics. Calculations of calcite and dolomite saturation indices in conduits show changes between super- and under-saturation at different sampling times, because of the nature of quick flow in these features, which transmit younger, more dilute recharge waters rapidly during and after storms. Saturation indices in GW-704, and other wells dominated by diffuse flow, show that the matrix parts of the aquifer are not influenced by quick flow (consistently supersaturated), but more diffuse flow (longer residence time fluids) toward fractures and conduits. Although this comes as no surprise, these data were included to demonstrate further the different flow behavior between matrix (microporosity) and conduit (macroporosity) portions of the aquifer. Jones and Davies point out that wells completed inside and outside of conduits may display quite different responses to storms and yet drain to a single spring. That is true, and there was never any suggestion in the paper that waters in matrix zones are isolated from waters in conduit/fracture zones. In fact, a previous paper (Shevenell *et al*, 1994) addressed specifically the process of matrix diffusion into fractures at the site, although not in the

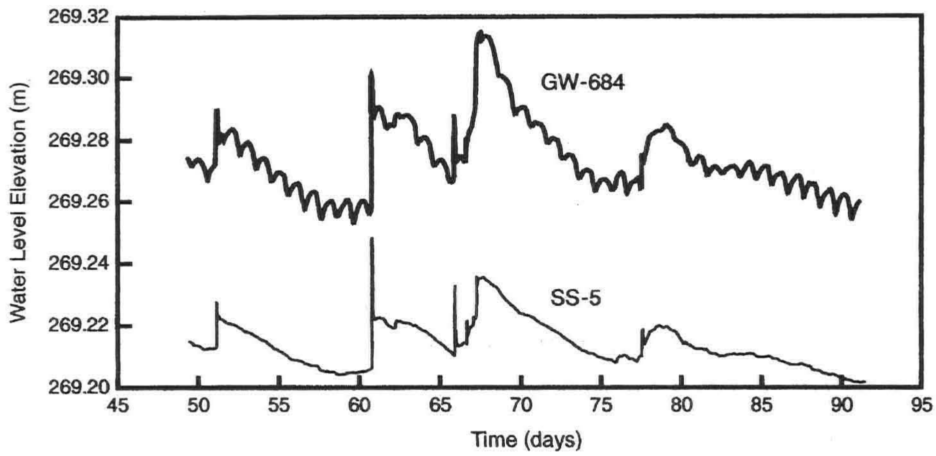

Figure 1. Spring and well hydrographs, Oak Ridge, Tennessee, August 1994 (after Desmarais, 1995). See text for discussion.

carbonates. It is unreasonable to assume the two adjacent aquifer waters in the two types of porosity discussed would discharge in different locations, and this suggestion was not made in the paper.

In looking at hydrograph responses in a highly heterogeneous karst aquifer, Jones and Davies suggest that only the simplest cases could be analyzed quantitatively and they provide one example of a simple case. Another simplistic case is illustrated in Fig. 1. One would not expect a well at much greater distance than the one depicted in Fig. 1 to have hydrograph responses that are so similar to those at a discharge location. This is because discharge locations can be an agglomeration of flows from a network of conduits that receive flow from a considerable volume of the aquifer composed of microporosity. Hydrographs from each of those wells throughout the drainage area of the spring could have markedly different rises and recessions. The latter differences are due to, among other things, their location relative to the recharge area, and the local hydrogeologic characteristics where macroporosity (conduits) experiences quick flow and wells monitoring only microporosity (matrix intervals) do not. One would not expect that the sum of these responses, observed at the discharge site, would equal any of the responses in individual well hydrographs.

Jones and Davies suggest that the hydrograph data presented in the paper could be augmented with chemograph analyses and groundwater tracing to or from these wells. I couldn't agree more that this type of data would help greatly in understanding the system.

I spoke with Dr Jones on 12/1/98. It appeared that his main concern with the paper was the use of the quantitative hydrograph results when all of the other qualitative data presented would have sufficed to make the point of the importance of multiple porosities in karst aquifers. I agree that the point could have been made without the quantitative hydrograph data. As written in the comments, Jones and Davies indicate that the hydrograph analysis presented here and in Shevenell (1996) *"...goes against the grain of conventional thinking about carbonates"*, and that the *"...assignment of local aquifer parameters based on hydrographs is confusing and misleading."* In this hydrograph work, I use these very commonly collected hydrograph data to try to go beyond conventional, qualitative methods and, in using this method, begin to quantify some aspects of the karst aquifer. What transmissivities (T) mean in a highly heterogeneous karst aquifer is a very different issue, and is certainly subject to considerable debate. That being said, ongoing work using the hydrograph analysis technique in over 40 karst wells at three different karst sites (Oak Ridge, TN, Ft. Campbell, KY, and Crane, IN) is being conducted to compare the results of the hydrograph analyses with those of more traditional aquifer testing methods (pumping, slug). At all three sites, the hydrograph T (which estimate matrix T) agree quite well with data obtained from pumping tests from the same wells, or from slug tests in nearby matrix dominated wells. These data are currently being compiled for inclusion within a future paper to be submitted for review. What the T from hydrograph, pump or slug test results really mean in the context of a karst aquifer is debatable. However, the latter two methods are now used frequently, and the hydrograph data appear at least to provide the same level of information as other more traditional methods that stress the aquifer. Therefore, I do not believe that the hydrograph analysis method should be discarded so quickly, but that additional work should be conducted to understand better its limitations and try to improve on the basic method presented in Shevenell (1996).

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CANGO CAVE IN THE 1930s: A HISTORICALLY IMPORTANT PHOTOGRAPH

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Cango Cave, situated in the Swartberg foothills about 27km north of Oudtshoorn in the (new) Western Cape Province, is South Africa's leading show cave. Many aspects of its history are buried in the *Oudtshoorn Courant* and other newspapers, and in obscure archives, but details have recently been summarised and published (Craven, 1994). Ownership of the Cave has always lain with the State, but control and management were transferred to the Oudtshoorn Municipality in 1921 (Anon, 1921). These responsibilities came without land and without money; nor was the Cave equipped with the conveniences that tourists and local businessmen demanded. There was neither electricity, toilet, ablutions nor running water, though these facilities were available at the now long defunct Cango Hotel, 4km to the south.

The Oudtshoorn Municipality first turned its attention to the problem of providing these essential services from the limited funds at its disposal. Surrounding land remained in private ownership and the landowner refused to sell, even at an inflated price, because he wanted to provide the necessary facilities on his own account. However, his financial resources were even more limited than those of the Municipality, and no private development ever took place.

Municipal solutions to the land problem are well illustrated in the accompanying photograph, which was found recently in the archives of the National Monuments Council in Cape Town. The electrification was effected in 1928, using a diesel generator, which was so underpowered that it could illuminate only a third of the Cave at a time! The photograph shows the engine house at the right, within the 8m public road reserve. Consent for this was obtained from the Oudtshoorn Divisional Council, which was responsible for the road (Craven, 1987a). The engine house was demolished in the mid-1960s, when provision of electricity from the national grid finally rendered the generator obsolete.

The next problem was overcome in 1930, when a tea room was provided. Built underneath the overhang, this was technically inside the Cave, so permission was not required from either the landowner or the Divisional Council. The tea room, shown on the left side of the photograph, survives today as one of the curio shops. The identity of the lady in the doorway is not known with certainty. She may be the lessee, Mrs S du Plessis, wife of Junior Guide Wynand du Plessis (Craven, 1987b).

The problem of providing toilets was not solved effectively until the mid-1960s, when a modern building was erected at the cave-mouth. Initially the Divisional Council refused to allow toilets and ablutions to be built on the road reserve, so it was necessary to provide them inside the Cave. Bucket latrines and hand basins were installed in the first and second chambers, before the descent into Van Zyl's Hall. Water was taken from the adjacent Grobbelaars River. A labourer put river water into a 200-litre galvanised drum (visible in the bottom left of the photograph) and a donkey pulled it up the hill to the Cave entrance. The labourer then carried buckets of water into the Cave. Despite the concerns of the landowner and of the Divisional Council, the slops were dumped in the adjacent veld (Anon, 1937)!

ACKNOWLEDGEMENTS

I am grateful to Miss J McD Marx for bringing the photograph to my attention, and to the National Monuments Council for permission to publish it. The photographer is unknown.

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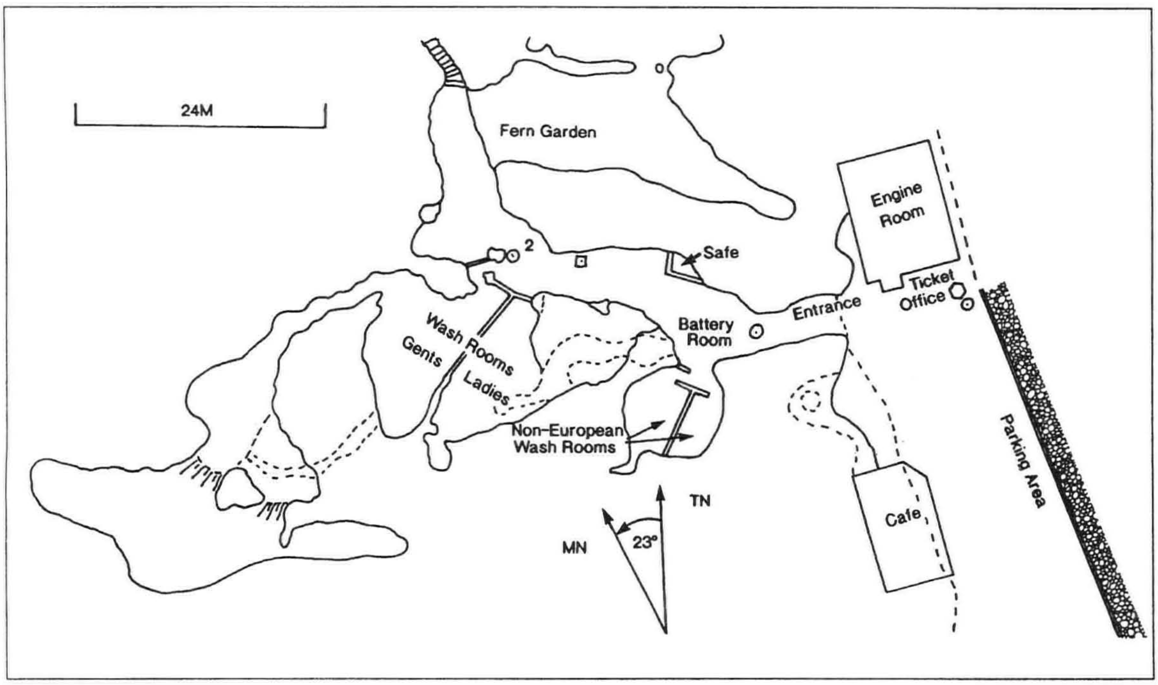

Figure 1. Part of the 1956 survey of Cango Cave, showing the positions of the engine room, café, toilets and ablutions (South African Spelaeological Association, Cape Section).

Cango Cave in the 1930s.

CAVES IN THE UNITED ARAB EMIRATES

Tony WALTHAM [1] and Pierre-Yves JEANNIN [2]

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The recent report on the caves of Jabel Hafeet (Waltham and Fogg, 1998) in *Cave and Karst Science* indicated that no other caves were recorded in the United Arab Emirates. This was incorrect. A Swiss expedition that visited the country in 1990 (Jeannin, 1992; Anon, 1990) found many caves (all less than 100m long) in the northern Emirate of Ras al Khaimah, and explored a few caves in Jebel Hafeet.

The main Swiss exploration in Hafeet was in Kahf Hamam, which yielded 340m of passages. This cave's significance lies in its extensive development of smooth-walled, beautifully rounded, bulbous chambers, which link to form the phreatic passages. Kahf Hamam also has extensive gypsum deposits in its lower passages. These two features led the Swiss team to suggest that the Jebel Hafeet caves were formed by hydrothermal fluids and gases enriched in hydrogen sulphide that originated in the adjacent oil-bearing basins (Jeannin, 1992). Analogies were drawn with the now-famous hydrogen sulphide-excavated caves of Carlsbad Caverns (Hill, 1987) and Lechuguilla Cave, in New Mexico, USA.

This concept of hydrothermal cave genesis still appears to be reasonable, and could perhaps be applied to Magharet Qasir Hafeet. The bulbous chambered style of passage is only poorly represented, in Top Passage (Plate 6 in Waltham and Fogg, 1998), and no gypsum is known in the explored passages. The British team described the cave as a conventional phreatic system, formed by meteoric (i.e. rainfall) waters. Unfortunately, there is a shortage of positive evidence in the very old abandoned passages for either of the proposed development theories. However, the concept of a hydrothermal origin should certainly be considered by anyone examining the geomorphology of Magharet Qasir Hafeet and any other caves in this region.

The foot caves of Jebel Hafeet do appear to be conventional dissolutional features related to meteoric groundwater (Waltham and Fogg, 1998). These caves formed at recent base levels of the desert basins, where hydrothermal fluids constitute only a minor component of the groundwater regime. The Swiss team did not explore them when they were developing their hydrothermal cave genesis concept.

Kahf Hamam is also notable for its temperature; 37.6°C was recorded in one blind chamber (Jeannin, 1992), and the cave entrance sometimes emits blasts of hot air. The British team looked into the first few unpleasant rifts in 1997, but did not reach the spectacular bulbous passages, and considered their time would be better spent in other caves in the mountain. The hot air blast prompted suspicions of a link to a geothermal vent. Consequently the radon level in the first chamber was monitored and found to be 2371 Bq/m^3; this is not exceptional and was much lower than levels found in Magharet Qasir Hafeet. On the return visit to collect the detector, the hot wind was absent. It appears that the cave merely breathes, and notions of possible modern geothermal activity have been dismissed.

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SYMPOSIUM REVIEW

INTERNATIONAL SYMPOSIUM ON KARST AND TECTONICS

Held at Han-sur-Lesse in Belgium from 9 - 12 March, 1998, the Symposium was organised by Yves Quinif of the Faculté Polytechnic de Mons, Belgium, with assistance from Belgian and French geological and karst research organisations. 38 papers and 16 poster sessions were presented, and scientific visits were conducted in 3 local caves. There were over 100 attendees, including 2 from the UK. This review summarises the main ideas presented, and includes some personal observations. Much of the background literature is in French and Italian, with little written in the English language. Hence, an English-speaking audience may be generally unaware of recent developments in understanding relationships between karst and tectonics. The Symposium had two main themes: the influence of tectonics upon karstification, and the role of caves as recorders of tectonic events. In the Symposium context "tectonics" included slow crustal processes, such as deformation, isostatic uplift and pressure release, and rapid seismic phenomena.

Claude Drogue's opening paper introduced the historical development of ideas. Tests on limestone cylinders show that compressive axial pressure causes brittle fracture at 35 bars. Fracturing increases with pressure until deformation becomes ductile at circa 1 kbar. Geological deformational processes were reviewed. Any large-scale compression or extension force could locally cause smaller-scale compressional *and* extensional movements, creating fractures. This is because the movement boundary is usually wavy rather than planar. Hence fracture opening can arise from either local extension or compression within a primary or secondary tectonic fault or joint. If fractures interconnect, water circulation is possible and karstification promoted. Secondary permeability is zero in unfractured rocks and increases to provide braided channels as fracturing increases. By the 1990s accumulated evidence suggested that the recording of tectonic events in caves is a common phenomenon. Studies of fallen speleothems and cracked flowstones have led to conclusions that some must have broken by seismic activity. Rock movements were deduced in cave walls from observations of dislocated calcite veins and stylolites. (Many Symposium presentations included photographs of displaced karst shapes on opposite sides of passages, and bedding plane slips revealed in passage cross-sections).

Yves Quinif's paper started from the assertion that three conditions are necessary for karstification (rather than surface flow) to succeed. There must be an adequate water supply, uplift to generate potential energy, and tectonic activity to create the fractures needed for karstification. Whereas the first two conditions are well known, the premise that all karstification relies on tectonic movement seemed novel to this reviewer, if not to others in the audience. From this premise it could be deduced that all karst cave passages originate as openings created by tectonic processes. [It should be noted that, due to the themed objectives of the Symposium, there was no contrasting appraisal of more complex published chemical, stratigraphical and hydrological theories of speleogenesis].

Evidence leading to the "hole in one" tectonic conclusion is both spatial and temporal. Many speakers showed examples of correspondences between karst locations and tectonic regions. This was supposedly related to a common association of carbonate rocks with active plate boundaries and associated deformation zones, though other explanations are possible. Similarly, rose and Schmidt diagrams were used widely to demonstrate the familiar concept of alignments between passage direction and fracture orientations. However, it appears that karstification does not just follow pre-existing geological structures. An increasing body of evidence from palaeokarst studies indicates that there is always a date correspondence between karstification and major tectonic activity, which are claimed to occur together.

Paulo Forti's presentation re-emphasised the potential for speleothem studies to reveal details of palaeo-planetary conditions back to about 500,000 - 750,000 years BP. In favourable situations it is now possible to evaluate palaeo-earthquakes in highly seismic karst areas by using broken speleothems and still actively growing stalagmites. Previously it had been difficult to discriminate between speleothems broken by earthquakes and those broken by other processes (floods, fluvial undercutting of underlying sediments, slow movement of ice, freeze-thaw during glaciations, and human activity). The solution is to examine many broken speleothems statistically, and couple the results with detailed morphological analysis. Evidence that a group of speleothems from different situations in an area broke at the same date can suggest that a single seismic event was responsible. A good diagnostic is to examine the broken face of a stalagmite, which can be modelled as a cylinder clamped firmly to the floor. At its location, the horizontal component of a strong high frequency seismic wave may correspond with the resonant frequency of the stalagmite. It can then shear with a smooth horizontal break in the plane that coincides with the weaker c-axis of its calcite crystal structure. At the first harmonic frequency, this will be fairly near the floor. Other different sized stalagmites in the same group may not resonate and can therefore be left standing. If several fallen stalagmites lie in the same direction, they align with the direction of shaking of past earthquakes. When new stalagmite growth occurs on a fallen stalagmite, then dating the tip of the fallen stalagmite and the start of the new growth gives an age range for the earthquake. Also, it should be possible to determine theoretically the location, epicentre and magnitude of past earthquakes, using calculations derived, for example, from the analysis of collapsed buildings and leaning tombstones. However, there are many practical difficulties to overcome. Forti also reported that Schillat (1977) had shown that a still-active stalactite-stalagmite pair records any change in position of the stalactite over the stalagmite. Hence a relative movement of the ceiling causes a shift in the stalagmite growth direction, and is datable. The method can be used for observing both slow movements and seismic events. In the latter case, all tectonic structures vibrate during an earthquake and may come to rest in a new position, giving a discontinuous growth pattern. Also, there can be a sharp variation in colour and texture. Similarly, an abrupt change in cross section of a speleothem shows a sudden change in drip rate that may have a seismic cause. Practical tests of these concepts have taken place in recent years. Measurements from many different stalagmites in the same cave enable reconstruction of the fairly recent seismic history of the host region. This has economic importance in the prediction of earthquake hazards in the highest risk tectonic zones.

Several speakers showed evidence, from broken stalactites, of previous earthquakes in areas now regarded as stable. In fact, strong earthquakes may occur anywhere, but recurrence intervals vary. Locally, seismic accelerations can be magnified by the topography, and underground by the presence of cavities. The British geologist Colin Davenport reviewed the evidence for a strong ($m \sim 6.25$) shallow earthquake during the late glacial history of the Scottish Grampian Highlands. This evidence comprises an extensive database of records of soft-sediment deformation and landslides which, using the pattern recognition method of isoseismal mapping, provides a palaeo-earthquake map. Use of similar techniques was recommended when studying speleothem damage. Other speakers discussed the theory that very large underground chambers may have a mainly tectonic origin, formed by slow moving extension. Supporting evidence may be provided by preserved slabs fallen from walls and ceiling.

Paola Tognini reported that in the well-known Lombard karst region in Italy, vertical parts of caves are located under crests and ridges close to the steep slopes of deeply embedded valleys. She suggested that postglacial, slow, gravitational slope movements and tensional release are the mechanisms for the apparent and continuing tectonic extension of joints into straight walled shafts that cut down to pre-existing cave systems. A photograph of a stalactite that is fracturing its partner stalagmite by compression supported the evidence for slow movement. The caves are in Jurassic limestone with 30-80cm-thick parallel beds separated by cm-scale beds of marls and clays along which the movements may occur. This mechanism seems very similar to the one described by Charlie Self a few days beforehand [at the 1998 BCRA Cave Science Symposium]. He explained the origins of recently discovered caves east of Bath by mass movement caused by slope dynamics down the valley side of the River Avon.

A paper presented by Vaclav Suchy described the development of hydrothermal caves in the Bohemian karst of the Czech Republic. The available data show that movements of hot fluids along fractures may have occurred episodically throughout geological time and may have been tied to earthquake cycles. The fractures remain active to this day, as evidenced by micro-earthquakes. Apparently the caves developed both within calcite veins and in the host limestone, which also contains hydrocarbons. This leads to the possibility of karstification promoted by strong acids moving upwards.

During a Symposium visit to La Grotte de Han, signs of movement along faults and fallen stalactites and stalagmites were observed, some of the latter covered by later deposits. In the Fontaine de Baghdad passage in the disused La Grotte de Rochfort show cave, Yves Quinif provided an overwhelming amount of evidence for tectonic movement rather than internal gravitational collapse. Stalagmites placed by cave guides on a ledge are now pinned in position by compression from the roof. A 20cm movement along a bedding plane that dips at 45° E is visible along the top of an uneven wall. Angular rocks lie on the floor below, and the ceiling has longitudinal cracks several cm wide. Complementary karstic forms can be seen to have moved apart near to an alcove where the limestone has collapsed by compression. The passage, which was previously a stream route, ends at a choke of angular rocks that have not fallen from high above but result from compression of the bedrock. This passage is now being utilised as an underground tectonic laboratory. Unpublished results (Quinif and Vandycke - in press) show that the movements in the cave can be accounted for by the tension field that has been measured in the rock mass. A 0.03mm movement along the slipped bedding plane has been measured since December 1997. It should be noted that another presentation at the Symposium described a karst cave near Paris where movement along a fault has been measured at 1mm in 10 years, and 3.4mm of movement in 18 years has been recorded in an Italian cave.

La Grotte de Pere Noel is a large, long, relict, strike-aligned cavern lying in a topographically high position on the opposite side of the anticline to La Grotte de Rochfort. The bedding dips at 45° W. There are many huge formations and flowstones throughout the cave, many of which have fallen. One large flowstone now rests perpendicular to its original position and displays (vertically) a previous underside. This consists of a sediment bank comprising black pebbles that had been transported 50km along the palaeo river Lesse into the cave at an early stage of its development. Since its fall, tall vertical stalagmites have grown on the flowstone. Another 6m x 3m x 3m fallen stalagmite block has 1m-high stalagmites growing on it. Yet another moved block of flowstone reveals many broken stalagmites lying horizontally that were completely buried by the flowstone. Since its fall, new stalagmites are now growing on the new upper side of the block. High on the side of the passage, compression from the roof has broken several pillars. Nearby along a ledge is a line of 40cm-long stalagmites that have all fallen and lie parallel to each other. They are now re-cemented to the floor. Apparently the cave ends where movement along a fault has cut the passage. A speleothem from another cave in the area was dated at over 400,000 years BP. This is believed to indicate the general geomorphic stability of the whole area after rapid uplift in the Tertiary and early Pleistocene. Although crushed tectonically, the speleothem grew at a similar level to the present external river. During this time the River Lesse is thought to have cut down only a few metres, into its own alluvium. Ice movement and freeze thaw effects are ruled out as possible mechanisms for breaking the large speleothems and flowstones. No Pliocene or Pleistocene glaciations are believed to have been persistent enough in this area to have this effect. Hence La Grotte Pere Noel is believed to hold a true record of damage caused by ancient palaeo-earthquakes.

Trevor Ford (1997) has called for readers of *Cave and Karst Science* to look for shattered stalagmite sheets in British caves. The Karst and Tectonics Symposium has revealed that there are many more diagnostic features that it would be rewarding to find. The Symposium also gave new insight into karst inception, which, rather than contradict the Inception Horizon Hypothesis (Lowe, 1992), could provide a supporting mechanism. For example, Knez (1996) has studied the 150m-high Velika Doline, Skocjanska Jama, Slovenia. He found that underground karstification was concentrated at just 3 "formative bedding planes" (Inception Horizons) from a total of 62 bedding planes. He did not find contrasting lithologies between the beds, as might be expected if inception horizons are viewed in a narrow sense. However, he observed that calcite veins are essentially more numerous in the vicinity of the formative bedding planes than in the rocks between them. His conclusion is that these bedding planes have opened by sliding, allowing both carbonate dissolution to enlarge inception fractures and carbonate recrystallisation to form the veins. With the evidence from the River Avon and from Lombardy, it is possible that where non-carbonate beds do exist within a limestone succession, seismic and slow tectonic movements could occur along them. The main limestone beds could move together as coherent blocks. The fractures would then be along the previously defined Inception Horizons, with karstification promoted by both new voids and the presence of non-carbonate chemicals. Inception by tectonic movement could also perhaps explain the origins of silicate endokarst. As well as widening the "tectonic" scope to include gravitational mass movement, the independent reports from Tognini and Self indicate that in some situations cave inception and enlargement can be essentially "dry". Thereafter, both vadose and phreatic developments, as well as calcite deposition, are possible.

To summarise, the evidence from the Symposium is that tectonic activity is all around us, with tiny but continuous bedding and fault movements interrupted by large seismic events at infrequent intervals. These movements create voids from which cave inception can start and be repeated. Cave development is an integral part of the geological history of the host region. After endokarstic enlargement the caves created can themselves record the later tectonic history of the area.

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THESIS ABSTRACTS

BUNTING, B, 1998

The Impacts of Recreational Caving on the Physical Environment of Wild Caves

MSc dissertation, Department of Earth Sciences, University of Waikato, Private Bag 3105, Hamilton, New Zealand.

The aesthetic and scientific values of wild caves (caves not modified for tourist development) are being degraded as a result of recreational use. Although the impacts are recognised, little research has previously been undertaken on recreational impact assessment, mitigation or monitoring in caves. The physical impacts of recreational use on caves were investigated, and research methods were developed to assess and monitor caver impacts on the Zweihohlen and Henry Lambert Sections of Gardner's Gut Cave, Waitomo (an open access cave heavily used by recreational cavers) and Honeycomb Hill Cave, North Westland (a restricted access cave with low visitor numbers).

A Cave Impact Assessment Rating System (CIARS) was developed using a set of criteria to visually assess and quantify the physical impacts of recreational cavers on a wide range of cave environments. Results indicate that the more severely impacted areas of a cave are those with trails located on clastic floor materials, areas with unmarked or non-defined trails and those areas where trails are located close to walls or are in confined sections of passage. An accurate base map has been prepared for the Zweihohlen and Henry Lambert Sections of Gardner's Gut Cave. Visitor Area Impact Maps, which indicate the location, extent, and severity of physical impacts to cave floor features, were developed for sections of Gardner's Gut Cave. The results of the Visitor Area Impact Mapping indicate that severe impacts were most apparent on clastic (sand/silt/mud) floor material and least apparent on trails located on rockfall deposits.

Photomonitoring was used to determine the extent of recreational impacts in Honeycomb Hill Cave, which has a photomonitoring record of key sites within the Cave taken in 1986. The 1986 sites were re-photographed and compared to the initial photographs to determine changes caused by recreational cavers. From the photographic comparison, significant physical changes such as speleothem breakage, disturbance to sub-fossil deposits, trail widening, significant disturbances to sediment and rock deposits, and significant sediment transfer onto previously clean areas had occurred in the intervening period. A limited amount of photomonitoring had been undertaken in Gardner's Gut Cave in 1981, which was also repeated. A photomonitoring method was devised and baseline photomonitoring survey was undertaken in the Zweihohlen and Henry Lambert Sections of Gardner's Gut Cave.

Monitoring of floor cross-sections was established on trails at seven sites within the Zweihohlen and Henry Lambert sections of Gardner's Gut Cave to determine whether significant changes to floor deposits had occurred at these sites. Erosion of material occurred at four of the monitoring sites, deposition occurred at two sites and one site remained unchanged.

A boot-washing experiment was also undertaken near the entrance to the Zweihohlen and Henry Lambert Sections of Gardner's Gut Cave to determine the amount of sediment transported into the Cave by cavers. The results indicate that each caver transports an average of 100 grams (dry weight) of sediment into the Cave. With an estimated 1800 visitors to the Zweihohlen and Henry Lambert Sections of Gardner's Gut Cave between June 1996 and December 1997, the total amount of sediment transported into the Cave over this time was estimated to be approximately 180kg.

The impacts of recreational caving are more severe in the Zweihohlen and Henry Lambert Sections of Gardner's Gut Cave than at Honeycomb Hill Cave, reflecting differences in levels of recreational use and management.

BURGESS, S, 1998

The microbial biomass of forest soils and cave sediment in Gunung Mulu National Park, Sarawak, Malaysia

Honours thesis, prepared in partial fulfilment of the requirements for the degree of Plant and Soil Science BSc (Hons), Department of Plant & Soil Science, University of Aberdeen, Aberdeen, UK.

The importance of soil microbial biomass (SMB) in maintaining soil fertility, and as the base of the food web, has now been widely recognised. Despite its significance, studies on the microbial ecology of tropical forests are sparse, and almost no previous work has been done on the microbial ecology of forest soils and cave sediments in Gunung Mulu National Park (Sarawak).

The biomass, activity and potential activity of these soils was studied by incubation methods (SIR) in situ. Using soil/sediment from Mulu, incubations were also carried-out in Aberdeen to determine the composition of the biomass and a unique substrate preference test to observe whether microbes were adapted to an indigenous substrate (bat guano) or could metabolise a "good" microbial substrate (glucose) equally well. Environmental conditions (soil matric potential, pH, temperature, nitrate and ammonium-N, TOC and light at the soil surface) of the sites were also measured and correlated to microbial data.

Biomass and activity were greater in the forest than in the cave and the sediments at the entrance to the cave showed an overlap with both, indicating a threshold in microbial characteristics as well as in environmental factors. Microbial activity was increased by the optimisation of soil matric potential in some sites, which showed strong correlations between potential activity, total organic carbon and lower pH values, indicating that the biomass of these sites was only limited by water. Other sites were concluded to have more than one limiting factor, and one site was not limited by soil water. The main environmental characteristics that influenced microbial activity were organic carbon, available nitrogen and soil pH. Fungal and bacterial biomass differed only at the entrance to the cave, both were strongly associated with the above environmental factors. Bacterial biomass was related to light intensity, due to the effects upon soil temperature.

The forest displayed a balanced microbial community, whereas fungal biomass dominated in the cave. Microbial communities showed a preference for bat guano as a substrate over glucose. It was concluded that the selection of an indigenous substrate was fundamental in characterising the kinetics of respiration response of soil microbial populations from different ecological sources.

RESEARCH FUNDS AND GRANTS

THE BCRA RESEARCH FUND

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

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

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

GHAR PARAU FOUNDATION EXPEDITION AWARDS

An award, or awards, with a minimum of around £1000 available annually, to overseas caving expeditions originating from within the United Kingdom. Grants are normally given to those expeditions with an emphasis on a scientific approach and/or exploration in remote or little known areas. Application forms are available from the GPF Secretary, David Judson, Hurst Farm Barn, Cutler's Lane, Castlemorton, Malvern, Worcs., WR13 6LF, UK. Closing dates for applications: 31st August and 31st January.

THE E.K.TRATMAN AWARD

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

BRITISH CAVE RESEARCH ASSOCIATION PUBLICATIONS

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

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

CAVE STUDIES SERIES - occasional series of booklets on various speleological or karst subjects.
No. 1 *Caves & 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.
No. 7 *Caves and Karst of the Brecon Beacons National Park;* by Mike Simms, 1998.

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.

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

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

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