

# Cave and Karst Science

*The Transactions of the British Cave Research Association*



Volume 22

Number 3

December 1995



**Surface soils and cave sediments, Florida**  
**Pinnacle karst of Gunang Api, Sarawak**  
**Rimstone pools at Pamukkale, Turkey**  
**Crystallogenesis of gypsum flowers**  
**Symposium abstracts**  
**Hydrothermal caves**  
**Forum**

# Cave and Karst Science

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

## 1. Mainstream Articles

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

## 2. Development Articles

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

## 3. Forum

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

## 4. Abstracts

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

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

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

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

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

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

# Cave and Karst Science

TRANSACTIONS OF THE BRITISH CAVE RESEARCH ASSOCIATION

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#### **The travertine deposits at Pamukkale, Turkey.**

Photo by John Gunn (see article by M. Ekmekci, G. Gunay and S. Simsek).

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

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## EDITORIAL

David Lowe and John Gunn

After two busy years as editors of *Cave and Karst Science* (the *Transactions of the British Cave Research Association*) this issue gives us a feeling of déjà vu. Our first issue contained a series of symposium abstracts, as does the current one. Despite this superficial similarity much has changed during this two years, but the abstracts and their follow-up papers emphasise that the broad expanse of cave and karst science is flourishing.

Our editorship began with a change of title for the *Transactions*. The decision to change was not taken lightly - indeed there were those who advised strongly against it as being change for change's sake and an unnecessary break in continuity. Nonetheless the change went ahead, on the basis that the new title would provide an incentive for authors outside the accepted confines of "cave science" to submit work for consideration. A secondary motive was that adoption of the new title would mark a milestone in the history of BCRA and its *Transactions*. Since then the name has stayed the same but the cover has metamorphosed from an initial format that was based closely (but not slavishly) upon that of *Cave Science* to one using a more modern typeface and layout that will hopefully remain unchanged during the life of the publication.

When we took over some fears were expressed that we would define the limits of "cave and karst" science too closely and in doing so we would deprive authors of a means to publish on subjects such as cave technology and expedition explorations. Such draconian policies were never intended, though we did reserve the right to accept or decline potential papers on the basis of various criteria such as scientific content, general interest, quality of presentation or broad relevance. The results of two expeditions have been published in *Cave and Karst Science* to date, and both were well up to the standards we had hoped for. The opportunity to include colour printed illustrations inside and on the cover of the last issue would not have arisen if our policies had been too strict, and initial feedback suggests that this "one-off" departure from tradition was generally well received.

On taking over it was also stressed that we hoped to provide younger or less experienced authors and those whose native language was not English with the opportunity to publish their work in a quality, refereed journal. Response to the opportunities offered has been relatively slow to date, but encouraging. There is a healthy background of material from these sources coming to us along with a somewhat greater number of submissions from more experienced home-grown authors. We can only hope that the trend will continue.

One important aspect of producing *Cave and Karst Science* presents a recurring problem, and that is the question of finding a suitable cover illustration. We generally try to use a photograph that relates to a paper inside the journal, but photographs that are acceptable to illustrate a particular point within a paper are not necessarily ideal for the cover. Authors should bear this in mind, and if they have a good quality black and white photograph that might contribute an eye-catching cover, send it along, together with a few sentences describing the context of the picture and any interesting features that it shows. Rarely we may have to use a cover photograph that is not linked directly to a paper in the journal, and we would be pleased to receive good black and white prints, again with a few descriptive sentences, that we can hold on file for possible futures use as cover illustrations.

To end this brief review of our first two volumes, we would like to acknowledge the important roles played by other individuals during the transition from *Cave Science* to *Cave and Karst Science*. As we have entered the world of digital technology we have tried to make the best and most economical use of the advantages that are offered. Most of our contributors now supply the text of their papers in digital form, and such digital files feed directly into a desk top publishing package operated on our behalf by Mrs Jean Reeve. Jean has quickly come to terms with the requirements of *Cave and Karst Science*, and refined her formatting skills in the face of the specialised words and pictures of an initially alien subject. Our printers, The Sherwood Press in Nottingham, have been very patient during the various changes we have made, and now that things have settled down a mutually beneficial working relationship seems set to continue. Central to the success of the *Transactions*, however, are the efforts of those individuals that we call upon to read and comment on the papers submitted. Their number grows with every issue, but the efforts of the following referees are acknowledged with thanks: Dr S Bottrell, Mr B M Ellis, Dr T D Ford, Dr D Gillieson, Dr P Hardwick, Dr C A Hill, Dr C O Hunt, Dr S-E Lauritzen, Dr T Shaw and Dr A C Waltham.



## The relationship between surface soils and cave sediments in west-central Florida, U.S.A.

Robert BRINKMANN<sup>1</sup> and Philip REEDER<sup>2</sup>

<sup>1</sup>Department of Geography, University of South Florida, Tampa, Florida USA 33620

<sup>2</sup>Department of Geography and Geology, University of Nebraska at Omaha, Omaha, Nebraska USA 68182

**Abstract:** In order to assess the relationship between surface soils and sediment deposits in the karst of west-central Florida, excavations were completed within a cave and on the surface above the cave. Historical climatic and land use data were also compiled for the area. A one metre deep excavation in the cave revealed seven distinguishable strata, with the uppermost 0.52m (five strata) formed over the last 18 years. Below 0.52m, the sediments contain thin laminae that formed when sandy sediments washed into the cave during the summer rainy season. The surface soil consists of sandy A, E, and B horizons underlain by a Bt horizon which formed as a weathering product of the limestone bedrock located 0.76m below the surface. Grain size, roundness, and sphericity data from the cave sediment strata and soil horizons indicate that the cave sediment is allogenic, with the source being the sandy surficial soil horizons (A, E, and B). The rate of sedimentation in the cave has been accelerated by the construction and maintenance of area forest roads, and general forestry practices.

### INTRODUCTION

Cave sedimentation can result from both allogenic or autogenic deposition (White, 1988). Allogenic sedimentation occurs when surface sediments wash into a cave, and autogenic sediments form as a weathering product of the cave's parent rock with clay being an autogenic cave sediment that forms as a weathering product of limestone.

Allogenic and autogenic sediments can often be similar (Ford, 1976), but each has characteristics that can be used to discern sediment type (Reems, 1972). Typical autogenic sediments in limestone caverns are physical breakdown products such as boulders and cobbles from roof or wall collapse, and/or clays from weathering of the limestone bedrock. Allogenic sediments have the physical characteristics of the sediments which mantle the surface above the cave.

Stratigraphic analysis of cave sediments is useful to interpret the environmental history of an area (Milske et al., 1983). The presence or absence of allogenic or autogenic sediments, and the thickness of the strata assist in reconstruction of the sedimentary history; and the physical and chemical characteristics of individual strata can assist in the interpretation of area landscape evolution (Cothers, 1983; Ferrand, 1985).

This project analyses a sediment sequence in Peace Sign Cave in Citrus County, Florida, compares these sediments with surface soils directly above the cave, and establishes a linkage between area climate, land use, and geomorphology. The measurement of physical and chemical characteristics of the sediments and soils assists in understanding the sedimentary history and geomorphic evolution of this area, as well as other mantled karst landscapes.

### THE STUDY AREA

The study area is located in southern Citrus County in the Citrus Tract of the Withlacoochee State Forest (Fig. 1). The physical landscape of the area is typical of the karst terrain of the Brooksville Ridge region of west-central Florida. There are no surface streams within a 20km radius, and all of the drainage is by direct infiltration or through sinkholes.

The elevation within a two kilometre radius of the study area varies from 6m to 45m above mean sea level, with the local relief being 39m (Fig. 1). The minimum elevations occur at the bottom of two compound sinkholes. These sinkholes intercept the local water table at an elevation of approximately 7m above mean sea level.

The carbonate bedrock in the study area is the Suwannee Limestone which is Oligocene in age and unconformably overlies the Eocene aged Ocala Limestone (Krause, 1979). The Suwannee Limestone is a yellow to white fossiliferous porous crystalline limestone (Randazzo, 1972). This formation is a lithologic unit within the principal artesian aquifer (the Floridan Aquifer) of south Georgia and Florida (Krause, 1979). In the study area, the Suwannee Limestone is mantled by quartz sands of varying thickness.

Within the study area six caves have been mapped (Brinkmann and Reeder, 1994). Erosion, sinkhole collapse and deposition has truncated the once interconnected cave system into these six fossil segments. Peace Sign Cave (Fig. 2), which is the northwestern-most cave, has two entrances which lead to a three metres wide, one metre high, low gradient passage. Three tributary passages end in fill and/or breakdown, and the cave floor is covered with collapsed rock and sediment. The surveyed length of the cave is 41m.

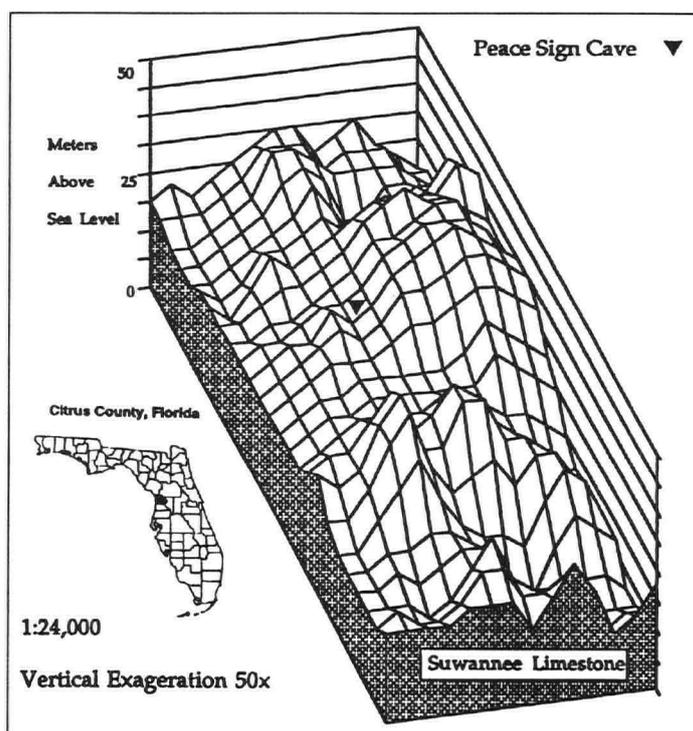


Figure 1. Location map and terrain model of the study site showing the location of Peace Sign Cave in the Withlacoochee State Forest, west-central Florida.

According to the soil survey of Citrus County (USDA, 1988), the study area is underlain by Kendrick fine sands which are deep, well drained Arenic Paleudults that form on upland ridges. Sand dominates the soil texture to a depth of 0.71m. A textural B horizon, that extends to a depth of 1.52m or more, contains sandy clay. Kendrick fine sands cover extensive portions of the upland ridges in Citrus County (USDA, 1988).

## METHODS

A pit 0.5m on a side and 1.0m deep was excavated in the northern portion of the main passage of Peace Sign Cave (Fig. 3). One wall of the pit was fully cleaned and described in the field. Individual layers were identified by texture, colour, or consistence. Composite samples were collected from each layer and at 0.1m intervals.

A one cubic metre soil pit, excavated on the land surface directly above the pit in the cave, was described pedogenically. Composite samples were collected from each horizon and at 0.1m intervals.

In the laboratory, soil and sediment samples were air dried and mechanically split to obtain representative samples for sieve analysis at whole phi intervals (Folk, 1972). Bouyoucos texture analysis (Liegel et al., 1980) was used to measure the percentage of fine particles present in the samples and pH (Liegel et al., 1980) was measured to give an indication of the chemical environment. The roundness and sphericity of 100 sand grains 0.25-0.50mm in diameter were separated from each

sample and measured using visual charts (Folk, 1972) to compare the surface and cave sediments. Data about area land use and climate were also compiled using contemporary and historical records.

## RESULTS

### Sediment Stratigraphy and Soil Horizonation

The spatial relationship between the cave sediments and the surface soils, and the thickness and designation of each soil horizon and sediment strata are presented in Fig. 3. Seven strata were identified in the cave sediment sequence with the description of the strata outlined in Table 1. It is important to note that the cave sediments contain anthropogenic evidence (a beer bottle dated to 1976 was found at -0.52m in the excavation) which indicates that the sedimentation above 0.52m occurred between 1976 and the present. The beer bottle was dated by contacting the brewery and providing them with the serial number stamped into the bottom of the bottle.

The soil profile located directly above the excavation in the cave contains five soils horizons (Fig. 3). A description of each of the soil horizons appears in Table 2. This soil is a typical Ultisols noted to form in the area (USDA, 1988). It is important to note, however, that the Bt horizon is not translocated clay, but rather a weathering product produced by in situ weathering of the limestone bedrock.

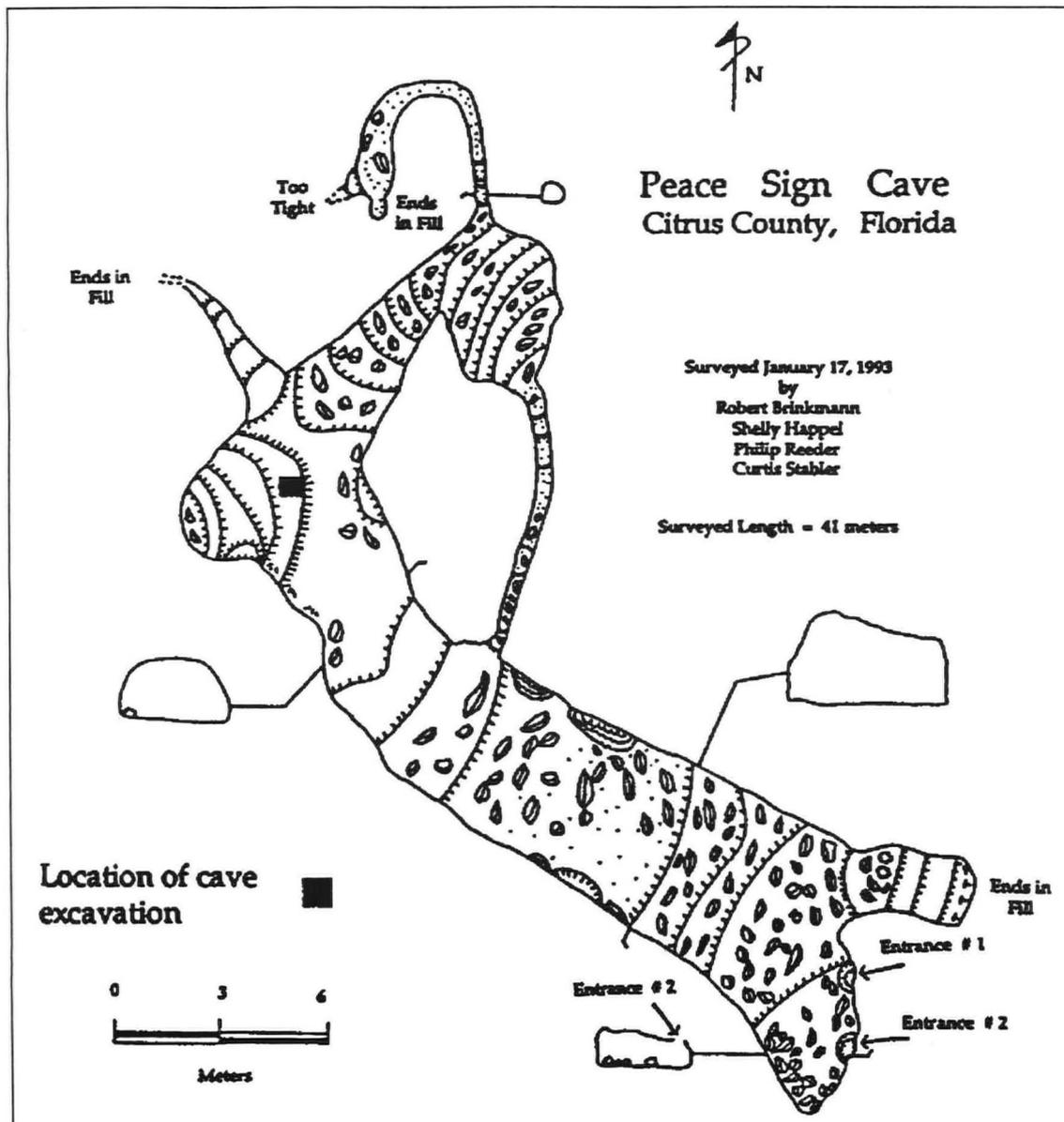


Figure 2. Map of Peace Sign Cave with the location of the excavation within the cave indicated.

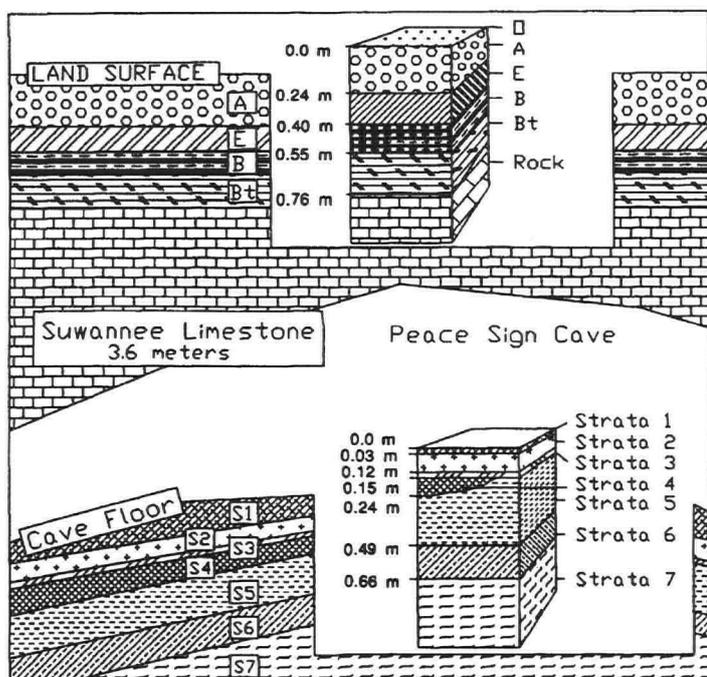


Figure 3. Cross section of Peace Sign Cave showing the excavation within the cave and the soil profile. Strata identified in the cave excavation and horizons present in the soil profile are also indicated.

### Sieve Analysis

Histograms of grain size sieve analysis (at whole phi intervals) for samples collected from each strata in the cave excavation are presented in Fig. 4. Percentage of each size interval from each strata are also presented in Table 3. The distribution of grain sizes in Strata 1-7 are similar, with most of the sediments being well sorted fine sands. These histograms display a high kurtosis and uniform symmetry. The very fine sands are the secondary grain size class in all but Strata 7, where medium sand is the secondary grain size.

The grain size histograms for each soil horizon indicate three distinct textural types (Fig. 4 and Table 3). The A and E soil horizons are similar to the cave deposits in that they are well sorted sands, have a high kurtosis and a uniform symmetry, fine sands are the primary grain size, and very fine sands are secondary. The B horizon is not as well sorted as the overlying A and E horizons. Fine sand is the dominant textural class, but medium sand is the secondary class in the B horizon. Kurtosis is low, but the grains are distributed somewhat symmetrically. The Bt horizon is very poorly sorted. Medium sand, coarse sand, and fine sand are the dominant textural categories, with medium sand being the most common. The distribution of the sediment classes are skewed, with medium to coarse sand dominant and lesser amounts of fine and very fine sand present.

### Bouyoucos texture analysis

Bouyoucos texture analysis was completed to determine the percentage of sand, silt and clay in the surface soil horizons and sediment strata in the cave. Sieve analysis is accurate for sandy soils and sediments, but may be inaccurate for finer sediments. The results of the textural analysis are presented in Table 4 and are graphed in Fig. 5. The samples collected from the cave contain between 80 and 86 percent sand, 8 and 20 percent silt, and 0 and 6 percent clay.

Stratum	Depth (m)	Description
one	0.00 - 0.03	Compact, dark sand. Modern floor surface.
two	0.03 - 0.12	Light brown sand. Compact, but less dense than surface floor.
three	0.12 - 0.15	Compact, dark sand. Buried floor surface.
four	0.15 - 0.24	Light brown sand. Lenticular form. Fill beneath overlying floor.
five	0.24 - 0.49	Highly variable. Contains some large rock fragments. Layer of bioturbation with some laminae of sands out of stratigraphic position. Individual areas of sediment mixed as a whole, possibly a result of shoveling. Fine laminations or white sands alternate with dark sands.
six	0.49 - 0.66	Uniform friable brown sands. Beer bottle dating to 1976 found at a depth of 0.52m.
seven	0.66 - 1.0	Alternating fine laminations of clean white sand and dark sand. This is a zone of non- anthropogenic sedimentation.

Table 1. Description of the seven strata identified in the cave sediment sequence in Peace Sign Cave.

The texture of the soils collected from each horizon vary considerably (Fig. 5 and Table 4). The A and E horizon texture closely resembles the cave sediments, whereas the B and Bt horizons are a distinctly different texture. The B horizon contains 40 percent clay, 14 percent silt and 46 percent sand, and the Bt horizon contains 41 percent clay, 36 percent silt and 23 percent sand. An R horizon of limestone bedrock underlies the Bt horizon.

Horizon	Depth (m)	Description
A	0.00 - 0.24	Dark brown (7.5 YR3/2), granular structure, friable sand, clear boundary.
E	0.24 - 0.40	Dark yellowish brown (10 YR4/4), single grain, structureless, friable sand.
B	0.40 - 0.55	Strong brown (7.5 YR5/6), medium blocky structure, firm, gradual boundary.
Bt	0.55 - 0.76	Dark brown (7.5 YR4/4), strong blocky structure, firm, lithic boundary at base.
R	0.76+	Very pale brown (10YR8/4), dense foraminiferous limestone. A joint and solution pocket exist in the limestone at the base of the excavation.

Table 2. Description of the soil horizons above the excavation in Peace Sign Cave.

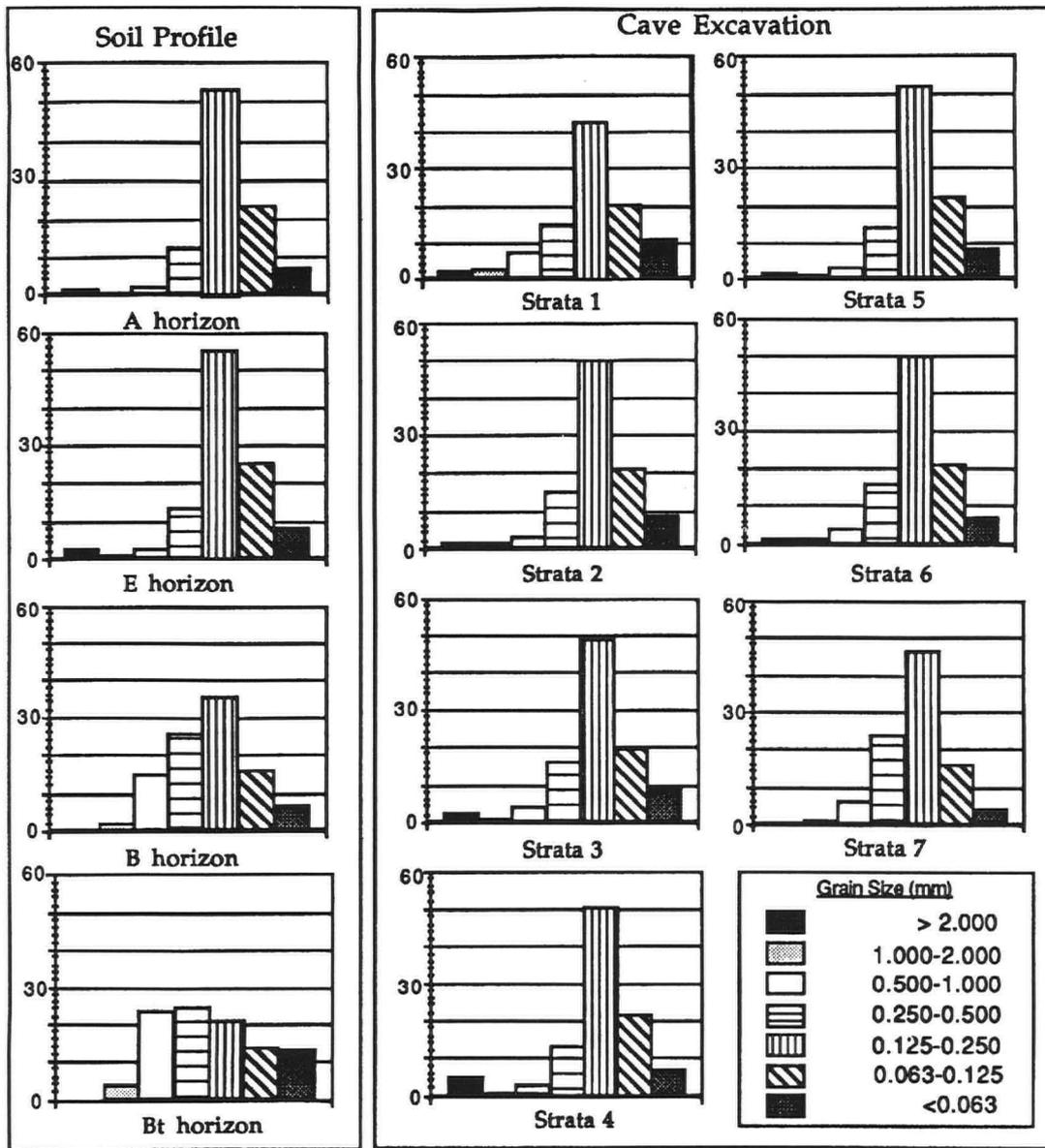


Figure 4. Histograms showing the weight percent of whole phi size classes of composite samples collected from each soil horizon and each cave sediment strata.

Strata or Horizon	Percent Sand	Percent Silt	Percent Clay
Strata 1	80	20	0
Strata 2	84	11	5
Strata 3	80	16	4
Strata 4	84	14	2
Strata 5	82	18	0
Strata 6	80	14	6
Strata 7	86	8	6
A Horizon	90	4	6
E Horizon	88	8	4
B Horizon	46	14	40
Bt Horizon	23	36	41

Table 4. Results of Bouyoucos textural analysis completed on soil and cave sediment samples collected from within and above Peace Sign Cave.

## pH

The pH of composite samples collected every 0.10m was quantified to give an indication of the chemical environment of the cave sediments and the surface soils. The data are presented in Table 5 and are graphed in Fig. 6. The pH of the sediments in the cave range from 7.9 to 8.2. The lowest pH values occurred at the surface and at a depth of 0.50-0.60m. The soils in the surface excavation are more acidic than the sediments in the cave, ranging from 5.6 to 6.6. The lowest pH occurs at a depth of 0.4 to 0.5m and the highest pH is found near the bottom of the soil pit near the limestone/soil interface.

## Roundness and Sphericity

The roundness and sphericity of the cave sediments and surface soils are presented in Tables 6 and 7 and are graphed in Figs. 7a and b. The sphericity of the cave sediments are relatively uniform throughout the excavation. They are mainly sub prismoidal (56-86 percent) to spherical (13-44 percent). The sphericity of the A, E, and B soil horizons are similar to the cave sediments, with sub prismoidal (47-76 percent) and spherical (24-53 percent) most common. Sphericity in the Bt horizon is distinctly different from the cave sediments and the A, E, and B soil horizons. The Bt horizon has three distinct sphericity classes: sub prismoidal (31 percent), sub discoidal (26 percent), and discoidal (42 percent).

Strata or horizon	Abundance by size (weight percent)						
	>2,000	2,000-1,000	1,000-500	500-250	250-125	125-63	<63
Strata 1	1.9	2.7	6.8	14.5	42.6	20.6	10.9
Strata 2	1.4	1.2	3.0	14.9	49.8	21.0	8.7
Strata 3	2.4	0.8	3.9	16.1	48.8	19.3	8.7
Strata 4	4.5	0.8	2.5	13.3	50.2	21.6	7.1
Strata 5	1.2	0.6	2.8	13.6	51.6	22.1	8.1
Strata 6	1.6	1.2	3.8	15.9	49.5	20.7	7.2
Strata 7	0.4	0.6	6.1	23.6	49.6	16.1	3.6
A Horizon	1.4	0.4	2.0	12.7	53.3	23.3	6.8
E Horizon	2.4	0.8	2.6	13.2	55.4	24.5	1.0
B Horizon	0.1	2.0	14.6	25.5	35.4	16.0	6.5
Bt Horizon	0.1	3.9	23.7	24.5	21.0	13.7	13.3

Table 3. Results of sieve analysis completed on soil and cave sediment samples collected from within and above Peace Sign Cave, Citrus County, Florida (size in micrometres).

The roundness of the cave sediments vary considerably, although most grains are rounded, sub rounded, or sub angular. Only strata 4 contained a significant number of angular sediment fragments. The A, E, and B soil horizons contain only rounded, sub rounded, or subangular sediments. The Bt horizon contains only angular fragments.

Analysis of the roundness and sphericity data indicates that the cave sediments contain mostly sub prismatic to spherical, rounded, sub rounded, or sub angular sediments. The soil is comprised of two distinct roundness and sphericity zones. The A, E, and B horizons are mostly sub prismatic to spherical, rounded, sub rounded, or sub angular. The Bt horizon is distinctly different in that it contains sub prismatic, sub discoidal, or discoidal very angular, angular or sub angular sediments.

Soils		Cave Sediments	
Depth (in cm)	pH	Depth (in cm)	pH
0-10	5.9	0-10	7.9
10-20	5.7	10-20	8.0
20-30	6.2	20-30	8.0
30-40	5.8	30-40	8.2
40-50	5.6	40-50	8.0
50-60	6.6	50-60	7.9
60-70	6.2	60-70	8.1
		70-80	8.2
		80-90	8.0

Table 5. Results of pH analysis completed on soil and cave sediment samples collected from within and above Peace Sign Cave, Citrus County, Florida.

## DISCUSSION

Based upon the sieve, texture, roundness, and sphericity data, it was determined that the cave sediments are mostly allogenic with autogenic sediments only a minor component. The cave sediments are also anthropogenically disturbed with 0.52m of sediments noted to exist above a beer bottle dated to 1976.

During that 18 year period, two floors (strata 1 and 3) developed within the sedimentary sequence indicating two periods of relative quiescence. Cave visitors compacted the sediment surface creating the floors at 0.0-0.03 and 0.12-0.15m. The zone of light brown, less dense sand from 0.03-0.12m (strata 2) may represent a zone of rapid deposition of allogenic sediments. A 0.09m thick lens of less dense, light brown sand (strata 4) which underlies the floor at 0.12-0.15m may also represent a rapid depositional event. From 0.24-0.49m (strata 5) is a zone of mixed sands which appear to be anthropogenically disturbed. Beneath this zone are friable brown sands which extend from 0.49-0.66m (strata 6), wherein the beer bottle dated to 1976 was found at -0.52m. A disconformity exists beneath strata 6. Below the disconformity is a zone of alternating white and brown sand laminations (strata 7) which extend from 0.66-1.0m.

White (1988) notes that cave streams alternate from aggrading (depositional) to degrading (erosional) streams and it is common to find old channel deposits, relic stream channels, and other features buried in later sediments. In Peace Sign Cave a degrading ephemeral stream created the disconformity found at 0.66m. The zone of laminae (strata 7) are not anthropogenically disturbed and are a natural depositional sequence.

It was determined from cave sedimentary sequences measured in Kentucky (Davies and Chao, 1959), Missouri (Reams, 1968; Helwig, 1964), West Virginia (Wolfe, 1973), Texas (Frank, 1965), as well as in Europe (Schmid, 1958), Australia and New Zealand (Frank, 1975) that layering and lithology vary greatly over a distance of a few metres and that rapid facies changes occur. These observations were interpreted as evidence for deposition by streams subject to large annual fluctuations (White, 1988). The zone of alternating light and dark sands in Peace Sign Cave (strata 7) may have formed as a result of annual sedimentation during the rainy season. Most of the rainfall in west-central Florida

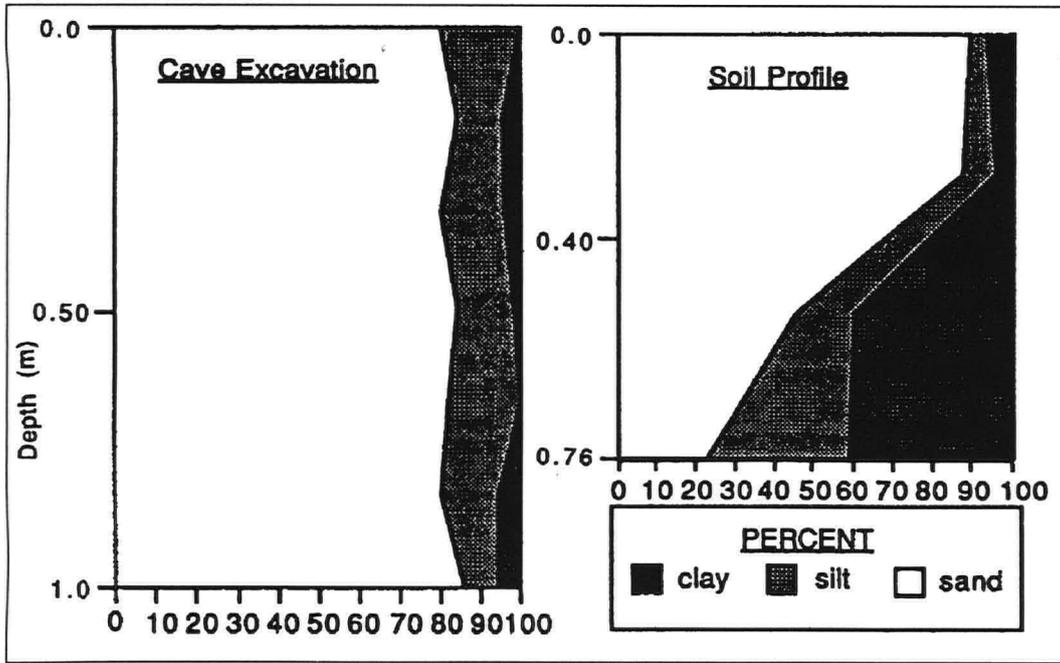


Figure 5. Weight percent of sand, silt, and clay in composite samples collected from each soil horizon and cave sediment strata.

currently occurs from June to August, with intense thunderstorms very common. These storms may have transported sediment laden water into the cave which ran down the walls and deposited the sands in thin water films on the cave floor. Personal observations in a near by cave, after a prolonged period of precipitation, indicates that this scenario of deposition is occurring within the study area. During the winter dry season, the sands at the surface of the cave floor were stained by organic debris such as bat guano (White, 1988) and/or organic material transported into the cave from the surface.

The rate of sedimentation in the cave appears to have fluctuated over the last 18 years. The less dense zones at 0.03-0.12 and 0.15-0.24m represent periods of rapid deposition, and the floors at 0.0-0.03 and 0.12-0.15m represent more stable periods. The periods of rapid deposition are probably related to extreme climatic events and/or changes in land use above the cave. A review of weather data for the last 18 years indicates extreme precipitation events from frontal and tropical thunderstorms in the vicinity of the caves (Brooksville-Chinsegut Hill weather station) on May 15, 1976 (171mm), June 17-18th, 1982 (203mm), and March 30-31, 1987 (160mm). Land use near the cave has been managed pine forest for

Strata or Horizon	Prismoidal	Sub-Prismoidal	Spherical	Sub-Discoidal	Discoidal
Strata 1	0	80	20	0	0
Strata 2	0	86	14	0	0
Strata 3	0	74	26	0	0
Strata 4	0	60	40	0	0
Strata 5	0	60	40	0	0
Strata 6	9	78	13	0	0
Strata 7	0	56	44	0	0
A Horizon	0	73	27	0	0
E Horizon	0	76	24	0	0
B Horizon	0	47	53	-	-
Bt Horizon	0	31	1	26	42

Table 6. Results of sphericity analysis completed on soil and cave sediment samples collected from within and above Peace Sign Cave, Citrus County Florida (given as a percent).

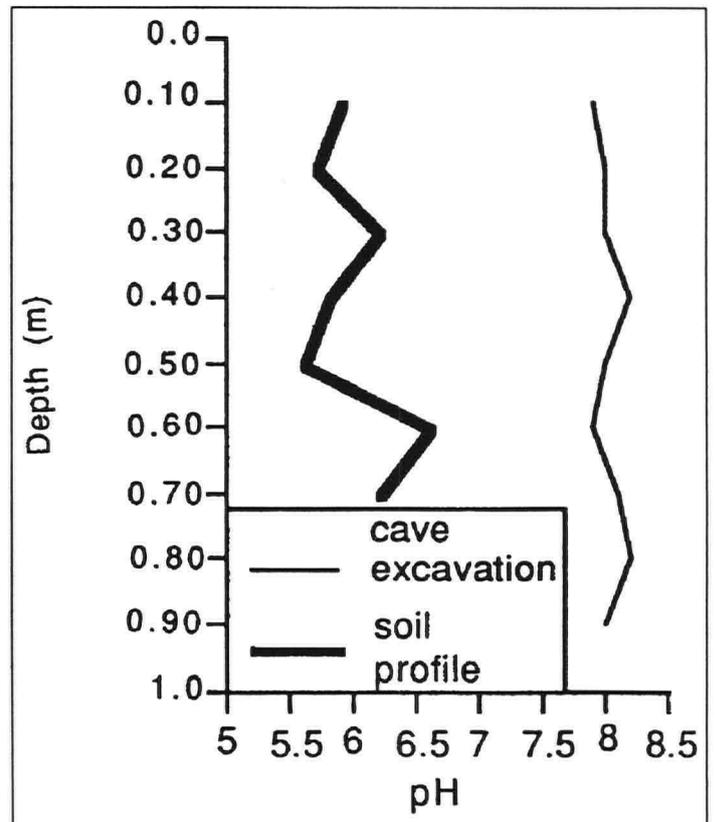


Figure 6. The pH of composite samples collected at 10cm intervals from each soil horizon and cave sediment strata.

Table 7. Results of roundness analysis completed on soil and cave sediment samples collected from within and above Peace Sign Cave, Citrus County, Florida (given as a percent).

Strata or Horizon	Very Angular	Angular	Sub Angular	Sub Rounded	Rounded
Strata 1	0	0	13	13	74
Strata 2	0	0	33	67	0
Strata 3	0	0	7	14	79
Strata 4	5	28	0	52	15
Strata 5	6	0	0	94	0
Strata 6	0	0	12	88	0
Strata 7	0	0	18	64	18
A Horizon	0	0	8	80	12
E Horizon	0	0	16	75	9
B Horizon	0	0	37	53	10
Bt Horizon	28	54	13	0	5

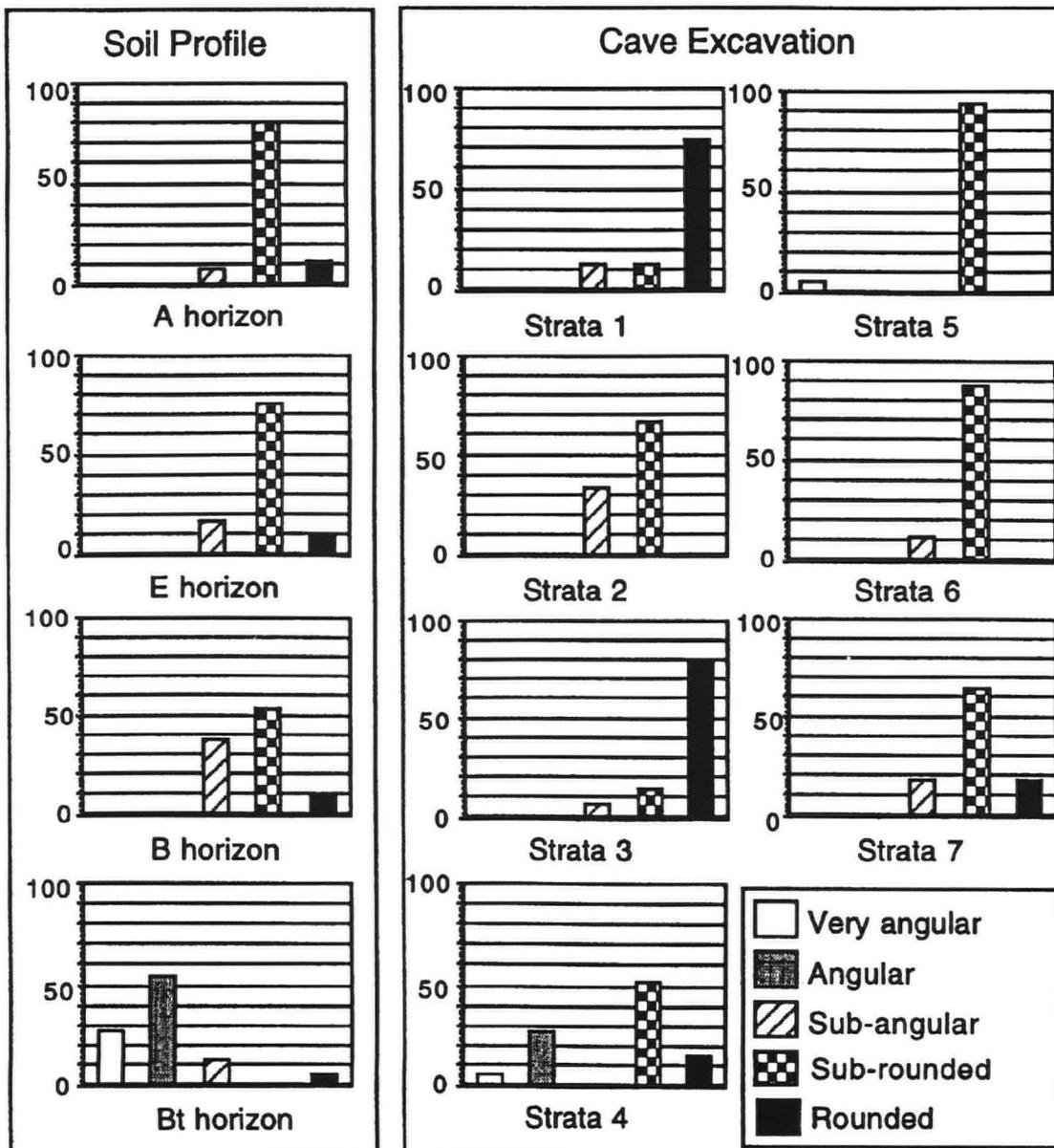


Figure 7. Roundness (Figure 7a) and sphericity (Figure 7b) of grains from composite samples from each soil horizon and cave sediment strata.

the last 18 years to the north and northeast, and natural forest in the remaining surrounding area. The managed forest has been cut and planted once in the last 18 years (Duval, E, personal communication). During the same period, forest road construction, maintenance, and use near the cave disturbed the natural landscape thus providing a continual source of sediment to the cave (Duval, E, personal communication). A combination of the intense precipitation events, landscape destabilisation by forest management practices, and forest road maintenance and use has led to increased deposition in the cave.

Sediment strata 5, which extends from 0.24-0.49m, is unique in that it appears to be backfill from a 0.50m deep v-shaped pit that was excavated in the cave (probably by looters looking for Native American artifacts). The beer bottle dated to 1976 was found at the bottom of this excavation. The bottle was probably thrown into the pit and covered with mixed backfill sediments. All of the sediments above strata 5, based upon stratification and horizontal layering, were naturally deposited. The friable brown sand layer (strata 6) that extends from 0.49-0.66m below the v-shaped excavation, also extends upward to the cave floor around the excavation. Below strata 6 is the disconformity and zone of laminations (strata 7). The change in colour of the sediments above the disconformity (from alternating white and brown laminations below to all brown above) may indicate that the same forces which formed the disconformity, eroded the white sands from the land surface.

Interestingly, the cave sediments have a much higher pH than the surface soils, even though the A, E, and B soil horizons and their parent material are the source of the cave sediments. A chemical transformation is occurring in the cave which causes the decreased acidity. As vadose water infiltrates through the soil (where CO<sub>2</sub> is abundant), it aggressively dissolves the limestone bedrock increasing the pH of the water solution (White, 1988), and upon mixing with cave sediments the water solution increases the pH of these sediments. This vadose water also transports surface sands and deposits these sediments in thin water films on the cave floor.

## CONCLUSION

Allogenic sediment accumulation of over 0.50m has occurred in Peace Sign Cave in west-central Florida over the last 18 years. Below 0.66m, annual laminae formed as sediment washed into the cave during the summer rainy season. These sediments were separated from the overlying strata by a disconformity formed during a degradational period. The grain size, roundness, and sphericity of the allogenic sediments in the cave are similar to sediments in the A, E, and B soil horizons. The cave sediments and A, E, and B soil horizons are sub prismoidal to spherical, rounded, sub rounded, or sub angular sands. The Bt soil horizon above the cave formed as a weathering product of the limestone bedrock and is distinctly different from all other cave sediment and soil samples.

It was determined that cave sedimentation rates varied throughout the last 18 years, with these variations attributed to road building, forestry practices and extreme precipitation events. These phenomena directly affected cave sedimentation rates during the last 18 years because of their destabilizing effect upon the landscape. The sediments in Peace Sign Cave are thus in many respects similar to those often called post settlement alluvium (PSA) or post-Euro-American settlement alluvium which bury floodplains throughout much of North America. PSA forms when sediments from destabilised landscapes, such as farm fields, are washed from the upper reaches of drainage basins and are redeposited within the floodplain of a stream. In karst areas, caves are often the equivalent of floodplains in that they serve as locations where sediments are stored. Hence, caves can serve as significant indicators of recent sedimentation and of the sedimentary history of an area. Peace Sign Cave is one such cave in that it contains information regarding the recent sedimentary history of west-central Florida. The study and interpretation of such sediment sequences can provide valuable information about the linkages which exist between landscape evolution, land use, and the deposition and erosion of allogenic cave sediments in karst environments world-wide.

## ACKNOWLEDGEMENTS

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## Morphology of rimstone pools at Pamukkale, Western Turkey

Mehmet EKMEKCI, Gultekin GUNAY and Sakir SIMSEK

Hacettepe University, International Research Center For Karst Water Resources, Beytepe,06532, Ankara, Turkey

**Abstract:** Hot waters that emerge at 36 °C from open fissures and fault zones deposit snow-white travertine at Pamukkale in Western Turkey. Five principal morphological varieties of travertine mass have previously been described. However, no serious work on the rimstone pools that have been formed on almost all types of travertine masses has taken place. The principal aim of this study was to determine the morphometry of the terraces and their relation to the continuity and velocity of flow. Field measurement of the dimension of 467 rimstone pools were related to the gradient of the flow path of hot water. The role of the flow regime was examined by relating size of terraces to flow velocity. A logarithmic relation was established between the size of terraces and the gradient of the flow path. The flow regime was found to strongly affect the grading from micro-terraces to flowstone. Previous workers have shown that the formation of rimstone (equivalent to terraces) in caves requires some critical conditions. The morphometrical data and relations presented in this paper may help in describing at least some of these critical conditions.

### INTRODUCTION

Rimstone dams occur commonly in caves. Hill and Forti (1986) describe them as barriers of calcite, aragonite or other material that obstruct cave streams or shallow pools. Sweeting (1973), again regarding it as a cave deposit, relates the rimstone to flowstone, and indicates the lack of knowledge on the critical conditions for the formation of rimstone barriers rather than smooth flowstone. Hill and Forti (1986) relate the height of the dams to the gradient of the cave passages and conclude that higher dams form as the slope gets greater. As the slope decreases, the dams become not only lower but also more convoluted. They claim that formation of dams is known to occur on slopes more than 30 degrees. The term 'dam' does not provide a quantitative definition and it is sometimes a problem to distinguish rimstone dams from 'microgours', a word used for 'tiny rimstone dams'.

Rimstone dams and pools are also common as terraces on recent travertines deposited from springs outside of caves. The snow-white recent travertines of Pamukkale exhibit one of the best examples to this type of formation (Plate 1). The word 'rimstone dams' is used here as the equivalent of terraced-mounds of Chafetz and Folk (1984) who have recognized the same morphology at the Minevra Spring deposit at Mammoth Hot Springs, Yellowstone National Park, Wyoming. Their 'micro terraces' correspond to 'microgours' in caves. The spectacular travertine terraces at Pamukkale (meaning 'cotton castle' for their colour

and morphology) have been deposited from a series of geothermal springs that are brought to the surface along faults bordering the graben that forms the Curuksu Valley (Fig.1) (Gunay et al., 1994). The waters from the springs are of calcium bicarbonate character with a very high content (up to about 500 mg/l) of carbon dioxide. These waters have deposited travertines over a large area of about 20 km<sup>2</sup> and of at least 70m thickness.

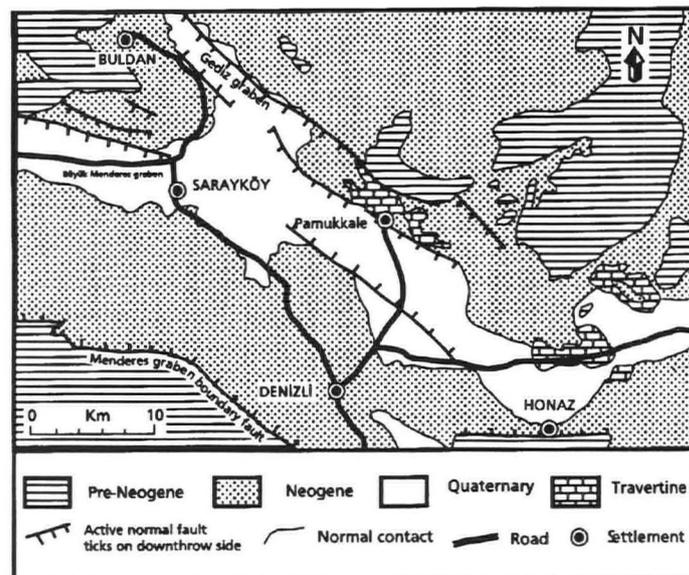


Plate 1. General view from Pamukkale travertine area.

Figure 1. Location and geological map of the Pamukkale travertine area.

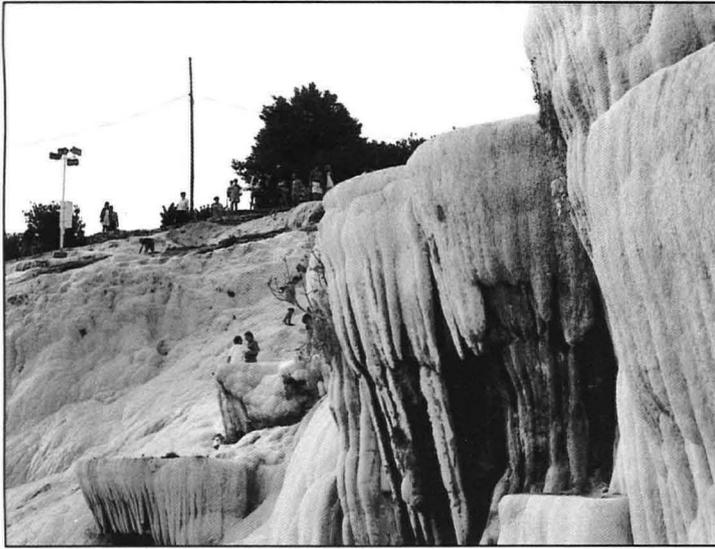


Plate 2. Giant rimstones at Pamukkale area.

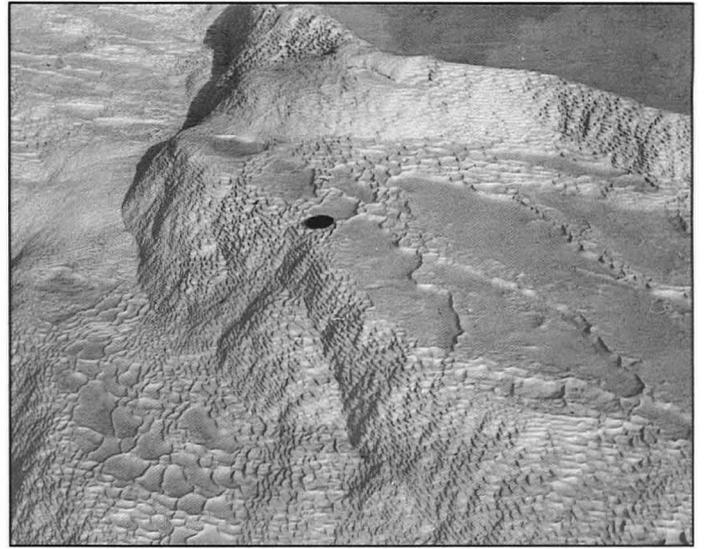


Plate 3. Rimstone dams of various size in different sections.

## MORPHOLOGY

The bulk morphology of the travertines at Pamukkale are very similar to those in Tivoli, Italy and particularly to those in Mammoth Hot Springs, Wyoming, USA. Chafetz and Folk (1984) have recorded five main morphological classes, largely on the basis of their survey in Tivoli, Italy. Altunel and Hancock (1994) studied the morphology and structural setting at Pamukkale, their principal aim being to classify the resulting morphology rather than to provide a detailed explanation of the conditions that causes varieties of this morphology. Based on this study they have recognized five main morphological forms, two of which are the same as in Chafetz and Folk (1984): 1) terraced-mound travertines, 2) fissure-ridge travertines, 3) range-front travertines, 4) eroded-sheet travertines, and 5) self-built channel travertines.

The terraced-mound travertines represent the giant rimstone dams and the pools behind (Plate 2). However, rimstones of various size are very common on all type of the aforementioned travertine morphology classes, and are not restricted only to this class. Plate 3 depicts the varieties of rimstone dams formed at different sections. This suggests that formation of rimstones is not controlled only by the factors that affect the bulk morphology, but they can form everywhere where some critical conditions are provided. Hill and Forti (1986) regard these conditions as: a degree of slope, at least a semi-continuous flow of water and the pre-existence of irregularities in the floor.

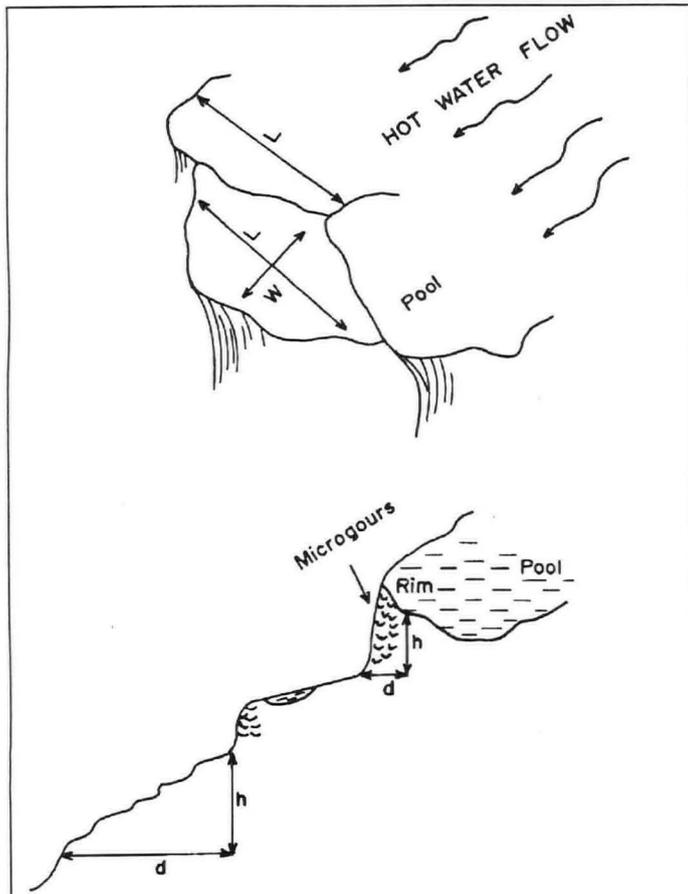


Figure 2. Size measurements of the rimstone dams.

N	Size		Slope	
	Width (mm)	Length (mm)	h/d	Degree
41	3	5	75	89.23
38	7	12	6	80.537
36	8	13	4	75.96
32	13	21	2.2	65.55
31	18	32	1.83	61.39
28	17	30	1.75	60.25
36	26	48	1.66	59.03
40	38	76	0.66	33.69
34	60	100	0.33	18.43
32	130	250	0.24	13.49
27	90	200	0.16	9.46
30	26	480	0.13	7.4
31	140	300	0.1	5.71
19	1800	3500	0.05	2.86
12	4500	8000	0.04	2.29
467				

Table 1. Size and slope measurements of rimstones on travertines at Pamukkale.

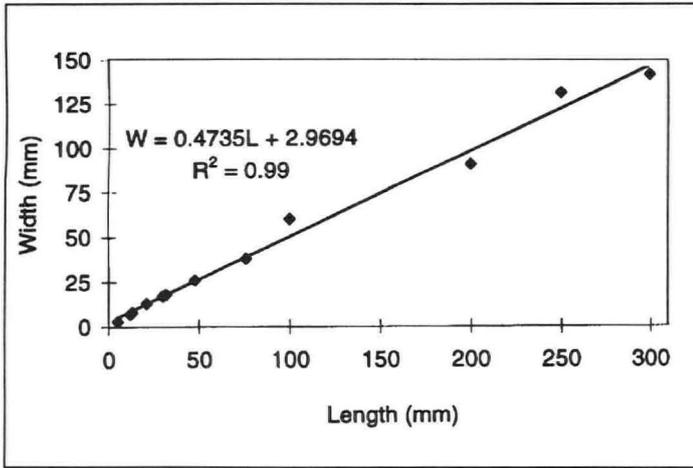


Figure 3. Width-Length relation for the rimstone dams.

### MORPHOMETRIC ANALYSES OF RIMSTONES

A representative area of travertines of about 100m x 100m was selected for field measurements. The research was conducted in two phases. First, the size of the rimstone dams and the pools behind the dams was measured in terms of width and length (Fig. 2). A total of 467 measurements were clustered under 15 groups of different slope and dimension (Table 1). As can be seen from the table, the size of rimstones at Pamukkale varies from 3mm to 4500mm in width and from 5mm to 8000mm in length. Width and length measurements were correlated using Pearsonian product-moment correlation analyses. All correlation's were tested for significance by t-test and the test statistics were found to fall into the upper critical region, which means that there are significant correlations between width and length, length and slope and width and slope.

The width of the rimstone dam was found to be proportional to the length (Fig. 3). The mathematical expression of this relation is as follows:

$$W = 0.47 L + 0.97 \quad r^2 = 0.99$$

where,

W = width of the rimstone pool  
 L = Length of the pool (see Fig. 2)  
 $r^2$  = determination coefficient.

The ratio between the width and length of the rimstone varies between 0.83 and 0.91 when the slope is less than 65 degrees. However, this proportion becomes irregular and decreases to 0.68 when the slope exceeds 65 degrees (Fig. 4).

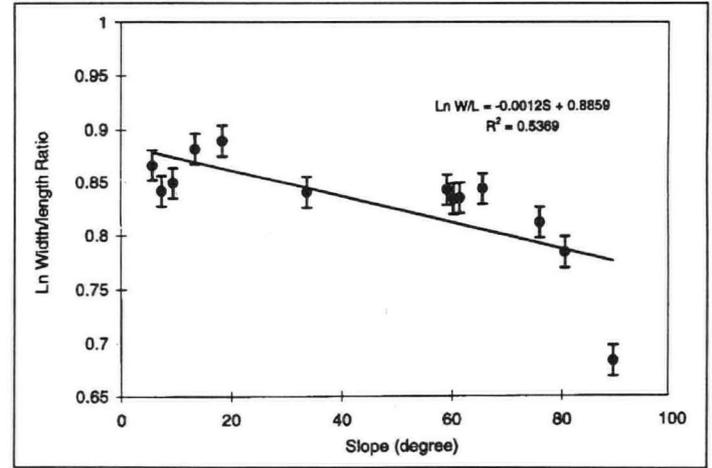


Figure 4. Variation of Width-Length ratio with slope of the surface.

The size of the rimstones is related to the slope of the surfaces on which they are deposited. Fig. 5 depicts this relation which gave the following regression equations:

$$\begin{aligned} \text{Ln} W &= -0.035 S + 4.77 \quad r^2 = 0.83 \text{ and} \\ \text{Ln} L &= -0.037 S + 5.48 \quad r^2 = 0.83 \end{aligned}$$

where,

W = width of the rimstone pool, L = Length of the pool,  
 S = slope of the surface on which the rimstones form,  
 $r^2$  = determination coefficient.

These relations become looser when rimstone dams longer than 1m are included in the analysis:

$$\begin{aligned} \text{Ln} W &= -0.045 S + 5.47 \quad r^2 = 0.75 \text{ and,} \\ \text{Ln} L &= -0.047 S + 6.15 \quad r^2 = 0.74. \end{aligned}$$

### ROLE OF FLOW REGIME

The function of the flow regime in the formation and size of rimstone dams was examined in terms of flow velocity and flow thickness. When a flow of constant rate exists, the gradient of the flow path is the controlling factor in the flow continuity and velocity. The flow thickness, however is another important factor controlling travertine deposition. Flow thickness was measured directly by an accurate ruler. The flow velocity was estimated on the basis of dye-dilution computations.

The formation of the rimstones is strongly dependent on the flow regime. The flow thickness is important, primarily in controlling the rate of deposition (Gunay et al, 1995). Therefore, it has a secondary impor-

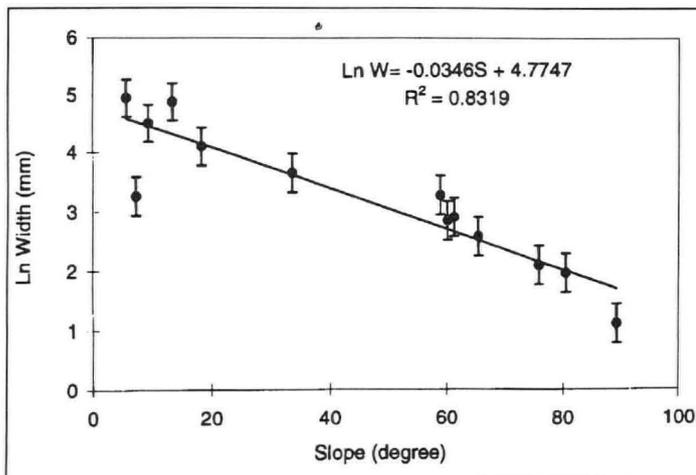


Figure 5. Relation of Size to Slope: a) Width-Slope Relation

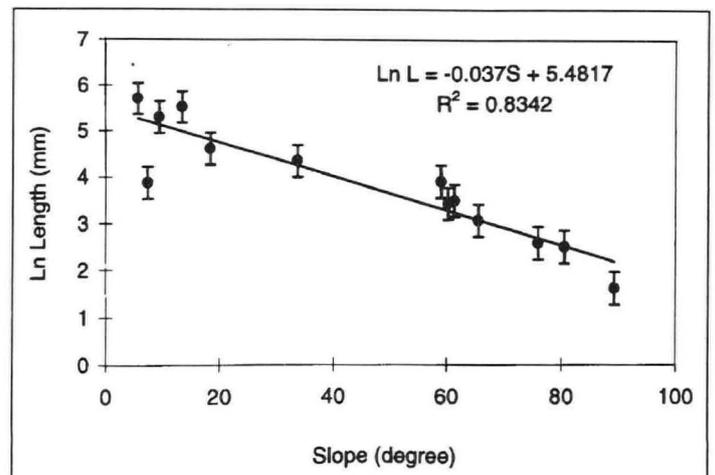


Figure 5. Relation of Size to Slope: b) Length-Slope Relation

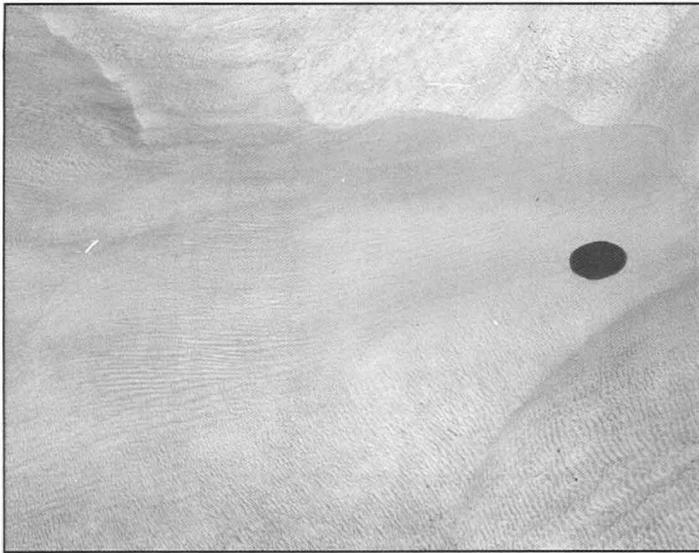


Plate 4. Flowstone -rimstone formation at different flow regimes.

tance in the morphology of the rimstone dams. Rimstones however, were found to occur only at sections where the flow is semicontinuous, regardless of the slope of the surface. The grading from flowstone to rimstone is mainly controlled by the flow continuity, rather than flow velocity (Plate 4).

At Pamukkale, sections where the flow is continuous exhibit a typical flowstone morphology. However, the flow velocity becomes more important when the water flows over previously formed rimstone dams. When the flow velocity increases at these sections, the outgassing of  $\text{CO}_2$  is enhanced and consequently the rate of deposition is increased (Ekmekci et al, 1995). Thus, the newly deposited travertine fills the previously formed microgours (tiny rimstone dams). Here, the microgours change their morphology gradually to flowstone.

Originally, rimstones formed at sections where the flow was semicontinuous and recent rimstones continue to form where the flow is semicontinuous. However, today the water flow at Pamukkale is controlled artificially by hydraulic structures. Therefore the flow regime is no longer natural and the critical conditions for rimstone formation occur only when the water ceases to flow but is impounded behind the giant rimstone dams (rimstone pools) of a dimension in the order of a few metres long and 50cm deep. The semicontinuous flow is provided by wind which is very effective after 4 pm at Pamukkale area in all seasons. The wind creates waves which drive the impounded water semicontinuously over the rims (Fig. 6).

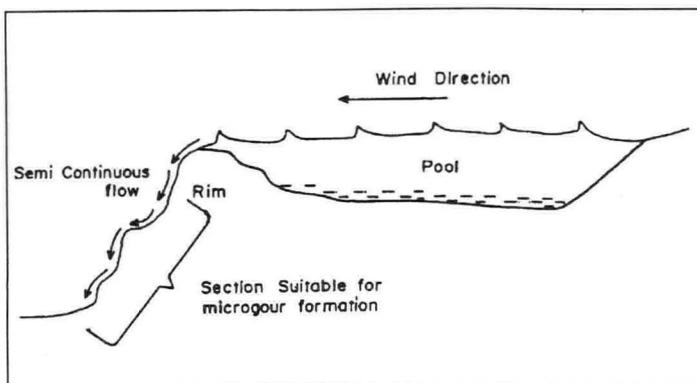


Figure 6. Wind Driven Semicontinuous Flow.

Obstacles or irregularities on the surface over which the water flows were found to play an important role only when they change the flow regime from continuous to semicontinuous. This is controlled by the flow velocity. The irregularities are more capable to change the flow to a semicontinuous regime when the flow thickness is less than 1mm and the flow velocity is as low as 0.05m/s. However, these critical values may change according to the size of the obstacle or the irregularity. The obstacles and irregularities are covered by travertine very easily when the flow thickness is large and the velocity is high enough to allow continuous overflow. The resulting morphology is only an obstacle covered by flowstone.

## CONCLUSIONS

On the basis of morphological measurements and analyses, together with field observations, in the Pamukkale travertine area, it is concluded that the formation of rimstones is mainly controlled by the flow regime. The gradient of the surface on which the rimstone dams form is an important factor in determining the size of the rimstones, rather than their original formation. Therefore, the limit of 30 degrees of slope for rimstone formation suggested by Hill and Forti (1986) does not seem to be satisfactory, since, rimstone formation is observed at Pamukkale, at sections of slope ranging from 0.04 degrees to 90 degrees, but at different sizes. The size of the rimstone dams becomes smaller when the slope becomes steeper. An inverse relation between the size of the rimstone pools and the slope on which they were formed was established as follows:

$$\begin{aligned} \text{LnWidth} &= -0.035 \text{ Slope} + 4.77 \text{ and} \\ \text{Ln Length} &= -0.037 \text{ Slope} + 5.48 \\ &\text{with a determination coefficient of } r^2 = 0.83 \text{ for both} \\ &\text{regressions.} \end{aligned}$$

The flow regime was found to be more important in the formation of rimstone dams than as a control on their size. It was found that formation of rimstone requires a semicontinuous flow. When the flow is continuous even at very low velocities, the result is flowstone. Irregularities on the surface were found to be important only when they change the flow regime from continuous to semicontinuous. This means that formation of rimstones seem to require a semi-continuous flow regime as a prerequisite, rather than a certain slope.

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## Some thoughts on hydrothermal caves

Trevor D. FORD

Geology Department, University of Leicester, Leicester LE1 7RH

**Abstract:** Hydrothermal caves are defined as those in which development has involved solution by waters considerably hotter than the ambient temperatures to be expected in a normal meteoric cave system. Some of the diagnostic features are noted, the geological relationships and the processes involved are outlined. An overview of selected hydrothermal cave systems emphasizes the considerations which must be taken into account in recognizing a hydrothermal phase in a cave system's history.

### INTRODUCTION

Hydrothermal simply means "hot water" so hydrothermal caves are those in which hot water has played some part in their genesis and development. This category of caves has only received limited attention in western literature, though rather more in eastern Europe. Dublyansky (1990) has compiled a bibliography of 324 items covering 1984-9 only; of these 131 are in Russian and many others are in eastern European languages. It is the purpose of the present communication to review some of the literature and to examine the processes involved in an attempt to stimulate further research on this subject. The features said to be diagnostic will be outlined in brief descriptions of selected hydrothermal caves.

The term hydrothermal has been restricted in some literature, particularly in Hungary, to situations where the heat is thought to be of volcanic origin, active or dormant (Takacs-Bolner and Kraus, 1989), but Western geological literature uses the term to include any hot water system, volcanic or not, and this is the usage taken herein. The Hungarian term thermal-karstic, sometimes used for warm water systems with no volcanic heat source, is thus unnecessary.

What temperature is necessary for water to be considered hydrothermal? Schoeller (1962) considered that the resurging water should be at least 4°C warmer than the ambient temperatures one would expect from normal meteoric/karstic circulation. In practice most hydrothermal springs are much hotter than this definition and resurge at between 20° and 80°C. A European standard for the definition of thermal waters has been taken at 20°C but some meteoric-karstic systems in hot desert countries may exceed this without any thermal input. A few hydrothermal springs erupt boiling water or even a mixture of steam and boiling water. Hot springs are often developed for commercial purposes either for geothermal power generation or for therapeutic purposes particularly in Eastern Europe; geothermal power generally requires temperatures well above 50°C whilst therapeutic waters are usually at least 20°C. Caves are unknown in geothermal power situations but some East European caves with associated warm springs are used therapeutically.

### PROCESSES, FACTORS AND FEATURES

The rate of solutional removal of limestone by meteoric waters is fairly well known. By contrast little is known of the effect of considerably higher temperatures on the rate of dissolution. Whilst the speed of the reaction may be increased by temperature it is probably the increased partial pressure of CO<sub>2</sub> from deep circulation which is more important. Geothermal waters often contain H<sub>2</sub>S and SO<sub>2</sub> which increase reactivity.

The sources of the extra heat are many and varied. Some hydrothermal systems depend on deep circulation of meteoric water within the Earth's crust whence the waters rise as hot springs. The rate of cooling on rising through already warm strata seems to be less than the rate of warming of meteoric water as it descends into the system. The conduits used by rising

thermal waters are limited to relatively small volumes of warmed rock, often along fault fissures, whereas the recharge areas are much more diffuse; the residence time at depth will also provide the opportunity for heating before rising up the conduit. Examples in Britain include the well-known springs at Bath and Buxton in both of which water is thought to circulate within Carboniferous Limestone at least a kilometre deep, probably for several years to judge from tritium ratios (Edmunds, 1971).

A long-standing explanation offering a heat source is the exothermal reaction of the oxidation of pyrite but this heat source is probably more mythical than scientific. In small quantities pyrite oxidation within shale partings yielding acid is probably an important contributing factor in opening inception horizons within meteoric water cave systems. In substantial amounts, the oxidation of pyrite in rock masses may be an exothermic reaction but only where the water supply is very slow and constrained. With any significant flow the heat is soon dissipated. Moreover, no such reaction system has yet been demonstrated to result in hot springs in carbonate terrains. Even the Xingwen Caves in China with their high content of pyrite introduced as a by-product of industry were not noticeably warmer than ambient temperatures (Bottrell, 1993).

Elsewhere hot springs may result from local volcanic activities with the waters being heated by nearby lavas, or the heat may come from deeply buried cooling igneous rock masses. The hot waters concerned may be meteoric (from rainfall) or juvenile (derived from within the Earth) or a mixture of the two. Some granite batholiths are thought to take as much as 100 million years to cool down after crystallization. In these igneous rock cases the hot springs are generally far removed from carbonate rock masses and so have little connection with caves, though a few may pass through carbonate rocks en route to the surface. An example is the Mammoth Hot Springs in Yellowstone National Park where there are extensive thermal tufa deposits. Carbonate sedimentary strata laid down over a still cooling granite batholith may receive sufficient heat for the water circulation to take on a thermal aspect, as in the North Pennines of England.

Ore deposits of Mississippi Valley Type (MVT) containing concentrations of galena, sphalerite, fluorite and baryte, are regarded by geologists as "hydrothermal deposits". Crystallization from aqueous solution is the principal mode of deposition and fluid inclusion studies have shown that temperatures around 70°C to 150°C were common at the time of ore deposition, and in a few cases temperatures up to 230°C have been determined. Deep circulation through large masses of buried clastic sedimentary rocks is required to yield the amount of hydrothermal fluid and the ore minerals contained therein. Such fluids, on rising up faults and pre-existing caves, affect only a restricted part of a carbonate rock mass and result in mineral veins of Mississippi Valley Type. Hydrothermal ore deposits often show a late phase with large calcite crystals, but these may be indicative of slow crystallization on a limited number of sites of nucleation rather than of high temperatures. There is an extensive literature on MVTs and a scan soon reveals that many deposits show ore-textures indicative of void-filling; in other words some MVT ore deposits were emplaced in ancient hydrothermal caves.

Carbonate rock masses hosting hydrothermal ore deposits may have been mineralized at depths of 2, 3 or even 4 kilometres but subsequent uplift and erosion has brought them to the surface. If the voids filled or lined with the ore minerals are considered separately from the related fissure fillings and replacement deposits, then "fossil" hydrothermal caves may be recognized. Some of these mineralized caves may have been developed from pre-existing cavity systems such as ancient palaeokarsts.

The search for oil and gas in the world's sedimentary basins shows that heated fluids, oil, gas or water or mixtures of these, accumulate and migrate slowly at depths as much as or even exceeding 4km until trapped in some geological structure which then forms an oil reservoir. Temperatures are often high but boiling is precluded by hydrostatic pressure. On average temperatures increase by 1°C with each 30m increase of depth, i.e. 33°C per km. Movement of the fluids without the stimulus of man's oil production may be very slow, of the order of a few millimetres per annum, but fluid-rock interactions can increase transmissivity, and may thus initiate the inception horizons for future caves. If the high temperatures of oil-water fluids are maintained perhaps such initial stages of cave formation can be regarded as hydrothermal.

The generation of hydrocarbons (oil and gas) in sulphur or pyrite-bearing rocks usually results in the production of H<sub>2</sub>S and SO<sub>2</sub> giving the "sour" characteristics of many oil and gas fields. Migration of sour oil or gas through carbonate rocks to situations where it meets oxygenated meteoric water will yield sulphuric acid and large caves may be dissolved out, e.g. Carlsbad and Lechuguilla Caves in New Mexico (Hill, 1987, 1990). Higher than normal temperatures would be expected in such reaction zones but the temperatures reached are difficult to determine, so it is still unclear whether such caves should be regarded as hydrothermal.

A common feature of hot springs is that the waters rise from within the Earth's crust, and the resultant conduits normally show evidence of upward flow. Whilst the hot springs are active obviously the conduits are full of hot water and inaccessible for exploration. However, equivalent systems in the past may have ceased to function and, if sufficient erosion of the surrounding area has taken place, the conduits can become available for exploration as hydrothermal caves as in Hungary. One cannot help wondering what the form of the conduits of the Bath and Buxton hot springs will be when revealed by general erosion of the surrounding area and falling water-tables in millennia to come. Pen Park Hole at Bristol is a possible equivalent conduit (Mullan, 1993).

The geological record in many sedimentary basins contains evidence of palaeokarsts. If these become deeply buried they can provide the circulation routes for water, oil and related fluids and, with the heat due to deep burial, these may develop hydrothermal features either superimposed on or even obliterating palaeokarstic characteristics. Thus an ancient meteoric cave may go through a later hydrothermal phase and hydrothermal features may then be superimposed on normal vadose and phreatic features, for example in a palaeokarst. Similarly an inactive or fossil hydrothermal system may be utilized by meteoric drainage at a later date. So, if an alternation of cold, shallow, meteoric and hot, deep, hydrothermal phases has affected a cave system during its geological history, its morphological development may be difficult to unravel. Some of the caves of the Buda Hills in Hungary appear to fall into this category (Muller and Sarvary, 1977). Multi-phase cave systems of the general character of meteoric-hydrothermal-meteoric are probably far more common than generally realized.

Whatever the source of the heat and hot water, drained hydrothermal conduit systems are likely to show features indicating upward water flow. But any resurgence wherein water rises from deep meteoric phreatic flow may show some such features without hot water being involved. Something more is needed to demonstrate the former presence of hot water. The hydrothermal caves of the Buda Hills in Hungary commonly show a dendritic upward division of conduits with many coming to a blank end: other conduits rise to the surface or reach a meteoric water table and

phreatic-vadose system. The blank-ended conduits often terminate in a rounded cavity variously known as a "cupola", "dome" or "kettle". Since these terms have different meanings in other contexts, the adjective hydrothermal must be used in conjunction to distinguish them, i.e. the rounded terminations are perhaps best known as "hydrothermal cupolas". Suffice it to say that a hydrothermal conduit cave will commonly show upward dendritic branching with many branches terminating in rounded cavities known as hydrothermal cupolas.

Any of three different chemical processes may be active in the formation of hydrothermal caves: solution by "pure" hot water; solution by waters rich in carbonic acid; and solution by waters containing at least dilute sulphuric acid. The first of these three is unlikely to be an effective process for any length of time in limestone terrains, as the water will no longer be pure after any solution has occurred. The process then moves into the second category - carbonic acid solution. Most hot springs yield at least some CO<sub>2</sub> by degassing with resultant tufa deposition, demonstrating that solution of limestone has taken place within the conduit system beneath. The third process is demonstrated by hot springs which smell strongly of H<sub>2</sub>S and their waters are dilute sulphuric acid. When this attacks limestone the result is usually either the formation of gypsum which, being more soluble, is easily removed or the replacement of wall-rock by gypsum through attack by gaseous H<sub>2</sub>S or SO<sub>2</sub> in the vadose zone or in trapped gas pockets. Some cave systems clearly originated by acid attack though whether high temperatures were involved is less clear. Such systems are perhaps best described as hydrothermal/chemical and may have been developed by warm waters rich in both SO<sub>2</sub> and H<sub>2</sub>S as well as CO<sub>2</sub>.

As with meteoric caves the movement of hot water through a limestone mass requires some initial weakness. Such weaknesses are the equivalent of the Inception Horizons proposed by Lowe (1993). Thus hydrothermal caves may show evidence of inception along bedding planes, through palaeokarsts or via joints and faults.

At least three different patterns of passage lay-out in hydrothermal caves have been distinguished by Hungarian investigators (summarised by D.C.Ford in James and Choquette, 1988). The first is the simple upwardly dendritic form with hydrothermal cupola swellings at the tops of the branches. The second is a two-dimensional rectilinear maze, whilst the third is a three-dimensional, multistorey, rectilinear maze. The first such pattern is clearly the result of upward movement of hot waters and is the pattern which may be expected when present day hot springs are drained in the future. The second and third patterns obviously depend in part on the stratigraphic or structural situation. A two dimensional maze will often be restricted between two aquicludes, whilst a three dimensional maze is less restricted. Either may be guided by tectonics, i.e. utilizing joint systems, or by palaeokarsts. Thus, placing any particular cave system within such categories may be no more than a useful guide and every potentially hydrothermal cave system must be looked at in its own geological context.

Hydrothermal caves are often characterized by mineral deposits of types not seen in meteoric cave systems. The best known examples are the calcite "pop-corn" deposits of the Buda Hills caves in Hungary, though the calcite spar linings of Jewel Cave in the Black Hills of South Dakota, USA, may also indicate a hydrothermal mechanism (Bakalowicz et al., 1987). Calcite is a common constituent of hydrothermal systems but may form at ambient temperatures too. In cases such as the Black Hills the temperature of crystallization need not have been much above the ambient meteoric temperature, but the presence of "ore" minerals such as galena in addition to calcite signifies considerably elevated temperatures, which may be revealed by fluid inclusion studies. Fluorite and baryte in association with galena similarly indicate elevated temperatures, though on their own they do not prove hydrothermal conditions. Alteration of the wall-rock may also indicate hydrothermal activity: limestone walls may be dolomitized, fluoritized or even replaced by galena.

The following descriptions are an attempt to examine some classic examples of hydrothermal cave systems so as to assess the mechanisms involved and the features resulting from them.

### THE HYDROTHERMAL CAVES OF BUDAPEST

The best known and most intensely studied hydrothermal caves are those of the Buda Hills within the western half of the Hungarian capital. Their hydrothermal origin was first suggested by Pavai-Vajna (1931) and their genesis has since been studied by many scientists (e.g. Muller and Sarvary, 1977; Jakucs, 1977; Kovacs and Muller, 1984; Muller, 1989; Takacs-Bolner and Kraus, 1989; Ford and Williams, 1989; Nador, 1992, 1993, 1994). A comprehensive review has been provided by Dublyansky (1995).

The Buda Hills are part of the Transdanubian Range of mountains which extends across northern Hungary from WSW to ENE and which contains several examples of hydrothermal karst. The Buda Hills cave systems are the best developed and are within a sequence of Triassic and Eocene limestones separated by a Cretaceous-Eocene palaeokarst surface with buried dolines, towers, and residual bauxite soils. Most of the caves are within late Eocene limestones. There is some evidence of an earlier palaeokarst developed in late Triassic times, and a later sub-Oligocene palaeokarst in places. Nador (1994) has suggested that there may be as many as five palaeokarstic phases superimposed in the Buda Hills. After tilting at 25-30° towards the south east, i.e. towards the River Danube, block-faulting occurred in late Eocene-Miocene times with downthrows towards the southeast, i.e. towards the Danube. The cover of Oligocene clays was progressively stripped off by erosion exhuming the limestone on the highest, western blocks first. Most of the hydrothermal karst is within the Eocene limestones (Fig. 1).

The sedimentary basin around Budapest is thought to lie on a relatively thin part of the Earth's crust, with a higher geothermal gradient than most of Europe at 50°C per km and this may account for the greater heat flow represented by the hydrothermal systems.

Whilst some hydrothermal caves may have developed before the Cretaceous-Eocene palaeokarst they have been so modified by the later development of Neogene hydrothermal systems that they are difficult to distinguish. The cave systems appear to have developed as a result of earth movements causing deep circulation within the adjacent basin with hot waters rising up-dip and overflowing at different points on the surface as the Oligocene clays were stripped off. An oft-quoted hypothesis is that the early phases of thermal speleogenesis may have been caused by the

circulation of waters warmed by the residual heat from late Eocene volcanic activity, but geochemical data summarized by Dublyansky (1995) indicate that deep circulation of meteoric waters in basins adjacent to the Transdanubian mountains is sufficient to explain the features of the hydrothermal karst without resort to a volcanic heat input. Early phases were largely in confined situations with the Oligocene clay cover still in place, but with cooling waters able to escape up or along faults. Later phases had progressively less confinement.

Two hydrothermal zones can be distinguished - a deep slow-moving zone with a low thermal gradient, possibly extending downwards for several kilometres, and a shallow zone with a high thermal gradient and more rapidly moving waters, extending downwards only for a few tens of metres below the thermal water-table. Speleogenesis may be initiated in the deep zone but the bulk of development goes on in the shallow zone. Both the usual mix-corrosion and a special thermal mix-corrosion may play a part. As the thermal water-table falls waters of different chemical composition and with markedly different temperatures may meet and mix.

There appear to be two types of hydrothermal cave: the first is rare and is an upward dendritic form wherein a series of branch passages rise from a basal chamber at which hot water appears to have entered the limestone mass. Convection cells developed in many branches so that dome-shaped cupolas or kettles a metre or more in diameter occur either singly or in groups at the upper ends. These appear to have been enlarged either by condensation corrosion during the drainage phases (Szunyogh, 1982) or by slower convection currents below the water-table (Rudnicki, 1978).

The second type of hydrothermal cave is the rectilinear maze developed by phreatic solution in a limestone aquifer between impervious aquicludes crossed by numerous faults and joints. The impervious shale partings are sometimes thin enough to be breached and multi-storey mazes have resulted from joint networks crossing successive limestones. The hot water is thought to have been rich in dissolved CO<sub>2</sub> and diffused upwards from underlying strata throughout the systems rather than at isolated inputs. Whilst the form of the maze caves resembles phreatic solution mazes formed at normal ground water temperatures, the Buda Hills caves are distinguished by their hydrothermal corrosion cupolas. Overflowing waters have produced resurgence caves at various levels. The form of these suggests that mix-corrosion was effective. Waters at different temperatures with different CO<sub>2</sub> content focused on a limited number of outlets and appear to have been responsible for enlargement of passages there. Some caves have adjacent hot springs within them with different temperatures ranging up to 40°C, thereby enhancing the mix-corrosion effect.

Figure 1. Diagrammatic section through the block-faulted Buda Hills, Budapest. (redrawn after Kovacs and Muller, 1984).

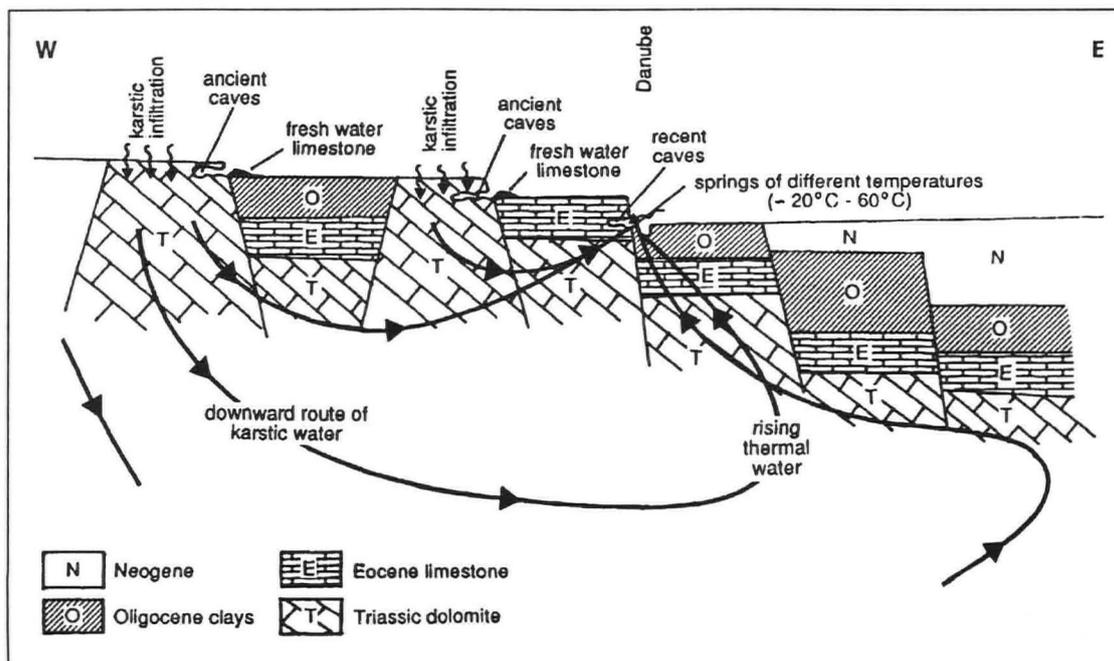




Plate 1. Popcorn calcite coating with gypsum crystals in Josef Cave, Hungary.  
(Photo by J. Gunn).

Baryte-calcite mineral veins with trace quantities of cinnabar and fluorite cut the limestones and appear to represent an early mineralization phase prior to hydrothermal speleogenesis (Nador, 1993). Alteration of the limestone walls of fissures has yielded quartz and clay minerals (Nador, 1992). Fluid inclusion studies indicate temperatures perhaps as high as 200°C for calcite vein formation. Being less soluble the calcite veins now project from cave walls. Localized silicification and dolomitization of wall rock is also indicative of early mineralization. The vein calcite temperatures claimed to be up to 200°C contrast with those determined for cave calcites where fluid inclusions indicate temperatures around 35-70°C (Nador, 1994). However, as calcite inclusions are subject to leakage not too much significance should be attached to these figures.

Carbon and oxygen isotope studies indicate a deep origin for the CO<sub>2</sub> distinct from present day soil gases, but a source for the system by infiltration of meteoric waters over perhaps 1000km<sup>2</sup> has been proposed. Those parts of the hydrothermal systems which were deep beneath the water-table might be expected to be coated with calcite scalenohedra like Jewel Cave, South Dakota, but little sign of such crystal cave development has been found so far. Mineral deposition from CO<sub>2</sub>-enriched hot water is represented by extensive botryoidal and coralloid calcareous deposits at palaeo-waterlines, in which fluid inclusion studies have indicated temperatures of formation as high as 79°C (Nador, 1993, 1994). During phases of falling water-table with concomitant drainage of conduits and cupolas there was much calcite deposition in chambers largely filled with steam. The presence of much "popcorn" calcite (some replacing aragonite) coating walls (Plate 1) and thick accumulations of former calcite raft deposits which have sunk from pool surfaces suggest somewhat accelerated chemical reactions, which could in turn depend on at least moderately high temperatures in very quiet conditions within such partially drained caves. Hollow calcite geyser-like stalagmites suggest late effusion of hot waters through cavern floors after drainage.

Hydrothermal activity continues to the present day and over a hundred thermal springs currently resurge mainly along N-S fault lines close to the River Danube; lukewarm spring temperatures are around 20-30°C whilst thermal springs range up to 65°C and are utilised in hot baths. Dissolved solid content is much higher than normal karst waters and ranges from 650-2000 ppm. Among the dominant components are sodium-calcium carbonates, chlorides and sulphates. It is generally thought that the hydrothermal waters are ultimately of meteoric origin but they have had a long and deep residence time within the limestones.

Encrustations of calcite and gypsum coat the walls and roofs of many Buda Hills caves (Nador, 1993). Needle-shaped calcite deposits suggestive of replacement of aragonite are widespread and are also regarded as

indicating elevated temperatures as aragonite is unstable below about 29°C. Much of the calcite is of the "pop-corn" variety, often with gypsum spikes protruding from it. However, some of the Buda Hills caves show features suggestive of the superimposition of meteoric water solution, even of vadose streamways though none are active today. The gypsum and replaced aragonite are taken as further evidence of hydrothermal activity, in the form of water-vapour carrying H<sub>2</sub>S or SO<sub>2</sub> invading the chambers after drainage. The presence of such acidic water-vapour suggests temperatures locally approaching boiling point.

The overflowing hot springs have deposited extensive sheets of tufa, now much built over. A series of eight geomorphological levels extends from 400-120m above sea level. Five of these are clearly hydrothermal in origin and have tufa sheets associated. Whilst the caves show little relationship to present-day topography, they do reflect the irregular incision of the River Danube with concomitant falling water-tables interrupted by still-stands. Meteoric speleothems (stalagmites) formed during such phases were occasionally resubmerged and coated with thermal calcite. Some of the older and higher tufas have been somewhat uncertainly dated back to Pliocene times, so the still-stands may apparently cover the whole of the Pleistocene. Whether the sequence of still-stands can be related to the glacial-interglacial alternations is very uncertain at present.

The polyphase development of the Buda Hills caves shows undoubted hydrothermal activity superimposed on a variety of guiding factors, such as the successive palaeokarsts, tectonic fissuring and progressive drainage by incision of the River Danube. The detailed studies of the systems by Hungarian speleologists has provided models for the study of the evolution of hydrothermal cave systems elsewhere, and much can be learnt from them.

Other hydrothermal cave systems are widespread in other parts of Hungary and show many of the features of the Buda Hills caves.

## THE CUPP-COUTUNN CAVE SYSTEM, TURKMENISTAN

Also known as Kap-Kutan, the massive Cupp-Coutunn cave system and its linked neighbour Promeszutchnaya total some 53km of passages within Upper Jurassic limestones on the western flank of the Kugitangtau uplift in Turkmenistan. The nearby Geophizicheskaya adds a further 20km though it is not connected. The caves and their history have been described by Maltsev and Self (1992) on whose work the following is based.

Cored with Precambrian gneiss and Hercynian granite the Kugitangtau massif forms the eastern boundary of Turkmenistan. The limestones are some 400m thick and dip at up to 15° to the west. They overlie flysch clastic strata, and are flanked by a variety of gypsum beds, thin limestones, shales and sandstones ranging up into the Cretaceous along the margin of the uplift. The latter dip into a Tertiary basin to the west. In spite of the length of passages the two main caves are concentrated within little more than 2km<sup>2</sup> giving a multi-storey complex elongated along north-south faults and parallel joints. The area is arid with little development of surface karst today. The caves have been breached by canyons cut into the dip-slope and the entrances are in the canyon walls.

A thermal phase in the caves' evolution is attested by widespread occurrences of "giganto-crystalline" calcite with fluid inclusion homogenization temperatures around 100-150°C. Later galena, meta-cinnabar and fluorite were deposited on the calcite. Fluorite shows homogenization temperatures up to 170°C. In places the limestone walls have been altered to a depth of up to 1 metre with re-crystallization of calcite with dispersed sulphides and silicates such as quartz and plagioclase feldspar, plus coatings of gypsum. There are widespread clay deposits with secondary minerals such as goethite, cerussite, celestite, dolomite, sulphur and gypsum, as well as clay alteration products such as sauconite (a zinc-bearing montmorillonite). The driest areas of the caves have a variety of unusual cave minerals, including hydromagnesite, epsomite, halite and mirabilite, all highly soluble except in a very arid environment.

The evolutionary history of the Cupp-Coutunn caves is thought to be multi-phase. An ancient palaeokarstic episode in mid-Cretaceous times is regarded by Maltsev and Self (1992) as setting the scene by phreatic solution in a planar configuration, extended along faults and joints. A clay fill stage followed, owing to the effects of fine-grained surface sediments washing down into ponded waters. Uplift of the Kugitangtau massif in Neogene times is thought to have allowed progressive drainage with partial removal of the clay fill as a rejuvenation phase. This was followed by invasion up joints by thermal mineralizing waters entering partly drained caverns, and mineral deposition occurred as the thermal waters lost their power to dissolve calcite. In a modern phase condensation corrosion attacked walls and ceilings as the cave air contained a mixture of CO<sub>2</sub>, H<sub>2</sub>S and SO<sub>2</sub> which dissolved in the thin film of water thereon. As air temperatures in the caves still reach 22°C in places, this phase may be said to approach hydrothermal conditions. In the Pleistocene the caves were breached by canyon erosion and irregular floods entered the caverns from flash floods, and percolation water yielded abundant calcite speleothems, with helictites particularly common. Gypsum forms crusts and stalagmites. Among the speleothems are rare instances of minerals normally regarded as hydrothermal growing in today's cool conditions on speleothems, e.g. purple fluorite has been found on both a helictite and on gypsum crystals.

In spite of the high fluid inclusion temperatures, Maltsev and Self (1992) regard the hydrothermal phase as a waning, non-aggressive equivalent of the chemical attack which formed the Carlsbad and Lechuguilla caves of New Mexico, the Jewel and Wind Caves of South Dakota and the hydrothermal caves of the Buda Hills. At Cupp-Coutunn this late phase is superimposed on a Mid-Cretaceous palaeokarst. However, the present author wonders if the alleged palaeokarst with its multi-level phreatic maze is not an equivalent of the sulphuric acid speleogenesis seen in Carlsbad and the other caves noted above. Regrettably no evidence is available to the writer regarding the nature of any neighbouring sedimentary basin or of possible hydrocarbon and H<sub>2</sub>S generating processes therein. The source of the hydrothermal mineral suite and the reasons for the elevated temperatures are unknown. Research on this topic is in progress (Bottrell, Crowley and Self, 1995).

### THE TYUYA-MUYUN KARST OF KYRGYZSTAN

A "channel-like cavity network" enclosed in the Tyuya-Muyun ridge has been formed within the Carboniferous Limestone and is host to uranium and copper vanadates, together with a gangue mineral assemblage

dominated by baryte with some celestine; lead and zinc sulphides occur in the deeper part of the ridge. Tyuyamyunite is a rare calcium-uranovanadate mineral found in the weathering zone. A late meteoric phase generated gypsum and calcite speleothems (Dublyansky, 1988; Bosak, 1993a). Following karstification in early Mesozoic times, the complex geological history culminated in Cretaceous-Palaeocene and Eocene times with uplift of the ridge and deep circulation of mineralizing fluids passing upwards from the adjacent basins into the ridge. The main deposit in Fersman's Cave is an irregular chimney-like system which has been explored by uranium miners to a depth of 220 metres (Hromas et al., 1993). Whilst no temperatures are available for the sulphides, fluid inclusions in calcite indicate temperatures between 40° and 65°C. Two generations of baryte were both deposited at around 30-35°C. These mild thermal conditions resulted in a network of hydrothermal caves. They were modified by normal meteoric waters in post-Eocene times when the vanadates were deposited.

### BANDAR-E-KHAMIR AREA, SOUTHEAST IRAN

The very arid part of Iran north of the Straits of Hormuz is characterized by numerous anticlines composed mostly of limestone with some gypsum and halite strata. The rocks range from Permian to Eocene in age and total up to 18km thick. Folding commenced in the Miocene and is still continuing. Beneath the Permian is thick Cambrian salt, which has risen as diapirs (salt-plugs) some of which breach the surface and carry a salt karst with dolines and swallow holes. Some of the anticlines contain oil reservoirs which have been exploited since the 1920s.

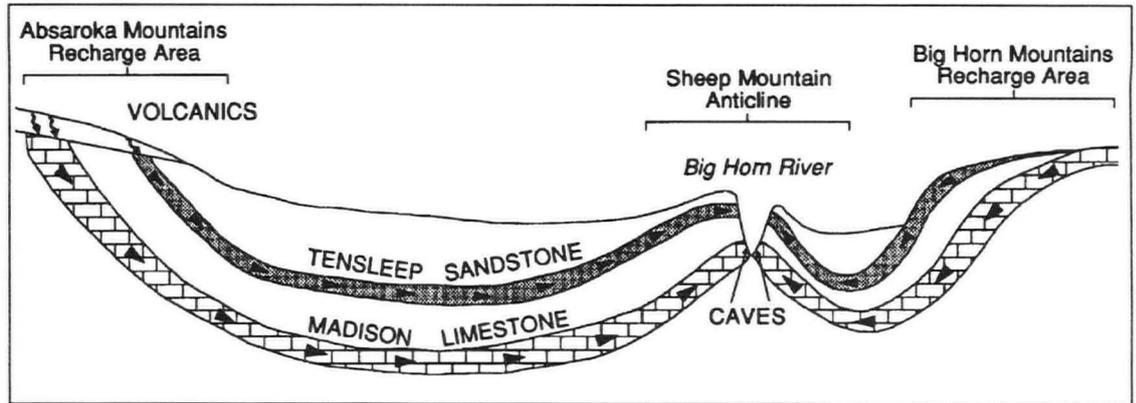
The Bandar-e-Khamir area also has many manifestations of thermo-karst (Bosak, 1993b). This includes many springs of warm to hot water, mostly highly mineralized with high values of NaCl, KCl and CaSO<sub>4</sub>, and often giving off large volumes of H<sub>2</sub>S. As the area is highly arid, the emergence of springs has to be explained by other means. The oilfields rest on oil-rich brines and the continued folding displaces the brine outwards and upwards by any available conduits, which may be faults or the disrupted strata along the margins of the salt plugs. Temperatures of emergent waters reach 42°C. There is little doubt that the hydrothermal conduits will become cave systems in the future when folding ceases and erosion lowers water-tables, but at present the few caves yielding hot streams have such a high content of H<sub>2</sub>S in their atmospheres that exploration is impossible.

The general environment of this area of thermo-karst has much in common with that of the Carlsbad and Lechuguilla caves of New Mexico and it may be that vast caves of this type may be revealed one day. Indeed drillers have already encountered cavities in several oil-wells.

### THE FENGFENG AREA, CHINA

In this area of the Hebei Province, coal-bearing strata overlie Carboniferous Limestone which suffered a major magmatic intrusion (Chen, 1993). One of the effects of this was the metamorphism of the limestones closest to the intrusion to form a skarn rock, a mixture of carbonates and silicates. This rock alteration resulted in the formation water in the limestone being raised to high temperatures and driven off through the more distant limestones up chimney-like conduits. These penetrated the overlying coal measures to produce collapse structures, some open to the surface. Heated waters circulated and convected in the collapse chimneys causing further enlargement. Chen (1993) suggested that the reduction of hydrostatic pressure in the collapses may have allowed the water to boil at times. Although the full story is difficult to extract from the Chinese publication, it does seem that the Fengfeng conduits are classic hydrothermal caves caused by igneous activity.

Figure 2. Diagrammatic section through the Sheep Mountain Anticline, Wyoming, to show its relationship with the Absaroka Mountains recharge area. (redrawn after Egemeier, 1981).



## ALGERIA

Caves apparently associated with former hot springs at El Bibans, Algeria, are encrusted with phreatic calcite crusts similar to those of Tyuya-Muyun and Budapest (Collignon, 1990; Dublyansky and Collignon, 1993).

## BIGHORN MOUNTAINS AND BASIN, WYOMING

Extending for some 130km east of Yellowstone National Park, the Bighorn Basin is a wide syncline with strata from Cambrian to Quaternary age. Its eastern limit in the Bighorn Mountains uplift carries the prominent Sheep Mountain and Little Sheep Mountain anticlines. Cored by Precambrian granite these have outward dipping cuestas of Palaeozoic and Mesozoic strata on their flanks. Among these is the Mississippian Madison Limestone, from 150 to 250m thick, which contains a group of small but important hydrothermal caves, investigated in detail by Egemeier (1981).

The caves are all single passage resurgences, the longest barely 400 metres, with passage widths up to 10m. Some are no longer active but others discharge thermal waters high in sulphuric acid, with traces of oil and of uranium and thorium. The waters rise into the caves from slots in the floor and are high in  $H_2S$ . There is little percolation contribution in the rather arid area, but on meeting the atmosphere in the caves the  $H_2S$  is soon oxidized to sulphuric acid and this is the main speleogenetic factor. Condensation on the roof and walls leads to reaction with the limestone and converts it to gypsum and there are floor deposits of collapsed gypsum crusts as well as large selenite crystals. Clay deposits on the floors are thought to result from temporary ponding by external factors with water locally influent. Where present the clays protect the floors from lowering by trenching. During gypsum formation carbon dioxide is released into the cave air. The combination of high concentrations of  $H_2S$  and  $CO_2$  means that visits to these caves cannot be protracted! Temperatures at the springs in the active caves range up to 23.5°C, generally 10-15° warmer than the mean air temperature of the area. The caves are still developing in the vicinity of the hot springs, demonstrating that the mode of speleogenesis here has been headward retreat from former surface springs.

The mechanism proposed by Egemeier (1981) is that there is a hydraulic drive for at least 100km under the Bighorn Basin from the higher Absaroka Mountains to the west (Fig. 2). This takes the waters to depths of more than 2km within the Madison Limestone, where temperatures may well exceed 67°C on the basis of the average geothermal gradient there. At these depths hydrocarbons have been generated within shales adjacent to the limestone, with the usual attendant generation of  $H_2S$  and mobilization of uranium and thorium traces. The hydraulic drive forces the hot waters, partly cooled as they rise, through a joint system to the surface to feed the hot springs and thus to generate the caves.

Doubtless similar geological and hydrological circumstances occur elsewhere but the extra factor of a near-desert climate and lack of meteoric water has allowed the hot  $H_2S$  rich waters to rise and develop

these unusual warm sulphuric acid caves in Wyoming. The overall geological situation has parallels with the Guadalupe Mountains and Delaware Basin in New Mexico. However, there the much more dolomitized limestones, and the former higher rainfall in the Pleistocene "pluvial" periods together with the intermittently falling meteoric water-table over a longer period of time has yielded the much larger cave systems of Carlsbad and Lechuguilla Caverns.

Comparable conditions may have been widespread but as erosion removed the cause of the hydraulic drive these Wyoming caves would become available for normal meteoric development provided there was adequate rainfall, and their hydrothermal origin might become so masked that it was unrecognizable.

## THE HYDROTHERMAL CAVES OF THE BLACK HILLS

The Laramide (early Tertiary) uplift of the Black Hills structural dome in western South Dakota, U.S.A. has resulted in the core of Precambrian crystalline rocks being flanked on all sides by outward-dipping Pahasapa Limestone of Mississippian age (early Carboniferous) and by the overlying Minnelusa Sandstone of Pennsylvanian age (late Carboniferous). A late Mississippian/early Pennsylvanian palaeokarst surface separates the two formations. Igneous intrusions of Tertiary age penetrate both Precambrian and Palaeozoic strata at the northern end of the Black Hills.

The Pahasapa Limestone is mostly little more than 100m thick, and is much dolomitized and locally silicified. It dips beneath the sandstone cover at angles between 20 and 40°. On the southern and southwestern flanks of the Black Hills the Pahasapa Limestone contains two of the world's longest and most complex cave systems. Jewel Cave, with at least 118km of surveyed passages, lies on the southwest flank, whilst Wind Cave is some 30km away at the southern tip of the structure. Wind Cave has about 70km of passages (Fig. 3). Both are multi-storey mazes with little sign of vadose development or of relationship to the present surface. Both are partly beneath the Minnelusa Sandstone "umbrella". Both are devoid of running water and only Wind Cave has been explored down to the local water-table where there are static lakes with a high content of carbonate in solution. Regional drainage is towards thermal springs of which the most important, Cascade Springs, is some 20km south of the limestone outcrop. Mildly thermal waters rise at these springs at 17-26°C and have high carbonate contents resulting in much tufa deposition.

The passages of Jewel Cave are characterised by a coating up to 15cm thick of calcite crystals through most of the system (Plate 2). Both scalenohedral and nail-head calcite crystals are present sometimes occurring together without any obvious explanation for the difference in crystal form. Wind Cave has a similar but thinner crystalline calcite coatings in the lower levels only. Wind Cave is noted for its box-work of calcite-filled joints which now project from the cave walls owing to slow quiet solution of the intervening wall-rock. Neither cave has much in the way of speleothems as little water percolates through the overlying sandstone. The calcite coatings are comparable with some of the Hungarian hydrothermal caves.

Several hypotheses have been proposed for the genesis of these maze caves, mostly involving slow solution by confined meteoric waters. However, a much more compelling scenario is that of Bakalowicz et al. (1987), who propose that solution by rising thermal waters moving slowly towards overflow springs was the main mechanism involved. Further details may be found in Palmer and Palmer (1989) and D.C.Ford (1989). This upward movement of water probably took place during mid-Tertiary times and incision of drainage marginal to the Black Hills has resulted in the caves being left as high and dry residuals in Pleistocene times, with little evidence of the position of the catchments driving the thermal waters up-dip. The evidence for their conclusions on thermal speleogenesis falls into five categories:

- a) the multi-storey mazes are comparable in morphology to the undoubted thermal caves of the Buda Hills. Hydrothermal cupolas like those of the Buda Hills occur at the upper ends of some Black Hills cave passages.
- b) mineralogical evidence suggests selective dissolution of dolomite in calcite-saturated waters, more likely to occur at higher temperatures than low. Transport and reprecipitation of silica is also more likely with higher temperatures.
- c) the presence of thermal springs nearby.

- d) isotope studies suggest temperatures of 20-40°C for the deposition of the calcite crusts.
- e) uranium series dating of speleothems and hot spring tufas indicates an age for this late phase as Pleistocene with Jewel Cave deposits being considerably older than Wind Cave. Isotope data is similar to that obtained from the Buda Hills caves.

The source of the heat remains a problem. Expulsion of heated groundwaters from adjacent basins is not regarded as significant by Bakalowicz et al (1987). Palmer and Palmer (1989) point out that there is little evidence for sulphuric acid waters as at Carlsbad Caverns, and any waters expelled through the limestones from basins around the Black Hills might be so rich in carbonate that little solution could be expected. They suggest that residual heat from the Tertiary intrusions is enough. However, the known intrusions are at the northern end of the Black Hills and the caves are at the southern, so that it becomes necessary to postulate the presence of other still-buried intrusions beneath the central and/or southern Black Hills to provide a heat source for hydrothermal speleogenesis in late Tertiary times, with somewhat reduced effects still being manifested as hot springs today. The presence of buried intrusions in the southern Black Hills is as yet unproven so any arguments for the potential heat source may need modification. As catchments outside the

Figure 3. (a) Sketch plan of Wind Cave, South Dakota, showing the rectilinear maze typical of hydrothermal caves, and (b) Diagrammatic section through Wind Cave. (redrawn after D.C.Ford et al. 1993).

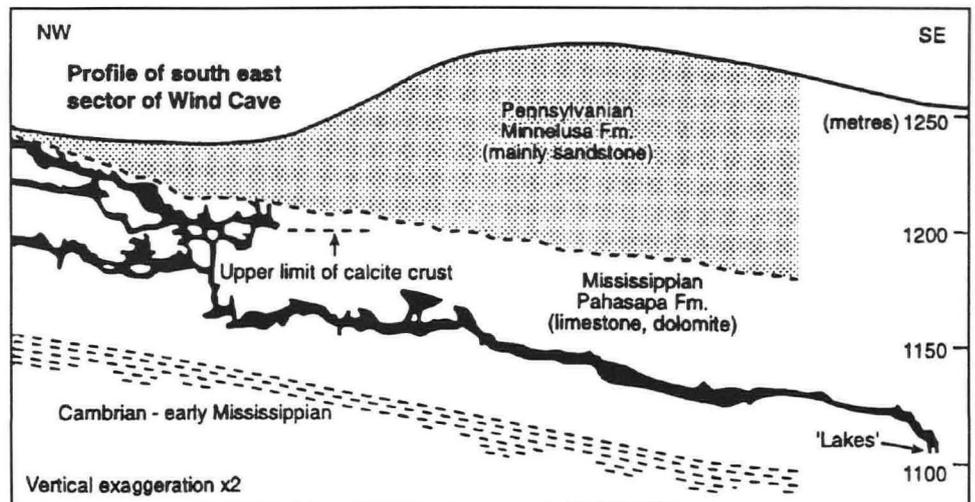
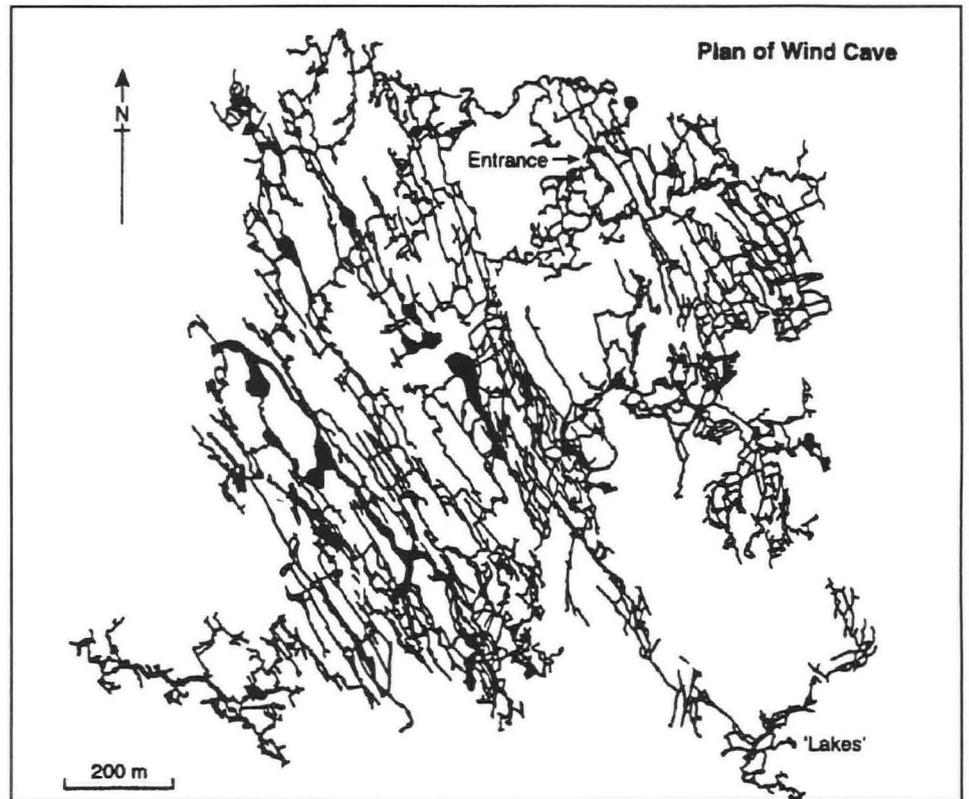




Plate 2. Part of the lining of calcite crystals, each 5-10 cm long, in Jewel Cave, Black Hills, South Dakota.

Black Hills are difficult to visualize, the drive may have come from recharge by slow percolation through the Precambrian crystalline rocks rising to the Pahasapa limestone cover around the flanks of the Black Hills structure.

Whilst intrusion-heated waters may have been responsible for the solutional development of the mazes, the calcite crystal coatings are thought to indicate decreasing hydrostatic pressure with outgassing of  $\text{CO}_2$  near the contemporary hot water-table, with resultant crystal deposition in quiet non-turbulent waters with a restricted number of nucleation sites. The determination of temperatures during the various phases still requires further investigation. At present the only temperatures known with any accuracy are 20-40°C for the early phase of calcite crystal growth, and 17-26°C for the present hot springs.

Whilst Jewel and Wind Caves are clearly multi-storey phreatic mazes with very little vadose modification, the temperature at which they developed and the heat source are still somewhat uncertain and require further investigation.

## THE GUADALUPE MOUNTAINS, NEW MEXICO

The vast caverns of Carlsbad and Lechuguilla in New Mexico, U.S.A. are characterized by large chambers with limited passage lengths and frequent blind ends unlike the usual pattern of meteoric caves. They fall loosely within the multi-storey category.

Carlsbad and Lechuguilla Caves are hosted in a Permian dolomitized reef complex in the Guadalupe Mountains, here represented by an escarpment facing the contemporary Delaware Basin (Fig. 4). Thick later Permian deposits with much gypsum and halite filled this basin and overlapped the reef complex. Carlsbad Caverns are within the Capitan Reef limestones whilst Lechuguilla Cave is partly in the reef limestone

and partly in the contemporary back-reef Yates Formation of the Artesia Group. The area now has a rather arid climate though there is some evidence of wetter "pluvial" phases during the Pleistocene.

The origin of these large caves has been explained by a hypothesis of up-dip lateral expulsion of  $\text{H}_2\text{S}$ -rich gases and fluids from the adjacent basin where they were confined by thick beds of gypsum and halite (Davis, 1980; Hill, 1990; Palmer et al., 1991). Carried in solution in expelled basinal waters the  $\text{H}_2\text{S}$  reacted with meteoric waters in the reef limestones of the escarpment generating large quantities of sulphuric acid. It is envisaged that the acid attacked the limestone converting it to gypsum which then dissolved. Some was later reprecipitated as sheets, blocks and encrustations in the caverns (Hill, 1986, 1987, 1990). Studies of sulphur isotopes have linked the gypsum phases with the hydrocarbons of the Delaware Basin. The morphology of the large caverns indicates activity by uprising corrosive fluids with only limited modification by vadose erosion later: later vadose deposition, however, has been responsible for the magnificent speleothems in both cave systems.

Whilst it is likely that the expelled gas and the carrier fluid was warmer than one would expect of meteoric waters in the area, no evidence for elevated temperatures has been detected so far and so it might perhaps be more appropriate to designate these cave systems as geochemical rather than hydrothermal. However, their morphology and the fact that they are characterized by much calcite popcorn and calcite rafts are suggestive of elevated temperatures like those obtaining during the drainage phases of the hydrothermal caves of the Buda Hills in Hungary. The spectacular speleothems for which the Carlsbad and Lechuguilla Caves are famous were of course formed later during the wetter phases of the Pleistocene.

Speleogenesis by sulphuric acid is no longer operating in the accessible caves of the Guadalupe Mountains, and the caves no longer have atmospheres enriched in  $\text{H}_2\text{S}$  as erosion has lowered the whole surface of the Delaware Basin and so removed the hydraulic driving force for gas expulsion.

The Guadalupe Mountains carry numerous sub-economic occurrences of minerals such as galena, sphalerite, baryte, copper and arsenic minerals in veins of Mississippi Valley type. Their genesis is thought to be related to an early, perhaps Mid-Tertiary, phase of expulsion of hydrocarbon gases and mineralizing fluids from the Delaware Basin; the driving force for the expulsion was probably compaction beneath younger strata which once filled the Basin. These veins again suggest a phase of elevated temperatures preceding the main speleogenetic phase in Plio-Pleistocene times though there could have been some chronological overlap in the operation of the two processes.

Comparable cave systems are known in Wyoming (see elsewhere in this review), at Grotte di Frasassi, Ancona, Italy, and at Akhali Atoni Cave, Georgia, CIS. At the latter springs rich in  $\text{H}_2\text{S}$  and  $\text{CO}_2$  are warmer than those of the Guadalupe Mountains suggesting a moderate degree of hydrothermal input to current speleogenesis. In view of the hydrocarbons in the adjacent basins being produced by oil-wells at temperatures commensurate with their depths, the possibility that naturally expelled gases and petroliferous waters are at least warmer than ambient should not be overlooked in this or any comparable geological situation. The potential speleogenetic effect of such warm fluids is yet to be assessed. Taking the average geothermal gradient (increase of crustal temperature with depth) as 1°C per 30m, temperatures in excess of 60°C would be normal in oilfields or the underlying waters at depth of around 2 kilometres. Hydrothermal solution could be the norm for oil reservoirs in carbonate strata and indeed many reports on such oilfields make brief comment on the limestones being cavernous. Some of this cavernous porosity may be of palaeokarstic origin, so a meteoric-hydrothermal-meteorite alternation may exist here as noted in the introductory remarks to this review.

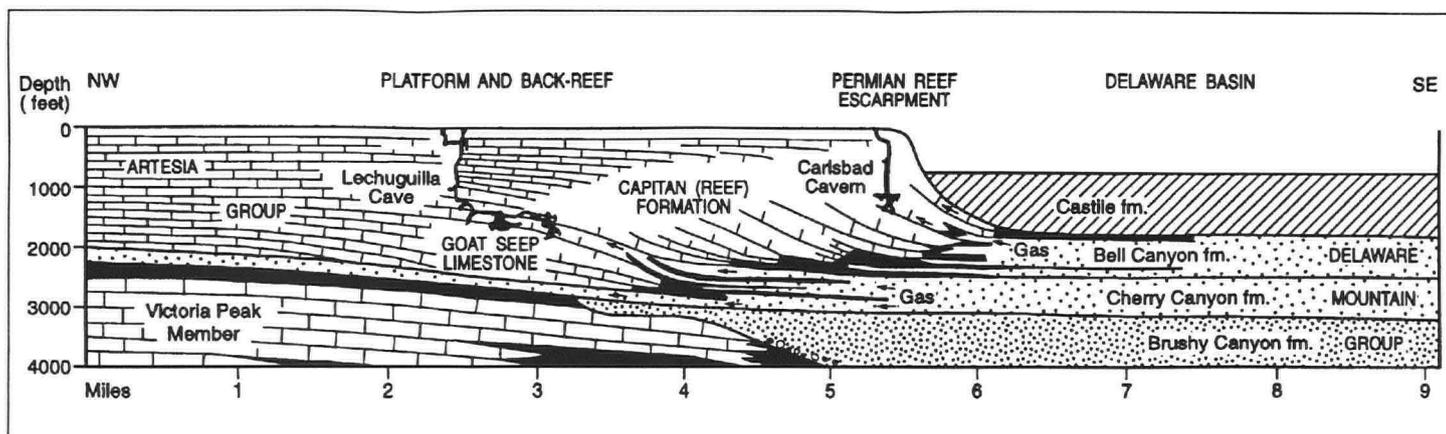


Figure 4. Diagrammatic section through the Capitan Reef scarp showing the relationship of Carlsbad and Lechuguilla caves, and the probable migration route for  $H_2S$  out of the Delaware Basin into the reef limestones. (redrawn after Hill, 1990).

### PEN PARK HOLE, BRISTOL

This unusual cave lies within the suburbs of Bristol. It is within steeply dipping Carboniferous Limestone, oriented along a SW-NE fault roughly parallel to the bedding. It is about 60m deep and consists of a large main chamber with several rising branch passages, one of which now forms the entrance. Described by Tratman (1963) it has been re-assessed by Mullan (1993). The latter noted that the form resembled that of the rising, branching conduits of simple hydrothermal caves, with cupolas at the top ends of some branches. Much of the system has its walls encrusted with some 10cm of scalenohedral calcite, similar to the coating in Jewel Cave, South Dakota.

The age of the cave is unknown but Mullan presented arguments for a Jurassic phase of solution, perhaps related to exhalative springs on the contemporary sea-floor. The age of the calcite crust on the walls is similarly unknown and could be anywhere between the Jurassic and the Pleistocene incision of the nearby Avon Gorge, when the cave would be drained as the water-table fell.

There are still some warm springs in the area: the nearest is at Hotwells about 2km to the south at a much lower altitude. Well-known hot springs occur at Bath, some 12km to the southeast, fed by water circulating deep with a complex synclinal structure in the Carboniferous Limestone, here covered by Triassic and lower Jurassic strata. It is thus tempting to think of Pen Park Hole as a putative Jurassic fore-runner of the Bath springs and thus as a fossil hydrothermal cave.

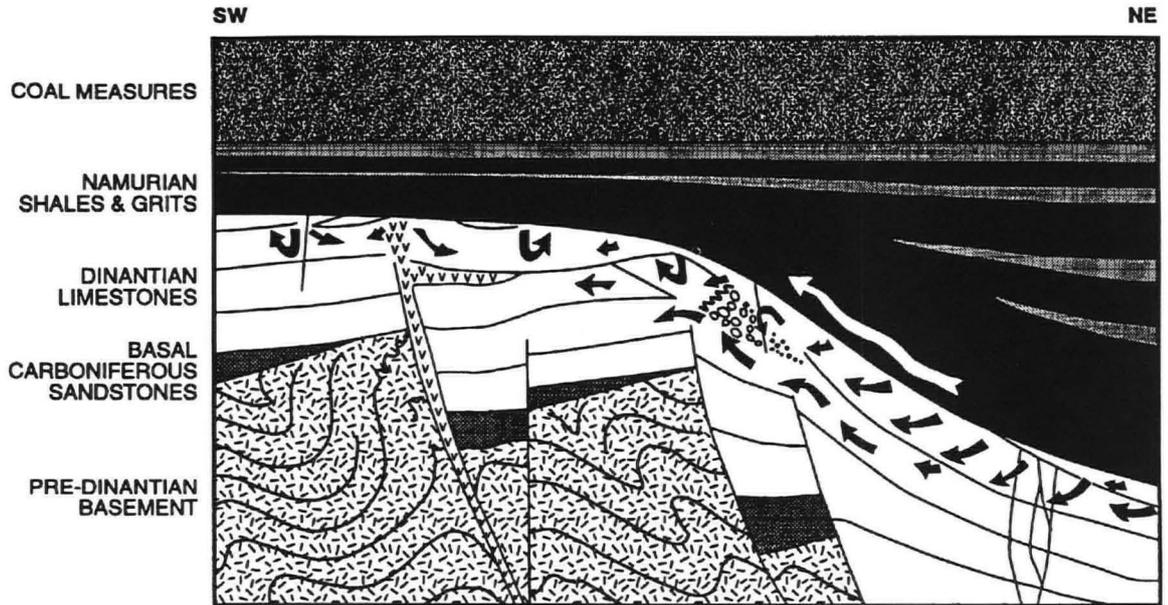
### HYDROTHERMAL ORE DEPOSIT CAVES IN THE ENGLISH PENNINES

Apart from being the host rock for most of Britain's meteoric cave systems, the Carboniferous Limestone is also the host to Britain's largest extensive MVT ore deposits. Large tonnages of galena, sphalerite, fluorite, baryte and calcite have been mined since Roman times in both North and South Pennines. As a result the ore deposits are well known. They consist primarily of near-vertical fissure-fillings known as rakes (large) and scrins (small). More or less horizontal deposits are known as flats, generally disposed along bedding planes or similar structures, frequently as "wings" along the sides of rakes. Replacement deposits are less common and often consist of limestone fluoritized in situ. The remaining category of ore deposit is that of "pipes", best known in the South Pennines. These generally follow bedding planes, sometimes along the contacts of limestones and thin volcanic horizons, some of which lie on palaeokarstic surfaces (Walkden, 1974; Ford, T.D., 1989). It is these pipes which include hydrothermal caves. At least some fall broadly within the two-dimensional maze category.

Many of the pipes consist of lenticular cavities with limited inter-connection, containing linings or even fillings of ore minerals. Incompletely filled cavities are in effect large geodes or vughs, lined with crystals of the ore minerals. The cavities are not often seen in a pristine state owing to the ore minerals and some wall-rock being removed by mining. Thus the pre-mineralization form is difficult to deduce, but the general impression is of solution cavities developed along an inception horizon (Lowe, 1993) which is often a thin (5cm) volcanic tuff, and further guided by intersecting joints. The host limestone is Lower Carboniferous in age and mineralization was episodic but mainly late Carboniferous. Fluid inclusion temperatures are generally 70-150°C indicating a depth of burial by Upper Carboniferous clastic sediments (Millstone Grit and Coal Measures) to around 2-4km. The solution phase required by the pipe caverns is generally regarded as having taken place as an early phase of mineralization, i.e. when temperatures were elevated and the early ore fluids were aggressive rather than passively depositing their minerals. This aggressive phase of solution may have utilized pre-existing palaeokarst surfaces or even caves but the textural evidence is as yet unrecognized. It seems likely that the aggressive early ore-hydrothermal fluids dissolved out the pipes at depths of 2-4km and that later phases of mineralization lined or filled the pipes. Excess de-mineralized waters required an escape route, possibly via faults, to emerge at the surface as hot springs, now eroded away, or to enter the groundwater circulation in the clastic sediments of the Upper Carboniferous. At this stage of knowledge the pipes demonstrate lateral rather than upward movement of hot waters, but this was largely because of lateral guidance by volcanic horizons in gently dipping strata. The source of the hot mineralizing fluids is thought to be by expulsion from nearby subsiding sedimentary basins, with the ions sequestered from the clay minerals of a more or less age-equivalent shale facies.

Perhaps the best known pipe caverns are in the Matlock area of Derbyshire, where examples may be seen in Masson Cavern. These have been breached by a much later (early Pleistocene) meteoric cave system part of which is a tourist cave (Ford and Worley, 1977). Some 5km to the north the deep lead-zinc mine workings of Millclose Mine penetrated mineral-lined solution caverns apparently resulting from an early phase of aggressive hot mineralizing fluids; this mine has not been accessible since mining stopped in 1940 so that details are difficult to unravel. At Magpie Mine, west of Bakewell, the Blende vein shows large vughs (2m across) lined with calcite and sphalerite as another instance of hydrothermal mineral caverns (Plate 3). The Blue John fluorspar deposits at Castleton show comparable mineral-lined vughs, generally less than 1m wide, related to a palaeokarst surface (Plate 4). The Blue John fluorite fills or lines voids between limestone boulders and ancient cave systems within the immediately underlying reef complex limestones (Fig. 5).

Figure 5. Diagram to show the probable migration route of mineralization fluids into the Carboniferous reef limestone complex at Castleton, Derbyshire, with its associated pre-Millstone Grit palaeokarst, which resulted in mineralized hydrothermal caves lined with Blue John fluorite. (redrawn after D.G. Quirk).



Many other Pennine mineral deposits show comparable cavities which may be hydrothermal caverns. Some of the solutionally enlarged joint network caves have also been ascribed to hydrothermal activity; for example Devis Hole Mine Cave has a complex passage network partly lined with galena, enlarged by later Pleistocene solution (Ryder, 1975; Ford and Williams, 1989).

hot waters are few and only a brief comment that the ancient caves were probably enlarged by the flushes of hot fluids has been found.

A similar history has been determined in southern Illinois where the bulk of the fluorite mineralization is in fractures in Mississippian limestones and only a limited amount is associated with the pre-Pennsylvanian palaeokarst. The Jefferson City lead-zinc mine of eastern Tennessee has a two-storey maze of cave passages largely filled with sulphides and gangue minerals showing sedimentary structures (Fulweiler and McDougal, 1971). Other examples are many, e.g. Pine Point, N.W. Canada (Rhodes et al., 1984; Sangster, in James and Choquette, 1988).

### HYDROTHERMAL ORE DEPOSITS EMLACED IN PALAEOKARST

As with the English Pennines there are many other examples of palaeokarsts penetrated by hydrothermal mineralizing fluids much later in their geological history. Some are discussed in works on palaeokarst such as James and Choquette (1988), Bosak et al. (1989) and Ford and Williams (1989). A good example is provided by the silver-lead-zinc mining fields of central Colorado (De Voto, in James and Choquette, 1988). Here a pre-Pennsylvanian karst with numerous sink-holes, cave systems and solution collapses was permeated by hydrothermal fluids generally thought to have emanated from mid-Tertiary intrusive igneous complexes. Temperatures of deposition reached as high as 300°C when the palaeokarst was buried by at least a kilometre of overlying sediments. Unfortunately descriptions of features specifically related to the action of

### HYDROTHERMAL ORE KARST IN POLISH SILESIA

Dolomitized limestones of Middle Triassic age (Muschelkalk) in the Krakow region of Silesia in southern Poland are characterized by ancient cave collapses with sphalerite and galena (Bogacz et al., 1970). These appear either as coarse boulder breccias with the sulphide ores in the voids between boulders or as disaggregated and re-sedimented dolomite-sand with sulphides between the dolomite crystal grains in the ancient caves. Bogacz et al. (1970) regard these as evidence of a palaeokarst formed prior to ore deposition by the movement of groundwater. The



Plate 3. A hydrothermal pipe-vein cave lined with calcite and sphalerite, Magpie Mine, Sheldon, Derbyshire.

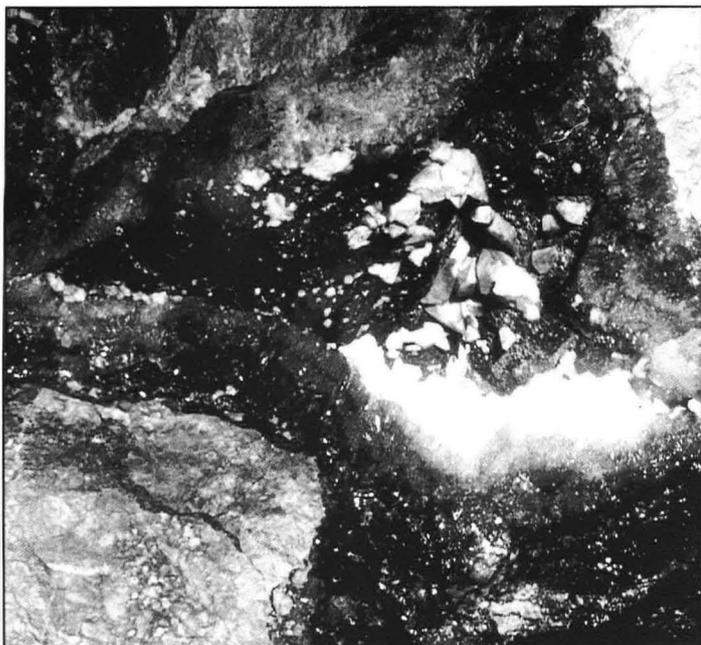


Plate 4. Void between limestone boulders, lined with fluorite (dark blue John variety) and calcite scalenohedra on the palaeokarstic surface of Carboniferous Limestone, Treak Cliff Cavern, Castleton, Derbyshire.

sulphides have yielded evidence of fluid inclusion temperatures between 50° and 150°C and arguments were presented for the sulphide mineralization being of late Triassic to mid Jurassic age, when the Muschelkalk was buried deep beneath younger strata. However, the collapse breccias almost fill the ancient caves and the little open space accessible suggests the presence of hydrothermal cupolas like those of the Buda Hills. No pattern of cave passages suggestive of a meteoric cave system has been detected and so it seems possible that the void formation prior to ore deposition was in fact effected by early phases of the ore-fluids at elevated temperatures and that the caves are really hydrothermal.

## CONCLUSIONS

Perhaps the main conclusions of this review are that hydrothermal caves are probably more common than usually thought, that hydrothermal speleogenesis may often be overlooked, and that cave features can sometimes be used to diagnose former hydrothermal activity. It has become evident that the whole geological history of any cave region must be taken into account. When were the host rocks formed? What cover once lay on top of the limestone? How thick was it? Are there adjacent basins from which fluids could have migrated? Are any igneous intrusions present in the vicinity? When did uplift take place, and what is the erosional history resulting there from?

The geological situations most conducive to hydrothermal speleogenesis are:

- (1) where carbonate platform sediments are marginal to deep sedimentary basins where the depth of subsequent burial has been sufficient to generate hot fluids and gases. Burial by later strata is necessary to expel the fluids up-dip into the carbonate platforms, but these too must have been deeply buried to explain the temperatures revealed by fluid inclusions. The Cupp-Coutunn system appears to fall into this category.
- (2) In the basin-expulsion model of (1) above, if the expelled fluids and gases are "sour" with H<sub>2</sub>S and SO<sub>2</sub> sulphuric acid may be an important part in the development of cave systems and any gypsum deposits therein. The large Carlsbad and Lechuguilla cave systems appear to be of this geochemical/hydrothermal type.

- (3) A variant of category (1) above is where substantial amounts of hydrothermal minerals such as galena, fluorite, baryte and calcite are involved, derived by reactions within a deeply buried clastic sedimentary sequence. The "pipe-vein" cavities of the Pennine orefields are within this category together with other MVT orefields. The Tyuya-Muyun system is another variant.
- (4) If magmatism has provided a heat source within crustal rocks, as appears to be the case in the carbonate rocks of the Buda Hills, and the Fengfeng thermokarst of China. The maze caves of the Black Hills may have had a magmatic heat input.
- (5) Deep circulation from a catchment area under a synclinal basin and up into shallower resurgence areas at lower altitudes may yield hot waters where neither diagenesis nor hydrocarbon generation are involved. Rising hot waters with perhaps minimal acidic gases cause speleogenesis. A good example is provided by the caves of the Big Horn Mountains of Wyoming. Other examples may include Pen Park Hole and possibly the Black Hills if the concept of a hidden volcanic heat source is discounted.
- (6) Tectonic stresses such as the continuing uplift of parts of the Himalayas may cause expulsion of hot oil-field brines, as seen at Band-e-Khamir, Iran.

The above categories are far from being mutually exclusive and some examples could be classified in more than one category. The possibility of cave systems being polycyclic (e.g. meteoric-hydrothermal-meteoric) further complicates the issue if it can be demonstrated that a cave system has passed through different categories in its geological history.

In any investigation of a potentially hydrothermal cave system, the following questions must be asked and answered. Is there any evidence of hot springs, past or present, in the area of the cave? Have the strata enclosing or adjacent to any particular cave been buried to depths of at least a kilometre at some period of their history? Do they contain any evidence of hydrothermal minerals such as galena and fluorite? Are the field relations such that hydrocarbon-related fluids rich in H<sub>2</sub>S could have migrated out of an adjacent sedimentary basin? Is there any evidence of magmatic activity in the vicinity?

When the Inception Horizon hypothesis (Lowe, 1993) is applied with the above questions in mind, it is possible that we must look far back into geological history for the origination of many cave systems. Just to take one example: the classic "meteoric" cave systems of Ingleborough clearly had their inception along bedding planes and joints; nobody doubts this. But there was once a cover of Upper Carboniferous sandstones and shales at least one, if not two, kilometres thick above the limestone, and there is some mineralization with galena and fluorite. The Craven Block is part of a carbonate platform marginal to both the Central Pennine and the larger North Sea Basins wherein hydrothermal and hydrocarbon fluids could have been generated. Does this lead to a possible conclusion that the inception took place whilst the limestones were deeply buried and receiving fluids hot enough to be considered hydrothermal? Whilst the main development of Ingleborough's caves was undoubtedly meteoric, perhaps inception was hydrothermal.

## ACKNOWLEDGMENTS

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# The crystallogenes of gypsum flowers

Lucretia GHERGARI<sup>1</sup> and Bogdan-Petroniu ONAC<sup>2</sup>

<sup>1</sup>Mineralogy Department, "Babes-Bolyai" University, Kogalniceanu 1, 3400 Cluj-Napoca, Romania

<sup>2</sup>Speological Institute "Emil Racovita", Clinicilor 5, 3400 Cluj-Napoca, Romania

**Abstract:** This paper focuses on some crystallographical observations carried out on samples of gypsum flowers (anthodite and oulopholite) in order to explain their morphology (i.e. the way they are curved). It has been found that most of these speleothems are either aggregates or parallel growths, made up of fibrous and/or prismatic crystals. Three mechanisms of curving were observed, which can be related mainly to changes in the calcium sulphate solution flow rate and concentration.

## HISTORICAL APPROACH

At present two terms are used to describe gypsum flowers: anthodite (flower, Greek) and oulopholite (curved leaf stones, Greek). The first term is used mostly in Europe, corresponding to the French, fleur de gypse (Choppy, 1985; Hill and Forti, 1986). It is interpreted differently by the American-English specialists, who use it to define acicular crystals radiating from a common centre or stem.

One of the first works that referred to gypsum flowers is dated 1810 (Shaw, 1992, p. 217). After a brief presentation of this unusual speleothem, an explanation for its genesis was suggested. An early explanation of the gypsum flower's origin (here called oulopholite) was given by Locke (1842), who assumed the following process:

*"...from the rocks by increments to the base the solid parts already formed being continually pushed forward. If the growth be a little more rapid on one side than on the other, a well proportioned curve will be the result;..."*

Wright (1858) suggested that the gypsum crystals were extruded from the walls as a result of the pressure created by their hydration.

After 1866 the genesis and morphology of gypsum flowers became the subject of study for many authors. Among these the experiment of Huff (1940) was one of the most important. He "grew" gypsum flowers in the laboratory, using sodium thiosulphate (much more soluble) rather than calcium sulphate, in order to decrease the time required to form the speleothems. His conclusions were that crystals forming gypsum flowers grew from the base and the curvature was due to a more rapid growth on one side, and not because of internal pressure as Wright (1858) had supposed.

Most of the recent work on gypsum flowers has attempted to classify them with respect to their external morphology (White, 1968; Choppy, 1975; Hill and Forti, 1986) or to present genetic aspects typical of a certain cave or karst area (Pohl and White, 1965; Jude, 1972; Calandri, 1980; Forti and Rabbi, 1981; Diaconu, 1983; Onac, 1991). The genetic model proposed by Huff (1940) has been accepted to date, but no other recent study has approached the crystallographical side of gypsum flower genesis. This paper attempts to remedy this deficiency.

## LABORATORY DATA

Crystallographical studies of gypsum flowers were made on the basis of microscopic observations (using a transmission polarizing microscope) and crystal orientation using Fedorov's universal stage. Thin sections were cut parallel to the curve plane. Fifty seven gypsum flowers (anthodite and oulopholite) collected in the Vântului, Tausoare, Valea Rea and Rastoci caves were studied.

The microscopic studies revealed two aspects:

- neither anthodite nor oulopholite is monocrystalline; both are aggregates and/or parallel growth crystals
- gypsum twinning does not essentially influence the crystal curvature.

Crystallographical analysis performed on different kinds of anthodites and oulopholites revealed two morphological aspects and three curving mechanisms.

### A. Types of aggregates and parallel growth

#### 1. Aggregates and parallel ( $\pm$ symmetric) growth of fibrous crystals which developed parallel to the c-axis

Zones with parallel crystal growth and twins of two crystals after (100) can be noticed in the fibrous aggregates. Fibrous crystals (parallel to the c-axis) tend to appear along the speleothem growth direction, being disposed parallel to it (Plate 1). The crystals have a different position

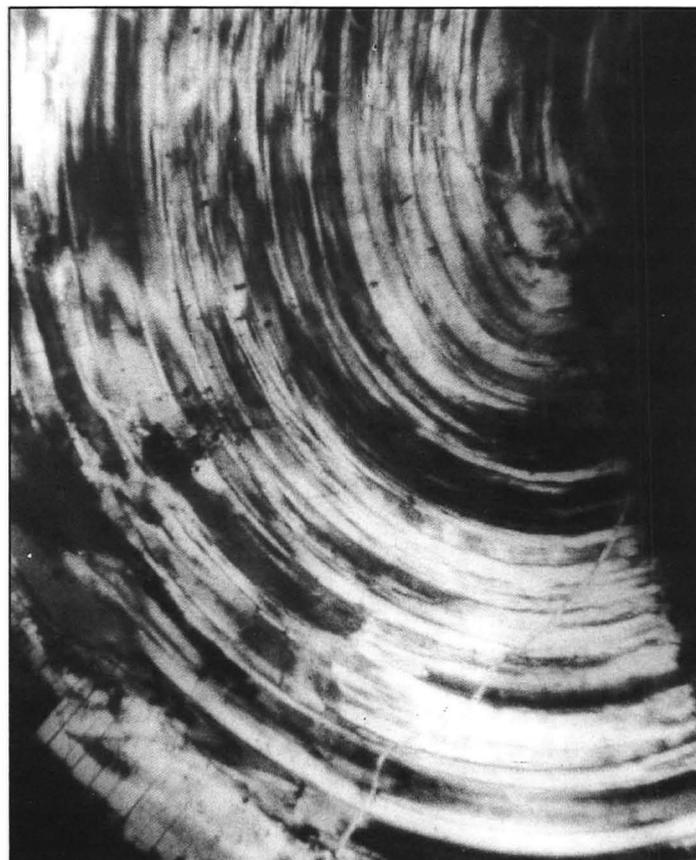


Plate 1. Aggregates and parallel growth of fibrous gypsum crystals developed parallel to the c-axis (N+, 60x); the thin section was cut parallel to the curve plane.

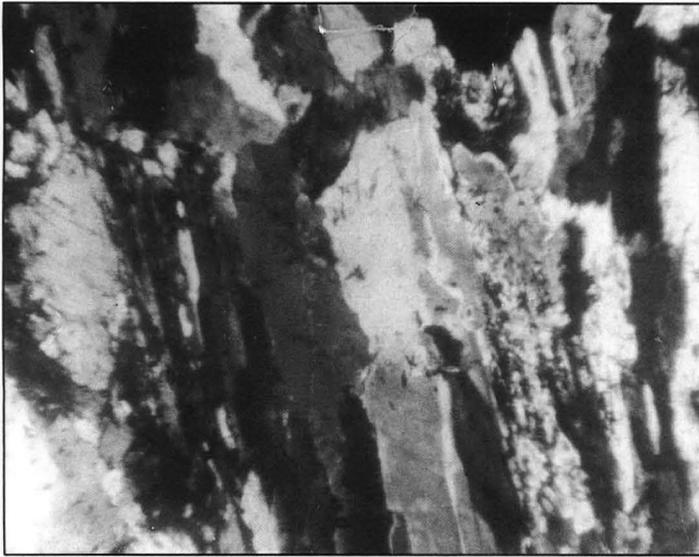


Plate 2. Parallel growth of prismatic crystals in a gypsum flower (N+, 60x).

when checked in thin-section, where they are developed mostly after (100) and (010). The outside parts of the gypsum flowers show stripes parallel to the growth direction. These are due to fibrous crystals that are outwardly limited by the prismatic faces (110), (120) or (180).

## 2. Aggregates and/or parallel growth of prismatic crystals

The aggregates consist of several single crystals, most showing a saccharoidal (mosaic) texture. These are parallel to the elongation of the speleothem (Plate 2). The crystals that lie in the curving plane show two different orientations: parallel with (100), or with (010). Crystals made up of twins after (100) are uncommon compared to the previous class.

## B. Curving mechanisms

The curvature of prismatic and fibrous gypsum crystals can be framed in one of the following categories:

### 1. Parallel growth of prismatic/fibrous crystals interrupted by narrow stripes made-up of quasi-isometric crystals showing different orientations and saccharoidal texture (Plate 3b).

This manner of curving is characteristic of oulopholites. Interruption in the growth of prismatic crystals produces a pronounced stripe on the surface of the blade-like gypsum crystal (Plate 3a). Alternation of the two crystal habits (prismatic and isometric) occurs continuously. The longer and more constant the flow rate of calcium sulphate solution, the longer is the growth of the prismatic crystals. The curvature is given by the height of the gypsum crystals which are shorter and shorter towards the inside of the curve. The way these speleothems are curved is related to interruption in the calcium sulphate solution supply and changes in its flow rate. Both phenomena can be explained by local topo-climatic conditions.

### 2. Aggregates of prismatic crystals (saccharoidal texture) which curved because the calcium sulphate concentration in solution changed.

The curved crystals in this category display normal optical behaviour and the position of their indicatrix remains along the crystal. To understand the curving process two composite crystals (A+B) (Plate 4) with different orientations were studied (one was parallel to 100 and the other to 010). For each crystal the position of the indicatrix was established at 6 different points (the distance between I and VI was 15mm). The contact surface indices were deduced by referring to the crystallographical elements obtained on the basis of the cleavage plane.

The contact surface position was marked - I - VI for the main crystal (normal orientation ; vertical c-axis) and - I' - VI' for the other crystal (Fig. 1). It was noticed that normals to the contact faces each relate to a zone plane having as index [112] for the main crystal and [111] for the other one. No regular laws governing twinning were found when the two composite crystals were analysed, so twins are excluded. The directions of growth in points number I, II, IV and VI are marked with squares (Fig. 1) and they describe a zone plane. It changes from one that is close to [101], to one perpendicular [010], close to the b-axis.

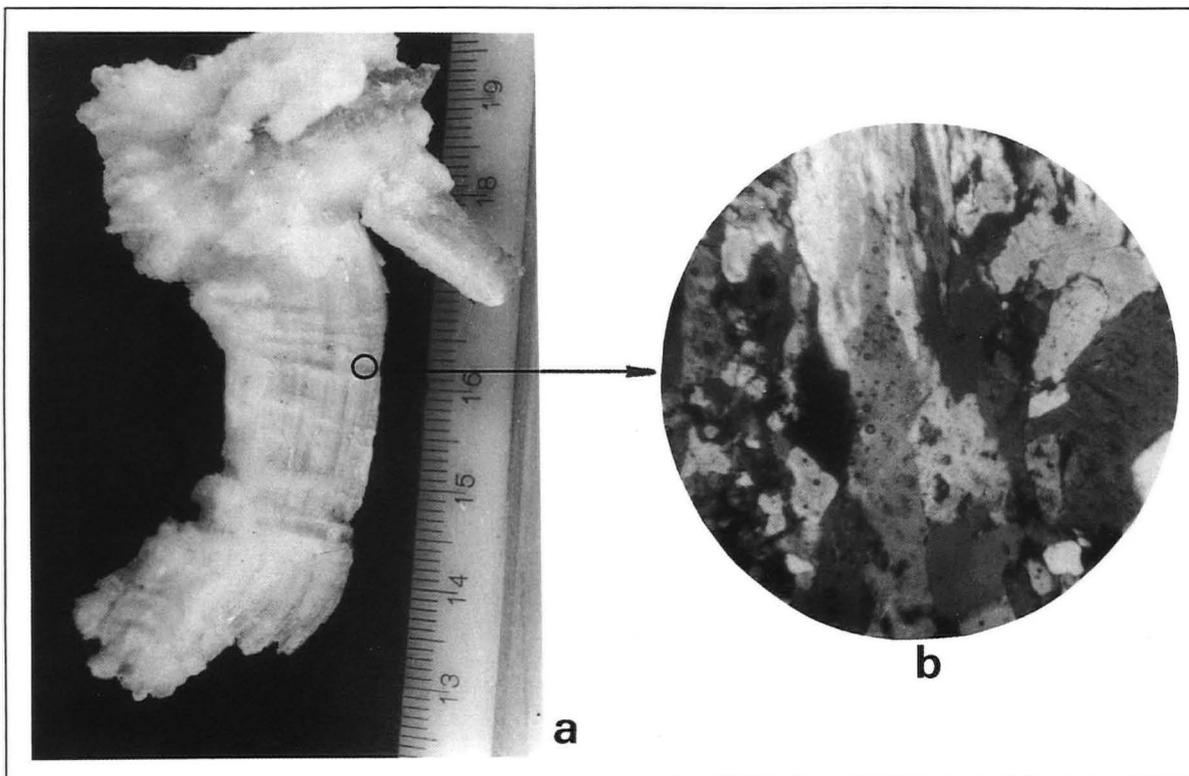
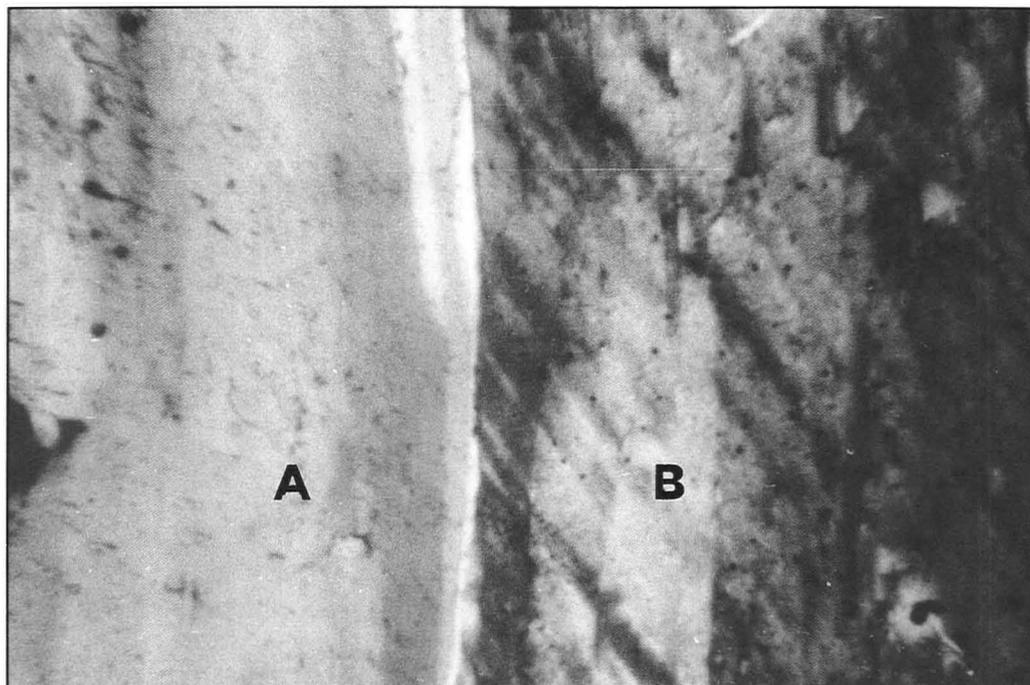


Plate 3. a) Oulopholite showing several narrow stripes (1:1.); b) microscopic view of the gypsum crystals as they appear in these stripes (N+, 60x)

Plate 4. The joined crystals on which the crystallographical elements ( $N+$ , 60x) were analysed.



All crystal faces identified on different gypsum speleothems (anthodite and oulopholite) are represented and marked with circles of various sizes on the stereogram (Fig. 1). The higher the circle, the more common the face.

3. *Crystal growth interrupted at various stages of its development and a new crystal, slowly deviate, begins to grow.*

Fibrous anthodites showing a short curving radius were ascribed to this group. Their genesis is controlled mainly by variations in the sulphate solution supply.

Along some prismatic aggregates (at the base or on the gypsum blade sides) in both anthodites and oulopholites, narrow zones (Plate 5) with fine to medium grain size, closely interlocking gypsum crystals (saccharoidal texture) occur. In these small crystals light-brown liquid inclusions and celestite microcrystals (stronger relief when compared with gypsum) were noticed (Plate 6).

The solubility of the celestite in supergene solutions behaves qualitatively somewhat like that of gypsum. In solution it exists as ions, and the quantity of celestite that can be precipitated from a particular solution depends in large part on the temperature, pressure and salinity, as well as on the ratio of the activity of the alkaline earth to that of sulphate in solution.

The precipitation of celestite as microcrystals can result from recrystallization of high-magnesian calcite in the presence of solutions containing fairly high concentrations of sulphate. As this study has strongly indicated the presence of more than one type of solution during the formation of gypsum flowers, it is likely that mixing has played a role in the precipitation of celestite. The celestite microcrystals were probably precipitated from residual solutions at different stages.

Inclusions are trapped by advancing growth surfaces and variations in either the supply or the rates of absorptions. Following the orientation of the microcrystals and inclusions, it can be stated that the calcium sulphate solution was stored and/or moved upward within the gypsum flowers along these channels with small gypsum crystals. Kendall and Broughton (1978) found that inclusions in calcite sometimes impeded crystal growth, and discontinuities in the crystal mosaic may occur at these growth surfaces. The inclusions recognized in the gypsum flowers never caused discontinuities sufficient to define growth-layering.

## CONCLUSIONS

Although both terms (anthodite and oulopholite) described the same kind of speleothem - gypsum flowers - the following distinction can be made in European speleological literature. It is better to use the term anthodite to describe all speleothems that resemble a flower and oulopholite to describe a singly curved and/or contorted crystal. The two morphological terms should be used for speleothems made up of different minerals (not only gypsum), their mineralogical composition being mentioned separately (e.g. aragonitic anthodite, gypsum oulopholite) if appropriate..



Plate 5. Capillary channels along gypsum flowers ( $N+$ , 60x).



# The pinnacle karst of Gunung Api, Mulu, Sarawak

Tony WALTHAM

Civil Engineering Department, Nottingham Trent University, Nottingham, NG1 4BU.

**Abstract:** Pinnacle karst is recognised as a very large variety of karren, and is distinguished from pinnacles, which are isolated erosional remnants. The Pinnacles on Gunung Api, in the Mulu karst, form sharp blades of rock up to 50m high, projecting through the rain forest canopy. They are the largest of the pinnacles that are formed on nearly all the steep limestone mountain slopes.

## THE DEFINITION OF PINNACLE KARSTS

The weathering and erosion of limestones produces spectacular small landforms by preferential incision on fracture weaknesses and dissolutional etching of the remaining rock. Within a spectrum of micro-landforms, pinnacle karst has the greatest local relief and is therefore the most spectacular.

Pinnacle karst is a landform of the wet tropics and sub-tropics; these areas are distinguished by high rates of limestone dissolution that have been active for long periods, uninterrupted by Pleistocene climatic variations. The size and pattern of pinnacles are dictated by bed thickness and tectonic fracture patterns, and their morphological details are a feature of dissolutional fretting. Karren of some style are developed on most limestone surfaces (Bögli, 1960), and the style at any one location is determined largely by the local climate and climatic history. Pinnacle karst is a large scale version of karren that is found in tropical karst (Fig 1). It lies at one end of a spectrum of karren forms, with the limestone pavement of glaciokarst at the opposite end. Pinnacles are an order of magnitude larger than spitzkarren, which are details related to fracture patterns in glaciated karsts.

Two types of pinnacle karst may be recognised. Normal pinnacle karst has formed on the steep slopes of high limestone mountains in the rain forests of Papua New Guinea (Jennings and Bik, 1962), Sarawak and the Phillipines. A distinctive sub-type of pinnacle karst is the shilin (which translates from the Chinese as *stone forest*). This has formed on single beds of strong, gently dipping limestone in the plateau lands of southern China, where its most famous locality is also known as Shilin, in Yunnan province (Waltham, 1984). The large numbers of pinnacles tend to be more closely packed in the shilin type. The tsingi karst of Madagascar (Rossi, 1974) is another variety of pinnacled landform, more closely related to the shilin of China than the main pinnacle karsts of the East Indies.

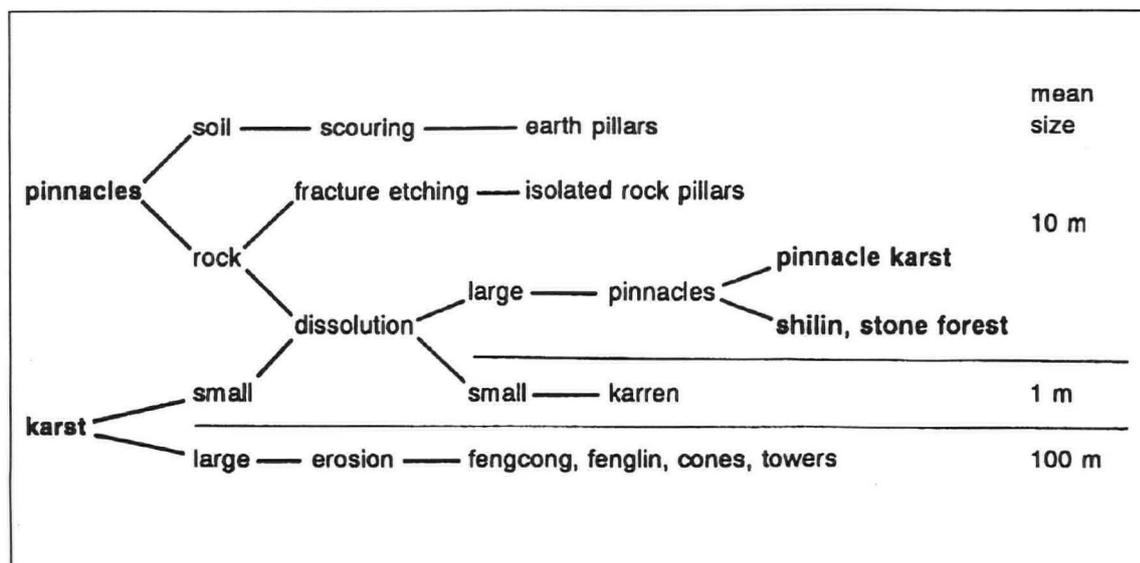
Pinnacle karst and shilin are clearly distinguished from the larger landforms of cone karst, tower karst, fengcong and fenglin (Fig 1). Sizes of individual pinnacles (in both pinnacle karst and shilin) are one or two orders of magnitude smaller than those of individual cones and towers. Plan dimensions of pinnacles are generally in the order of metres, and their heights are typically over 10m. Cones and towers are typically 50-200m high and wide; they are residual hills composed of masses of fractured limestones. Within pinnacle karst (and shilin), individual pinnacles are carved in single blocks of limestone. Landform height is partially a function of age and geological structure, but its definition within an order of magnitude does identify these karst types; most normal karren are another order of magnitude smaller than pinnacles (Fig 1). Pinnacles are micro-landforms on many cones and towers, but they do not evolve into them (Waltham et al, 1993).

Pinnacle karst is also distinguished from the non-karstic pinnacles or pillars that can occur in many rocks and soils (Fig 1). Earth pillars are remnants due to erosion by rainwash in soils and very soft rocks. Rock pinnacles may survive as erosional remnants isolated by selective weathering along fractures in any strong rock. They include the sandstone buttes in some deserts, many sea stacks, and also individual, isolated limestone pillars that survive in many karst regions.

## THE PINNACLE KARST ON THE MULU HILLS

The limestone mountains of Gunung Api and Gunung Benarat form a broken ridge, 30km long and less than 5km wide, across the Gunung Mulu National Park, within the rain forest interior of northern Sarawak, Malaysia. They rise steeply to altitudes of about 1700m, overlooking an alluviated plain at less than 100m. The Pinnacles lie on the northern ridge of Gunung Api at an altitude of about 1200m (Fig 2). The Melinau Limestone, which forms the whole range, is a strong, pure carbonate of

Figure 1. Relationships of pinnacles and similar landforms.



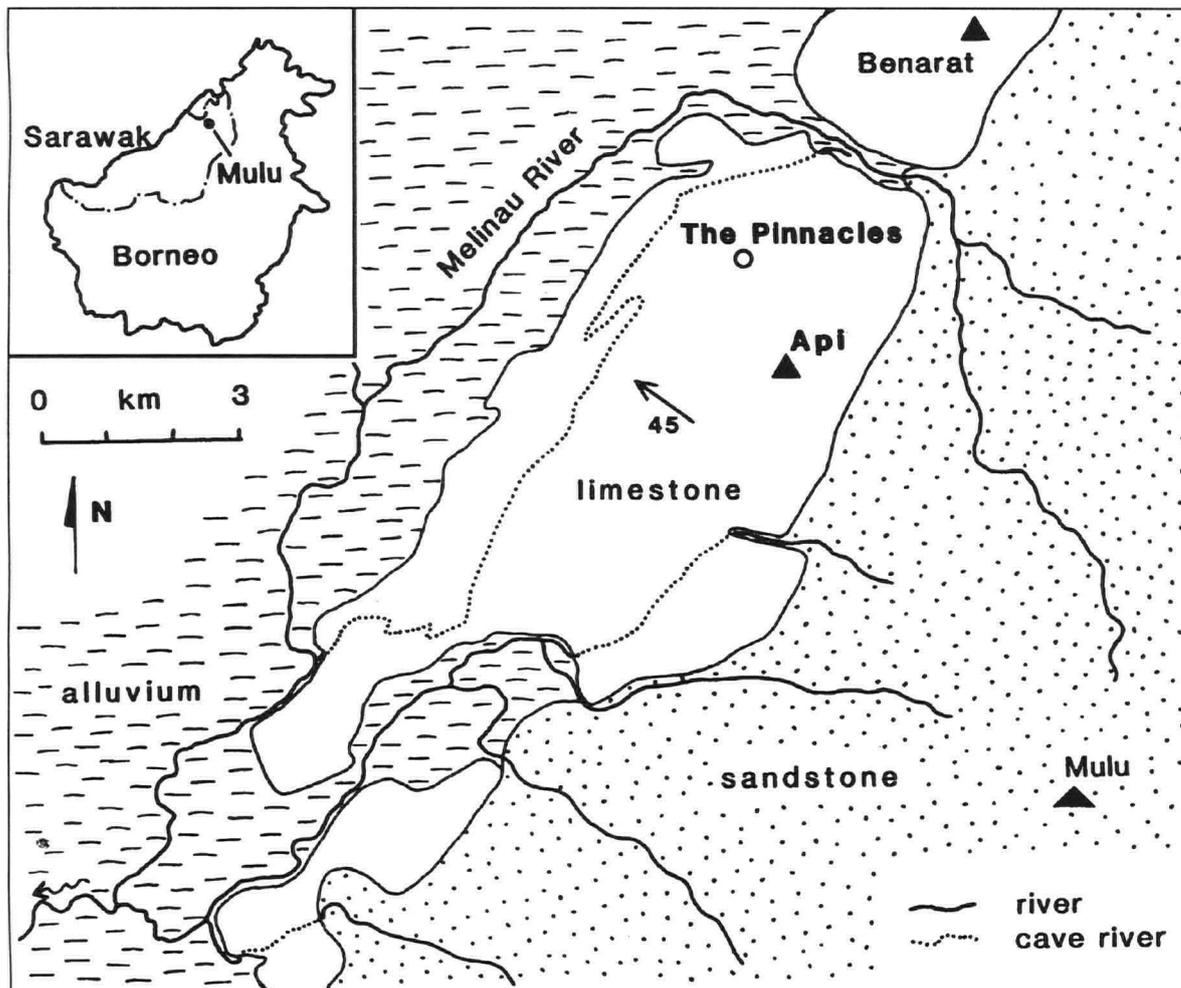


Figure 2. Location of The Pinnacles in the Mulu karst. The cave river locations are taken from various surveys by the British "Caves of Mulu" expeditions.

Mid Tertiary age, and is over 1500m thick. Its regional dip is 40-50° WNW, but individual beds are commonly greater than 50m thick and bedding planes are rarely seen in surface exposures.

Mulu lies in a zone of equatorial monsoonal climate, at a latitude of 4° N. Annual rainfall is around 5000mm, distributed evenly through the year on about 275 rainy days (Walsh, 1982). The mean annual temperature is 27°C at plain level; it is close to 23°C at the altitude of the Pinnacles, and about 21°C beneath the forest canopy at the same site. The entire area is covered by dense equatorial rain forest (Anderson and Chai, 1982). There are some vertical cliffs of bare limestone, but many slopes only 10° from the vertical retain a cladding of vegetation. The strong limestone forms high mountains rising steeply above adjacent outcrops of other rocks. Above the alluviated plains, there is almost no clastic detritus on the limestone; the only soils are formed of organic matter and limestone rubble.

The surfaces of Mulu's limestone mountains provide an incredibly inhospitable terrain of fretted rock within and beneath a tangle of vegetation. Tectonic fractures in the limestone have been etched out by vast quantities of rainfall, so that the remaining blocks are eroded and fluted into cones, blades and pinnacles. The intervening fissures are partly blocked by roots and fallen vegetation, but some continue to unplumbed depths. All rainfall sinks vertically, into the massive cave systems that lace the limestone. The exposed pinnacles of limestone, rising above any organic soil but still beneath the forest canopy, have razor sharp crests and edges, with their faces scored by large rinnenkarren and smaller rillenkarren. Those that lie beneath an organic soil cover, or are only recently exposed, have rounded tops and shoulders; they are either fluted by deep runnels in the style of rundkarren, or are irregularly pitted.

Pinnacles of different sizes cover almost all the limestone hills. Seen from the air, much of the ground appears to be an unbroken forest canopy, but this is a function of the scale and density of the tree cover. Large numbers of pinnacles, 1-5m high, are invisible from above. Many areas of forest have pinnacles 5-25m high, some of which can be seen from the air, especially in areas recently cleared by lightning-induced fires. Many of the largest and best developed pinnacles are formed on the slopes between the ridges and depressions (on a scale of 100-500m wide and deep) that create a disorganised relief on the steep limestone hills (Friederich, 1980). At just a few locations, the limestone pinnacles are greater than 25m high, and rise clear of the forest canopy to create truly dramatic profiles. The largest and most spectacular of these, standing on the northern ridge of Gunung Api, are known as The Pinnacles.

### THE PINNACLES OF GUNUNG API

The Pinnacles occupy an area of about 2 ha, where the blades of limestone reach heights of 30-50m. Within the main group there are less than a hundred of the very tall pinnacles, whose height causes them to rise 10-20m above the forest canopy. Bedding planes are very widely spaced in the massive limestone and, even though the limestone dips at about 40°, there are few opportunities for sliding failure. The overall dimensions of the pinnacles appear to be dictated by two sets of vertical joints, each with spacing of 10-20m and aligned at 90° to each other (Osmaston, 1980). They lie on the lower slopes close to the thalweg of a shallow valley in the western flank of the Api ridge, where there has been no surface drainage on the limestone for a long time. There are no other recognisable factors that account for these Pinnacles being so much larger than the pinnacles hidden beneath the forest canopy on all sides. No caves are yet known directly beneath The Pinnacles, but stream caves carry drainage at a depth of 1000m along the length of Gunung Api at a level close to that of the adjacent alluvial plain.

Plate 1. View across The Pinnacles.



The morphology of The Pinnacles is broadly comparable to that of the smaller pinnacles elsewhere on the Mulu limestones. They are mainly vertical blades of rock, apparently aligned between the fractures of the better defined joint-set. Their crests are razor sharp, and their walls are inclined at 70-85°. These are scored by karren grooves that appear to form three distinct size sets (Osmaston and Sweeting, 1982). Rillenkarrren are about 15mm wide and up to 500mm long; rinnenkarren grooves are either about 100 or 600mm wide and may be greater than 10m long. The upper parts of the pinnacles are white, and there appears to be little or no algal development on or in the limestone. Periods of sluicing by intense rainfall, alternating with total desiccation under a hot sun, may severely restrict biogenic development. The lower parts of the pinnacles descend into the forest undergrowth and patches of organic soils; their rounded forms include rundkarren and honeycomb pitting, and the limestone surfaces are commonly grey due to growth of algae and lichen. Progressive removal of the plant cover allows sharp rillenkarrren to develop on the exposed rock surfaces.

It is difficult to assess the age of The Pinnacles. Erosion and stripping of the cover rocks after Pliocene uplift and folding has produced the mountain ridge of massive limestone. The Tertiary Setap Shales have been completely stripped from the steep dip slopes of the limestone mountains. There is a clear possibility that these shales overlay a Tertiary fossil karst, which was exhumed to provide an initial stage of development of the modern pinnacles. This multi-stage evolution would match the geological history of the Chinese shilin, but field evidence from the forest-clad karst of Mulu does not resolve questions over this hypothesis.

Modern karst development at Mulu has a long history, and cave passages hundreds of metres beneath The Pinnacles were formed at least 3 million years ago (Farrant et al, 1995). The pinnacle karst is in a state of continual development, as the limestone surface is slowly lowered. Solute loads in the rapid runoff are low (Friederich, 1980), but total carbonate dissolution rates are high due to the very high rainfalls. Individual small landforms, including The Pinnacles, are sensibly viewed in relation to timescales of 10-100 ka.

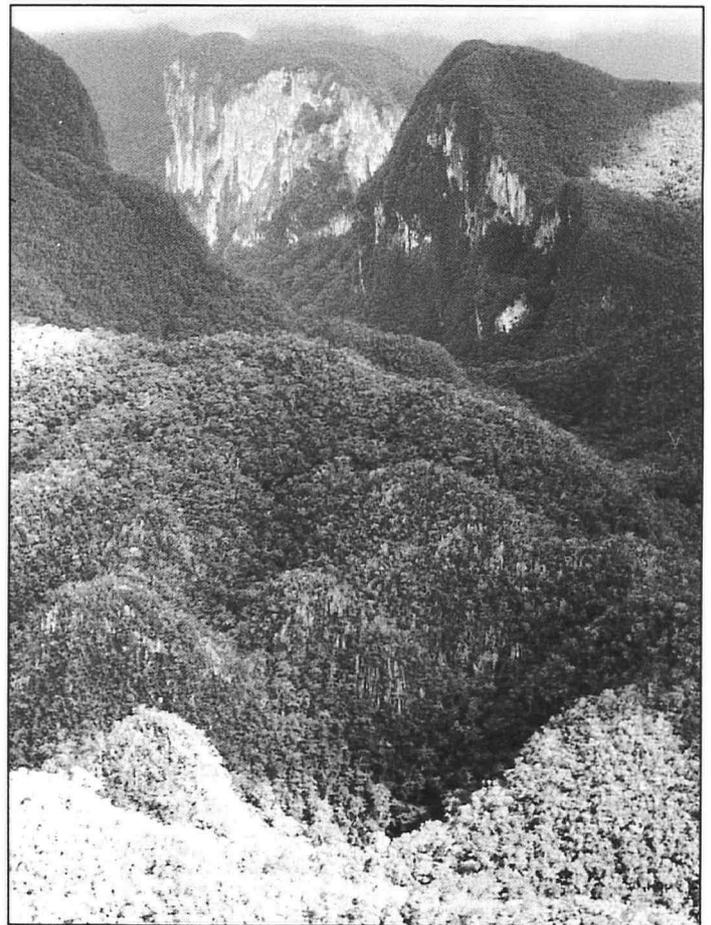


Plate 2. View across the limestone flanks of Gunung Api, with the cliffs of Hidden Valley in the distance; small pinnacles project through some of the tree cover on the flanks of steep sided dolines.

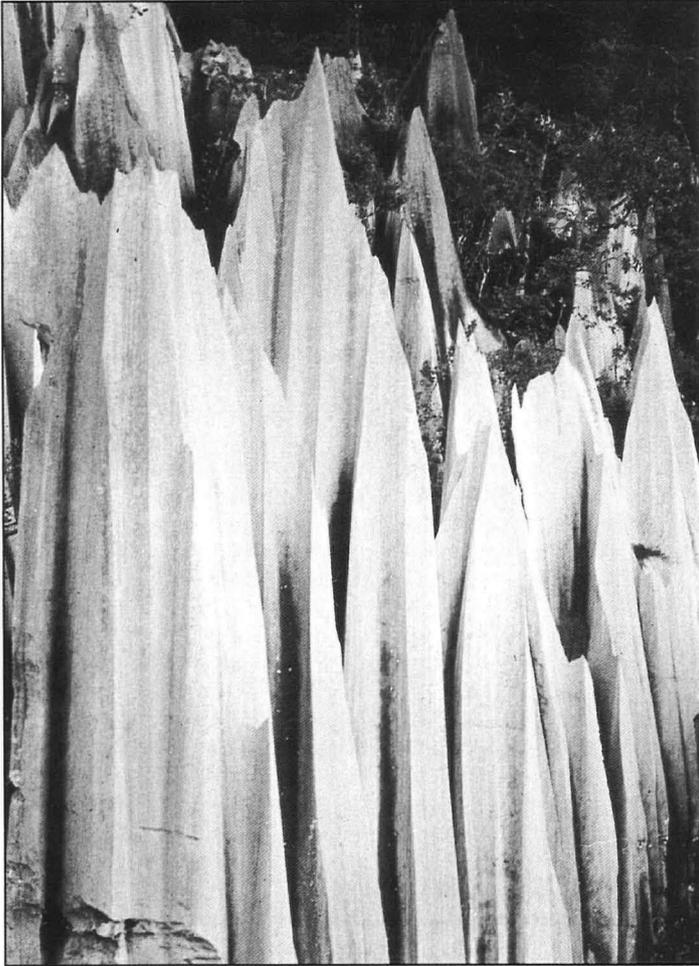


Plate 3. The crests of The Pinnacles are crenulated by large rinnenkarren that plunge almost vertically.

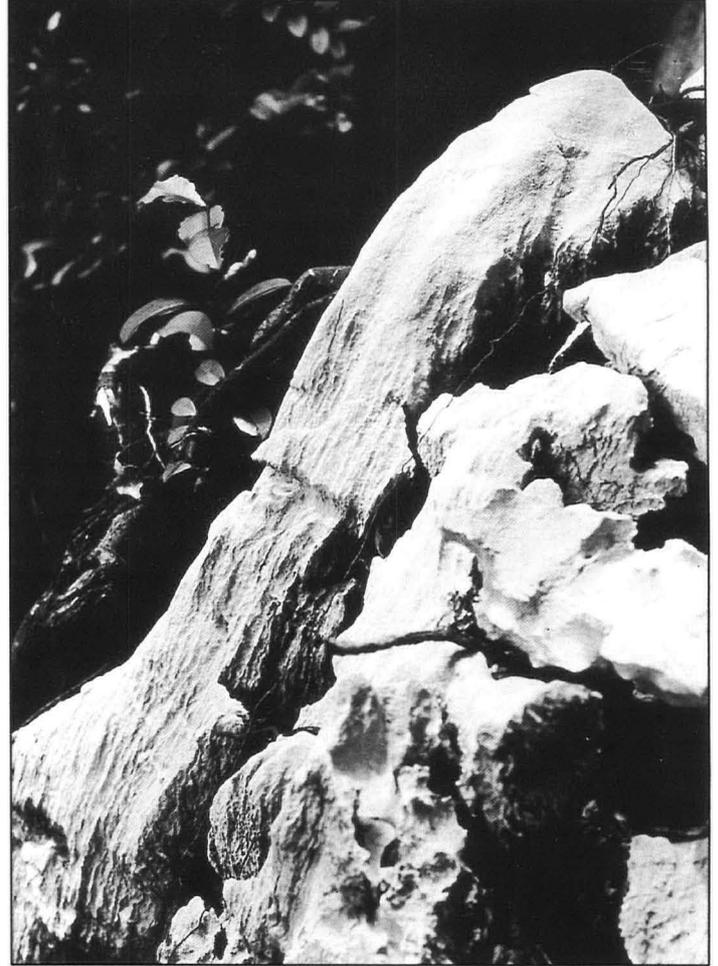


Plate 4. Limestone rib exposed on the slope below The Pinnacles; it has a rounded rundkarren form as it is only recently exposed from a thick organic soil, but immature rillenkarren have already formed on its bare surface.

#### ACKNOWLEDGEMENTS

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## Abstracts of papers presented at the B.C.R.A. Cave Science Symposium, Staffordshire University, February 1996

### HYPOGENIC KARST AND CLIMATIC CHANGES IN NORTH-EASTERN BRAZIL

Augusto S. Auler, Department of Geography, University of Bristol,  
Bristol, BS8 1SS.

A sulphuric acid karst occurs in the Precambrian carbonates of Una Group, north-eastern Brazil. The surface karst has relatively few solution landforms, collapse dolines being the most common feature. On the other hand, underground karst is highly developed, including the longest known cave in the Southern Hemisphere, the 65km long Toca da Boa Vista. Regional hydrochemistry shows high values of  $\text{SO}_4^{2-}$  (mean of 143 mg/l for 234 samples). The caves contain abundant gypsum deposits. A "shallow" sulphuric acid speleogenetic model is proposed, in which the dissolution of pyrite would produce acidity, as seen in present day vadose groundwater. There is no evidence for deep seated origin for the sulphuric acid. The climate at present is semi-arid and the karst is largely relict. Surface canyons, river channels and cave passages are either dry or contain small water volumes. Profuse speleothem deposits and fossil remains point towards formation under wetter palaeoclimates.

### CHEMICAL AND ISOTOPIC EVIDENCE FOR PROCESSES AFFECTING SHALLOW AND DEEP GROUNDWATERS IN THE DERBYSHIRE DOME

Simon Bottrell and Neil Webber, Dept. Earth Sciences, University of  
Leeds, Leeds LS2 9JT.

Analyses of anionic and cationic compositions, together with stable sulphur isotopic compositions of sulphate, have been made on rainwater, surface waters and groundwaters from the Derbyshire Dome. Sulphur is comprised dominantly of two stable isotopes,  $^{32}\text{S}$  and the heavier isotope  $^{34}\text{S}$ . Naturally-occurring variations in the ratio of these stable sulphur isotopes potentially provide a powerful discriminant between the sources of sulphate in natural waters. In this study they are applied as tracers of sulphate sources and weathering processes within the Castleton karst catchment and used to determine the sulphate sources of shallow and deep groundwaters elsewhere in the Derbyshire Dome. Analyses streams sinking along the western limestone contact of the Castleton karst shows varying degrees of influence of agricultural inputs vs. natural weathering reactions in different stream catchments. In one catchment bacterial sulphate reduction within the soilzone is identified as a significant process affecting sulphate. Sulphate concentrations are consistently higher at Main Rising in Speedwell Cavern, where these streams "resurge", than at the sinks. Analysis of sulphur isotopic mass balance shows that this extra sulphate is derived by oxidation of sulphide ore minerals in the phreatic conduits (which are believed to follow mineralized faults or "rakes"). Shallow groundwaters from other areas in the central Derbyshire Dome have sulphate sulphur isotopic compositions which are lighter than those from the Castleton karst. This is despite the allogenic inputs from shale weathering at Castleton which produce isotopically light sulphur. This difference could be due to land use, but this would appear to be similar across the region. Weathering of pyrite within the limestone aquifer would produce the same effect, and this would tend to support the "inception horizon" hypothesis that acidity produced by pyrite oxidation might play a role in limestone dissolution and early porosity/permeability development in karst. Groundwaters resurging from deep, long-residence time flowpaths in Derbyshire are distinguished by their thermal nature and high Sr concentration. Sulphate sources in these waters are varied. Buxton waters contain low sulphate concentrations and are probably pre-industrial recharge which has gained little sulphate

from geological sources (there is no evidence for sulphate reduction). The majority of Bakewell/Matlock thermal waters have elevated sulphate and chloride concentrations and their sulphate isotopic composition is identical to Lower Carboniferous evaporites. The isotopic composition of one thermal sough water at Stoney Middleton has gained elevated sulphate concentrations by extensive interaction with sulphide ore minerals.

### HUMAN REMAINS FROM NEOLITHIC CAVE BURIALS

Andrew Chamberlain, Department of Archaeology and Prehistory,  
University of Sheffield, Sheffield, S1 4ET.

The Neolithic period in Britain extends from approximately 4000 BC to 2500 BC. During this period people engaged in a variety of funerary rituals, including burial of the dead in above-ground chambered tombs and in long mounds, in so-called flat graves and in the ditches of causewayed enclosures. Another very important natural mortuary environment utilised in the Neolithic, but one which is often ignored by prehistoric archaeologists, is that of caves, fissures and rock shelters. From an archaeological perspective, cave deposits are notorious for their difficulty of access, their stratigraphical complexity and their liability to post-depositional disturbance, so it is perhaps unsurprising that archaeologists have tended to underestimate the prevalence of Neolithic cave burials. My interest in this topic was stimulated by my discovery in 1995 of Neolithic human skeletons in caves in the Devonian limestone at Yealmpton, South Devon. A comprehensive search of the published literature and of unpublished records held in local authority Sites and Monuments Records revealed evidence for more than 100 localities throughout Britain where probable Neolithic human remains have been found in caves. The purpose of the present paper is to document some of the radiocarbon dating evidence that allows the cave burials to be compared to the complementary rite of inhumation in above-ground monuments, and also to undertake a preliminary demographic analysis of the population of individuals interred in caves during Neolithic times.

### BANDED SODA STRAWS AND GEOCHEMICAL RECORDS OF CLIMATE

Ian J. Fairchild, Department of Earth Sciences, Keele University, Staffs  
ST5 5BG.

The use of speleothem (stalagmite and stalactite) geochemistry to record climatic change has been enhanced by the advent of modern precise mass spectrometric U-series age determinations. Stable isotopic compositions can potentially be interpreted in terms of temperature given that the ambient temperature of a cave approximates that of the ground outside. The cationic composition of speleothems reflects the cave water chemistry which in turn reflects that of the overlying soils, variably modified by passage through overlying rock strata. If the variability in water chemistry can be shown to be primarily a function of residence time of water in the soil, then speleothem geochemistry could serve as a proxy for climatic humidity. This idea is being investigated as part of an EC programme in which the geochemistry of late glacial to Holocene stalagmites from caves in western Ireland, Belgium, southern France and northern Italy is being studied. The chemistry of cave waters is being monitored throughout the year and will be compared with the results of experimental leachates and the chemistry of apparently annually-banded soda straw stalactites. Macroscopically banded soda straws have been found in three of the caves, and periodic chemical variations in soda straws from a fourth cave, suggesting that the soda straws record changes,

probably annual in water chemistry. In the most common type, the bands represent zig-zag growth steps on the inner margin of the straw. An example from Italy exhibits around 130 such bands, around 4 or 5 per mm, but the next 50 bands at least, are significantly more narrow. This change may reflect climatic warming at the end of the Little Ice Age in the Alps. Waters from Grotte Père-Noël, Belgium display high spatial variability in chemistry which presumably relates to lack of mixing of water parcels within the vertically-bedded strata. Nevertheless, individual soda straw stalactites can exhibit repeated Mg-Sr peaks which could reflect a signature of an annual climatic cycle. In contrast, Grotta d'Ernesto, Italy shows a much closer grouping of the chemistry of the chemistry of cave waters and recent precipitates in the cave. Leachates of weathered host rocks above the Grotta d'Ernesto indicate varying trace element compositions depending on water-rock contact time, with cave waters more resembling short-term (1 day) than long-term (1 month) leachates. Mg chemistry is consistent with greater leaching of the less reactive mineral dolomite when contact times are longer. Thus, by tempering general principles with a knowledge of the mineralogy and hydrology of individual sites, and the behaviour of the carbonate system, new palaeoclimatic inferences may be obtainable. A test of a crucial part of this system will be a comparison of the characteristics of soil leachates and cave waters; this investigation will be carried out by Anna Tooth (Keele researcher from 1996).

### **SOME THOUGHTS ON HYDROTHERMAL CAVES**

Trevor D Ford, 21 Elizabeth Drive, Oadby, Leicester LE2 4RD.

Hydrothermal caves are defined as those in which development has involved solution by waters considerably hotter than the ambient temperatures to be expected in a normal meteoric cave system. Some of the diagnostic features are noted, the geological relationships and the processes involved are outlined. An overview of selected hydrothermal cave systems emphasises the considerations which must be taken into account in recognising a hydrothermal phase in a cave system's history.

### **3-D VECTOR PROCESSING OF MAGNETOMETER AND INCLINOMETER DATA**

David Gibson, 12 Well House Drive, Leeds, LS8 4BX.

Cave surveying currently relies on visually reading a compass and clinometer. The price of magnetometers and solid-state inclinometers is falling rapidly. An electronic compass/clino with automatic data-logging is now feasible at an affordable price. However, the interpretation of the readings needs to be done with care. If the instruments are not gimbaled then small errors in "pitch" and "roll" can have noticeable effects on the accuracy. Surprisingly, perhaps, more than three axes of measurement are required to compensate for this, and other sources of error. Four axes are essential, and five or six are an advantage. The 3-D processing of this information is straight-forward to implement, but difficult to derive. This paper gives formulae for the processing of multi-axis information, and explains the derivation using 3x3 rotation matrices.

### **WATER TRACING EXPERIMENTS IN THE CUILCAGH KARST, CO. FERMANAGH, IRELAND**

John Gunn, Limestone Research Group, Department of Geographical and Environmental Sciences, The University of Huddersfield, Queensgate, Huddersfield, HD1 3DH.

The Cuilcagh karst is probably the finest example of a classical fluviokarst landscape in Ireland with large stream-sinks at the end of deep blind valleys, impressive collapse dolines, extensive cave systems and large resurgences. Until recently, the hydrogeology was thought to be relatively simple with streams having their headwaters on Namurian sandstones and shales, sinking soon after crossing on to the limestone and

flowing through conduits to large springs formed at the junction with underlying, less permeable, beds. However, recent water tracing experiments have shown the situation to be very much more complex as individual sinks may feed to several springs, in some cases 10-15 km apart. Cave passages may be very much older than previously thought and provide evidence of multiple occupation and flow-switching.

### **AUTOGENIC SEDIMENT TRANSMISSION TO CAVES: A REVISED MODEL FROM A DRIFT-COVERED KARST, CASTLETON, DERBYSHIRE**

Paul Hardwick, Limestone Research Group, Department of Geographical and Environmental Sciences, The University of Huddersfield, HD1 3DH.

The hydrological and geomorphological links between the surface of a drift-covered limestone hillslope and an underlying cave are examined. The importance of soil macropores as natural extensions of karst drainage systems into the soil zone is emphasised. The 'translatory flow' mechanism for autogenic sediment transmission, proposed by Bull (1981), is reviewed in the light of <sup>137</sup>Cs radionuclide-labelled sediment transmission rates to the cave of c. 0.5m a<sup>-1</sup>, and a revised model for sediment transmission is proposed. The use and limitations of <sup>137</sup>Cs analysis, and the use of caves as natural lysimeters is also reviewed.

### **THE EFFECTS OF DECOMPOSING ANIMALS ON CAVE INVERTEBRATE COMMUNITIES**

Chris Terrell-Nield, Dept. of Life Sciences, Nottingham Trent University.

The colonisation, deterioration and disarticulation of rat carcasses, exposed in two caves at Creswell Crags near Worksop, Nottinghamshire has been investigated over a five-year period, and the involvement of arthropods with the decomposing material has been examined. It is found that following consumption of carcass soft tissue by dipteran larvae, the subsequent fate of the remainder differs according to depth in the cave. Animals close to the entrance are likely to be mummified, those deposited farther into the cave are colonised by fungi, only being attacked by diptera later in the decomposition process. Disarticulation and skeletalisation then occurs, usually after 2-4 years if scavengers are excluded. For several years, this carrion provides a habitat for both cavernicolous and non-cavernicolous arthropods, the latter disrupting the cave community particularly in the threshold region. In the hypogean region the over-representation of certain troglomorphic species changes community structure. The persistence of this change is being examined.

### **USE OF A CONVENTIONAL SPREADSHEET TO SIMULATE CAVE HYDROLOGY**

John Wilcock, Department of Computing, Staffordshire University, P.O. Box 334, Stafford, ST18 0DG.

Simulation of the characteristics of a karst conduit system can provide insights into possible passage configurations based on input and output waveforms. This has been well known since the work of Ashton in the mid 1960s, the most common parameters of interest being flow, total hardness and pH, at sinks, in the cave and at resurgences. The possibility now exists of using personal computers in an interactive fashion to simulate streams and cave characteristics using standard software, such as the Excel spreadsheet package of Microsoft Office. Far from being a boring accounting aid, this package allows use of colour graphics, a wide range of charts, the representation of time series, formulae for evaluation at run time, logical decisions, buttons for the execution of complex macros written in Visual Basic, and facilities for importing hydrological data from other packages, such as word processors and databases. The paper will illustrate these run-time features on screen by manipulating a numerically-based stream and cave model.

## 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.

### THESIS ABSTRACTS

#### ANDER, L., 1994

*A hydrogeological assessment of the Lower Carboniferous Limestone Series, western Forest of Dean.*

*Unpublished M.Sc. dissertation, School of Environmental Sciences, University of East Anglia, Norwich NR4 7TJ, 105 pp. [Available from the University].*

A study of the physical hydrogeology of the Carboniferous Limestone in the Forest of Dean was undertaken. After a literature review and analysis a conceptual model of the hydrogeology of the Carboniferous Limestone was produced. This divided the Carboniferous Limestone Series into four hydrogeological units, bounded by aquitards of the Old Red Sandstone and Carboniferous Coal Measures. The conceptual model was then tested in a selected study area. Water balances enabled the catchment areas of springs to be semi-quantitatively evaluated. Groundwater tracing aimed to provide information on the extent and physical flow regime of the main limestone aquifer unit. This was undertaken using three fluorescent dyes. The qualitative tracing test results proved inconclusive, although they showed that the methods used were not suitable for the system under investigation. The quantitative tracer tests showed that groundwater velocities of c.1.5 km/day can be expected in the Slaughter catchment. In this experiment high dispersion and low recovery of the dye occurred. This has implications for the behaviour of organic pollutants entering the system (such as raw, undiluted sewage), which may be expected to behave in the same way as the organic molecules of the dye. This information is useful in showing the high vulnerability of the aquifer to groundwater pollution, from hazards which exist in the area.

#### CULLEN, R.W., 1995

*The colonisation and establishment of surface active invertebrate communities in restoration blasted limestone quarries.*

*Unpublished Ph.D thesis, Manchester Metropolitan University. [Available from the University].*

Restoration blasting is a new technique for limestone quarry reclamation which, through the creation of daleside landform sequences, attempts to produce ecosystems similar to those on natural dalesides. Vegetation establishment is encouraged by the application of a daleside seed mix in a phase of habitat reconstruction. However, invertebrates establish by natural processes. Since invertebrates are integral and essential to self-sustaining ecosystems, assessment of the success of reclamation techniques should not rely solely on examination of the vegetation communities. Here, assessments of the plant and selected surface-active invertebrate communities have been made by direct comparison of restoration blast piles with a natural daleside model and seven naturally recolonised disused limestone quarries.

At all sites, vegetation surveys were carried out and pitfall trap networks were established to sample the surface-active invertebrates. The characteristic species of plants and selected surface-active invertebrates were identified for each site and these have been discussed with reference to their potential colonisation mechanisms. The potential influence of rabbit grazing on the vegetation and invertebrates of the restoration blast piles has been assessed.

The vegetation communities which have established are more similar to the natural daleside model than are the surface-active invertebrate communities studied. Opportunity, linked to proximity of source populations, appears to be as important as dispersal mechanisms in the initial colonisation of restoration blast piles by some invertebrates. However, a wide geographical distribution and the ability to exploit a wide range of habitat types is generally important. Rabbit grazing has significant effects on the establishment of vegetation cover and this may subsequently affect the invertebrate communities. The results are discussed in terms of their implication for future reclamation and restoration strategies.

#### FARRANT, A.R., 1995

*Long-term Quaternary Chronologies from Cave Deposits*

*Unpublished PhD thesis, University of Bristol, Bristol, England. [Available from the University].*

This thesis examines the use of caves to obtain rates of landscape evolution over the 0-1 Ma timescale. Former landscapes are reconstructed by studying and relating cave geomorphology and sedimentology to surface features. Dating cave deposits using uranium series, electron spin resonance and magnetostratigraphic techniques provides better chronological resolution than that possible using surface deposits.

Three field study areas were selected. The first is the Gunung Mulu National Park, Sarawak, Malaysia. Detailed geomorphological mapping and palaeomagnetic dating was carried out. The base-level lowering rate is estimated and is shown to have remained constant over the last 700 ka by comparison with the number and spacing of wall notches formed during interglacial/stadial periods with the delta 18 Oxygen isotope record. It is argued that base-level lowering occurs in response to uplift of the resistant limestone by regional denudation and possibly flexural isostasy associated with sedimentation offshore. The extensive integrated cave system permitted a detailed palaeohydrological and sedimentological study of the cave system, demonstrating periods of increased sediment transport through the cave, in response to aggradation of an external alluvial fan.

At the second site, Eldon Hill Quarry, Derbyshire, quarrying has intersected a sediment infilled cave system. Valley incision rates are estimated and the caves are shown by detailed sedimentological and geomorphological mapping to have developed paragenetically. The results from this area are compared with similar data from elsewhere in Derbyshire.

The third field site is the Mendip Hills, Somerset. Base-level lowering and incision rates in Cheddar Gorge are constrained by dating the resurgence caves. The effect of base-level lowering through the conduit system is assessed by comparing the former water-table levels at the resurgence with those seen in the swallet caves in the Charterhouse area. It is argued that regional base-level lowering is controlled by retreat of the Mesozoic scarp eastwards. This scarp retreat is exhuming the limestone which is then subject to karstic erosion. A preliminary rate of this scarp retreat is estimated by dating former resurgence caves along the southern flank of the Mendips. In addition to quantifying landform evolution rates (base-level lowering, valley incision, uplift and scarp retreat) over the 0-1 Ma timescale, the role of sediment influx and base-level lowering on cave geomorphology is discussed.

**TYC, A., 1994**

*Anthropogenic Impact on Karst Processes in the Olkusz-Zawiercie Karst Area (Silesian-Cracow Upland, South Poland)*

*Unpublished PhD thesis, the University of A. Mickiewicz, Poznań, Poland, 189 pp. plus appendices and photos [Available from the Library of the University of A. Mickiewicz in Poznań and Library of "Kras i speleologia" of the University of Silesia in Sosnowiec, Poland]*

This thesis outlines results of an investigation of environmental and anthropogenic impacts on processes within carbonate aquifers. Investigations were conducted at regional and detailed scales of two most important aquifers of the Silesian-Cracow Upland, South of Poland. Conditions and trends of changes in morphogenetic environments of karst under extremely anthropogenic impact of the Silesian Region are explained. Different methods to determine human impact on karst processes and to distinguish natural processes from anthropogenic once in carbonate environments are proposed.

Two factors of the anthropogenic impact: (1) large scale lowering of water level due to lead-zinc ore mining and water intakes (150 m deep hydraulic depression with discharge 380 m<sup>3</sup>/min.) and (2) influence of different anthropogenic activity on the physical and chemical properties of karst water, received particular attention. A general model of impact of these factors to the karst processes is proposed. The model is tested by a detailed study of processes within the area of hydraulic depression and catchments of eight springs, influenced by different intensity of population and land use.

Human activity should be taken as a predominant factor controlling border conditions of investigated aquifers of the Silesian-Cracow Upland. It means that recharge and drainage conditions are under control of anthropogenic impact and are extremely modified. Recharge transformation comprises quantity and quality changes of sinking and infiltrating water to the karst massif (amount and chemistry of precipitation, water chemistry changes within soil cover and epikarstic zone due to acid rain and fertilizers - dispersed source pollution, point source pollution from farms and surface hydrology etc.). Drainage modification consists mainly of substitution of natural runoff by the artificial one. "Anthropogenic runoff" in artificially drained aquifers of Silesian-Cracow Upland amounts to 18 l/s km<sup>2</sup> and is two times higher than that in natural conditions.

A chain of processes within karst aquifer under large scale water level lowering and water intake is distinguished: (1) changes in directions and gradients of water circulation, (2) evolution and new establishment of hydrogeological zones influencing sudden evolution of phreatic conduits to vadose channels, (3) development of underground suffosion within cave sediments, (4) development of subsidence, collapse and piping processes above ground (more than 100 forms of different size have been developed), (5) changes in chemical and mechanical denudation rates.

Model of karst spring chemograph in the international literature is reviewed. Traditional model from temperate karst areas in thawing recharge conditions of cold temperate climate is tested and modified. The idea of the "thawing effect" on karst water circulation and karst processes is proposed. "Thawing effect" is shown in water chemistry as a significant increase of calcium, sulphates and nitrates content, total hardness and conductivity of soil water, epikarst and spring water during maximum of thawing. This phenomena is accompanied by low content of bicarbonates. Calcium content and total hardness in water thawing discharge are more connected with sulphates and nitrates from pollution than with dissolution effects in system CaCO<sub>3</sub>-H<sub>2</sub>O-CO<sub>2</sub>. Examples from several thawing periods for springs of different regime are presented.

On basis of hydrological, hydrochemical and statistical methods the origin of ion composition of spring water is determined and natural components from anthropic are distinguished. Furthermore, ionic runoff, mass-flux and dissolution ratios for different hydrological conditions and stage of anthropogenic transformations in karst water chemistry were determined.

Connections between a present morphogenetic cycle due to human impact in karst and older stages of karst evolution were investigated, too. It manifests by a role of paleokarst features and well-developed epikarst in modification and stimulation of karst processes impacted by human. Subterranean paleodrainage established in pre-Quaternary karstification in South Poland is exhumed and develops because of deep hydraulic depression within the exploited aquifer. It is one of a main factor inducing development collapse processes and piping in zone of the depression.

Complexity of the anthropogenic impact within carbonate aquifers with predominant autogenic recharge of the Silesian-Cracow Upland is a model for karst plateaux impacted by the industry and agriculture activity in the Central-Eastern Europe.

**WEBBER, N., 1995**

*An investigation into the source of sulphate in groundwaters of the Derbyshire Dome.*

*Unpublished M.Sc. dissertation, University of Leeds, England, 29pp + appendices. [Available from the University].*

A variety of ground and surface waters in the Derbyshire Dome were sampled and analysed for basic chemistry (major cations and anions) and sulphate-sulphur isotopic compositions. Rainwater was also sampled and analysed as a basis for comparison. The major aims were to identify the sources of sulphate to the groundwaters and to distinguish any differences between processes affecting the shallow waters and deeper thermal waters.

The surface and shallow groundwaters generally show increased sulphate concentrations compared to rainfall and isotopic compositions of sulphate sulphur vary up to 5 per mille both above (<sup>34</sup>S enriched) and below (<sup>34</sup>S depleted) relative to the rainwater sulphate value. The <sup>34</sup>S enriched source is from agricultural inputs (slurries and/or fertilizers), while <sup>34</sup>S depleted sulphate is derived from weathering of sulphide minerals. These are either pyrite in the limestone (or in shales in the case of allogenic streams) or ore minerals in the mineralised rakes. At one site, the stream feeding P8, sulphate appears to have been affected by bacterial sulphate reduction in the soil zone, as both samples collected have low concentrations of sulphate (lower than rainwater) and are very <sup>34</sup>S enriched.

The thermal waters show much more variation in sulphate concentration and isotopic composition and all have elevated Sr/Ca and Cl compared to shallow groundwaters, indicative of long residence times and consequent increased water-rock interaction. They fall into three distinct groups:

Matlock/Bakewell thermals: high sulphate (90-140mgL<sup>-1</sup>) and strongly <sup>34</sup>S enriched (+14 to +15 per mille CDT) these waters have almost certainly interacted with evaporite minerals in the lowest parts of the Carboniferous sequence which have closely similar sulphur isotopic composition.

Buxton thermals: very low sulphate concentration (less than present day rainwater) and sulphur isotopic composition of +5.5 per mille CDT. The lack of strong <sup>34</sup>S enrichment in this water suggests that bacterial sulphate reduction is not responsible for the low sulphate concentration. The observed composition could reflect a pre-industrial, unpolluted rainfall source of sulphate.

Stoke Sough, Stoney Middleton: this water was formerly grouped with other thermals. Isotopic mass balance shows that the <sup>34</sup>S depleted sulphate in this water (188mgL<sup>-1</sup>) results from a mixture of that present in shallow groundwater dominated by a large component derived from oxidation of ore minerals. This is consistent with the geological setting of this resurgence, rising on a mined mineralised rake.

# RESEARCH FUNDS AND GRANTS

## THE JEFF JEFFERSON RESEARCH FUND

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

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

The award scheme will not support the salaries of the research worker(s) or assistants, attendance at conferences in Britain or abroad, nor the purchase of personal caving clothing, equipment or vehicles. The applicant(s) must be the principal investigator(s), and must be members of the BCRA in order to qualify. Grants may be made to individuals or small groups, who need not be employed in universities or research establishments. Information and applications for Research Awards should be made on a form available from Simon Bottrell, Dept. of Earth Sciences, University of Leeds.

## GHAR PARAU FOUNDATION EXPEDITION AWARDS

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

## NCA/ENGLISH SPORTS COUNCIL GRANT AID IN SUPPORT OF CAVING EXPEDITIONS ABROAD

Grants are given annually to all types of caving expeditions going overseas from the UK (including cave diving), for the purpose of furthering cave exploration, survey, photography and training. NCA delegates administration of the awards to the Ghar Parau Foundation, to prevent duplication of cost and effort, and to provide a desirable degree of independence from NCA. Application arrangements are as for Ghar Parau Foundation Expedition Awards, see above.

Expedition organisers living in Wales, Scotland or Northern Ireland, or from caving clubs based in those regions should contact their own regional Sports Council directly in the first instance. It is possible that the inauguration of the National Lottery may result in different arrangements for grant aid.

## 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.

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## BRITISH CAVE RESEARCH ASSOCIATION PUBLICATIONS

**CAVE & KARST SCIENCE** - published three times annually, a scientific journal comprising original research papers, reviews and discussion forum, on all aspects of speleological investigation, geology and geomorphology related to karst and caves, archaeology, biospeleology, exploration and expedition reports.

Editors: Dr. D.J. Lowe, c/o British Geological Survey, Keyworth, Notts NG12 5GG and Professor J. Gunn, Limestone Research Group, Dept. of Geographical and Environmental Sciences, University of Huddersfield, Huddersfield HD1 3DH.

**CAVES AND CAVING** - quarterly news magazine of current events in caving, with brief reports or latest explorations and expeditions, news of new techniques and equipment, Association personalia etc.

Editor: Hugh St Lawrence, 5 Mayfield Rd., Bentham, Lancaster, LA2 7LP.

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

No. 1 *Caves & Karst of the Yorkshire Dales*; by Tony Waltham and Martin Davies, 1987. Reprinted 1991.

No. 2 *An Introduction to Cave Surveying*; by Bryan Ellis, 1988. Reprinted 1993.

No. 3 *Caves & Karst of the Peak District*; by Trevor Ford and John Gunn, 1990. Reprinted with corrections 1992.

No. 4 *An Introduction to Cave Photography*; by Sheena Stoddard, 1994.

No. 5 *An Introduction to British Limestone Karst Environments*; edited by John Gunn, 1994.

No. 6 *A Dictionary of Karst and Caves*; compiled by Dave Lowe and Tony Waltham, 1995.

**SPELEOHISTORY SERIES** - an occasional series.

No. 1 *The Ease Gill System-Forty Years of Exploration*; by Jim Eyre, 1989.

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

Obtainable from BCRA Administrator:

B M Ellis, 20 Woodland Avenue, Westonzoyleland, Bridgwater, Somerset TA7 0LQ.

