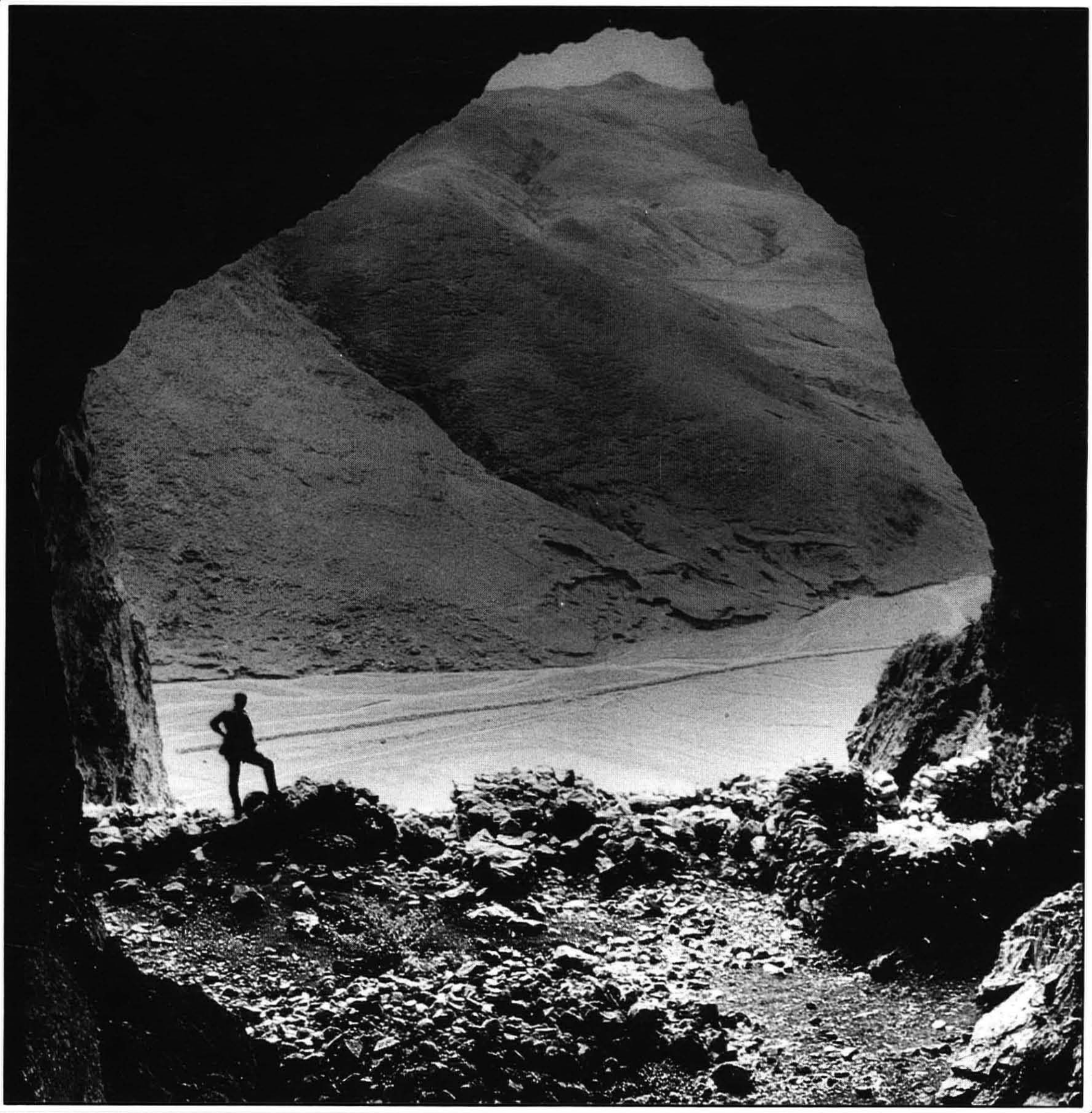
Cave Science

The Transactions of the British Cave Research Association

BCRA

Volume 19 Number 2 August 1992



Caves in Belize

Corrosion caverns in Hungary

Water chemistry at Drach, Majorca

Caves in chalk

Forum

Cave Science

The Transactions of the British Cave Research Association covers all aspects of speleological science, including geology, geomorphology, hydrology, chemistry, physics, archaeology and biology in their application to caves. It also publishes articles on technical matters such as exploration, equipment, diving, surveying, photography and documentation, as well as expedition reports and historical or biographical studies. Papers may be read at meetings held in various parts of Britain, but they may be submitted for publication without being read. Manuscripts should be sent to the Editor, Dr. T. D. Ford, at 21 Elizabeth Drive, Oadby, Leicester LE2 4RD. Intending authors are welcome to contact either the Editor or the Production Editor who will be pleased to advise in any cases of doubt concerning the preparation of manuscripts.

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All material should be presented in a format as close as possible to that of *Cave Science* since 1985. Text should be typed double-spaced on one side of the paper only. Subheadings within an article should follow the system used in *Cave Science;* a system of primary, secondary, and if necessary, tertiary subheadings should be clearly indicated.

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

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

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

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

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

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

Cave Science

TRANSACTIONS OF THE BRITISH CAVE RESEARCH ASSOCIATION

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Cover: Dick Willis stands in the entrance of Chagong Chimu, in the Longpoganlei Mountains of Tibet. Frost action has enlarged this entrance, and the cave closes down after only 50 metres. This was one of the caves found on the 1992 Tibet reconnaissance, the latest phase of the China Caves Project; a paper on the karst and caves of Tibet will appear in a future issue of Cave Science. Photo: Tony Waltham.

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Below Belize 91

Nick WILLIAMS

Abstract: A combined team of British civilian and military cavers visited southern Belize in March and April of 1991 to look for caves around the western end of Little Quartz Ridge. The amount of cave passage discovered was disappointingly small since the many sinks in the area are shallow and show signs of regular flooding. Many are blocked with mud and debris. Even in the three places where sizeable streams leave the impermeable rock of the Ridge itself, the sinks proved to be largely inaccessible.

Belize is a country of about 23,000km^2 situated on the Yucatan Peninsula in Central America, bordered by Mexico to the North, Guatemala to the west and south and the Caribbean Sea to the east (BGIS, 1989). The Little Quartz Ridge is situated in the Toledo district of southern Belize, about 50km to the north-west of the coastal town of Punta Gorda. The objective of the "Below Belize 1991" expedition was to explore the sinks of five major rivers which run off the Ridge and disappear into the surrounding limestone.

Miller (1990) gives a general account of previous work which has been done in Belizean caves. Work specific to the Toledo district of southern Belize has principally been confined to caves in the karst around the village of Blue Creek (Miller, 1980), to the Rio Grande (Dougherty, 1985) and to the Bladen Branch (Miller, 1989). In late 1990, a team of naturalists led by Sharon Matola of the Belize Zoo mounted an expedition to explore the Colombia River Forest Reserve, within which the Little Quartz Ridge is located. The zoo expedition was chiefly concerned with examining the fauna and flora of the reserve, but it also recorded a number of minor caves in a band of karst some 10km to the south of the western end of the Ridge (Matola, 1991).

Topography

The Little Quartz Ridge is a discrete entity quite separate from the larger mass of the Maya range which lies to its north. On the map the concentric contour lines which depict the Ridge give the impression that it is a striking and easily recognised feature rising out of the short range relief of the cockpit karst which surrounds it. In fact the ridge rises about 350m above its immediate surroundings to just over 1000m above mean sea level, and nowhere does it rise high enough, sharply enough to form a hillside or cliff visible for any great distance. This situation is exacerbated by the heavy vegetation surrounding the Ridge which can be fifty or more metres in height. A number of very steep sections of trail are encountered when traversing the Ridge.

From the air the line of the Ridge is clearer, particularly looking from the north at its steeper side. However, the forest cover makes accurate location of particular features very difficult, and even from a helicopter it was by no means easy to see the line of the rivers which run off the Ridge, or the magnitude of sink-holes where these rivers meet the limestone.

Geology

The geology of the area is complex and incompletely understood. Bateson and Hall (1977) did not include the Quartz Ridge within the area that they examined during their work on the Maya Mountains but they presumed the Ridge itself to be porphyritic lava, probably basing this assumption to work of the 1959 soil survey (Wright *et al*, 1959). Matola (1991) states that the dip slope of the Ridge is believed to consist of Palaeozoic metamorphosed sediments including shales, altered sandstones and conglomerates.

The caves, of course, form only in the limestone which surrounds the non-sedimentary rocks of the Ridge itself. The limestone beds are of three different types: the Coban formations date from the Cretaceous period, and are thus the oldest to be found in the vicinity of the Ridge. These underlie the younger Campur beds which were deposited during the Jurassic period. Finally, some shallow formations were laid down in the Tertiary period, and these are known as the Lacandon beds. The closest Lancandon beds to the Ridge are in the area around the village of San José, about 15km south of the Ridge, and are of interest only because they essentially define the limit of agriculture and hence habitation and practical vehicular access.

The Campur beds are the surface rock in much of the area and are very rugged in appearance: limestome pavement on a grand scale with countless solution depressions and ridges. Primary subterranean drainage is believed to be in the Coban beds, but these are usually deep underground and there is very little surface water throughout the limestone areas.

The Below Belize 91 expedition did not include a geologist amongst its personnel and thus no attempt was made to make geological observations or interpretations. Dougherty (1986) examined the karst in the vicinity of the Rio Grande which drains the north-eastern end of the Ridge, and concluded that the reasons for the large cave development in southern Belize essentially relate to rainfall conditions (climate, rain shadow, concentration of run-off on impermeable rocks etc.). One might reasonably expect these observations to apply equally to the south-western end of the Ridge, but the results of this expedition indicate that the situation must be more complex.

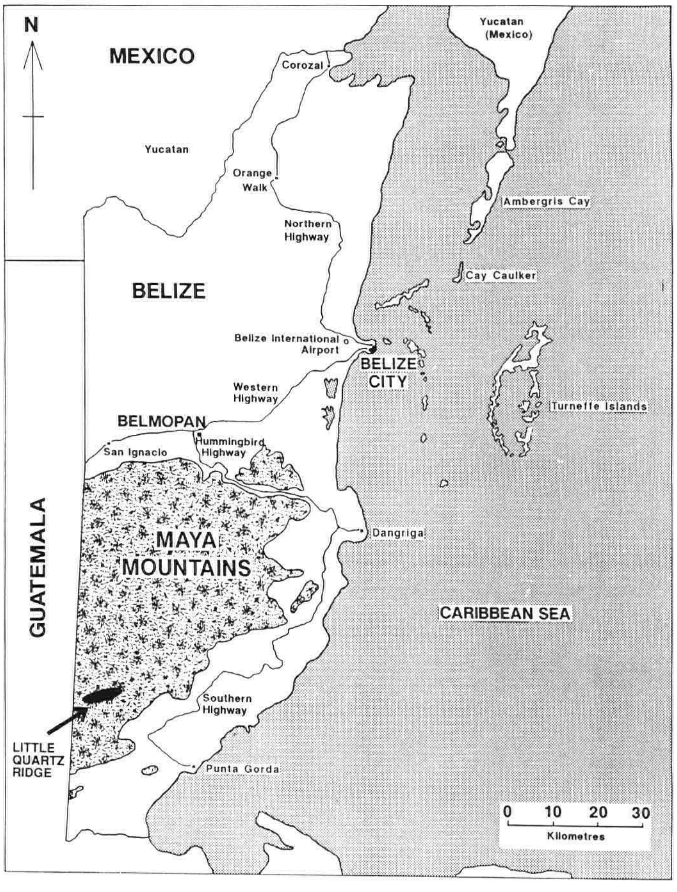
Biology

There are no human dwellings in the vicinity of the Ridge. Human presence is limited to hunters and Army patrols.

Matola (1991) gives a clear and comprehensive guide to the flora and fauna of the Little Quartz Ridge, but the following non-taxonomic description should give the reader a reasonable impression of what the bush is like to visit.

Despite the efforts of a number of conservation organisations to persuade people to the contrary, Belize is not covered either wholly or partly in true tropical rainforest, and its sub-tropical climate precludes it from ever being so. The climate to the south of the Maya Mountains is considerably wetter than that to the north (mean annual rainfall for southern Belize is about 4.5 metres), and the vegetation is correspondingly even more lush.

Figure 1.



The cockpit karst which surrounds the impermeable core of the Quartz Ridge prevents the development of any kind of consistent high level canopy, and on the sides of the steep limestone valleys there is always sufficient light to support both tall trees and secondary undergrowth.

The resulting vegetation is very difficult to move through, since not only does the traveller have to negotiate many short steep hills, but these are also covered in dense layer of bush consisting of lianas, assorted palm species and several varieties of "bastard tree". (Qualification as a bastard tree simply requires a thick layer of razor sharp thorns and a location anywhere a hand hold is required.) Larger trees, mostly varieties of cedar, cotton-wood, sapodilla, rosewood or mahogany are also dotted about, although many more of these have been removed during times past by logging companies. Paths are frequently obstructed by fallen trees which have to be climbed over, under or around. We were informed that many of these date from Hurricane Hattie (1961) but there have also been high winds in this area more recently, notably Hurricane Greta in 1978.

The progression of vegetation as one climbs onto the central spine of the Ridge is without doubt governed by the availability of water. Although the ground is covered by a layer of humus in places over a metre thick, the steep inclines are not conducive to holding the water, resulting in rapid run-off. Within hours of heavy rain the surface is dry. The gullies where run-off concentrates develop quickly into small valleys shaded by the canopy. These valleys provide an ideal environment for a multitude of ferns, mosses and fleshy palms.

There are more hardwood trees to be found on the flat areas around the southern end of the Ridge, probably due to the impracticality of logging. Nearer the summit there is a marked reduction in their presence, and we think it is likely that this is probably due to the increased exposure to the wind as there are large numbers of fallen trees. An additional factor is probably the soil, which is not very solid or stable.

Along the top of the Ridge we found broad leafed palms, many of which were heavy with over-ripe fruit which would seem to indicate a lack of foraging fauna during the dry season. Even the birds, common enough on the lower slopes, seemed uninterested in the higher ground.

The Little Quartz Ridge lies within the boundaries of the Colombia Forest Reserve, and the wildlife in the general area is abundant. Indicative of this, we were informed that the sighting of Great Curassow is only possible in areas of forest which are 'healthy' and unspoiled: three sightings of these spectacular birds were made by members of the expedition. Howler Monkeys made their presence felt by keeping several expedition members awake at night, and at the second camp there was strong evidence that they visited the camp and were directly overhead during the night.

Ants were a considerable problem at Union Camp, but this is a fairly commonly used camp, and they were obviously attracted to the location for this reason. We also saw a number of large spiders at this camp, but no scorpions. The river contained crabs up to about eight cm. across the carapace. Team one saw a coral snake "no bigger than a worm", but team two had several encounters with larger snakes including several pit vipers (*Bothrops atrox, B. Mummifer,* known locally as Tommigoff).

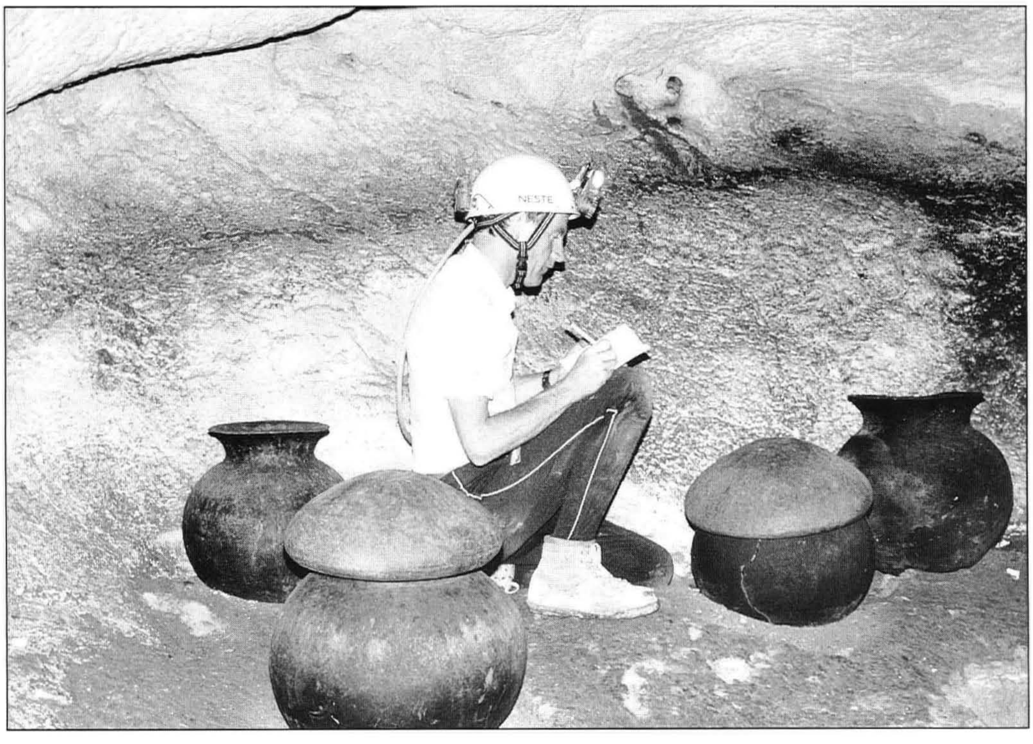
Logistics of the Expedition

The expedition consisted of both military and civilian cavers. Two civilian cavers arrived in Belize on 17 February 1991, and were followed by a further four civilians on 2 March. A few days later they were joined by six military cavers from the UK and Holland. The second team, of four further civilian cavers, arrived on 15 March. The first group of civilian and military cavers was extracted from the bush on 21 March, and returned to the U.K. shortly afterwards, while the second civilian team returned to the U.K. on 14 April.

Operations were dictated by a number of factors and responsibilities. Before any caving could be undertaken it was necessary to apply to the Department of Archaeology in Belmopan for a caving permit. All caves in Belize are considered to be sites of archaeological importance, and thus a permit is required before any exploration or even tourist caving can be undertaken in the country. While this was being arranged, the team underwent a period of acclimatisation in the well-known caves of the Caves Branch area — St. Herman's, Mountain Cow, Petroglyph and the Caves Branch River Cave.

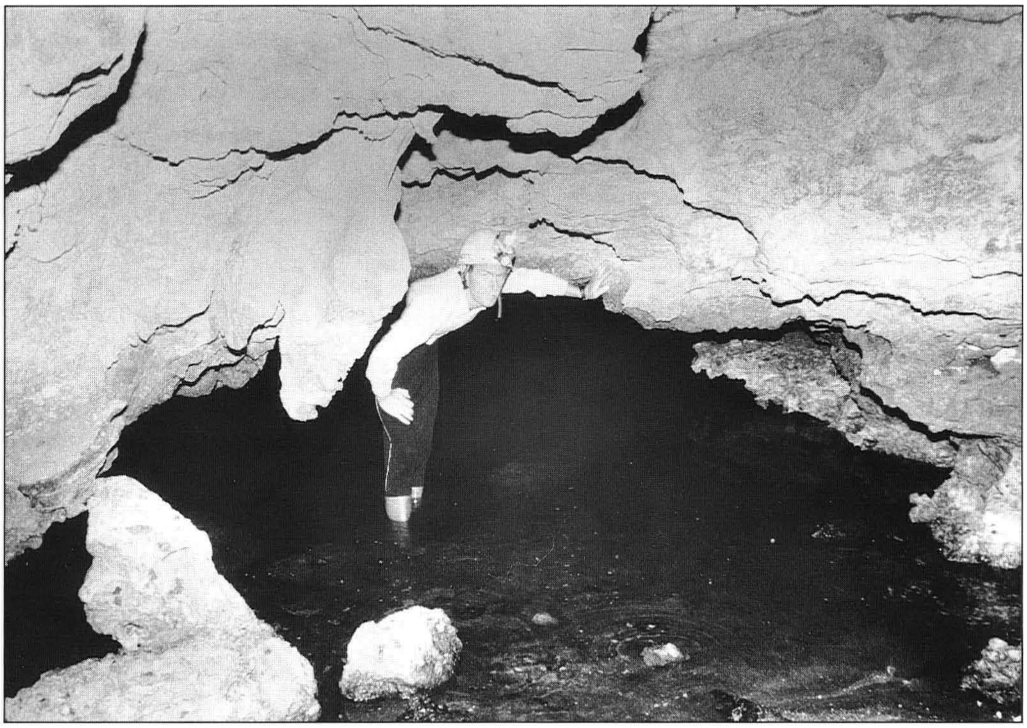
Access to the Ridge is difficult. About 60 years ago logging companies bulldozed a trail past the south-western end of the Ridge and on up into the Maya Mountains to extract mahogany and other hardwood logs from the forest. This track is now heavily overgrown and impassable except on foot; even four wheel drive vehicles can get no further than the village of San Jose, about 15km from the south-western end of the ridge. We hired guides from San Jose to show us the way to the ridge and point out water and camp sites along the route, and were also lucky enough to have the support of the RAF who airlifted items of personnel and equipment (Frew, in press).

Water is scarce throughout the whole of the limestone area surrounding the Ridge. All drainage in this area is subterranean except for one or two isolated streams such as that which flows past Union Camp. This river rises about three kilometres north of the camp and sinks about a kilometre further south. Its flow did not change significantly throughout the expedition. The streams which drain the impermeable rock of the Ridge itself are larger and more reliable. Without the specialist knowledge provided by local guides, these are the only sources of water which can be relied on during the dry season, and it was on the banks of one of these streams that the second camp was established.



Ollas *in Vaca Cave. Whole vessels such as these are unusual, particularly with lids. These may have been storage jars.*

Bat Cave closed down to a sump in foul smelling black water.



VACA CAVE

Positioned 15km due south of San Ignacio, Vaca is situated on the Vaca Plateau at about 200 metres altitude. The area is important because of impressive archaeological finds in Vaca Cave, discovered in November 1989 by the local farmer, Antonio Moralis.

At the request of the Belize Department of Archaeology two expedition members, Dave Arveschoug and Ern Hardy, were asked to survey the cave and in particular record the location of archaeological artifacts.

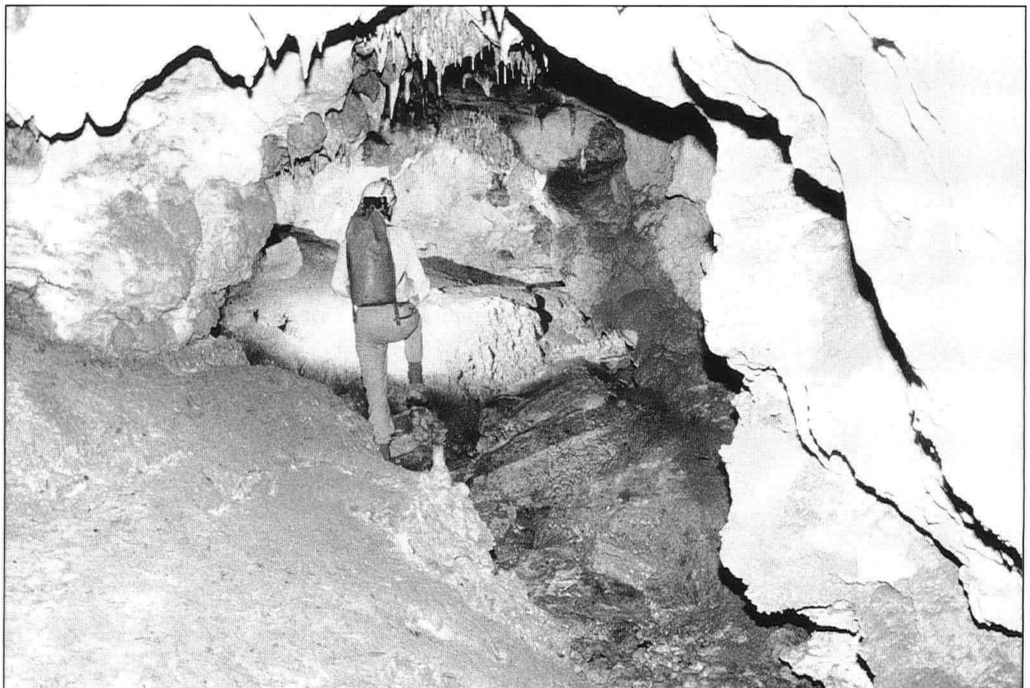
To reach Señor Moralis' farm (Cha Chen Hah) there are a number or possible routes. Fortunately Mick Fleming, the owner of Chaa Creek, an ecotourist hotel who is in contact with Cha Chen Hah by radio, arranged to take Dave and Ern part of the way by Landrover, where they were then met by Antonio Moralis with a mule. The route travels south along the Eastern Branch of the Belize river before climbing up to a 100 metre limestone scarp to the farm.

Antonio Moralis, although basically a subsistence farmer, is trying to attract the ecotourist too. Chaa Creek regards the area as a 'wilderness' area and sends visitors to stay in Antonio's simple mud huts. Both Antonio and his wife Leia were delightful hosts, Antonio in particular was very helpful in bringing about a better understanding of Belize and its peoples.

Vaca Cave is situated about 2km from the farm and at an altitude of about 360 metres. The entrance, discovered by Antonion Moralis in November 1989, has been fitted with a gate paid for by Mick Fleming. The cave is dry and consists of a main passage, on average 3m wide and 7m high, ending in a dry mud choke. A 2m climb about half way in eventually drops down into a large chamber, again with dry mud chokes, these being lower than the choke in the main passage.. Additionally, there are some short interconnecting roof passages. Cave air temperature was 25°C at 14.00 hours local time.

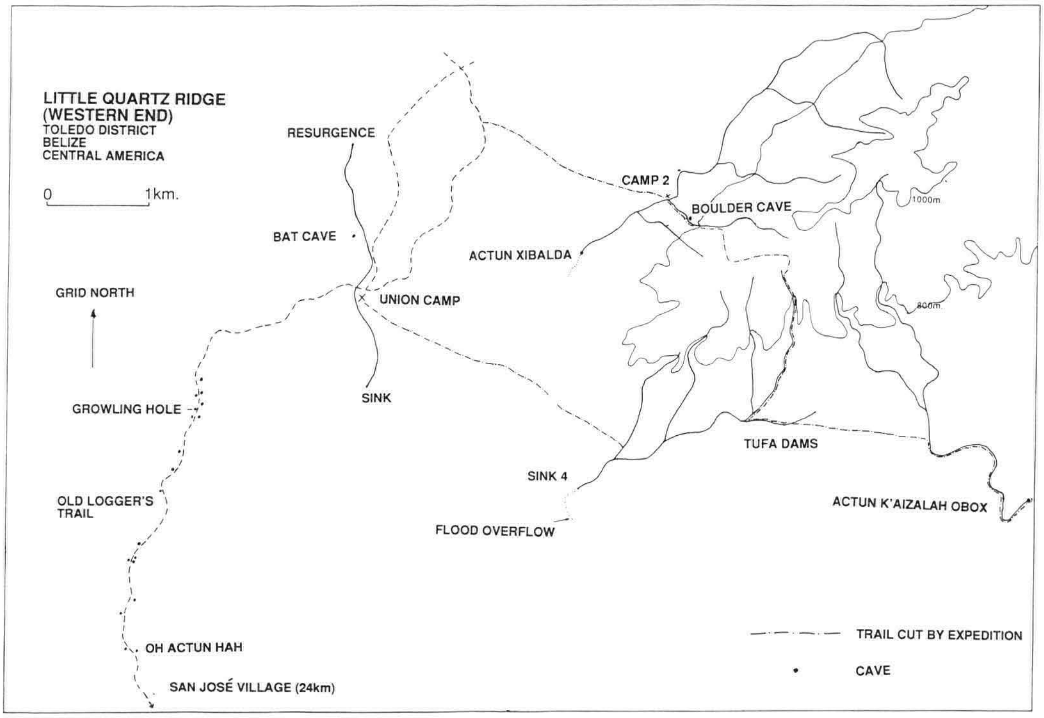
Of particular interest were the Mayan artifacts, pots and bowls, both whole and broken, and the constructed ledges the pots were often placed on. In total 64 whole artifacts were located. Some were difficult to find as they were hidden in roof alcoves and sometimes walled in. In addition to the pots, nests belonging to the Gibnut (a cat-sized rodent) were found.

There are many other caves in this area which we did not have time to explore. Some are described by Señor Moralis as being very wet.



This passageway in Growling Hole was typical of the caves found alongside the trail to Union Camp.

Figure 2.



LITTLE QUARTZ RIDGE CAVES

The river at Union Camp

This river rises in a deep pool at the base of a low cliff about 3km north of Union Camp, flows in a roughly southerly direction for about 4km and then sinks in an ill-defined area of muddy dolines and cave fragments. Sediment downstream of the rising consists of quartz gravels, indicating a fairly extensive phreatic system. The river is not marked on the 1:50,000 map and although the sediment indicates that the river rises somewhere in the igneous core of the Mountains, it is difficult to be more specific about the exact location of its source.

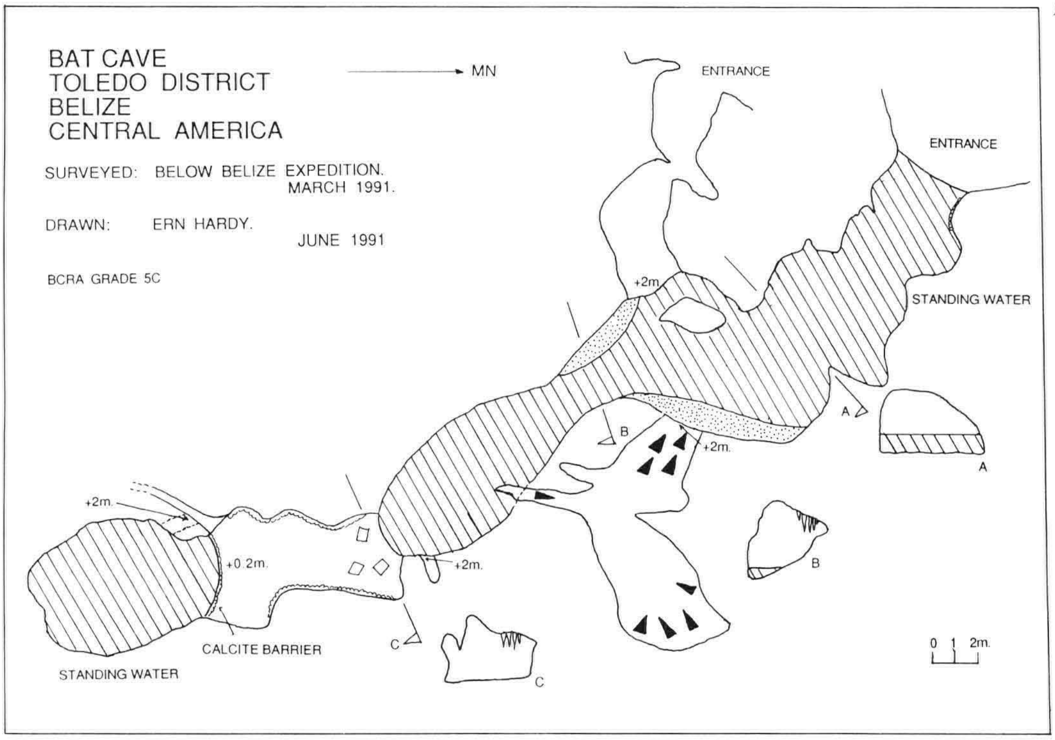
A couple of small entrances in the cliff above the rising were investigated. Crawling sized phreatic tubes led back to a shelf overlooking the sump pool, and no dry way on was found. An investigation was made around the back of the cliff from which the river rises, and although the land level drops to what was estimated to be only a few metres above the level of the resurgence, there was no sign of any access to the underground river. The area consisted of a basin which appeared to flood to form a shallow lake during the wet season.

Downstream of the resurgence, the river runs along a boulder-strewn stream bed, passing numerous limestone bluffs with shallow undercuts at water level. A number of cave entrances in these cliffs were investigated, but none was long enough to even need a light.

Bat Cave

Situated about 1km upstream of Union Camp, Bat Cave proved to be one of the most unpleasant caves found. The main entrance is about thirty metres from the river, and is a low arch with black standing water beyond. Once inside, the passage enlarges to about 2m high with a very strong smell of bat guano. After 20 metres two high level passages are met, the left one developing into a roomy chamber, whilst the right passage goes to an exit round the corner from the main entrance. Beyond the two side passages, a further spell of wading in foul smelling black water reaches a low calcite ledge, the passage beyond is damp underfoot with piles of guano and rotting food from the roosting bats. A few metres further on a decomposing calcite barrier 0.2m high holds back water in the final length of passage. At the end what appears to

Figure 3.



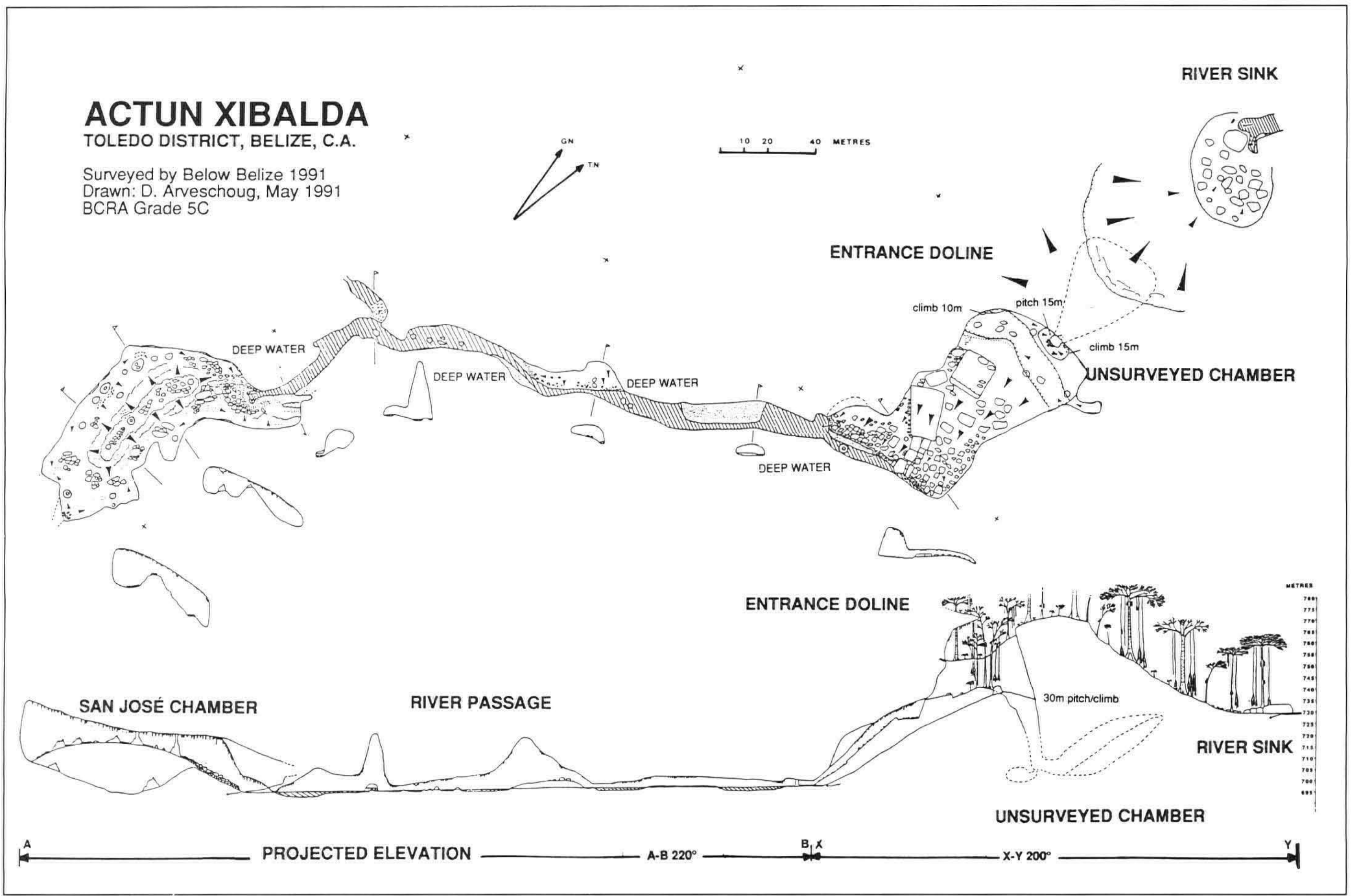


Figure 4.

be a sump prevents further progress — closer contact with the water was judged to be unwise. Figure 3 shows a survey of the cave.

The trail south-west of Union Camp

The area of limestone to the south of Union Camp, along the line of the old loggers trail, was examined and a good many small sinks were looked at. We closely examined an area around the track consisting of a band about 50m either side and about 2km long. In that distance we found twenty sinks of one description or another, none of which was more than 15m deep or 50m long before it became impassable. It is probably safe to assume that this is true of most if not all sinks in the wider area covered by the karst — some $100km^2$. While it is possible that there are entrances which will allow access to the underground drainage, the indications are that there are many thousands of sinks which will have to be investigated if such access routes are ever to be discovered.

It was obvious that in the wet season water backs up in these sinks for a considerable period. Large deposits of mud indicate a slow percolation of the water into the underground drainage, as do the razor sharp phreatic features found on the walls of the sinks. In only one case did we find flowing water underground, and even then the total flow was less than 1 litre/min.

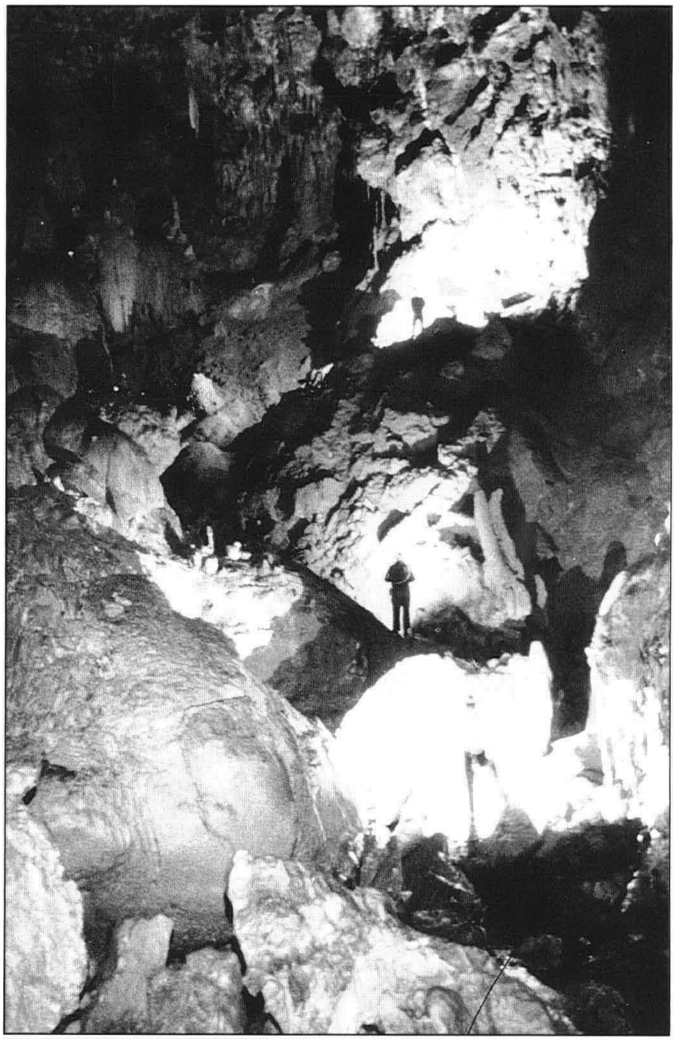
A great many blind dolines were also looked at, but it became apparent that the surface could be considered to be simply an outsize area of limestone pavement, covered in jungle litter and low (10-15m) vegetation. The water sinks where it hits the ground, and although there must be a large system of underground drainage there is little opportunity for surface water to form large enough streams to create negotiable access into the master system. The situation is exacerbated by the way in which the rain tends to fall in discrete spells, leaving dry periods in between for the water to soak away. The fact that the water is either there in large volumes or not at all means that there is no continuous flow to keep the sinks clear of sediment and as a result they block up.

Sink 5 — Actu Xibalda

This cave was the only major find of the expedition. It is 665 metres long, 31 metres deep and the entrance is at an altitude of 730 metres. The stream which feeds it drains an area of $4km^2$

Access to the cave from Union camp is by nearly two hours of

San José Chamber in Actun Xibalda was the largest discovery on the expedition.



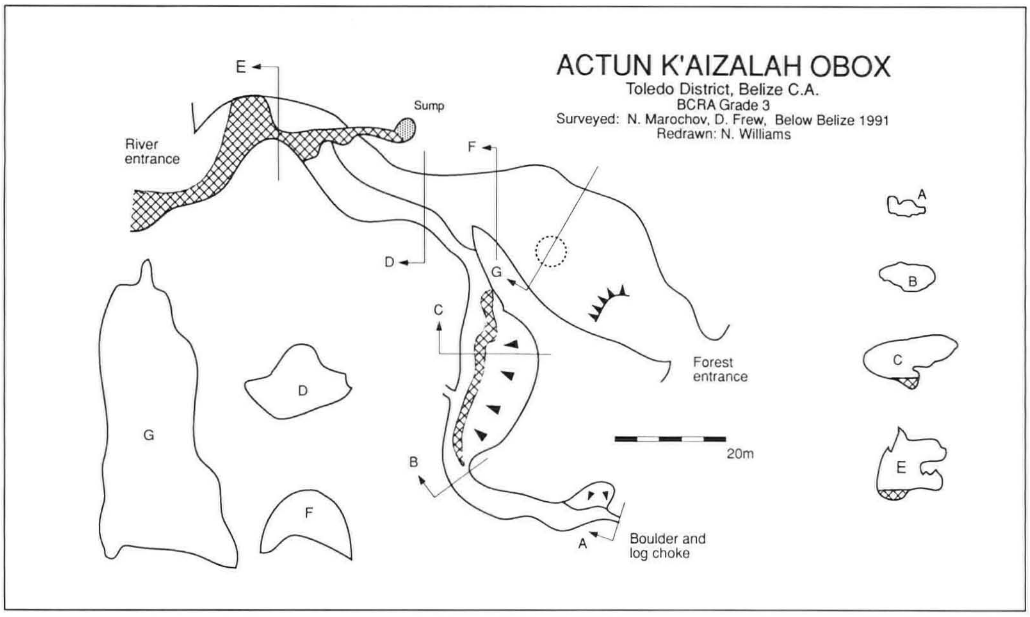


Figure 5.

walking, including forty minutes of wading. Unfortunately, when the sink is reached the river disappears between large boulders with no way in. The first team to visit the sink returned disappointed, but another assault a day later investigated more closely. Straight over a steep 40m hill above the sink we immediately found what we had been looking for: a slit in the jungle floor about 50m long and nearly 20m wide leading down about 30m to the top of a large mound of collapsed debris covered with jungle.

A climb of about 10 metres down the lower side of the slit lands on the debris and the daylight chamber opens out with a large slope following the dip southwards. Upstream there is a slippery climb down mud walls to a large dry chamber with a sloping boulder floor. No way on (to the stream sink) can be found here.

At the bottom of the boulder slope on the downstream side the water issues through the boulders to form a lake, a passage continuing off downstream on the far side in deep water. This is the first of three swims in a fairly large river passage averaging 8m in width and 6m in height, but up to 25m high in places. The river is slow and placid but sometimes deep, and feels cold after prolonged immersion. The passage is well decorated but in places looked to become completely filled in the rainy season. After 270m trending south-westward it led to a gravel beach in a large chamber.

The chamber we eventually named after the village of the two guides — San José. The river sinks into boulders straight away and the floor rears up as a massive heap of blocks, boulders, sand and mud, with some huge stalagmite formations. Every surface is covered in a layer of black, light absorbing mud which makes the whole place very disorientating.

Examination of the survey data revealed a kidney shaped chamber in plan, 130m long and 46m wide with a slope from one side to the other and a huge longitudinal mound of material along the middle. The circumference was 322m (Fig. 4). No way on was found, though the river could be heard again near the far end. The end of the cave seems to be fairly close to a doline area marked on the map and perhaps within only 100m and about 20m below the floor of it.

Upstream in Sink 5

About 1km upstream from the second team's basecamp, a limestone cliff appears on the left bank. Part of the stream flows through a rock arch approx 2m high and 2 or 3m long. Just around the corner the whole stream issues from an impressive entrance about 10m high. Disappointingly the passage closes down to the water after a swim of about 20m. Some small high level passages near the entrance were explored for 4 or 5m but proved to be blind alcoves.

Boulder Cave

Downstream of the second team's base camp, before the sink is reached, a small tributary joins from the south. A few hundred metres up this tributary the water emerges from under a limestone outcrop. The stream can be followed for a distance of 15m right through and out the other side. The water varies from waist to neck deep and the bottom is knee to thigh high deep in decomposing jungle litter. In two or three places the passage breaks out to the jungle above. The name of the cave comes from the small limestone outcrop, the size of which is no bigger than a large boulder.

Sink 4

The first team investigated sink four, to the south of Union Camp. This turned out to be a rather insignificant pool of stagnant water and mud. Later investigations by team two recognised a flood overflow channel which led for about 750m to an area of flat ground terminating in a 6m barrier of trees, thrown so hard against a cliff face that they had become a solid mass. The basin showed signs of being a massive collapse, cool draughts emanating from several scattered boulder ruckles. There was no obvious way into the underground drainage, and the rapid onset of a storm prevented closer investigation.

Sink 3 — Actun K'aizalah Obox

Sink three is the most remote of the sinks visited by the expedition. Even once the trail had been cleared, the journey from the second team's basecamp took five or six hours. The route involved a very long, steep ascent of the Little Quartz Ridge from the north side, up and over the 1000 metre contour, and then following the stream drainage for sink four in an equally steep descent. In three or four places there are waterfalls which have to be by-passed by cutting a trail around them on the steep and very slippery banks. After reaching level ground, a trail was cut due east for a couple of kilometres and eventually led into the drainage for sink three. Finally, following this river downstream past deeply undercut banks leads to the sink.

On entering the cave, the stream was found to disappear quickly into a low passage which sumps in a guano-filled pool after about 20m. The stream passage leads off a large fossil gallery which was followed for about 120m to an abrupt end in a pile of boulders and logs. Above this a high level chamber, some 15m wide and 30m long, leads out to the jungle again. A high level skylight in the chamber allowed an estimate of height of about 100m. A grade 3 survey only was performed.

CAVE ARCHAEOLOGY

It is virtually impossible to cave in Belize without coming face to face with archaeological artifacts ranging from calcited human skeletons and intact pot vessels to mounds of pottery shards. The physical environment of the cave soon becomes interwoven with the human aspects of indigenous Mayan peoples. For this reason all caves in the country are designated as sites of archaeological importance by the Belize Government, and it is necessary to get permission in writing from the Department of Archaeology in Belmopan before any caves can be entered or explored. Because of the risk of unscrupulous individuals looting artifacts from the caves, cave locations are not published in this report, but are availabled to *bona fide* cave explorers and archaeologists with appropriate authorisation from the Department of Archaeology by contacting the authors.

Archaeologists suggest that the Mayan civilisation began to develop between about 2000 and 1500 B.C. This civilisation evolved and became increasingly sophisticated, culminating in the Classic Mayan period from A.D. 300 to 900. At this point, the Mayan culture dominated Central America. Large and elaborate cities developed, many of the buildings exhibiting high standards of engineering and stone carving. Mathematics and astronomy were advanced and the Maya had introduced a quite intricate writing and calendar system. By A.D. 750 social and political changes began to appear, alliances broke down and the cities started to depopulate. Many reasons have been put forward for this breakdown in the Mayan civilisation; principally a revolt by peasants against the ruling elite, exhaustion of the fertility of the soil, and disease. The Spanish invasion in the 16th Century finally broke up the civilisation, but the Maya people still remain.

Caves had an important place in Mayan culture. They were an important source of fresh water (in some areas the only source) and they had a strong religious importance. The Mayan people had a very elaborate religion. Death was the first stage on a complex route to immortality, in which souls passed through the underworld "Xibalda" (literally "place of fright") on their way to hell. Caves' obvious association with the underworld led to them being sites of special religious significance, used for ceremonies, burials, sacrifices and the collection of 'holy' water (Roberts, 1990).

Many of the known caves, particularly those around the Caves Branch area of south Belmopan have been looted and their contents sold. Many of the settlements and religious centres such as Cahal Pech or Xunantunich were also plundered, often using techniques such as explosives to get at the artifacts which were then smuggled out of the country to museums and private collections. Unfortunately, despite Belizean laws aimed at preventing sale and export of antiquities, this still occurs when local people realise the black market value of the 'few pots in a nearby cave'!

Usually the pots, or *ollas*, found in caves were of a similar shape: a rounded foot, rounded body closing to a narrow neck and then opening out to form a lip. They varied in size, but typically were about 40cm in diameter at the widest part of the body and stood about 60cm high. One pot found was so large we could have boiled a small missionary in it! Often they have lids very similar in shape to a cultivated mushroom. Some bowls were also found measuring 20cm across the rim and about 12cm deep with outward sloping walls. Most of the pottery was lightly glazed and occasionally had patterns around the neck area. One pot depicted a human skeleton. Whilst some of the pots were found lying on the floor, most of the pottery was to be found placed in alcoves and passages at roof height. Sometimes they were almost walled in and at other times placed on what appeared to be small ceremonial ledges made up of limetsone blocks. Often the *ollas* has 'kill holes', small holes punched in them, usually around the based area to free the pot's spirit for the afterlife.

The small caves around Union Camp in the Little Quartz Ridge area yielded no archaeological material, probably due to wet season flooding, the proximity of the caves to an old loggers track and the use of the area by local hunters and *chicleros* (foresters who tapped the sapodilla trees to extract chicle, the gum base for chewing gum). However, caves discovered elsewhere contained well preserved artifacts. One active sink had pots in a small upper series of passages reached by a ledge. These finds were heavily calcited. Another site yielded one pot, with two kill holes in it near the base, lying inverted on a carefully constructed stone ledge. At another site two pots were discovered, still whole, which had obviously been washed further into the cave and were lying on their sides, partially buried behind a boulder just before the terminal choke. Elsewhere, four complete pots and half a larger pot were found lying on a mud slope. Of particular interest here was the wall constructed between two chambers in the cave.

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Evolution of Corrosion Caverns: Ördög-lik Cave, Bakony, Hungary

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Abstract: Dubljanszkij (1987) determined the differential equation describing the enlargement of hydrothermal kettles (spherical cavities). After determining the radius of the kettles, the absolute age of their evolution can be evaluated. Using the theory above, the evolutionary sequence of the components in a cavern system can be determined if the beginning of the evolution coincides with that of the kettles in the cave. By measuring the dimensions of the kettles of Ördög-lik cave their relative age can be determined. By knowing the cents of the kettles and their dimensions at different periods of the relative age of evolution we can plot the quality and quantity of dissolution at different periods in time. The history of dissolution of Ördög-lik can be depicted by comparing these maps.

The split-level Ördög-lik cave is located at the edge of Ördög-árok canyon in the Sürü-hegy mountains, NE of Zirc city in Bakony (Figure 1) which is part of the Dunántúli-középhegység (Transdanubian Mountain region). The history of research of the cave was summarised by Bertalan (1963) and its map was released by Kassai (1963). The geological characteristics of the enclosing rock, the morphological and genetical features of the cave may be summarised as follows.

Owing to uncertain knowledge of the enclosing rock (Veress 1981) samples have been collected mainly from the shaft connecting the two levels of the cave. It appears that the greater part of the lower level was formed in the Fenyöföi Formation (Triassic) but the rock surrounding the passages, is mainly a cemented fault breccia which indicates that the bulk of the passages have developed along faults.

The rock of the shaft also belongs to the Fenyöföi Formation and is interrupted by two dolomite layers. The cover of the Fenyöföi Formation is Dachstein limestone (Upper Triassic) in the uppermost part of the shaft. Its thickness is only 10-20 cm.

The upper level of the cave is mostly in Middle Eocene Nummulitic limestone of the Szöci Formation. It is possible that while the lower level developed downwards into the Triassic dolomite, the upper level advanced upwards into the Eocene limestone. To the south of points 16 and 17 the enclosing rock is exclusively Nummulitic limestone, with a significant amount of clay surrounding the entrance; to the north of the above points the Dachstein limestone appears in the sidewalls of the passages. Its surface is uneven, due to former erosional unconformity, but its position appears to be analogous with the covering Nummulitic limestone.

Fault breccia can be detected at two locations along the passage between points 10-12. In the western wall of the passage, starting from point 20, the Dachstein limestone appears at different heights.

The dip direction of the Eocene limestone is 180° to both the north and the south of the fault, but the dip angle is 26° to the north and 14° to the south of the fault. It is likely that the rock mass was separated into blocks along a NW-SE strike-slip fault. As the blocks tilted to the south they also sank to a lower position.

Consequently, dissolution at stratal contacts is in the direction of the dip in the blocks at the upper level; dissolution along the fault also occurred here. At the lower level, dissolution along the fault and the fissure may have been the more decisive factor.

"Kettles" are spheroidal or subspheroidal cavities in the cave walls. They are of varied dimensions and sometimes coalescent. As a result of their coalescence the upper level passages show nearly circular cross sections and those of the lower level are vertically elongated, so that coalescence may have occurred not only horizontally but also vertically. Vertical coalescence of two rows of kettles at the upper level and possibly three rows of kettles at the lower level may have taken place. The origin of such passages is easily recognised since there are ribs (sharp or rounded ridges) remaining between the adjacent kettles; thus the walls of the cave are arched when seen from above.

There are sections at the lower level where, due to the initial stage of coalescence, the partitions between the kettles are today sometimes fenestrated.

The kettles of the lower level are vertically more elongated than those of the upper level. On the lower level the partitions persist between the lower kettles.

Kettles appear primarily at rock and stratum boundaries. They are frequent at the Nummulitic/Dachstein limestone and the limestone/dolomite contacts within the Nummulitic limestone and the Fenyöföi Formation, respectively.

Vertical coalescence of kettles may form shafts in some places as in the case of the passage interconnecting the two levels.

Occasionally shapes differing from a sphere may occur. Kettles near the Eocene-Dachstein boundary and the fault zone are respectively horizontally and vertically elongated. It is also characteristic here that the kettles form series of 2, 3 or 4 elements above one another in the sidewall and especially in the roof of the cave becoming smaller toward the top. Cave-ins have more or less destroyed the coalesced kettles at the upper parts of the chambers of the upper level.

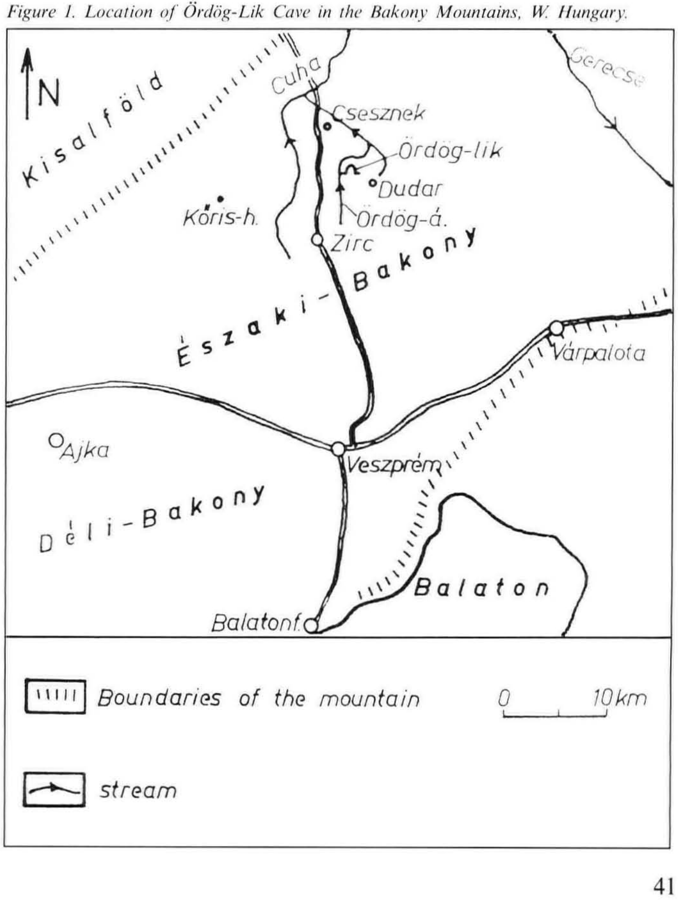
Where the kettles evolve along sloping surfaces, due to the coalescence of kettles developed in the succeeding strata remnants of the strata appear in the floor of the cave, forming steeper surfaces.

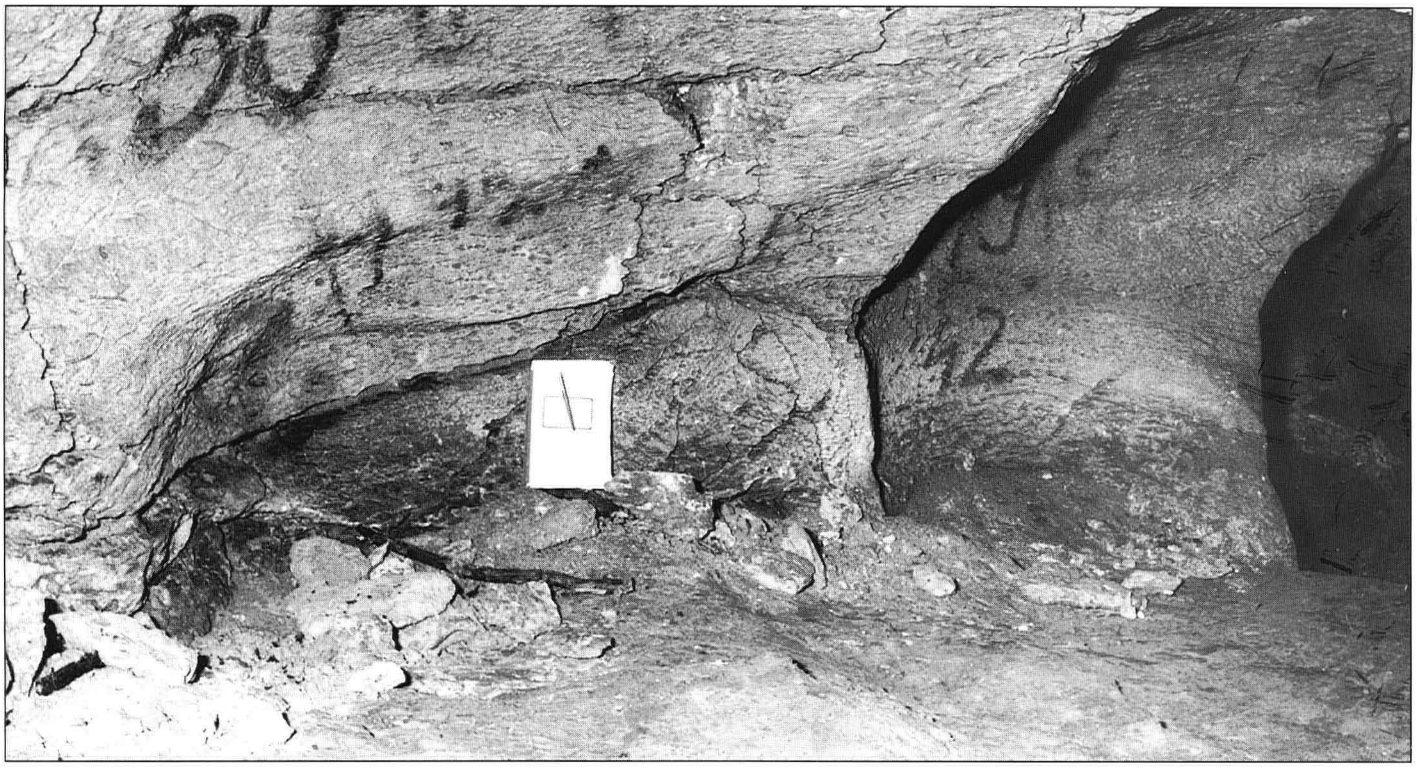
Although less common, formations developed by dissolution and not evolved from kettles, also occur. Such formations are the vertically or horizontally elongated passage sections, shafts, narrow channels in the roof and small depressions of 5 cm at most. The walls are covered so abundantly by the above that small aerial arches remain between them with breakdown particles inside. There are some parts of the vertically elongated passages, with walls coated with wavy and shell-shaped niches.

EVOLUTION OF COLD-WATER-GENERATED KETTLES

Laptyev (1939) pointed out that saturated karst waters, when mixing, are capable of further dissolution. Bögli (1963 a & b) proved that in carbonate rocks mixed-water corrosion (occurring below the karst water table) can form labyrinth-like passages

Figure 1. Location of Ördög-Lik Cave in the Bakony Mountains, W. Hungary.





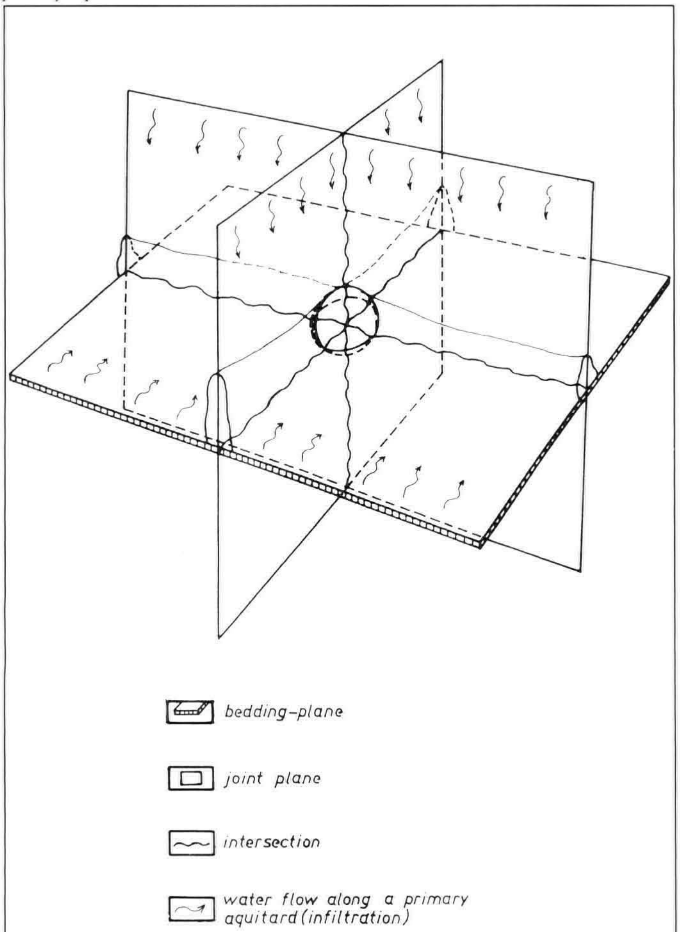
The remains of kettles No. 42, 49 and 73, and part of No. 50.

(network caves), corrosional pockets and dead-end shafts.

Since surface waters (precipitation) become saturated within a maximum of a few metres in or even on the surface of the limestone (Balázs 1969; Jakucs 1971, 1978, 1980), dissolutional formations in karst evolve by mixed-water corrosion (Balázs 1966).

As a consequence, dissolution-generated caves developed below the karst water table may be formed entirely by mixed-water corrosion. In some sections of such caves, where the features listed by Bögli (1963 a & b) are not characteristic or the structures are unrecognisable due to coalescence, other features may also appear by mixed-water corrosion.

Figure 2. Development of kettles at the inter-section of two vertical and a horizontal primary aquitards.



Due to the coalescence of features developed by mixed-water corrosion, bigger and bigger caverns emerge. Fusion is followed by the partial or total destruction of features evolved by mixed-water corrosion, since the partitions between the neighbouring features are partly or completely absorbed as a result of their growth.

Where features of mixed-water corrosion appear repeatedly in a cave, the mixing of waters of different hardness is not accidental, as certain mixing processes recur. Mixed-water corrosion is associated with definite solutional features.

Small numbers of mixed-water corrosion features indicate that few mixing types exist; conversely, certain features are abundant. These conditions exist if water flows occur on surfaces, arriving by various routes and of different hardness. On the other hand, these waters may mix at surface intersections.

Thus both number and location of inter-sections affect features developed during dissolution.

When two vertical or nearly vertical aquitards meet (fault planes), the intersection line will be also vertical. Along this line, where the infiltrating waters of the two aquitards are mixed, shafts evolve. At the upper part of the intersection the adjacent waters of the two fault planes mix. Downwaters in the shaft — because pressure increases, movement of infiltrating waters is not vertical — waters of the two fault planes, arriving from increasing distances, mix. This allows the mixing of waters differing in hardness resulting in an increased growth rate of the shafts downwards. The above process explains why solutional shafts often widen downwards.

The intersection line is horizontal when vertical and horizontal aquitards (fault plane and bedding-plane) are present. Passages of circular cross section are formed along such lines. Following the mixing, the resultant solvent activity is prevalent along the joint or the fault and water would most likely flow and mix along the other plane; circular features narrow in either bedding or fault planes. When the bedding-plane is not horizontal, in the case of dip-slip fault, the passages are dominantly fissure-like, while in association with a strike-slip fault the passages widen in the dip direction.

When water flows appear above each other (clearly not separated) along bedding planes several intersections may develop which, by vertical coalescence, form ravines, the walls of which are covered with shell-shaped depressions (for instance the passageway of the shaft leading to the lower level in Ördög-lik cave). This process is favourable in the case of a dip-slip fault.

Where at least three aquitards, two fault planes and a bedding-plane, meet, solution proceeds in every direction, thus spherical (kettles) are formed in the rock (Figure 2).

If streams along bedding-planes are clearly separated, kettles may develop at several levels above one another. The vertical orientation of the kettles, with a given karst water table, is determined by the depth where the moving and infiltrating waters are still capable of mixing.

Some passage sections in Ördög-lik cave are not of kettle-fusion origin, because among the triple intersections, double intersections also occurred along faults and bedding planes, so kettles did not develop.

Quantitative analysis of cold-water kettles

The results of boundary-layer theory and physical-chemical hydrodynamics may be used for the theoretical description of kettle evolution. The flowing karst water, which plays the central role in the cavity forming process, is supposed to be in thermal equilibrium with its environment and the flow is laminar. The solution process includes the following phases: chemical solution, diffusion of the dissolved material in the boundary zone and the transport of the dissolved material. The rates of the different phases can be described by the following values:

$k_K\left[\frac{m}{s}\right]$ rate of chemical solution,

$k_T\left[\frac{m}{s}\right]$ rate of material transport in the boundary zone,

$v\left[\frac{m}{s}\right]$ rate of karst water flow

In our experience, k_k and k_T are much more smaller than v flow rate, thus the maximum rate of the whole process is determined by one of the first two phases.

Chemical solution is described by

$$\left.\frac{dm}{dt}\right|_K = k_K \cdot S \cdot (C_e - C_s) \tag{1}$$

where $m[kg]$ is the amount of limestone dissolved from the surface (= walls) of the cavity,

$S[m^2]$ the surface area of the cavity,

$C_e\left[\frac{kg}{m^3}\right]$ the saturation concentration of the dissolved limestone,

$C_s\left[\frac{kg}{m^3}\right]$ concentration of the limestone, at the surface of the rock.

Diffusion in the boundary zone is described by the following equation:

$$\left.\frac{dm}{dt}\right|_T = k_T \cdot S \cdot (C_s - C_i) \tag{2}$$

where $C_i\left[\frac{kg}{m^3}\right]$ is the original $CaCO_3$ concentration of the incoming water.

As the process is stationary, thus

$$\left.\frac{dm}{dt}\right|_K = \left.\frac{dm}{dt}\right|_T, \tag{3}$$

from which, by using (1) and (2)

$$\frac{dm}{dt} = \frac{k_K \cdot k_T}{k_K + k_T} \cdot \rho \cdot (C_e - C_i) \tag{4}$$

follows. By using relation

$$\frac{dm}{dt} = \rho \cdot S \cdot \frac{dR}{dt}, \tag{5}$$

where $\rho = 2700\frac{kg}{m^3}$ is the density of the limestone, formula (4) can be as follows:

$$\frac{dR}{dt} = \frac{k_K \cdot k_T}{k_K + k_T} \cdot \frac{C_e - C_i}{\rho} \tag{6}$$

According to Levics (1959), Sarapov (1973), Dubljanszjij (1987) formula

$$k_T = \frac{85}{16} \cdot \frac{1}{R} \cdot \sqrt[3]{D^2 \cdot \nu} \tag{7}$$

is valid for the diffusion rate.

After the substitution of (7) into formula (6) and integration

$$t = \frac{\rho}{C_e - C_i} \cdot \left[\frac{R - R_0}{k_K} + \frac{8}{85} \cdot \frac{R^2 - R_0^2}{\sqrt[3]{D^2 \cdot \nu}}\right] \tag{8}$$

yields, where $D\left[\frac{m^2}{s}\right]$ is the diffusion constant,

$\nu\left[\frac{m^2}{s}\right]$ kinematic viscosity,

$R_0[m]$ the radius of the cavity when $t = 0$.

Formula (8) integrates the R radius of the developing kettle with its t age.

Let us now examine parameters of formula (8). The enlargement of the cold-water-kettles is due to the solvent power of the two saturated karst waters mixing in the centre of the kettle. According to Tillmans (1932), Balázs (1969) and Szunyogh (1991), equation

$$y = f(x) = a \cdot x + b \cdot e^{c \cdot T} \cdot x^3 \tag{9}$$

can be applied to the $x\left[\frac{kg}{m^3}\right] CaCO_3$ concentration and the $y\left[\frac{kg}{m^3}\right]$ total CO_2 concentration of the saturated solution, where $a = 0.4389$; $b = 4.607\times10^{-4}$; $c = 0.029\ \frac{1}{°K}$.

Let us assume, that in the centre of the examined kettle two saturated solutions mix, the parameters of which, according to equation (9): x_1, y_1, T_1 and x_2, y_2, T_2. If after mixing the solution can be characterised by x, y, T parameters and Δx denotes the $CaCo_3$ concentration increment due to the mixing, then, according to Ernst (1965) and Szunyogh (1991), the following equations hold:

$$\begin{aligned} x &= n_1 \cdot x_1 + n_2 \cdot x_2 + \Delta x \\ y &= n_1 \cdot y_1 + n_2 \cdot y_2 \\ T &= n_1 \cdot T_1 + n_2 \cdot T_2 \end{aligned} \tag{10}$$

when $n_1 : n_2$, is the mixing ratio of the solutions and $n_1 + n_2 = 1$. Thus, from formulae (10) by using (9)

$$\begin{aligned} \Delta x &= x - (n_1x_1 + n_2x_2) = f^{-1}(y, T) - (n_1x_1 + n_2x_2) = \\ &= f^{-1}(n_1y_1 + n_2y_2, n_1T_1 + n_2T_2) - (n_1x_1 + n_2x_2), \end{aligned} \tag{11}$$

that is

$$\Delta x = f^{-1}(n_1 \cdot f(x_1, T_1) + n_2 \cdot f(x_2, T_2), n_1T_1 + n_2T_2) - (n_1x_1 + n_2x_2) \tag{12}$$

follows. The explicit form of equation (12) was determined by Ernst (1965), and particularly by Szunyogh (1991):

$$\Delta x = \frac{\left(n_1x_1^3 \cdot e^{n_2 \cdot c \cdot (T_1 - T_2)} + n_2 \cdot x_2^3 \cdot e^{n_1 \cdot c \cdot (T_2 - T_1)}\right)^{1/3} - (n_1x_1 + n_2 \cdot x_2)}{1 + \frac{a}{3b} \cdot e^{-c(n_1 \cdot T_1 + n_2T_2)} \cdot \left(n_1x_1^3 \cdot e^{n_2 \cdot c \cdot (T_1 - T_2)} + n_2 \cdot x_2^3 \cdot e^{n_1 \cdot c \cdot (T_2 - T_1)}\right)^{-2/3}} \tag{13}$$

from which, in the case of $T_1=T_2=T$, that is the temperatures of the two solutions coincide,

$$\Delta x = \frac{(n_1 \cdot x_1^3 + n_2 \cdot x_2^3)^{1/3} - (n_1x_1 + n_2x_2)}{1 + \frac{a}{3b} \cdot e^{-cT} \cdot (n_1x_1^3 + n_2x_2^3)^{-2/3}} \tag{14}$$

the simpler form results.

In the case of mixing corrosion solution, the C_e-C_i concentration difference of formula (8) is just the Δx value determined in formulae (13) and (14), that is

$$C_e - C_i = \Delta x \tag{15}$$

For parameters k_k, D and v of formula (8), according to Sjöberg and Rickard (1984) and Dublyanszkij (1987), the Arrehenius equations

$$\begin{aligned} k_K &= A_K \cdot e^{\frac{-E_K}{R^1 \cdot T}}, \\ D &= A_D \cdot e^{\frac{-E_D}{R^1 \cdot T}}, \\ \nu &= A_\nu \cdot e^{\frac{E_\nu}{R^1 \cdot T}} \end{aligned} \tag{16}$$

are valid, where E_k, E_D, E_v, are the virtual empirical activation energies, and

$$A_K = 5.36 \cdot 10^5 \frac{m}{s},\ E_K = 5.41 \cdot 10^4 \frac{j}{mol},\ A_D = 2.37 \cdot 10^{-3} \frac{m^2}{s}.\ E_D = 3.72 \cdot 10^4 \frac{j}{mc}$$
$$A_\nu = 2.59 \cdot 10^{-9} \frac{m^2}{s},\ E_\nu = 1.46 \cdot 10^4 \frac{j}{mol},\ \text{and } R' = 8.314 \frac{j}{mol°K}.$$

Considering the above, calculations were made on the age of a kettle developed by mixing corrosion. If $\Delta x = C_e - C_i = 5.10^{-2} \frac{kg}{m^3}$ during the mixing, the the development of a kettle of $R = 1m$ radius takes 2.1×10^6 years at $T = 281°K$ temperature ($= 8°c$). The model allows the comparison of two kettles of a karstic cave in the case when the solutional conditions in the two kettles are approximately equal. That is, when t_1, R_1, Δx_1 and t_2, R_2, Δx_2 denote the age, the radius of the two kettles and the concentration increment occurring in the kettles during mixing corrosion, then, in the case of $\Delta x_1 \approx \Delta x_2$ formula (8) with close approximation (neglecting the linear term) has the form

$$t = \lambda \cdot R^2 \tag{17}$$

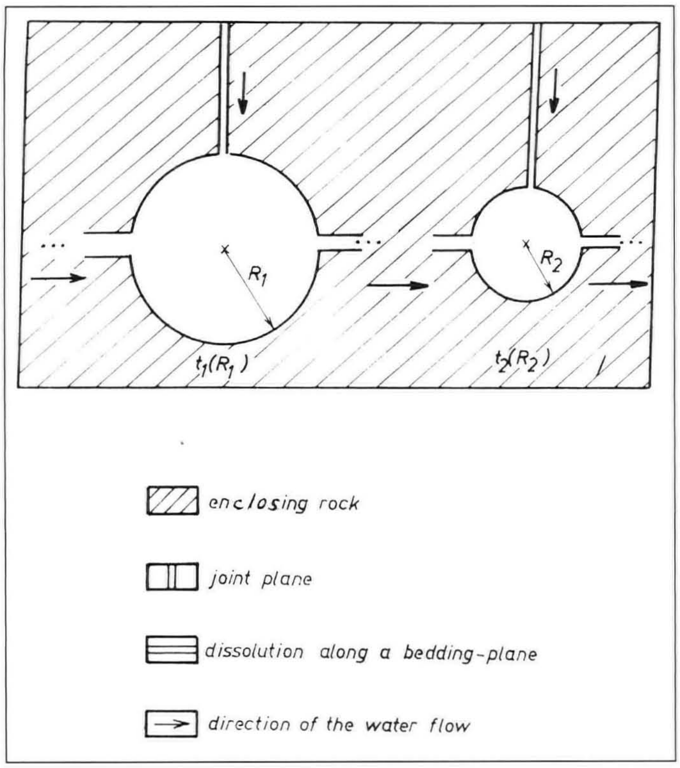


Figure 3. Relation of the radii and the ages of two kettles.

where

$$\lambda = \frac{8}{85} \cdot \frac{\rho}{(C_e - C_i) \cdot \sqrt[3]{D^2 \cdot \nu}}, \tag{18}$$

and $R_0 \approx o$. If we apply formula (17) to the kettle above then

$$t_1 = \lambda \cdot R_1^2, \quad t_2 = \lambda \cdot R_2^2. \tag{19}$$

from which

$$\frac{t_1}{t_2} = \frac{R_1^2}{R_2^2} \tag{20}$$

follows. Literally, the development ages of the kettles are in proportion to each other as the square of their radii (Figure 3). With the help of formula (20) two kettles can be compared, which are actually inactive and were once formed by the mixing corrosion of solutions of unknown concentration and mixing ratio. According to the above, the relative developmental age of a kettle, developed mostly under the same conditions, can be given in relation to the developmental age of another one, which is considered as the unit. For example, if $t_2 = 1$, then from (20)

$$t_1 = \frac{R_1^2}{R_2^2} \tag{21}$$

results, measured in t_2 time, which in the case of a kettle system is a fixed value, which is considered as the 1T unit time.

$$R = \frac{r^2 + h^2}{2h} \tag{22}$$

DISSOLUTION AND EVOLUTION HISTORY

With knowledge of the developmental rate and the dimensions of the kettles, the elapsed time between the beginning of evolution and the inactive stage of the kettles can be determined. Hereinafter it is called the (absolute) developmental age of kettles.

If the concentration of the forming (mixing) solutions is unknown, with the help of equation (21), the relative developmental age of a kettle can be given.

The beginning of evolution of a cave section can be dated if its age is identical with that of the coexisting kettles. (This stands for kettles that, though being more or less destroyed, form the whole cave itself). Smaller, non-cave forming kettles extend into the rock from the cave. Their evolution began when a cave section had already been developed by the coalescence of cave-forming kettles. The smaller kettles are not suitable for determining the beginning of cave formation.

In relation to the present, a given kettle or kettles became inactive at an unknown absolute age. At this period they emerged above the karst water table, but this date is not known. Therefore, beginning of evolution can be determined only in relation to each other in the case of kettles that become inactive at the same time. Simultaneous inactivation may concern kettles that developed below the karst water table, existing at a given time, as mixed-water corrosion most likely occurs around this zone. Since karst water tables may sink or rise, not only the beginning of evolution but also the date of inactivation of the kettles developed at different heights, may vary.

Similar inactivation ages are found in the case of kettles oriented in or nearly in the same plane that can also be oblique due to the orientation of the aquitard or a subsequent tilt. Inasmuch as the depth below the actual karst water level is not known, where mixed-water corrosion still can proceed, the kettles located under each other did not necessarily become inactive at different times. The greater the difference in heights of the kettles, the more probable the inactivation at different dates. Therefore, the developmental ages, mathematically given, may differ from the actual ages. However, it is certain that inactivation is not simultaneous when the bedrock, located vertically between the kettles, shows no signs of dissolution, i.e. no kettles.

In the case of multilevel caves, such as Ördög-lik cave, the inactivation dates of the kettles of various levels differ, because the levels approached the karst water table at different times.

In accordance with the relative developmental age of the kettles the dissolutional sequence of different cave segments can be defined. If the age when two optional kettles coalesce as they grow (relative age of coalescence) can be evaluated; the chronological sequence of the evolution of the cave segments and the development of separated kettles into a unified cave can be determined. The developmental age of a segment could date from the period when the adjacent kettles coalesced. This also holds true in the case of the kettle-free passage segments since the latter developed together with the kettles along the intersections of two primary aquitards, but the growth of the kettles was not enough to remove all the enclosing rock. For this the following data are needed: the present radii of the kettles; centres of the kettles and their distances; and, the actual radii of the kettles at any phase of the unit developmental age.

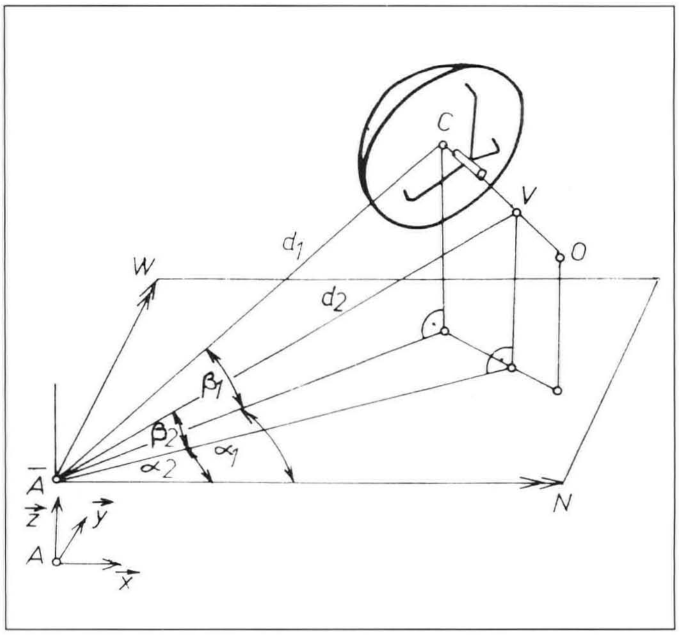


Figure 4. Method of measuring kettles.

Determination of the radii and the centres of the spheres and the distances of the latter is achieved by choosing a favourable point A in the cave's passage from which the desired kettles can be seen easily. Let us set our theodolite above point A and orientate it. The instrument automatically gives a $\{A, \vec{x}, \vec{y}, \vec{z}\}$ rectangular co-ordinate system where $\vec{x}$ is oriented to the north, $\vec{y}$ to the west and $\vec{z}$ vertically upwards (Figure 4).

In addition to a theodolite one needs a spherometer that matches the magnitudes of the kettles. Let us adjust the C tip and CV yardstick spherometer into the kettle as shown in Figure 4. The three legs and the C tip of the instrument touch the surface of the kettle and by the well known formula.

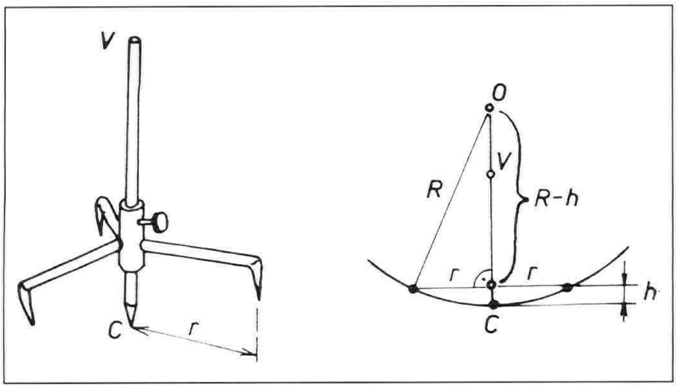


Figure 5. The spherometer used in the method and its parameters.

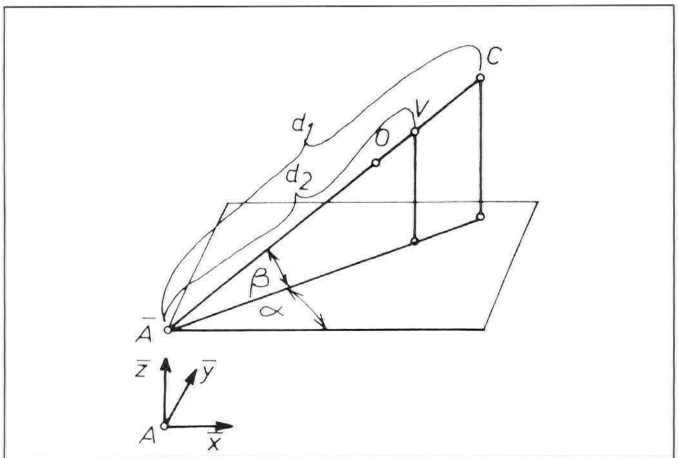


Figure 6. The theoretical model of the method in the specific case when the yardstick of the spherometer is directed to the lens of the theodolite.

gives the R radius of the kettle where r is the distance between a leg and the stick and h is that between C tip and the plane of the three legs according to Figure 5.

As shown in Figure 5, from point $\vec{A}$ we measure the d_1 distance of C tip, α_1 horizontal and β_1 vertical direction angles, and in a similar way the d_2 distance of point V, α_2 horizontal and β_2 vertical direction angles.

As is evident by the above data the co-ordinates of points C and V in the $\{A, \vec{x}, \vec{y}, \vec{z}\}$ rectangular co-ordinate system are:

$$
\begin{aligned}
&C(d_1 \cdot \cos\beta_1 \cdot \cos\alpha_1,\ d_1 \cdot \cos\beta_1 \cdot \sin\alpha_1,\ d_1 \cdot \sin\beta_1 + a) \\
&V(d_2 \cdot \cos\beta_2 \cdot \cos\alpha_2,\ d_2 \cdot \cos\beta_2 \cdot \sin\alpha_2,\ d_2 \cdot \sin\beta_2 + a)
\end{aligned} \tag{23}
$$

where $a = A\bar{A}$ is the height of the theodolite. Since O centre of the kettle falls on the CV line of the yardstick

$$\vec{A0} = \lambda \cdot \vec{AV} + (1-\lambda)\vec{AC} \tag{24}$$

where $\lambda = \frac{R}{e}$, here R = OC is the radius of the kettle, e = VC is the length of the yardstick of the spherometer. Therefore, by using (23) and (24) the co-ordinates of O centre in the $\{A, \vec{x}, \vec{y}, \vec{z}\}$ co-ordinate system are

$$
\begin{aligned}
x &= \lambda \cdot d_2 \cos\beta_2 \cdot \cos\alpha_2 + (1-\lambda) \cdot d_1 \cdot \cos\beta_1 \cdot \cos\alpha_1 \\
y &= \lambda \cdot d_2 \cdot \cos\beta_2 \cdot \sin\alpha_2 + (1-\lambda) \cdot d_1 \cdot \cos\beta_1 \sin\alpha_1 \\
z &= a + \lambda \cdot d_2 \cdot \sin\beta_2 + (1-\lambda) \cdot d_1 \cdot \sin\beta_1
\end{aligned} \tag{25}
$$

We note that the formulae of (25) can also be used in the special case when the stick of the spherometer is directed just to the lens of the theodolite when $\bar{A}$ O, V and C fall on the same line. Then as demonstrated in Figure 6: $\alpha_1 = \alpha_2$, $\beta_1 = \beta_2$ thus formulas of (25) yield the simpler

$$
\begin{aligned}
x &= [\lambda \cdot d_2 + (1-\lambda) \cdot d_1] \cdot \cos\beta \cdot \cos\alpha \\
y &= [\lambda \cdot d_2 + (1-\lambda) d_1] \cdot \cos\beta \cdot \sin\alpha \\
z &= a + [\lambda d_2 + (1-\lambda) d_1] \cdot \sin\beta
\end{aligned} \tag{26}
$$

formula, if $\alpha := \alpha_1 = \alpha_2$, $\beta := \beta_1 = \beta_2$

By knowing the distance

$$D = \sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2 + (z_1 - z_2)^2} \tag{27}$$

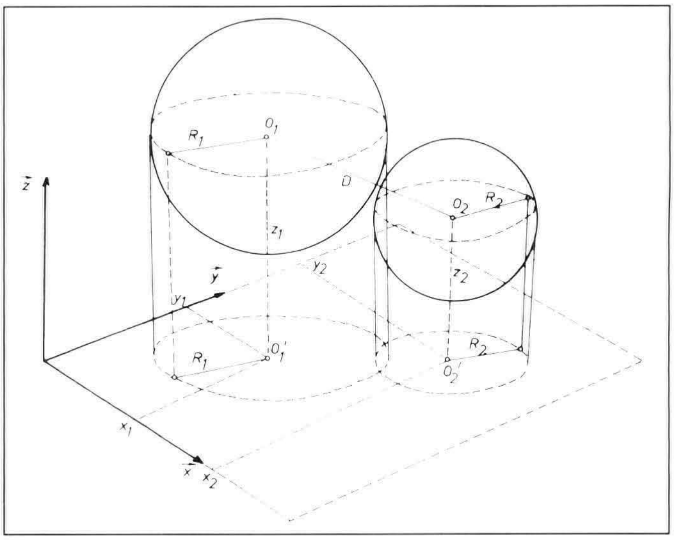


Figure 7. Situation of two kettles in the rectangular coordinate system.

of the O_1 (X_1, Y_1, Z_1) and O_2 (X_2, Y_2, Z_2) centres of the neighbouring kettles, we can determine whether the kettles have coalesced during their evolution or not (Figure 7). If R_1, R_2 are the radii of the kettles and $D < R_1 + R_2$, then the two kettles intersect (that is, coalescence occurred before inactivation). In the case of $D = R_1 + R_2$ the two kettles do not contact nor intersect.

Classification of the coalescence of the kettles

Let us choose the biggest measurable kettle in the cave as the reference kettle and let T denote its developmental age (henceforth the unit), and R the radius. If the developmental age and the radius of an optional kettle in the cave is T_1 and R_1 respectively, then according to (20)

$$\frac{T_1}{T} = \frac{R_1^2}{R^2} \tag{28}$$

holds. In relation with T developmental time of the reference kettle, as the unit, r radius of the kettle of T_1 developmental age an R_1 radius can be defined at any optional t time of its developmental process, which is also measured in T unit. Let us apply formula (20) to t and T conditions of the examined kettle:

$$\frac{t}{T_1} = \frac{r^2}{R_1^2} \tag{29}$$

from which after simple rearrangement;

$$r = \sqrt{\frac{t}{T_1}} \cdot R_1. \tag{30}$$

If we want to know the radius of the kettle, measured in T units of time, ΔT earlier than T full developmental age, that is

$$t = T_1 - \Delta T \tag{31}$$

then, by using (30) and (31),

$$r = \sqrt{\frac{T_1 - \Delta T}{T_1}} \cdot R_1$$

follows.

By knowing D, the younger ages within T unit of time can be determined whether coalescence of the adjacent kettles has already occurred or not. The fusion processes of the different periods of time can be graphed on the cave maps as well. Thereby, we gain a series of maps which represent the different phases of dissolution and coalescence. By evaluating the maps of the various relative developmental ages, in the formation process of the present cave (evolved from kettles), the following can be studied:

- the relative ages of the initial dissolutions (the beginning of the evolutions of the kettles) and thus, their sequence
- the trend or trends of the dissolution activity
- the relative age and sequence of coalescence
- the trend or trends of the ages of coalescence
- by the coalescence of which earlier developed, smaller segments were the larger cave sections formed (analysis of hierarchy)
- by knowing the developmental sequence, the history of the development of the cave segments of various optional magnitudes, from smaller sections

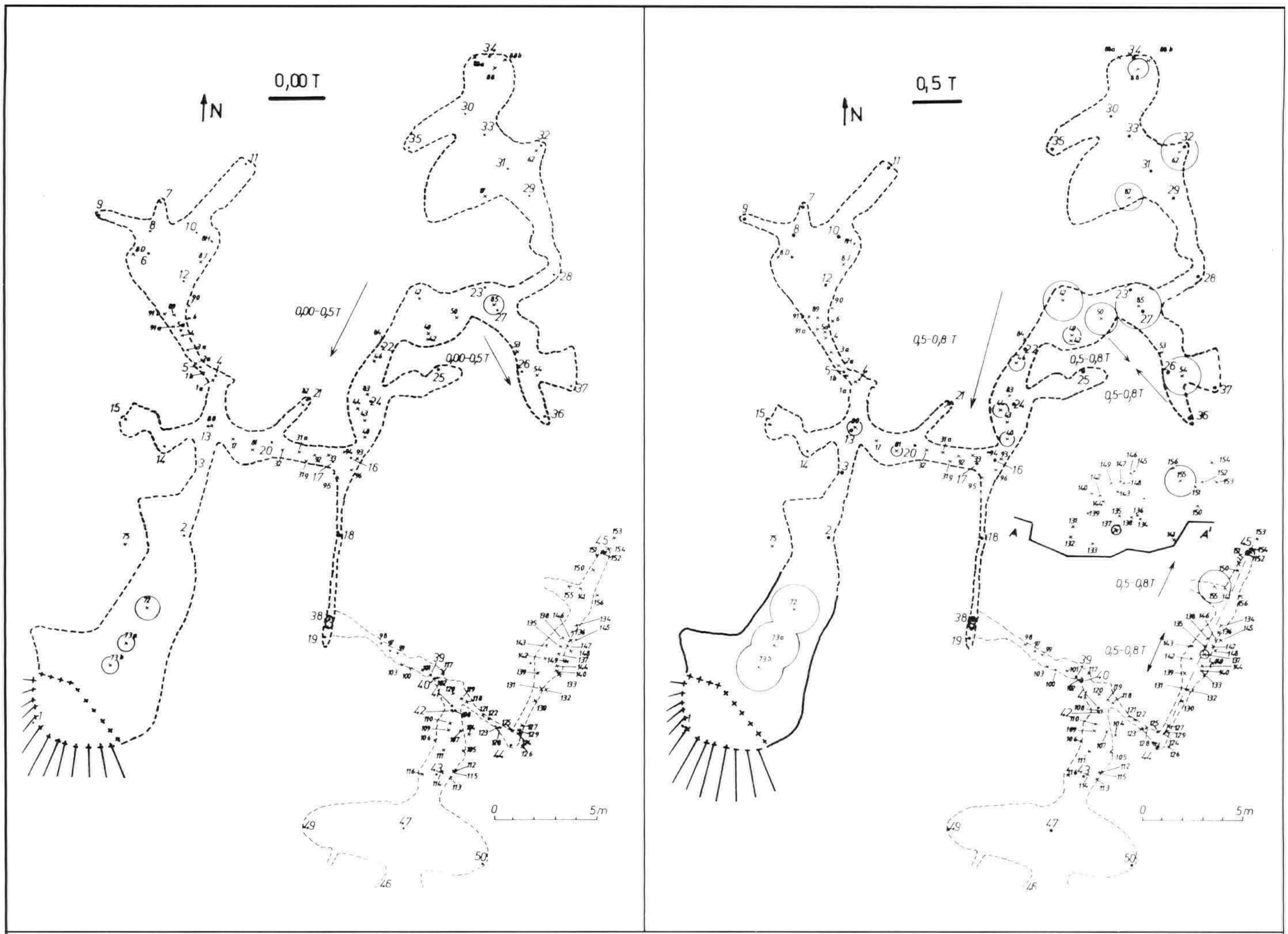
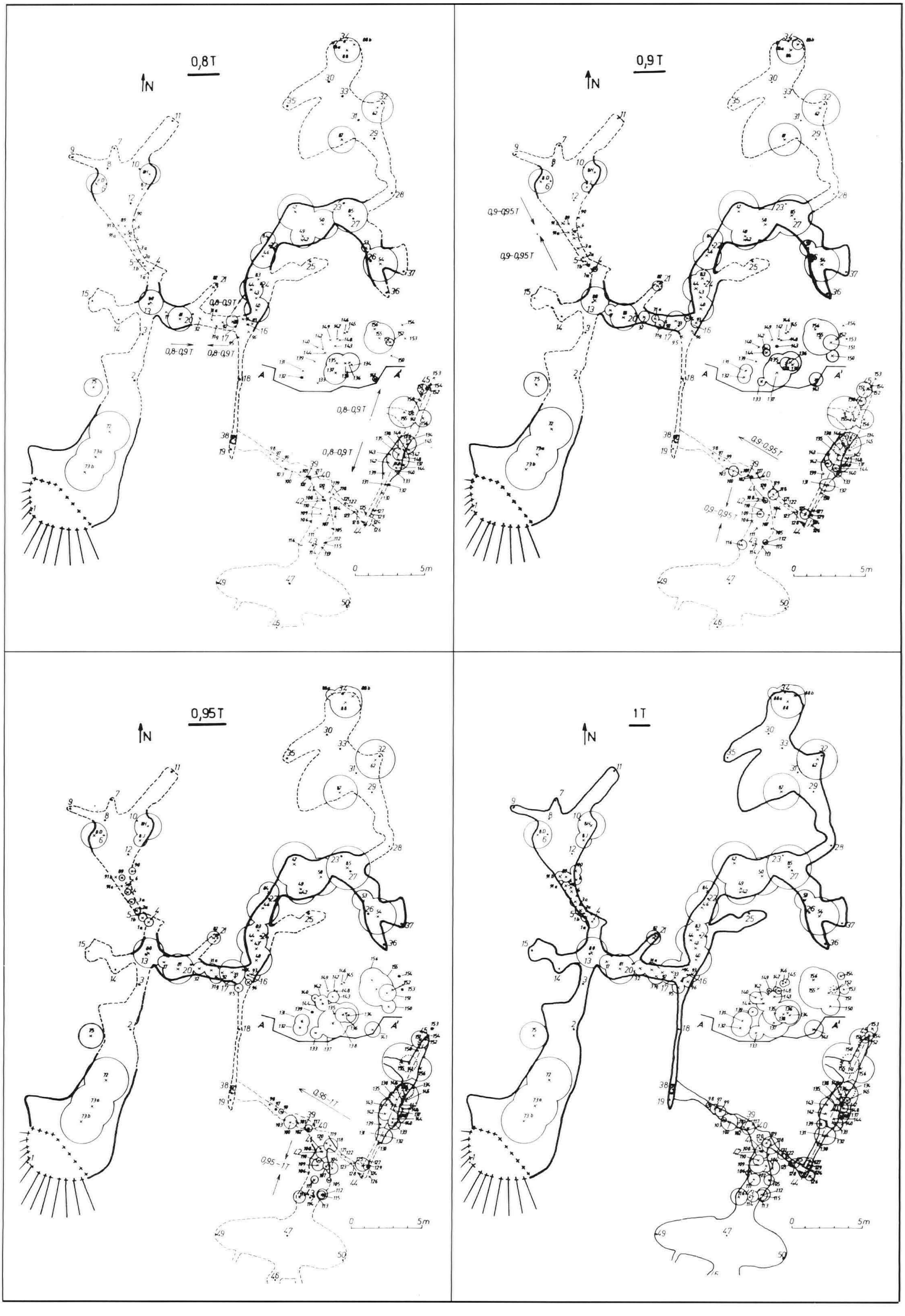


Figure 8. Dissolutional conditions of Ördög-lik Cave at stages of relative developmental age (T). Time passed between the development of the two levels is unknown. Kettle centres between points 44 and 45 are also projected onto the section A (44)-A[1](45).

- survey point
- side-view
- developed cave section (upper level)
- developed cave section (lower level)
- cave section yet undeveloped or of unknown developmental age (upper level)
- cave section yet undeveloped or of unknown developmental age (lower level)
- kettle
- coalesced kettles
- non-touching kettles located in different planes
- overlapped kettle
- direction of kettle development at phases of the relative ages (according to the relative age of the beginning of the evolution)
- kettle centre and reference number
- passage to the lower level
- rain line
- valley slope


0,8 T
N
0,8-0,9 T
0 5 m
0,9 T
0,9-0,95 T
0,95 T
0,95-1 T
1 T
A
A'

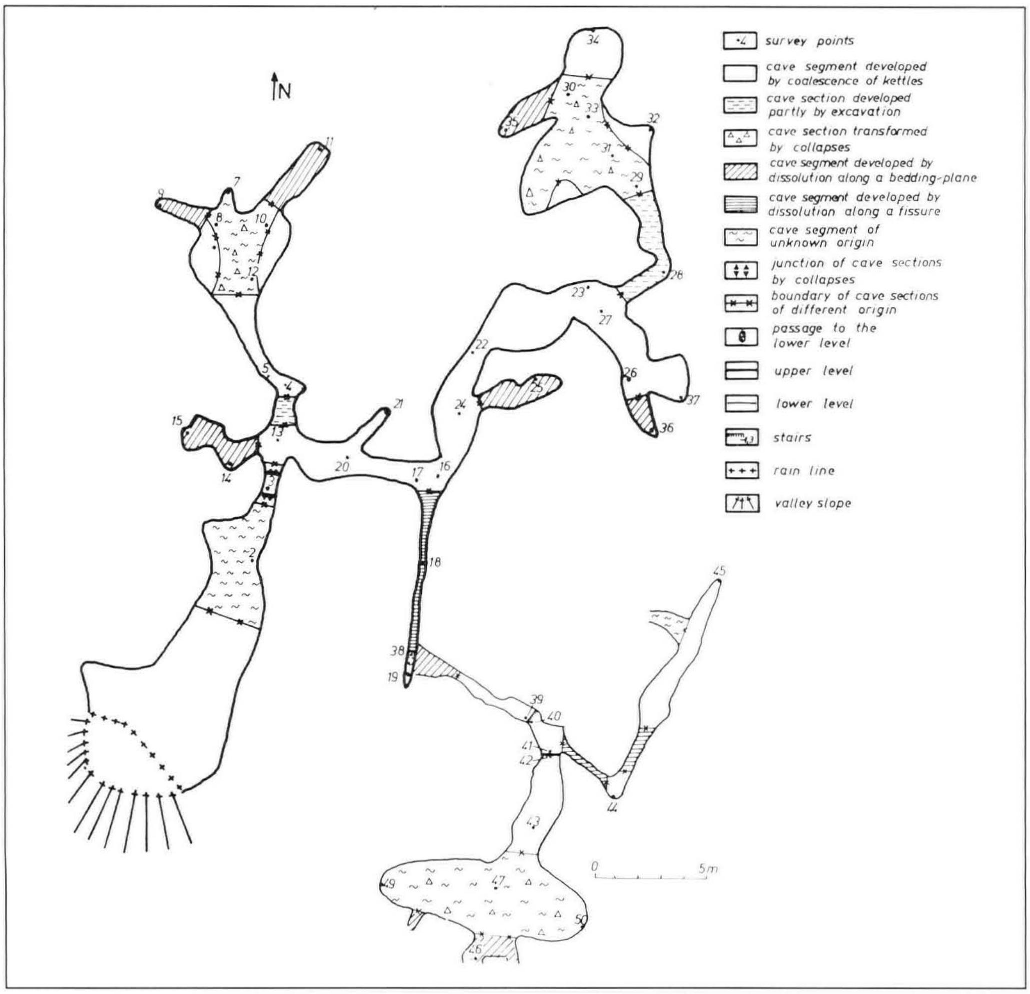


Figure 9. Genetical relations of Ördög-lik Cave.

— the quantity and quality of the kettle dissolution at some time

— comparison of changes in the quantitative and qualitative conditions of the kettle dissolution between two periods of time.

DISSOLUTION HISTORY OF ÖRDÖG-LIK

On the upper level 57% of the passages (out of this the reconstruction of 47% is possible), developed by the coalescence of kettles. Not considering the smaller branches, 69% of the upper level is of kettle origin, out of which 59% can be reconstructed (Figure 9).

Dissolution on the upper level can be divided into two stages (Figure 8):

a) Between 0.0-0.5T only kettles are formed (with the exception of the entrance area, where coalescence occurs at 0.5T).

b) Between 0.8-1T the fusion of the developed kettles place and simultaneously, or as a result of the latter, large numbers of new kettles are formed. At 0.8 T along segment points 16 and 26 adjacent kettles coalesced into several short passages (dissolution mostly follows the Eocene/Dachstein rock boundary here). From 0.9 T a continuous passage section develops between the points mentioned above. Coalescences begin, from the time mentioned, also between points 13 and 16. At 0.95 T the upper level shows a stage similar to the present (with exception of the segment

The remains of kettles No. 42, 49, 73.

The remains of kettle No. 84.

between points 4 and 12). In the case of the segments located north of the sections developed along the fault, dissolution activity very likely migrated toward the south in two parallel zones where the western zone is younger; consequently the developmental ages become younger, while the dissolution activity proceeds toward the north in the segments located to the south. Therefore, migration of the dissolution activity in these segments is unidirectional. This activity shift is indefinite in both zones; for instance, in the north, because the age becomes younger toward the eastern chamber (however, coalescences in the chambers are most likely to have been completed and thus the old kettles cannot be detected any longer).

The uncertainty in the south between points 1 and 3 is due to the small number of kettles. At the same time, even though not simultaneously, dissolution activity proceeded from outside towards the inside (two-directional migration) in the segment developed along the fault (between points 12 and 4, and 13 and 17).

At the lower level, 84% of the passages are of kettle origin (out of this 77% can be reconstructed). The relative ages of the kettles of the lower level are also determined in relation to kettle 47. (Obviously, the time passed between the evolution of the kettles of the two levels is not known. The absolute developmental age of kettle 47 can also be estimated here if we consider the concentration of the karst water of a rock the evolution of which is identical with that of the kettles' enclosing rock which in this case is of the Fenyöföi Formation).

At the lower level, at 0.8 T, several passage segments develop at the northeastern end of the cave section between points 44 and 45. Coalescences take place at 0.95 T between points 41 and 43 as well. At 1.0 T the passage between points 38 and 44 develops which, on the one hand, interconnects the two above-mentioned passages and, on the other hand connects the lower level to the shaft, and thus to the upper level. (Incidentally, it occurs at the end of the dissolution process).

The similarity in the dissolution processes of the two levels is that dissolution starts nearly north and south (where the shift to the south dominates), and is completed along the line perpendicular to the above.

Dissolution of the lower level differs from that of the upper level in several respects.

- Development of the kettles of the lower level took place mostly toward the end of the active period; the degree of the coalescence is smaller here.
- Unidirectional dissolution is typical in the segment developed along the fault in contradiction to the segment of similar genesis at the upper level, while it is two-directional with several dissolution centres along the section developed in the dip direction.

Since at the upper level the kettles become younger to the south, it is possible that the current along the bedding-plane (flowing karst water zone) appeared gradually (delayed) in this direction. However, some kettles near the entrance show the opposite tendency, indicating that the current system develops in the opposite direction. At the same place, the increasing age of the kettles toward the valley supports the opinion of Veress (1980, 1981), wherein the Ördög-lik cave opened up posteriorly as a result of the growth of the valley.

On the contrary, water movement along bedding-planes in the lower level was a less determining factor; even if only one common current system developed then it might have evolved towards the end of the unit developmental age.

Comparing the upper and lower levels it appears that the development of the karst water zone forming the lower level terminated at an earlier stage because the water-table sank to a deeper level.

CONCLUSIONS

Some parts of caves developed by mixing corrosion were formed by the coalescence of kettles.

Considering mixing corrosion the developmental rate of kettles has been determined with the help of differential equations describing the dissolution rate. With the help of the developmental rate and the radii of the kettles the absolute or the relative developmental age of a kettle can be determined. Since the coalescence age of the neighbouring kettles can also be calculated, thus the absolute or relative age of a cave, formed by kettles, is definable. Thus the developmental stage of a cave can be determined for the different periods of time and can be represented on maps. By this means we obtain a series of maps, which show the dissolution history of the examined cave.

Our thoughts are illustrated by the example of the dissolution history of the Ördög-lik cave in Sürü-hegy. The following can be stated:

- the relative beginning of the development of the different parts of the cave and the relative developmental ages of the cave segments (the coalescence age of the kettles forming the separate parts) can be determined,
- the direction of development of the different cave segments can be defined,
- one can see that the number of kettles increases as the cave grows older.

The examination should be extended to the development of other caves. Then one could see whether the method is also applicable in the case of other mixing corrosion caves. By this means we could not only better understand the evolution of caves and the carrier karst region but the history of development could also be fully revealed.

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Water Chemistry in Cuevas del Drach, Majorca

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Abstract: As part of the cave diving expedition to the caves of the eastern coastal region of Majorca, the lakes in the commercial Caves of Drach were sampled at various depths to see if the chemistry of the water could explain the presence of haloclines noticed by divers and the noticeable deposition, decay and discolorationof stalactites at and below the water surface. The results seem to indicate that acidity and a highly saline regime are present in the lakes at depth and that ion-exchange is taking place in the underwater stalactites and stalagmites resulting in their decay. The surface layers, being less acidic and saline however, allow deposition on stalactites to continue. Boats agitating the surface and underwater lights causing convection currents have altered this process in Lac Martel.

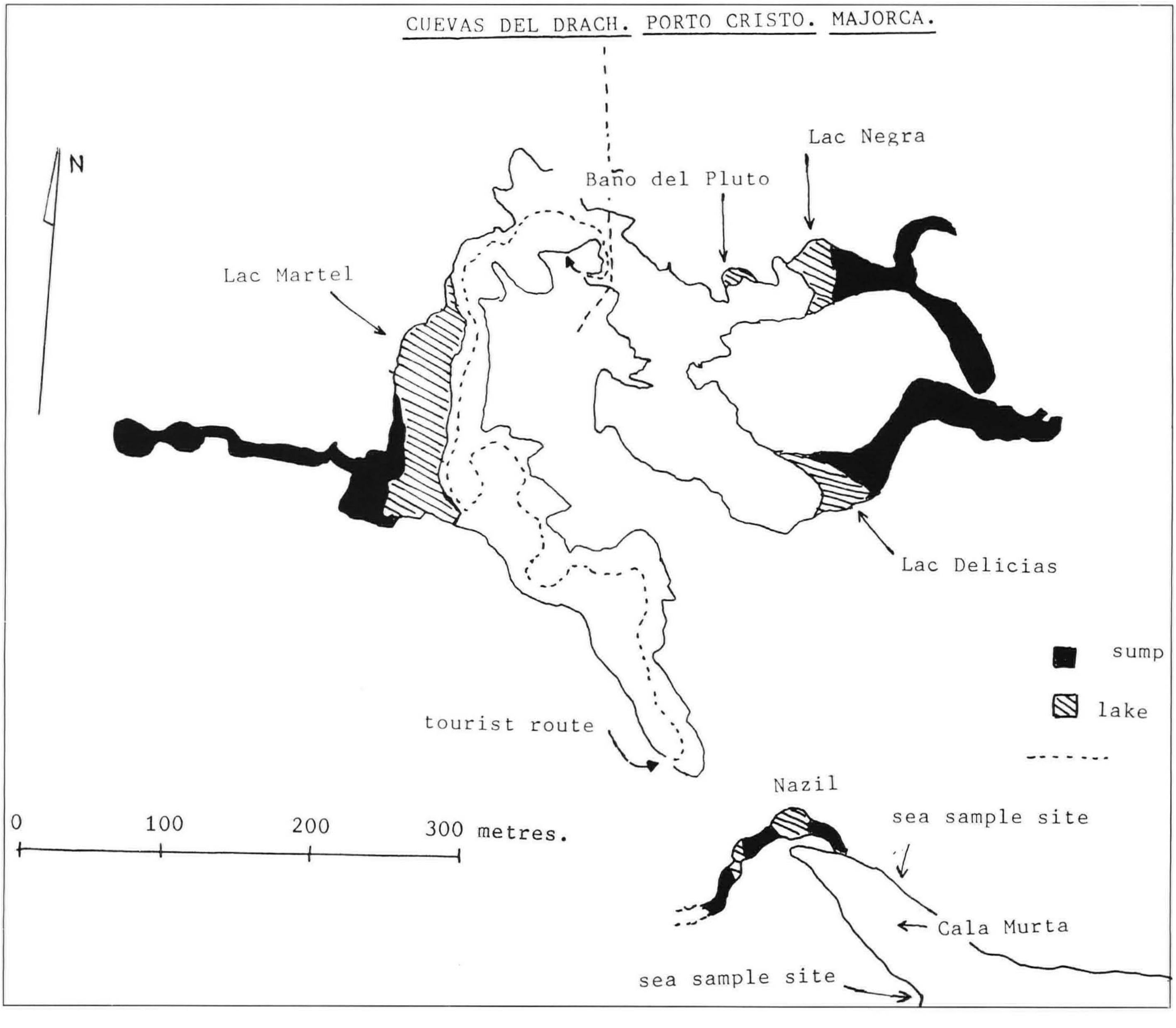
The Island of Majorca (or Mallorca) is the largest of The Balearic Islands which lie off the eastern coast of Spain; it is largely composed of limestone with a mountainous region in the north of the Island and an undulating plain stretching southwards to the sea.

There are caves on the Island which divide roughly into two groups: caves in the mountains with some vertical as well as horizontal development and with active resurgances in the deep valleys nearby; and caves near to the coast, especially in the southeast which are largely isolated chambers containing massive areas of collapse and deep, still lakes and sumps.

One such coastal cave is Cuevas del Drach, on the southeast coast, a long-established show cave, the mainstay of the many excursions available to holidaymakers using packages to Majorca. Cuevas del Drach is a series of interconnected large chambers containing enormous piles of calcited boulders, a profusion of stalactites and stalagmites and several deep blue lakes. It has a series of concreted paths passing through the cave, some used currently as a tourist route and others no longer used and also boats which transport visitors across Lac Martel and provide a platform for a small orchestra to play suitable music to enhance the spectacular scenery.

The lakes in Drach were dived in 1991 by a small number of cave divers from South Wales led by Owen Clarke and it was noticed that distinct layering was present causing haloclines in the water; levels at which differences in density caused refraction of light and a resultant blurring of visibility. These haloclines seemed also to correspond in part to deposition or solution of the stalactites and stalagmites which lie beneath the surface in great profusion. Some black staining was also noticed at different levels.

Figure 1.



A follow-up visit in February 1992 was made with a view to continuing the underwater exploration of the lakes by diving and also to sample the lake waters at different levels to see if the chemistry could explain the phenomena seen by the divers. In the event, the cave owners were unwilling to allow any further diving for reasons of safety and associated insurance, publicity etc., but the sampling of the lakes for chemical analysis was allowed and considerable help given to the project in terms of time and effort by the cave manager and his staff.

The Sampling Programme

Four areas of the cave were identified for sampling because of their accessibility and depth of water; they were: Lac Martel, the show cave lake used by visitors and Lac Delicias, Lac Negra and Bano del Pluto, all in the non-visited areas of the cave. The lakes, with the exception of Lac Martel, are not disturbed by visitors and, in the case of Lac Delicias, its location is even away from the effects of the large fans which circulate air around the show cave causing variations in temperature and humidity.

The water at these sites was sampled at the surface and at one metre intervals down to the bottom of the lake using a flexible hose attached to steel rods and connected to a windscreen-washer pump driven by re-chargeable batteries; see photographs.

The conductivity, pH and temperature for each sample was measure on site using instruments loaned by The Limestone Research Group from Manchester Polytechnic and the concentrations of sodium, calcium and magnesium ions were measured for each sample at Crosskeys College in South Wales using a pNa meter and EDTA titration techniques for sodium and calcium, magnesium respectively.

Lac Delicias was sampled from the bank in two locations at opposite ends of the lake, likewise Lac Negra. Bano del Pluto is a small deep pool so it was only sampled at a single site. Lac Martel was sampled from two bank locations near opposite ends of the lake but also from a boat over a deep trench in the floor of the lake. All the samples taken, after measurement of conductivity, pH and temperature, were sealed in plastic bottles and transported back to Wales at the end of the expedition.

In addition samples were taken of crystals which floated in some profusion on the surface of Lac Negra and Bano del Pluto. A few were also found on Lac Delicias but Lac Martel was devoid of crystals because it was sprayed each night with recirculated water to prevent the concentration of crystals and the resultant loss of water clarity. The temperature of the air near each site was also recorded.

Outside the cave, at the nearby coast, 500 metres distant, samples were taken of the sea water, from a headland location and also in an inlet called Cala Murta which contained a small resurgence cave called Nazil. This cave is thought to be associated with Cueva del Drach but as yet this is not proven. Its outflow however was sampled but the mixing zone between sea and cave water was difficult to delineate so the chemistry of the sample can only be taken as a rough guide to the waters of Nazil.

WATER CHEMISTRY

Temperature

The surface temperatures in all the sampled sites match well the air temperature at the site and this is largely controlled by the fan which is used to circulate fresh air around the show cave. Lac Martel is unusually warm because of, I suspect, the many lights both above and below water level, the number of bodies which throng around the lake for six hours each day and its location at the lowest point of the show cave circuit.

Lac Negra and Bano del Pluto both have percolation water dripping into them from stalactites and are relatively near to the draughtiest part of the cave.

Lac Delicias is in an area of virtually still air, with a noticeable high level of carbon dioxide gas if our breathlessness is any measure, and its surface warmth is not perturbed by any draught or percolation water. Indeed, access to the large chamber which contains Lac Delicias is through an excavated passage where the air temperature rises five degrees in only a few metres as the effect of the draught is lost.

The rise in temperature with depth is common to all the sites and is particualarly noticeable at Lac Negra and Bano del Pluto, mixing causing the effect at Lac Martel to be minimised and Lac Delicias, being so warm at the surface, is also not very temperature variable. The temperatures of Nazil and the sea give an indication of the difference in the temperatures of groundwater and seawater in Majorca in February.

SITE	DEPTH m	TEMP. C	pH.	COND. mS	Na.	Ca. mg/l	Mg.
Lac Delicias. air temp 18.2							
(D1)	surface	18.1	7.35	4.1	9000	360	740
	—1m	18.4	6.52	5.5	15000	560	1020
	—2m	18.3	6.60	7.2	>20000	660	1540
	—3m	19.0	6.67	8.0	>20000	680	1800
(D2)	surface	18.0	7.32	4.1	12000	420	660
	—1m	18.1	6.63	6.5	20000	580	1260
	—2m	18.6	6.62	7.9	>20000	680	1660
	—3m	18.8	6.64	8.1	>20000	700	1760
	—4m	18.8	6.63	8.8	>20000	640	1960
Lac Negra. air temp 14.9							
(N1)	surface	15.3	6.90	2.2	5000	380	660
	—1m	16.6	6.60	4.7	15000	520	760
	—2m	17.4	6.83	7.7	>20000	680	1400
	—3m	17.4	6.70	7.9	>20000	660	1480
(N2)	surface	14.4	6.96	3.3	9000	400	520
	—1m	16.1	7.17	4.7	12000	500	—
	—2m	17.1	6.88	7.7	>20000	680	1560
	—3m	17.0	6.90	8.0	>20000	720	1640
	—4m	17.2	6.89	8.3	>20000	700	1820
Bano del Pluto. air temp 13.3							
(BP)	surface	13.3	7.79	3.6	9000	440	500
	—1m	15.6	6.83	5.5	14000	600	940
	—2m	16.9	6.90	7.9	>20000	660	1680
	—3m	16.9	6.91	9.1	20000	760	1940
	—4m	16.9	6.91	9.1	20000	780	1960
Lac Martel. air temp 18.9							
(M1)	surface	18.9	6.88	8.0	>20000	680	1760
	—1m	18.8	6.88	8.4	>20000	720	1680
	—2m	19.3	6.90	8.7	>20000	740	1780
	—3m	19.5	6.89	9.1	20000	700	1980
	—4m	19.4	6.91	9.2	>20000	740	1900
	—5m	19.4	6.89	9.2	20000	720	2040
(M2)	surface	19.1	6.87	7.7	>20000	680	1500
	—1m	19.3	6.95	8.4	>20000	700	1700
	—2m	19.6	6.91	8.8	20000	700	1860
	—3m	19.6	6.91	9.1	20000	760	1940
	—4m	19.5	6.91	9.2	20000	620	2000
	—5m	19.4	7.00	10.1	12000	760	2220
(M2)Boat	—4m	19.5	6.89	9.5	20000	740	1940
	—6m	19.4	6.90	9.5	20000	760	1940
	—8m	19.3	6.85	13.2	10000	920	3440
Nazil resurgence.		18.9	7.20	8.4	20000	760	2050
Sea, near Nazil.		14.8	8.10	12.5	7000	1000	4000
headland.		14.0	7.26	13.8	7000	1060	5700

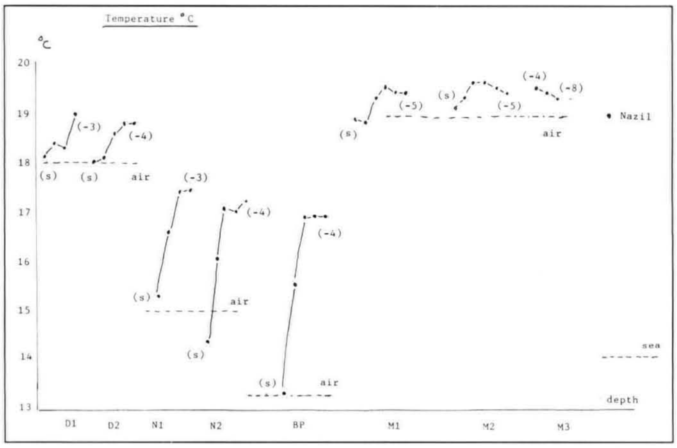


Figure 2.

Acidity

The results obtained from the samples indicate that a layer of mildly alkaline water lies on the surface of undisturbed lakes in the cave but it is only one metre deep. It is likely from the analysis that this is relatively fresh percolation water dripping in from stalactites and flowing down the travertine around the lakes. It is most marked in Bano del Pluto where there are many dripping stalactites and in Lac Delicias where the surface is most undisturbed. Lac Martel, because of the boats and underwater lights has lost this surface layer to mixing and is, as a result, slightly acidic throughout its depth; Nazil and the sea are both mildly alkaline. Lac Delicias shows the most acidity at a depth of one metre and below.

Note. Crystals which were found floating on the surface of Lac Negra, Bano del Pluto and, to a lesser extent Lac Delicias proved by chemical analysis to be of calcium carbonate, probably calcite, formed either from disintegrating stalactites within the lakes being re-crystallised in the surface layer, or from destroyed stalactites produced when the various footpaths were engineered nearby. The cave guides indicated that these crystals appear also on Lac Martel if it is left undisturbed so it is periodically sprayed to prevent rafts of crystals forming.

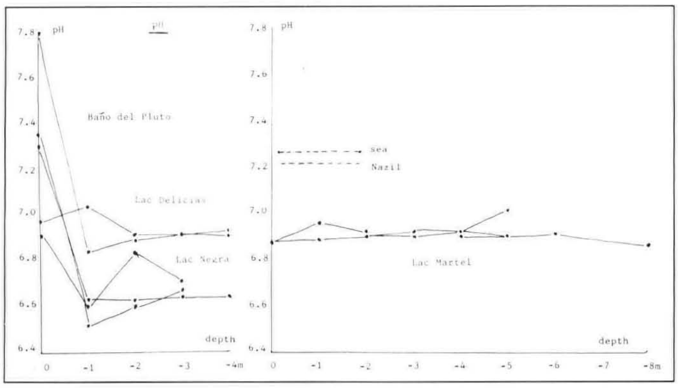


Figure 3.

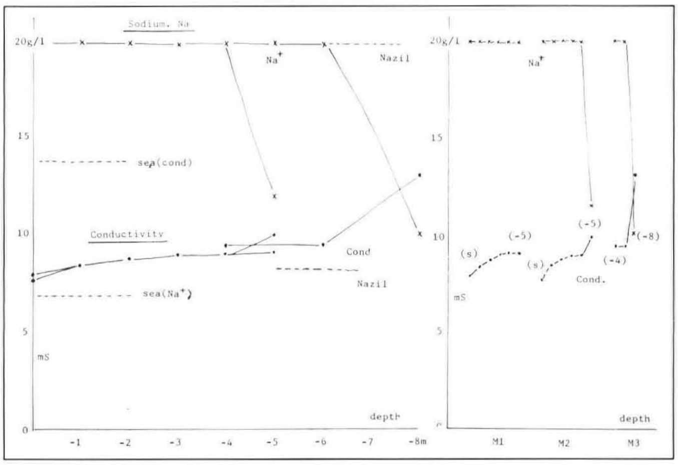


Figure 4.

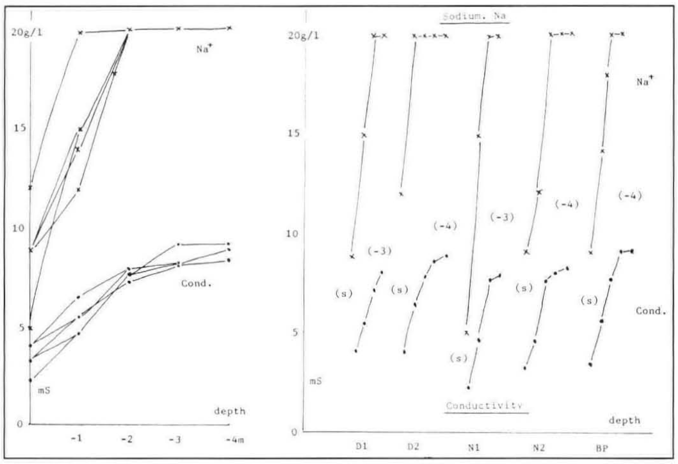


Figure 5.

Conductivity

It is in these measurements and those which follow of sodium, calcium and magnesium ion concentrations that the really interesting and unexpected results were obtained. The level of ion concentration in the waters proved to be too high for the sensitive meter provided by Manchester Polytechnic to measure, so a less sophisticated meter was needed.

The increase in conductivity in Lac Delicias, Lac Negra and Bano del Pluto with increase in depth is plain to see, with its most pronounced below the 3m level; a further large increase being noted in the 8m deep trench in Lac Martel. Again the boats and lights mixing Lac Martel diminish the changes in conductivity with depth and it is only in the trench where mixing is at a minimum that the conductivity increases markedly. Nazil resurgence has a conductivity very similar to Lac Martel so an underwater connection may be indicated: the sea is highly conductive as would be expected.

Sodium Ion Concentration

Sodium salts are present in all the lakes of Drach in large concentrations; indeed all the lakes proved to be more salty than the sea nearby, by a factor of three in most cases. The meter used to measure the sodium was a pNa meter and was only capable of

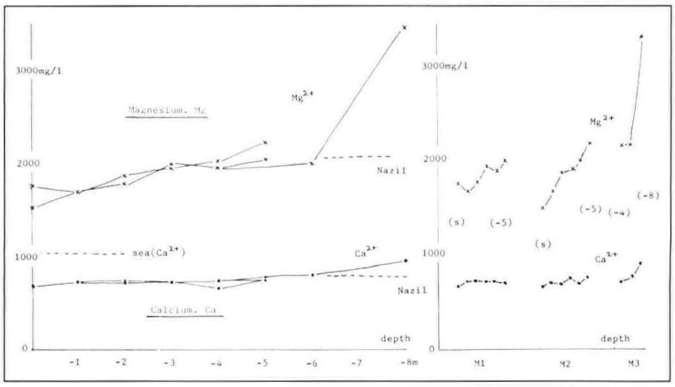


Figure 6.

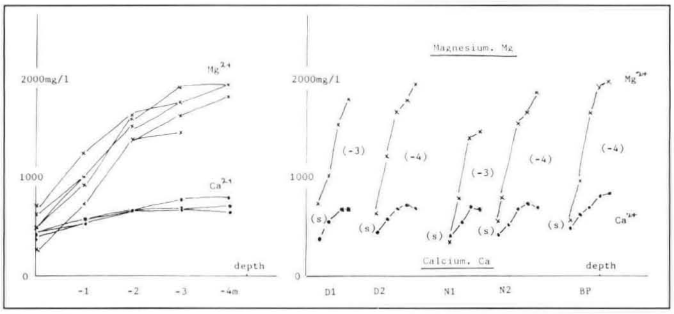


Figure 7.

measuring to an upper limit of 20g/1. Several samples exceeded this so accurate values for the most concentrated solutions were not possible to record; however the trends in sodium ion concentration with depth are very apparent. The surface layers down to about 2m depth are considerably less saline than those below, with the exception of Lac Martel where, again, mixing has caused the chemistry to alter. The increase in salinity with depth is common to all the lakes until the —6m and —8m deep areas of Lac Martel are reached. The 8m deep trench proved to be surprisingly only half as salty as the lake above and a similar phenomenon occurs at —6m in another are of Martel. What this drop in salinity indicates is not clear but a rise in the concentration of magnesium ions in the same samples may be related in some way, at least in the —8m sample from Martel.

Drawing conclusions about the origin of this salty water in the cave can only be speculative, but, I would hazard a guess that several inundations of sea water have occurred in the caves over geological time followed by periods of evaporation and this has resulted in strongly saline solutions now being present. The cave temperatures being around 18-19°C would made evaporation a relatively quick process and the proximity to the sea would make inundations a frequent event requiring only a small rise in sea level. In recent times the pumping out of groundwater which goes on all over the Island is probably exacerbating the process by causing a hydrological gradient down which the sea water may flow and enter the caves. Maximum values for salinity may also indicate the presence of open fissures at particular levels or passages to the sea, but the chemistry does not lead to such conclusions with any certainty.

Calcium and Magnesium Ion Concentrations

These ion concentrations measured using EDTA titration when back in Wales, show most markedly the loss of the surface layers in Lac Martel due to turbulence caused by boats and underwater lights. The marked levelling off of the calcium and magnesium concentrations at the intermediate depths may indicate a reaction is taking place between the water in the lakes and the contact rock, whether limestone or stalagmite, at these levels. Assuming the water was originally sea water, with its very high concentration of magnesium salts; 4000 to 5700mg/1; it is possible that much of the magnesium has since migrated into the limestone and stalagmites causing solutional exchange of ions and the resultant decomposition of the stalagmite. In 1991, Owen Clarke, when diving in the lakes noticed levels of stalagmite decay at these depths, the stalagmites crumbling to powder when touched. He also noticed deposition of crystals on stalactites nearer to the surface, especially in the top 1m.

The deep trench in Lac Martel has higher concentrations of magnesium ions, close to those in sea water, so perhaps the ion-exchange has not progressed very far at this level yet.

CONCLUSIONS

Fowles (1991) outlines possible mechanisms by which sea water can cause dolomitisation of limestones. It is possible, albeit without very much detailed knowledge of the process, that a comparable situation is present in the lakes of Cuevas del Drach. Namely, sea water has inundated these caves over time and concentrated in the system producing very saline waters with relatively high temperatures. The calcium content of these waters has fallen somewhat with respect to the sea outside because deposition is occurring at the higher levels in the lakes producing crystal growth on the stalactites and stalagmites and also rafts of crystals floating on the surface in undisturbed areas. The high concentrations of magnesium in the sea water has produced a process of ion exchange within the limestone and stalagmite at depth and, as a result, two things have happened: the magnesium content of the water has fallen to well below that of sea water; and the ingress of magnesium into the stalagmite has caused changes in crystal structure and resultant decay of the formations, the process probably aided by slight acidity.

The origin of this acidity is not evident from the data collected in this study, but I suggest hydrolysis of salts during the mixing of sea and cave waters may result in some equilibria where acidity is produced. I conclude therefore that all these differences in the chemistry of the water has resulted in layering in the undisturbed lakes in Cuevas del Drach and haloclines are visible to divers at levels where the chemistry has produced differences in density. The pumping out of groundwater from all areas of the Island is likely to speed up this process by encouraging the inflow of sea water into the limestone as a hydrological gradient is produced.

ACKNOWLEDGEMENTS

The work done in Cuevas del Drach was only possible with the permission and help of the cave owners and their staff; also previous diving detail from Owen Clarke suggested analysis of the cave water would be interesting. A grant from The Sports Council for Wales helped in financing the expedition and laboratory equipment from Manchester Polytechnic and Crosskeys College enabled on site work to be done. Thanks are due to the other members of the expedition, Ian William, Steven Thomas, Owen Clarke and Doreen Gascoine.

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Chalk Caves Revisited

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Abstract: The Cretaceous Chalk and, to a lesser extent, the Jurassic and Permian carbonates of the British Isles are commonly considered to be relatively uncavernous, despite being known to transmit underground drainage. Pre-existing explanations of this apparent paucity of caves are examined briefly on the basis of limited published data and in the light of recent developments in theories of speleogenesis, including the concept of inception horizons.

In a research thesis entitled *"The origin of limestone caverns: an inception horizon hypothesis"*, Lowe (1992) describes a view of speleogenesis which includes the early quantum jump from rock without caves to rock with caves, as well as subsequent, better documented, processes of cave development. This approach to the problem of cave origins necessitates recognition of the fact that the earliest micro-voids capable of transmitting groundfluids through a previously impermeable rock mass must be considered to form part of the continuum of caves, no less than the explorable voids which fall within most anthropocentric definitions of the term "cave"; A major element of Lowe's (1992) hypothetical review of speleogenesis is the postulation that caves, in the sense of the earliest micro-voids, are conceived in well-indurated and effectively impermeable carbonates only where the lithology is suitable. Rather than occurring in the massive and relatively pure carbonates through which the later phases of cave development ramify, these primitive cave forming processes are deduced to take place in or adjacent to beds of impure carbonate or non-carbonate within the succession. These foci of early activity are termed **inception horizons.** Cave inception processes in less well-indurated rocks with significant primary permeability, such as syndepositional coralline and aeolianite carbonates, may not be reliant upon the presence of such horizons, through the caves and other erosional phenomena associated with syngenetic karst processes *(sensu lato)* may potentially be preserved and re-activated in the role of inception foci in later phases of speleogensis.

Throughout much of Lowe's (1992) thesis great emphasis is placed upon the types of inception horizon which are readily seen in successions of well-indurated carbonate such as the "Carboniferous Limestone" of the British Isles. Within the sequences preserved here cave inception is seen to have been influenced by beds of sandstone, mudstone (sometimes termed shale, though this term hides the true origin and nature of some rocks), coal, seatearth or volcanic rocks of many types. In addition the carbonates themselves are locally sufficiently impure, due to the presence of clastic components, disseminated sulphides, such as pyrite, or evaporite minerals, such as gypsum, that they exhibit inception properties. The broad and general criterion which links a large proportion of possible inception lithologies is that they appear to be associated with depositional/erosional regimes that mark the boundaries between cycles of carbonate deposition. Such cycle boundaries may be major or minor and of regional or local extent, but they possess a common facet of atypical chemistry plus or minus a proportion of epiclastic and/or volcanoclastic debris.

Though outside the major theme of the research the potential application of the inception horizon concept to British rock types which are normally viewed as essentially "uncavernous" was assessed. The relatively short consideration (Lowe, 1992, section 4.6.5.) indicated that presence of inception horizons may at least partially explain a number of deficiencies in current explanations of why these rocks appear to lack caves.

The Chalk and inception horizon theory

Much of the discussion throughout Lowe's (1992) thesis is concerned with cave development in carbonate sequences which are assumed to be well-indurated and thus, at least prior to speleo-inception, of limited permeability. The major exception to this rule is a comparatively brief discussion of syngenetic or penecontemporaneous development processes in young, e.g. aeolian or reef limestones, in his chapter 3. Other carbonate sequences which are permeable as a reflection of their primary porosity are, however, represented, within some parts of the geological column. It must be emphasised that such porous lithologies are not found consistently at specific chronostratigraphical horizons, but are rather a function of a localised depositional facies and subsequent diagenetic processes. Thus the Upper Cretaceous Chalk of south-eastern England is not identical to rocks of the same name and age in northern England and differs to varying degrees from carbonates of the same age beneath much of France.

The English Chalk appears to be relatively non-cavernous when compared to, for instance, the Carboniferous carbonates of the United Kingdom or Mesozoic carbonates in the European Alps and Pyrenees. In reality this is a lack of explored cave systems in the English Chalk, but this apparent lack may or may not correlate with an actual absence of cave development (*sensu* Lowe, 1992) within these beds. There is another possibility, that these beds have yet to reach the same tectonic maturity achieved by various older rocks and by certain younger rocks in more heavily tectonized areas. That is, the very lack of tectonic fracturing and recrystallization, and the general (but not total) burial of the Chalk until relatively recent times, might weigh against caves of significant dimensions being exposed on the Chalk outcrops. The commonly held view that the Chalk is effectively uncavernous (in the anthropocentric sense) due to an almost total domination of diffuse flow over conduit flow may be insufficient to explain a number of paradoxes.

It is emphasised by Lowe (1992) that under conditions distanced from those of the littoral, freshwater/saltwater interface zone, speleo-inception within **pure** carbonate lithologies is rare. Much of the Chalk is a calcium carbonate rock of very high purity. Although it is generally considered to be an isotropic rock with a high primary porosity, in most Chalk areas the value is only high when compared to values for more crystalline limestones. The primary porosity of Chalk ranges between 14.4 - 46.0% (Bögli, 1980), with the higher values in this range (43.9 - 46.0%) occurring in English Chalk. This compares with primary porosity values of 0.67 - 2.55% for limestones in general (Bögli, 1980). Primary porosities for sandstones, the most widely exploited aquifer lithology, range between 3.32 - 39.8%, indicating that even the most compact sandstone is more porous than unfractured crystalline limestone.

Most authors (eg Bögli, 1980; Smith and others, 1976) point out that the actual percentage porosity is generally of lesser importance than the pore size in contributing to rock permeability. However, Smith and others (1976) record the primary permeability of Chalk (ie permeability due to primary porosity) as 1.5×10^{-4} to 3.7×10^{-3} m/day, a value which is at least partially coincident with values for clay, quoted by the same authors as 1.0×10^{-5} to 2.3×10^{-3} m/day. The total permeability for Chalk is 1.5 to 15 m/day, five orders of magnitude higher, supposedly due to the presence of open fracture zones. Thus it appears that the significance of pore size might be relatively less important under some circumstances. A broad view of the relative values for primary and secondary porosity, pore size and permeability for common carbonate lithologies is provided by figure 1, reproduced from Smith and other (1976, Fig. 6.3.).

On the stark evidence of figures quoted above it is unreasonable to assume that the diffuse flow through the primary pores within a Chalk mass would exert greater influence of overall water transmission that even sporadic fracture systems. If such sporadic fracture systems exist, and if they account for a dominant proportion of groundwater flow in the Chalk there is no possible argument that a lack of concentrated fissure flow accounts for the lack of cave development in the Chalk. Two broad, *ab absurdum,* possibilities remain; there must be another reason why caves do not form in the Chalk, or caves (*sensu* Lowe, 1992) must exist in the Chalk!

Another element within the mythology of why caves are uncommon in the Chalk is that the rock has insufficient strength to support a roof. Such a belief is patently unrealistic. If one is to accept that the roof of any dissolutional void formed within the

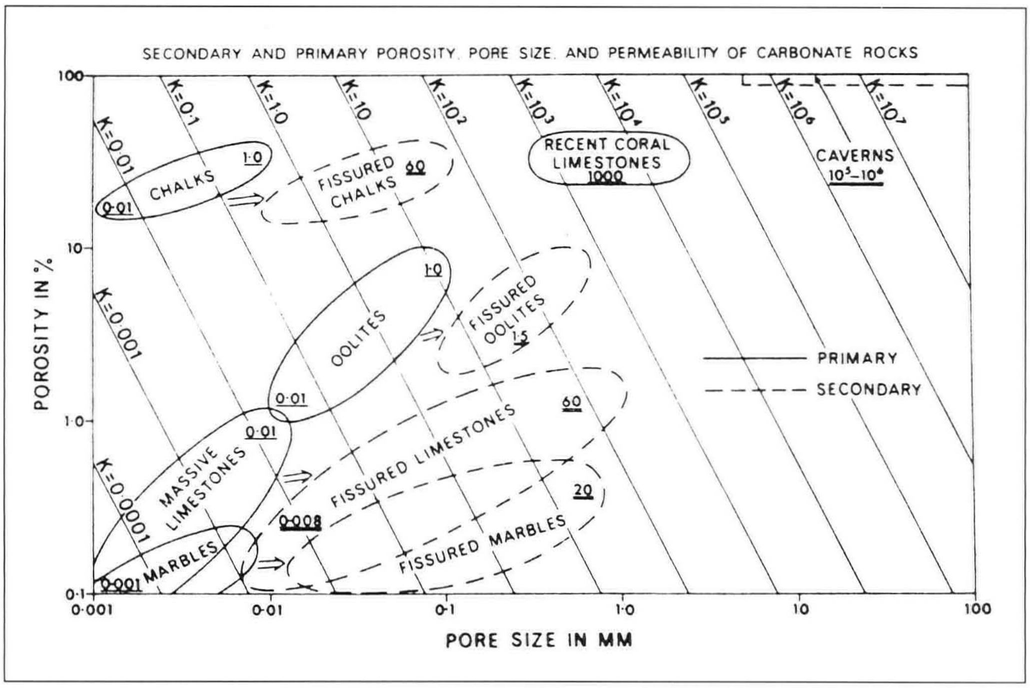

Figure 1. Porosity, pore size and permeability values for carbonate rocks. Contour values of K, the theoretical permeability, are based upon the assumption that the rock behaves as a bundle of straight, parallel capillary tubes. Values shown underlined indicate the general range of permeability found in the lithology concerned. Double underlining indicates total permeability, single underlining primary permeability. (Reproduced from Smith and others, 1976, Fig. 6.3).

Chalk will spontaneously collapse, one must also accept that collapse into a void will also create a void. Unless such voids are to propagate to the land surface (or the top of the Chalk in buried sequences) it must be accepted that caves and conduit flow will continue to exist. Moreover, examples of Chalk caves do exist. Many of these are accessible for exploration and range between relatively unmodified dissolutional tubes and spectacular 'sea-caves' such as those at Flamborough in Yorkshire. The attribution of the formation of the latter examples to marine (corrasional) erosion is in itself open to some debate, since ramifications of some exhibit classical 'Bretzian' dissolutional features (cf Bretz, 1942), but whatever their origins they demonstrably support extensive roof spans, up to 20 x 30m according to Reeve (1982). Additionally the Flamborough Chalk appears to be a highly indurated rock, comparable in aspect with rocks which are cavernous and which do not suffer destructive breakdown in other areas.

The Chalk of England (and France) is an important aquifer. Consideration of figures for primary and secondary permeability discussed above suggests that the more efficient wells must exploit fissure rather than diffuse flow. In a study of the Water End swallow hole complex near North Mimms in Hertfordshire, Walsh and Ockenden (1982) reported that these sinks could abosrb up to 1 cumec of surface drainage before overflowing. The sinking water is reported to travel south-eastward within the axial trough of a gently syncline with a flowrate which averages 5500 m/day. Lowe (1992, chapter 8) discusses the potential advantages of synclinal cores as favoured routes during the early stages of speleogenesis, the core zone theoretically possessing a greater number of more open fractures than the adjacent fold limbs. Walsh and Ockenden (1982, p.191) report that the flowrate from Water End indicates the presence of open, dissolutionally widened fissures, *"despite the fact that the structure is synclinal".*

If significant quantities of water do flow in such fissures, why should dissolutional development of the fissures, and hence cave development, be limited? One answer which must be given serious consideration is that the chalk, *en masse,* is simply too pure to support speleogenesis. In the exposed situation meteoric water falling upon the Chalk surface is absorbed homogeneously, via the primary pores, and loses its aggressiveness in the near surface zone due to dissolution of calcium carbonate. Thus dissolution of the Chalk outcrop will be effectively restricted to a gradual lowering of the surface. Sinking deeper into the rock there can be no mechanism for renewing its dissolving power within pure, unfissured rock. If diffuse flow encounters flow in fissures it is possible to envisage an increase in aggressiveness due to groundwater mixing (Bögli, 1964a,b). If such mixing occurs, renewed dissolution will be possible along the fissures, which will provide a mixing zone, and thus fracture-guided conduits would be expected to develop. Trevor Ford (oral communication, 1992) has noted natural chimneys in the roof of mined passages in Chislehurst "Caves", an old chalk mine in Kent. These chimneys were shown to be dissolutional, rather than tectonic, by the presence of flint bodies, left undissolved and protruding from the sides of the voids. It is important to realise, however, that such fissure-guided development may be fed by diffuse flow and debouch by diffuse flow, even assuming that the underground flow is in a geo-hydraulic system which necessitates emergence of the captured meteoric water. However, Waltham (1975) points out that there was a notable lack of seepage within an extensive Chalk cave he explored in France. Thus the caves developed along the fracture zones need never be obvious at the surface and would be equivalent to the *"nonintegrated caves"* of Ford and Ewere (1978). Waltham's (1975) observation that, of the many Chalk caves known in France, including at that time one 1900m in length, not one had a natural entrance, is clearly significant in this context.

Folklore associated with well-sinking suggests that in the past, if not so commonly in modern times, dowsers were employed to locate potential targets. These dowsers were reputedly able to pin-point suitable sites where 'conduit' flow would be intersected by wells or bores. Again according to the same folklore, wells sunk at such dowsed sites commonly intersected not only zones of fracture flow, but also water-filled, dissolutional tubes. Such tales are more common in France (eg Waltham, 1975) than in England, but is is unclear whether this reflects differences in the Chalk lithology, its depth of burial, a greater faith in dowsing in France, or a greater ability to create believable folklore. Whether or not there is any substance to the 'art' of dowsing, it is difficult to dismiss the implication that an unknown proportion of water wells into the Chalk have encountered dissolutional voids and that at least some of these cavities must have been guided by bedding partings rather than fractures.

In this context the question of bedding-related inception horizons existing in the Chalk must be considered. Bedding planes are locally common in the Chalk. Also present are deposits of flint, which occur as scattered nodules, tabular masses or, less commonly, continuous but irregular 'sheets'. Beds of marl or marly chalk are also found at some levels within the Chalk, and nodules rich in pyrite or marcasite occur, particularly in the Lower Chalk. Each of these non-typical deposits within the Chalk, even if appearing discontinuous, marks some kind of depositional hiatus and, hence, probably corresponds to a zone or non-typical chemistry within the otherwise fairly pure and homogeneous carbonate sequence. A slightly different possibility, though still reflecting lithological variation within the Chalk, is that some beds within the succession are more prone to fracturing during gentle folding than the majority of the rock mass. Beds locally referred to as Chalk Rock, were apparently a favoured target for well sinkers (Treveor Ford, oral communication, 1992) since their relatively highly fractured state within the otherwise uniform Chalk sequence provided higher yields than adjacent beds.

The present author's knowledge of Chalk caves is restricted to those examples, mentioned in passing above, commonly considered as *"sea caves",* at Flamborough, east Yorkshire. There is no significant dataset upon which to base even the broadest speculation concerning the role of bedding planes *sensu lato* or inception horizons. The Flamborough sea caves exhibit features which are certainly dissolutional, though the dissolution may be wholly or in part due to the action of saline water (cf Gillott, 1978 and Lowe, 1992, section 7.4.5.) rather than by 'normal' speleogenetic mechanisms. It is impossible to avoid comparing Chalk caves such as these with seashore caves in the tropical/sub-tropical environment, where formation has been by dissolution at the freshwater/saltwater interface and where the caves have subsequently moved into a cliff-line location due to uplift (cf Ollier, 1975). A survey elevation of a Chalk cave provided by Reeve (1977) bears a close similarity to elevations of certain littoral caves in Tonga (Lowe and Gunn, 1986), though this may simply be an example of convergent evolution. The questions of whether dissolutional mechanisms similar to those active in tropical and sub-tropical littoral zones might apply in suitably porous lithologies within temperate climatic belts or whether ancient voids formed by this process could survive later tectonic events are considered no further at this point.

Within the Flamborough caves, which can be seen to owe their origins to processes other than or additional to the various effects of wave action, minor inputs of fresh water appear from bedding plane guided sub-conduits at the landward limit of some caves. Though these limited trickles cannot be considered to prove the existence of dissolutional caves of anthropocentric dimensions within the Chalk, they might provide evidence for the potential for speleo-inception along bedding planes. In discussing the Flamborough caves, Reeve (1982) suggested that relict cave systems similar to those explored near Beachy Head (Reeve, 1981) might exist beneath the Yorkshire Wolds. He noted that the Yorkshire Chalk is harder than that in southern England, and compared the possibilities of caves existing to those in France, where (he states, with no reference) caves up to 5km long have been explored in the Chalk. Whether such development would involve inception horizon chemistry as discussed above, and whether this chemistry is related to marly beds, flinty horizons, horizons with pyrite/marcasite nodules, poorly recognised cycle boundary conditions or relict features due to syngenetic processes cannot be deduced on the scanty available evidence.

Rarer than caves of the Flamborough type, purely dissolutional caves have been reported, generally where passages have been truncated by cliff line retreat. Data are limited, but examples such as the Seven Sisters Cliff caves, other caves between Birling Gap and Beachy Head (Reeve, 1976 and 1977) and especially Beachy Head Cave itself (Reeve, 1981), appear to indicate that bedding guidance, whether of inception horizon or not, is important, if not crucial to dissolutional cave development in the Chalk. In Beachy Head Cave, more than 370m of cave has been explored from where the retreating cliffs have intersected a bend in a major passage, and ending inland at a water-filled section. Most of the explored passage is sub-horizontal (bedding-parallel) and follows a thin seam of tabular flint. Various drops/rises in the passage are due to displacement of this same horizon by minor faults.

Chalk in Ireland has not been discussed above, yet it provides one of the most striking examples of a Chalk cave known outside France. Campbell (1984) describes an active cave system more than 500m in length which is entered from a stream sink that normally swallows sufficient water to block entry to explorers. No details of geological features are given, but the cave is stated quite clearly as having formed without any maritime influence. Passage dimensions locally reach 6 x 2m, and the complex system includes several flooded (sump) sections. This description, when examined in parallel with that of Beachy Head Cave (Reeve, 1981) strongly suggests a cave which is guided by one or more favourable horizons within the Chalk, in which the susceptible horizon has been translocated by minor faults.

Limited cave development in the Chalk of Devon has been reported (Proctor, 1984). Though the detail provided is not substantial, it appears that these caves too are at least partly of dissolutional origin. No evidence in support of stratigraphical guidance is included.

From the above it is possible to speculate that conduit formation can take place in rocks such as the Chalk and may certainly focus upon fractures and possibly upon suitable bedding planes. Such conduits need not be integrated to either input or output points but may be fed by and feed into zones of diffuse drainage. The counterpoint of this argument is that the dominant reason for a commonly reported lack of cave development in the Chalk might be the purity of much of the Chalk sequence and the inadequacy of carbonic acid dissolution by meteoric water for dissolutional processes at depth. Even where mixing conditions or suitable inception chemistry are available, the aggressive waters generated are less efficient than those in less pure sequences. The importance of mixture dissolution must be assumed to be minimal in the Chalk context, since the co-existence of fissure flow (which is well documented) and seepage through rock of high primary permeability **ought** to provide ideal conditions for such activity. The apparent lack of large-dimension phreatic tubes therefore suggests that mixture dissolution is not an extravagant process in this context.

Permian and Jurassic carbonates

Arguments discussed above with regard to the Chalk may be equally applicable to pure carbonates of other ages, such as the Permian *"Magnesian Limestone"* and carbonates within the Jurassic Inferior Oolite and other formations. Relatively few dissolutional caves are recorded from beds of these ages in Britain, and little geological study of known examples has taken place. Herne Hill Cave at Maltby in Yorkshire is a relatively small system which is totally dissolutional in origin. It owes its location to a joint plexus in the core of a small fold, and the joints have guided much of the known cave's vertical development. Whether the cave's stratigraphical position close to the top of the *"Lower Magnesian Limestone"* (now part of the Cadeby Formation) has any bearing upon the dissolutional activity is unknown, but an undated and unpublished report by Lowe on behalf of the Institute of Geological Sciences (now the British Geological Survey) points out that a single bedding plane has exercised significant guidance of the cave's development. Both Herne Hill Cave and a similar dissolutional system nearby (Herne Hill Cave II) have only become accessible due to human activity in excavating surface rock prior to construction work. This and the more general lack of accessible dissolutional caves in the Magnesian Limestone presents an interesting parallel with situations in the Chalk discussed above.

As with the Chalk, relatively few dissolutional caves have been described within the Jurassic carbonates of Britain, though the number which are known are not insignificant. Of these, only a small proportion have been adequately surveyed and even fewer have been examined geologically. Those of the Portland area appear, on the basis of unpublished data (Ford and Hooper, 1964; Graham and Ryder, 1983) to be guided by stratigraphical as well as structural factors. Much of the roof of Sandy Hole, Portland, for instance, is formed by a continuous chert horizon, indicating that development was below, rather than above, a bed which might traditionally have been regarded as an aquiclude and a suitable site for the development of perched dissolutional passages.

Conclusions

Although few caves of anthropocentric (explorable) dimensions are currently recorded in the Chalk of the British Isles, there appears to be no reason why others should not exist, awaiting discovery. Those coastal Chalk caves traditionally considered to be the product of marine erosion may owe at least their initial development to dissolutional processes and may still connect to dissolutional inception systems, currently too immature to allow human entry. However, the immature, non-integrated nature of these (sub-) conduits does not disallow the potential presence of caves of explorable dimensions within the exposed or buried Chalk successions inland. Pending dissolutional enlargement of the currently immature links, or their removal by more extreme processes such as cliff-line retreat, however, the caves in the hinterland may be water-filled. Assuming the presence of such potentially explorable caves, it seems that their positions may be at least partly guided by fracture zones which provided an initial secondary permeability within the rock mass. Superimposed upon this fracture guidance there may be an element of bedding-related guidance due to the presence within the otherwise uniform rock mass of **inception horizons.** These have provided, and continue to provide, suitable chemistry to enable ongoing dissolution within the phreatic zone. If these arguments are applicable to the problem of the apparent lack of caves in the British Chalk, similar arguments may be at least partially applicable to older Jurassic and Permian carbonates.

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Forum

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

TYPE LOCALITY OF MONDMILCH

Hans FISCHER

Today, Mondmilch is an established and accepted term in speleology for (calcitic) speleothems. Earlier, Mondmilch was used as a medicament (Gesner, 1555; Sennert, 1667; Lang, 1708; Kappeler, 1767). Whereas the etymology of the term Mondmilch (Bernasconi, 1959; Heller, 1966; Fischer, 1988b), the terminology (Gèze & Pobeguin, 1962; Bernasconi, 1981; Hill & Forti, 1986), and the geneses of the deposit are contradictory (Caumartin & Renault, 1958; Gèze, 1961; Bernasconi, 1961; Pochon *et al.*, 1964; Bina, 1982; Fischer, 1988a), the site (type locality) of the first described (Gesner, 1555) Mondmilch is known.

Mondmilch (lat. Lac Lunae), a calcite speleothem was first described by Gesner (1555) from the cave Mondmilchloch (=moonmilk hole), now considered as the type locality (Fischer, 1987). Thus, the term "Mondmilch" should be used for carbonate speleothems only, and not for sulphate, phosphate or even silicate speleothems as proposed by Hill and Forti (1986).

The cave is situated on the South side of the Widderfeld at Mt. Pilatus, Alpnach in the Canton of Obwalden, Switzerland. The entry is reached by a difficult path, after the snowmelt, generally from July on. The cave Mondmilchloch is a historically prominent site (Scheuchzer, 1752; Fischer, 1987) for which three plans exist from three different centuries (Kappeler, 1767; Schär, 1894; Fischer, 1987, 1992; Fischer & Militzer, 1988).

The altitude of the entry was wrongly recorded as 1800m until the 20th century. The correct altitude for the cave entry is 1710m a.s.l. (Fischer, 1983, 1987, 1992; Fischer & Militzer, 1998) and the coordinates are 659'690/202'000 (Map sheet 1170, Alpnach, LK 1:25'000).

Genesis of Mondmilch

Mondmilch sensu stricto is a microcrystalline or cryptocrystalline calcite cave deposit and can be determined by optical methods and X-ray analysis. In a humid or wet state Mondmilch is spongy and plastic (Fig. 1), desiccated Mondmilch is white and hard (approx. hardness 3 on Moh's scale). Macroscopically, it has often a cauliflower-like appearance and is formed either by accumulation in layers on older Mondmilch deposits or by one of numerous hypotheses. Mondmilch from the cave Mondmilcloch at Pilatus is calcite carbonate (>95% $CaCO3$) (Fischer, 1988a).

With respect to the historical importance and according to mineralogical findings, the term Mondmilch should be reserved exclusively for calcite deposits. Since Mondmilch is formed primarily in a two-phase system (liquid/solid), but subsequently appears quite desiccated, it is necessary to include a precise specification for desiccated Mondmilch as well. In addition, criteria to unequivocally determine Mondmilch must be simple and measurable.

Mondmilch sensu stricto (= calcite moonmilk) is a calcite, microcrystalline or cryptocrystalline speleothem, which is formed primarily as a two-phase system (liquid/solid) with a minimum calcite content of 90 weight%. A carbonate speleothem of less than 90% calcite should be designated as a mondmilch-like deposit or as moonmilk. All other subterranean deposits, e.g., sulphates, phosphates and silicates, should not be related to the word Mondmilch nor to moonmilk.

Zusammenfassung

Die Typuslokalität der erstmals von Gesner (1555) erwähnten Mondmilch ist die Höhle Mondmilchloch und befindet sich am Süd-Pilatus (Gemeinde Alpnach, Kanton Obwalden, Schweiz). Der Höhleneingang liegt auf 1710m über Meer mit den Koordination 659'690/202'000 und die darin vorkommende Mondmilch ist ein kalzitisches Speleothem (>99% $CaCo_3$).

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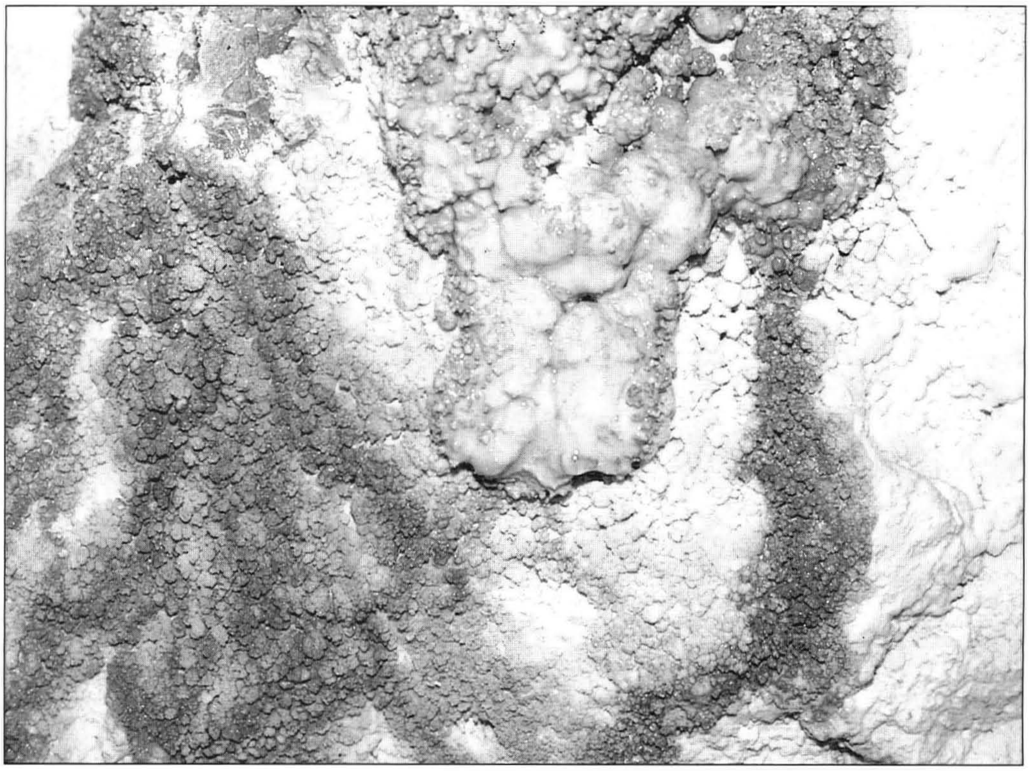

Figure 1. In situ formation of wet Mondmilch surrounded by older and desiccated Mondmilch.

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JAMES PLUMPTRE'S VISIT TO THE SPEEDWELL MINE, CASTLETON

Trevor D. FORD

The published accounts of visits to the inner regions of the Speedwell Mine and Caverns by the 18th century writers Bray (1777 & 1783), Sulivan (1780), Pilkington (1789) and Hatchett (1796, in Raistrick 1967) are well known, but unfortunately, with the possible exception of Pilkington, they are either too vague or exaggerated to be sure exactly what they are describing or even whether they are describing the same place. As discussed by Rieuwerts & Ford (1987), Marsden (1991) and Ford (1991), it has seemed likely but not proven that the cave systems descending from the hill-top to the Speedwell stream caverns noted by Bray, Sulivan and Hatchett were something separate from Pilkington's Cavern, which was climbed by Shaw (1983a & b). Martyn Farr's discovery of the Far Sump Extensions in Peak Cavern (Cordingley & Farr, 1981) with evidence of the old lead miners' activities therein has raised speculation about the possible relationship to an as yet unknown connection to Speedwell's workings though the route by which the miners entered Stemple Highway in Far Sump Extension has still not been found.

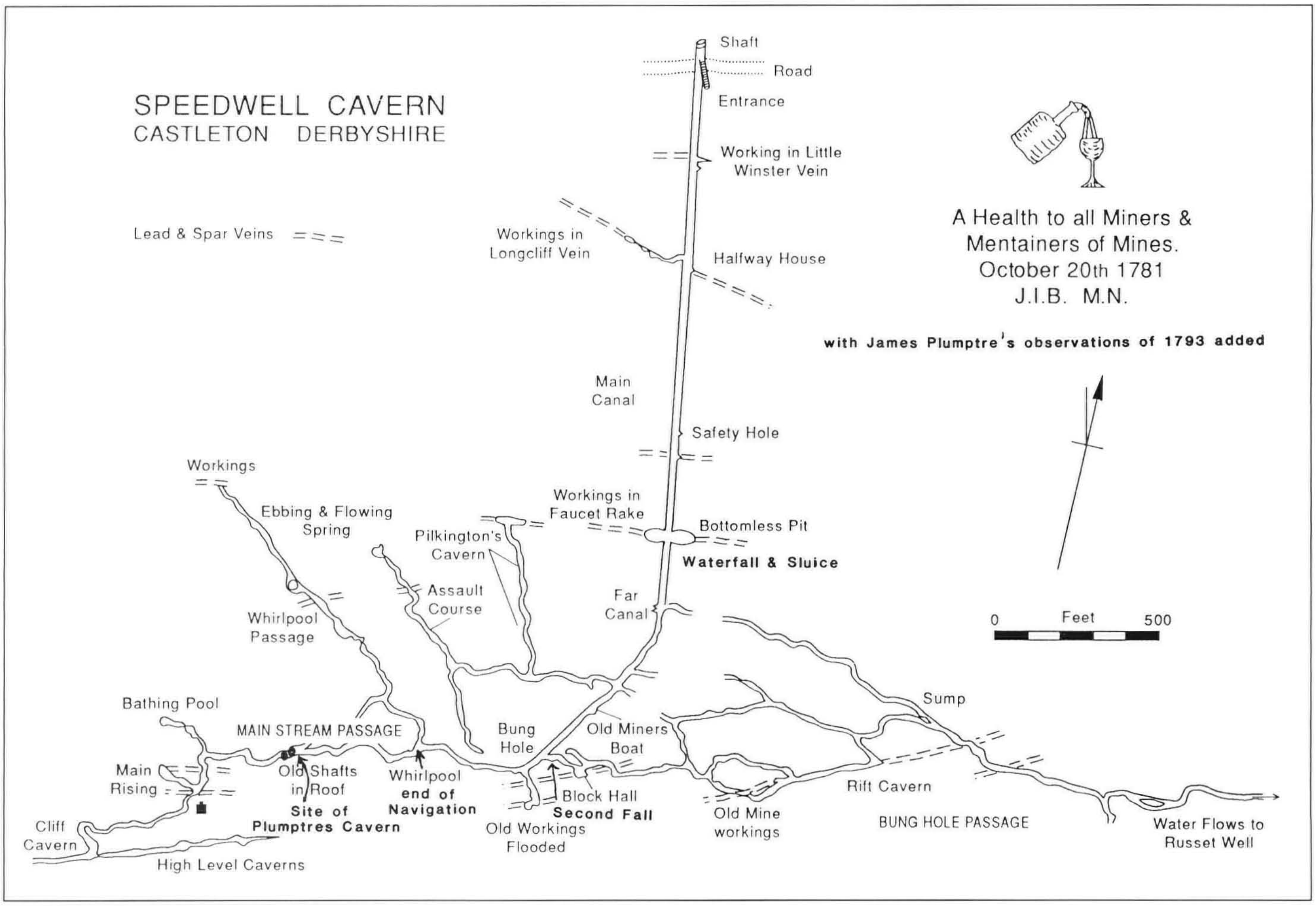
A hitherto unknown manuscript account by James Plumptre (Cambridge University Library manuscript collection Add. 5804) has recently been published by Ian Ousby (1922) and it throws sufficient light on the problem to warrant reproduction in full below (by kind permission of Ian Ousby). Some notes on James Plumptre and his tours provide necessary background.

James Plumptre was born on October 2nd 1771, the tenth child of Robert Plumptre, President of Queens College, Cambridge. He became a student at Cambridge University though later transferring his allegiance to Clare College. He graduated in 1792 and at first took a strong interest in theatrical matters, though later he was ordained and entered the church. After a few years a few miles south of Cambridge at Hinxton, he took the living of Great Gransden some 12 miles west of Cambridge in 1800 and remained there until his death on January 23rd 1832. He published some 33 works mainly on religious, theatrical and social matters and left a variety of manuscripts, some apparently intended for publication. Plumptre's tours covered much of northern and western Britain and he apparently liked theatrical scenery: Dovedale, Malham Cove, Gordale Scar, Weathercote Cave and Yordas Cave were visited and receive fairly detailed comment. Man-made wonders such as Chatsworth House did not really attract him. His manuscripts stayed in the vicarage at Great Cransden until they were passed to Cambridge University library in 1914. From his student days Plumptre embarked on a series of tours of various parts of Britain. Although he used stagecoaches at times most of the tours were on foot and he walked remarkable distances. He kept careful journals of most of his tours, and they have now been published by Ian Ousby and make fascinating reading. As an apparent "gentleman" though carrying a back-pack, he was treated with great suspicion by innkeepers. Some of the tours were solo, others accompanied by his college tutor John Dudley, and some by his dog, Rover.

Plumptre's Derbyshire tour was in the company of John Dudley and took place in the year after graduation, when was aged 22, on August 20th to 31st 1793, starting and finishing at Humberstone near Leicester. After visits to Poole's Cavern at Buxton and to Peak Cavern, on which his journals do not add much to what we know already, he went to an unnamed "Lead Mine" obviously the Speedwell, on Saturday 24th August 1793 and his journal recorded the visit thus (pages 69-71 of Ousby's book):

"On our return from seeing the Peak Cave, our Guide told us, that, if we were fond of sights of the kind, there was a *Lead Mine* not far off, which was well worth our notice. We assented to his proposal, and returned to the Inn to get our dinners; and, in the meantime, he went and brought one of the Miners to conduct us. The miner told us it was usual to take brandy on account of the cold; we took some, therefore, with us in a bottle, and set forward to the mouth of the mine, where we saw great quantities of lead ore ready prepared for smelting[1] and the people employed in their various departments. It was four o'clock, the time the miners come from out the mine: the women, we observed, wore breeches[2]. Here another Miner joined us, who was also to be the companion of our excursion. He was one of the stoutest men I ever saw: the very picture of health, well proportioned, and his muscles seemed of Herculean strength. It does not appear, from what we saw, that working in the mines is, as has been said, prejudicial to the health of either man or woman. They offered us miner's dresses, but, as we had our plaids on, we thought ourselves proof against wet, dirt or cold, and therefore declined them. The two miners[3] then put on their dresses, and my friend and I set forward with them.

We entered a hut at the side of the hill, where our guides provided themselves with lights, which they carried in their hands by sticking several in a lump of clay, and then proceeded down steps for near fifty yards, till we came to a canal[4]. This navigation is through a cavern cut in the rock, seven feet high, and four wide[5], the water about three feet, the length is 1000 yards. The miners have five guineas for every two yards[6], which they work by blasting the rock with gunpowder. We entered a boat, and my friend and I had each a chair to sit upon, our guides sitting one at the head, the other at the stern. When we had gone 600 yards[7], we came to a large natural cavern in the rock, where there was a most dreadful roar of waters; we stopped here to see a waterfall from an artificial dam, to keep up the level of the water through the navigation. One of the men pulled up the sluice, and the roar, added to the solemnity of the scene, was dread and awful[8]. Hence we went 250 yards to another fall[9], nothing to be compared to the former: this joins the other after running some little way, and the joint stream runs under the ground till it finds its way into the Peak cave[10]. The whole course of this stream is wonderful; it loses itself underground about four miles from Castleton, on the Manchester road, runs through this mine, and afterwards through the Peak Cave, whence it again merges to light, and takes it course through Castleton, Hopedale, &c. By means of this stream, there is a constant current of air through the mine, which keeps it free from any noxious vapours, which would otherwise be dangerous to the miners. One hundred and fifty yards farther brought us to the end of the navigation[11], when we chained our boat to a rail; and, with each of us a light, proceeded upon planks[12], laid upon rafters over the stream, for two hundred and fifty yards farther, stoping[13] almost all the way. At the end of this board-way, we got to a small cavern[14], and there stood upright to rest ourselves. The Miners here told us, that, if we went farther, we must climb up the rock by rails fixed into the side: that many went no farther than this place; but, if we were not afraid, we might proceed. We told them to lead on. We climbed for ten yards up the rock, by rails sometimes a yard asunder; and at length got into a large cavern dimly to be seen by our candlelight: that dashing noise of a waterfall[15], to be heard and not seen, added to the terror of the place. Here our guides again asked us if we would proceed. telling us it was forty yards[16], climbing up the same manner we got hither, to the shaft they worked at. They looked in our faces (as they told us afterwards) to see if we were frightened, but we were determined to go on; and, with much labour and difficulty, got to the end of our scrambling, which was sometimes through holes in the rock just big enough to admit the body. Here we saw the waterfall which dashes with a large stream from the top to the bottom of the cavern[17]. From this place we went on slanting up the rock ten yards to the place they worked at[18]. We stopped to rest and take some of our brandy, which we found refreshing, and



the miners explained the whole process of their work. We each worked out a piece of ore, as a memento of our expedition. The air here was unpleasant, the smell of smoaking and of gunpowder, used in blasting the rock, being not yet gone off. There was another way out, by climbing one hundred and fifty yards farther to the top of the hill; but, as the way lay through another proprietor's mine,[19] the miners never go by it, unless insisted upon by strangers; and, as we were somewhat fatigued with the exertions of the day, we judged it best to go back as we came. At the top of the cavern, the place we left off climbing, one of the men left a piece of candle alight, which we had brought for that purpose, and we went down, a miner accompanying each to direct our steps in the retrograde motion. We soon got to the bottom of the cavern, and our guides told us to look up. The sight was dreadful: the candle, forty yards above us, appeared like a star, and afforded a dim light just sufficient to give an idea of the danger we had braved. The cavern was sloped like a Bee-Hive,[20] the way to the top was by the stakes fixed into the sides sloping inwards, sometimes by ladders, many of the steps of which were nearly worn through, and only a slight balustrade, so that one false step, or the breaking of a rail had dashed us lifeless to the bottom: but all danger was now passed, and we congratulated ourselves that we had escaped it. The miners frequently go up this way *without lights*. They told us that there never was but one accident happened in this mine, when a man was drowned owing to his own groundless fears. We returned to the boat, and set forward again for daylight in high spirits, singing "God Save the King", "Rule Britannia", and a variety of songs, in which we all joined; the miners, (one of them in particular) having very fine voices. At the large cavern I first mentioned, we left another light; which, when we got to the end, (600 yards) had a most beautiful effect, appearing like a star with the beams playing upon the water. We, at length, after two hours absence from it, got to daylight again,[21] highly satisfied, and pleased with our excursion, and returned to Castleton, with the mixed emotions of terror and admiration."

Notes

1 "... great quantities of lead ore ..." ... this sounds more than Speedwell is known to have produced.

2 "... women ... wore breeches" ... confirmation that women worked at this mine, hinted at but not previously recorded.

3 "... two miners" ... Jim Rieuwerts says the following were working in Speedwell then: John Ashton, Thomas Ashton, Henry Barber, James and Joseph Hadfield, Isaac Royse, William White and John Wilson. As Joseph Hadfield was the guide by 1810 it seems likely that Plumptre's guides were one of the Hadfields and another miner from the above list.

4 "... steps ... to a canal ..." ... this confirms that the staircase was already in use during mining days.

5 "... 7 feet high and 4 feet wide" ... the height is reasonable, actually 6 ft 9 inches on average, but 4 feet wide is inexplicably too narrow; it averages 6 ft 6 inches.

6 "... £5-5-0 for every two yards ..." ... this confirms Bray's figure.

7 "... 600 yards ..." ... actually nearer 500 yards.

8 "... artificial dam ... sluice ... roar ... dread and awful" ... clearly the Bottomless Pit Cavern and cascade, but the lack of mention of leaving the boat confirms my previous idea that the Pit was crossed by an aqueduct, which would have been necessary to ship lead ore out and to dispose of waste rock into the Pit anyway.

9 "... 250 yards to another fall" ... this refers to the Bung Hole waterfall; obviously they did not descend it.

10 "... into Peak Cave ..." ... not strictly accurate except in flood conditions.

11 "... end of navigation ..." ... clearly the Whirlpool crossing!

12 "... planks ..." ... the plankway laid above the Main Stream up to the Boulder Piles; stemple holes for the supporting cross-beams can still be seen a foot or so above water. Unfortunately Plumptre makes no mention of the mode of transport on the plankway: presumably the miners dragged corves (sledge-like boxes) full of ore over the planks. (The only alternative plankway from the end of navigation would be up the Whirlpool Passage but there is no route up into the roof there).

13 "stoping" ... presumably he meant stooping, which would have been necessary along at least part of the plankway.

14 "... small cavern ..." ... the chamber above the Boulder Piles. There is nothing in Plumptre's account to suggest that they went beyond the Boulder Piles or to Cliff Cavern. Instead they climbed 10 yards up some route no longer accessible, presumably through one of the holes in the roof now seen to

be choked; this would probably take them up to the higher bedding plane level with the floor of Stemple Highway in Far Sump Extension.

[15] "... the dashing noise of a waterfall" ... the shower of drips from the roof chokes above the Boulder Piles is hardly big enough to explain this and it may have been that he heard (and later saw) either the inlet stream which falls down the 30 metres high Vortex III pitch in Far Sump Extension, or the apparently separate feeder to the Stemple Highway Inlet.

[16] "... proceed ... 40 yards ..." ... apparently on stemples; a hitherto unknown chamber above the Boulder Piles.

[17] "... waterfall ..." ... see Note 14 above.

[18] "... slanting up the rock 10 yards to the place, they worked at." ... this could have been either the E-W New Rake, the closely parallel Horse Pit Rake or the NW-SE vein through Stemple Highway, though only New Rake is recorded as producing ore in 1793.

[19] "... another way out by climbing 150 yards ... by another proprietor's mine," ... this could be James Hall's Over Engine mine — the engine shaft with an iron lid just west of the New Rake enclosure, operated in the 1790s by Micah Hall. This was descended in the 1960s by the Technical Speleological Unit, and it raised the question as to whether some route down into Plumptre's systems was missed through being blocked or covered. Some allowance for sideways movement must be made as Hall's mine is not directly above the Boulder Piles.

[20] "... candle, forty yards above use ... cavern sloped like a Bee-Hive .." this large cavern still awaits re-discovery by modern cavers!

[21] "... after two hours absence from ... daylight ..".. quite a trip for only 2 hours!

The importance of Plumptre's account is in confirming the presence of a plankway up the Main Stream Passage to the Boulder Piles and to caverns and workings high above these, long suspected but no longer accessible. If the distances quoted by Sulivan and Hatchett are anything to go by there could be an extensive series of passages here. Plumptre's account also provides us with an incomplete description of the entrance from the hill-top reported by Bray, Sulivan and Hatchett, now clearly different from that descended by Pilkington. Such an entrance to the Speedwell stream caverns was probably available before the canal tunnel existed and was a prime reason for its excavation. Though there are some discrepancies in measurements Plumptre's account is sufficiently accurate and objective for us to accept it at face value.

ACKNOWLEDGEMENTS

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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, polytechnics or research establishments. Information and applications for Research Awards should be made on a form available from S. A. Moore, 27 Parc Gwelfor, Dyserth, Clwyd LL18 6LN.

GHAR PARAU FOUNDATION EXPEDITION AWARDS

An award, or awards, with a maximum 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, Rowlands House, Summerseat, Bury, Lancs. BL9 5NF. Closing date 1st February.

SPORTS COUNCIL GRANT-AID IN SUPPORT OF CAVING EXPEDITIONS ABROAD

Grants are given annually to all types of caving expeditions going overseas from the U.K. (including cave diving), for the purpose of furthering cave exploration, survey, photography and training. Application forms and advice sheets are obtainable from the GPF Secretary, David Judson, Rowlands House, Summerseat, Bury, Lancs. BL9 5NF and must be returned to him for both GPF and Sports Council Awards not later than 1st February each year for the succeeding period, April to March.

Expedition organisers living in Wales, Scotland or Northern Ireland, or from caving clubs based in these regions should contact their own regional Sports Council directly in the first instance (N.B. the closing date for Sports Council for Wales Awards applications is 31st December).

THE E. K. TRATMAN AWARD

An annual award, currently £25, made for the most stimulating contribution towards speleological literature published within the United Kingdom during the past 12 months. Suggestions are always welcome to members of the GPF Awards Committee, or its Secretary, David Judson, not later than 1st February each year.

BRITISH CAVE RESEARCH ASSOCIATION PUBLICATIONS

CAVE 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.
Editor: Dr. Trevor D. Ford, 21 Elizabeth Drive, Oadby, Leicester LE2 4RD. (0533-715265).

CAVES & CAVING — quarterly news magazine of current events in caving, with brief reports of latest explorations and expeditions, news of new techniques and equipment, Association personalia etc.
Editor: A. Hall, 342 The Green, Eccleston, Chorley, Lancashire PR7 5TP. (0257-452763).

CAVE STUDIES SERIES — occasional series of booklets on various speleological or karst subjects.
Editor: Tony Waltham, Civil Engineering Department, Trent Polytechnic, Nottingham NG1 4BU. (0602-418418, ext. 2133).

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

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

No. 3 Caves & Karst of the Peak District; by Trevor Ford & John Gunn, 1990.

CURRENT TITLES IN SPELEOLOGY — annual listings of international publications.
Editor: Ray Mansfield, Downhead Cottage, Downhead, Shepton Mallet, Somerset BA4 4LG.

CAVING PRACTICE AND EQUIPMENT, edited by David Judson, 1984.

LIMESTONES AND CAVES OF NORTHWEST ENGLAND, edited by A. C. Waltham, 1974. (out of print)

LIMESTONES AND CAVES OF THE MENDIP HILLS, edited by D. I. Smith, 1975. (out of print)

LIMESTONES AND CAVES OF THE PEAK DISTRICT, edited by T. D. Ford, 1977. (out of print)

LIMESTONES AND CAVES OF WALES, edited by T. D. Ford, 1989.

Obtainable from B.C.R.A. Sales
B. M. Ellis, 20 Woodland Avenue, Westonzoyland, Bridgwater, Somerset TA7 0LQ.