Cave and Karst Science

The Transactions of the British Cave Research Association

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Cave and Karst Science

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

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

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

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Manuscripts may be sent to either of the Editors: Dr D J Lowe, c/o British Geological Survey, Keyworth, Nottingham, NG12 5GG, UK, and Professor J Gunn, Limestone Research Group, University of Huddersfield, Queensgate, Huddersfield, HDI 3DH. UK.
Intending authors are welcome to contact the Editors, who will be pleased to advise on manuscript preparation. Enquiries by E-mail are welcomed, to: d.lowe@bcra.org.uk or j.gunn@bcra.org.uk.

Notes for Contributors

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

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

If any problems are perceived regarding the nature, content or format of the material, please consult either of the Editors before submitting the manuscript.

Cave and Karst Science

TRANSACTIONS OF THE BRITISH CAVE RESEARCH ASSOCIATION

Volume 31, Number 3

Contents

Papers

Cover photo:

The Subway in Castleguard Cave, in the Canadian Rocky Mountains, is a splendid phreatic tube, almost dead straight for over 500 metres. It is formed along a bed-joint intersection in the gently dipping limestone. As part of a recognisable and descending phreatic trunk passage many kilometres long, this tube must have developed at a depth of some hundreds of metres below its contemporary water table [see the paper by Steve Worthington in this Issue].

Photograph by Tony Waltham.

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

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EDITORIAL

John Gunn and David Lowe

After an unusually long but completely unavoidable delay, we are pleased at last to be writing the Editorial to this final issue of *Cave and Karst Science*, Volume 31. A steady supply of fresh material is the lifeblood of any journal, and during the past nine months or so there has been an unprecedented dearth of submissions. Even now, with enough material accumulated to provide a viable and interesting issue, the famine continues. Despite the long delay, our hope is that there will be something to interest all our readers in this issue. Steve Worthington presents aspects of geology and hydrology, different facets of geomorphology are discussed by Ali Uzun and by Tim Stafford *et al.*, with cave ecology from Allan Pentecost and Zhaohui Zhang, historical science and modern dating techniques from Don McFarlane *et al.*, and cave history from Steve Craven. There is also a wide geographical coverage, encompassing the Mariana Islands, South Africa and Turkey as well as the Yorkshire Dales.

Sadly (from our viewpoint) this is likely to be the last Volume of *Cave and Karst Science* in the form that it has taken since 1994 when we took over as editors. Establishment of the British Caving Association (BCA) has introduced many positive benefits for British cavers but on the negative side there has been a dramatic fall in membership of the British Cave Research Association (BCRA), and hence in subscribers to this journal. As editors we have no direct involvement in financial matters but we understand that it will no longer be economical to produce printed copies of the journal. Current plans are that a small number of copies of the journal will be printed for libraries and for those members or subscribers who are prepared to pay a premium. Other members will receive the journal on CD, or possibly via the World Wide Web. Ultimately this is a decision for BCRA Council. Anyone with strong views should attend the Annual General Meeting and/or contact the BCRA Secretary and Chairman.

Production issues notwithstanding, our aim as editors is to continue to produce a leading scientific journal, with international content and appeal, for cave and karst scientists, whilst also providing a forum for British cavers to publish shorter works that may be of interest more to the local audience than to the international readership. To achieve this we need a steady stream of material and would again urge all British cavers who have an interest in scientific matters to send us their results and ideas, in the form of reports or short papers. As professional scientists as well as being editors of the journal, we remain committed to supporting cave science in Britain. Hence, we are strongly in favour of a suggestion that the BCRA should provide a series of annual undergraduate bursaries that would provide financial assistance for cave-related dissertations. One condition of these bursaries should be that the abstract be sent for publication in *Cave and Karst Science*. Ideally each award recipient should also write a brief report (or a full paper if they feel able). An example of what can be produced from an undergraduate dissertation can be found in *Transactions of the British Cave Research Association*, Vol.1(3), 1974, pp159–164, a submission that helped to launch the career of one of the editors!

As is customary in the final issue we thank all the reviewers who have helped us to evaluate and improve the papers submitted to this Volume: Marcus Buck, Ian Fairchild, Dave Gillieson, Rhian Hicks, Chris Hunt, Alexander Klimchouk, Allan Pentecost, Trevor Shaw, France Šušteršič, Tony Vann, Tony Waltham and Paul Wood.

Also, on the technical side, we once again thank our Desk Top Publishing associate, Rebecca Talbot, for somehow still managing to find the time to cope with this demanding task while at the same time dealing with the greater responsibilities and vastly increased work load of her new career track. We also express our gratitude to Steve Summers, Sales Director of the Sherwood Press, for his patience and, especially, for the individual attention and expert knowledge that he dedicates to our specific requirements and to providing a highly efficient interface between his colleagues and ourselves.

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Eogenetic karst development on a small, tectonically active, carbonate island: Aguijan, Mariana Islands.

Kevin STAFFORD [1], John MYLROIE [2], Danko TABOROŠI [3] and John JENSON [4]

[1] Department of Geosciences, Mississippi State University, Mississippi State, Mississippi, USA.
email: kwstafford@juno.com
[2] Department of Geosciences, Mississippi State University, Mississippi State, Mississippi, USA.
[3] Laboratory of Geoecology, School of Environmental Earth Science, Hokkaido University, Sapporo, Japan.
[4] Water and Environmental Institute of the West Pacific, University of Guam, Mangilao, Guam.

Abstract: Aguijan is a small carbonate island in the western Pacific Ocean on the tectonically active Mariana Arc. Eogenetic karst on Aguijan includes epikarst and caves that are controlled by the interaction of fresh and saline waters and brittle deformation. Epikarst proximal to coastlines (littoral eogenetic karren) exhibits jagged, irregular surfaces, while inland karren is more subdued, with metre-scale canyons present in highly fractured regions. Caves occupy two morphologically distinct classes, mixing zone and fissure caves, with different primary controls on dissolution, freshwater lens position, and structural features respectively. Mixing zone caves occupy distinct horizons reflecting previous freshwater lens positions. The decay of organic material trapped at density horizons and the mixing of fresh and saline groundwater at the margins of the lens produces mixing zone caves with globular chambers that are commonly interconnected. Fissure caves are linear caves that develop along planes of structural weakness associated with faults, margin failures and associated tension-release structures (i.e. joints). Although caves are primarily controlled by either mixing zone dissolution or brittle failure, specific sites show contributions of both controls on dissolution.

Horizons of karst development associated with island terrace levels suggest at least three previous sea-level stillstands. The absence of exposed non-carbonate (volcanic) rocks places Aguijan within the Simple Carbonate Island category for island karst development. However, island geomorphology and elevation suggest subsurface non-carbonate rocks modify freshwater lens morphology, which would place Aguijan within the Carbonate Cover Island category. Aguijan demonstrates the utility of the Carbonate Island Karst Model for describing and explaining caves and karst features found on small islands, although Aguijan's Liyang Atkiya, a cave of complex morphology that does not fit current models for island karst, suggests that more work is needed to understand fully the complex hydrology of small, tectonically active, carbonate islands.

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INTRODUCTION

Aguijan is one of seventeen islands in the Mariana Arc of the western Pacific Ocean, approximately 3000km east of mainland Asia (Fig.1). Aguijan is the second smallest of the southern six islands in the chain that contain volcanic, non-carbonate rocks mantled by carbonate rocks (Guam, Rota, Aguijan, Tinian, Saipan, and Farallon de Medinilla). The northern eleven islands are devoid of carbonate rocks (Cloud *et al.*, 1956). The Mariana Islands are governed by the Commonwealth of the Northern Mariana Islands (CNMI), with the exception of Guam, which is a politically separate United States territory.

Aguijan is currently unpopulated, but was inhabited beginning around 1500 B.C.E. when Chamorro people first settled the region. They remained the only inhabitants for over 3000 years, until Ferdinand Magellan claimed the Mariana Islands for Spain in 1521. Spain retained control over the islands until 1899, when they were sold to Germany to pay off debts from the Spanish–American War. During the beginning of World War I, Japan captured the northern Marianas and became recognized as administrator of the islands by the League of Nations after the War. Guam was administered by the United States until it was captured by Japan in 1941. In 1944, the United States liberated the Marianas during the Pacific War campaign of World War II, after which human occupation of Aguijan effectively ended. The island remained under United States control until 1975, when a covenant was signed between the people of the Marianas and the United States that made the Northern Mariana Islands a self-governing commonwealth, while Guam remained a United States territory (Hunt and Wheeler, 2000). Today, Aguijan functions primarily as a wildlife preserve governed by the Municipality of Tinian and Aguijan within the Commonwealth of the Northern Mariana Islands (Bormann, 1992).

Access to Aguijan is limited by the Department of Land and Natural Resources of the Commonwealth of the Northern Mariana Islands. In addition, the coastline contains no natural beaches or harbours to allow easy access. Geological studies on Aguijan have therefore been limited by island size, difficulty of access and absence of modern human habitation. No detailed geological map of Aguijan exists, and the work of Tayama (1936) conducted during the Japanese occupation remains the most detailed geological study. Other works briefly mention the geology in ecological and archeological studies (Butler, 1992). Karst and water resource studies have been limited to recent work and current studies (Stafford, 2003; Stafford et al., 2002). This paper is the first report to describe the karst development on Aguijan with respect to the Carbonate Island Karst Model (Jenson et al., 2002; Mylroie and Jenson, 2002; Mylroie and Jenson, 2001) and the controls on karst development imposed by geological structure and freshwater / saltwater mixing.

FIELD AREA

Aguijan is a small carbonate island located at 14.85° N latitude, with a surface area of 7.2km^2, 12.4km of coastline and a maximum elevation of 157m. In spite of the lack of previous geological study,

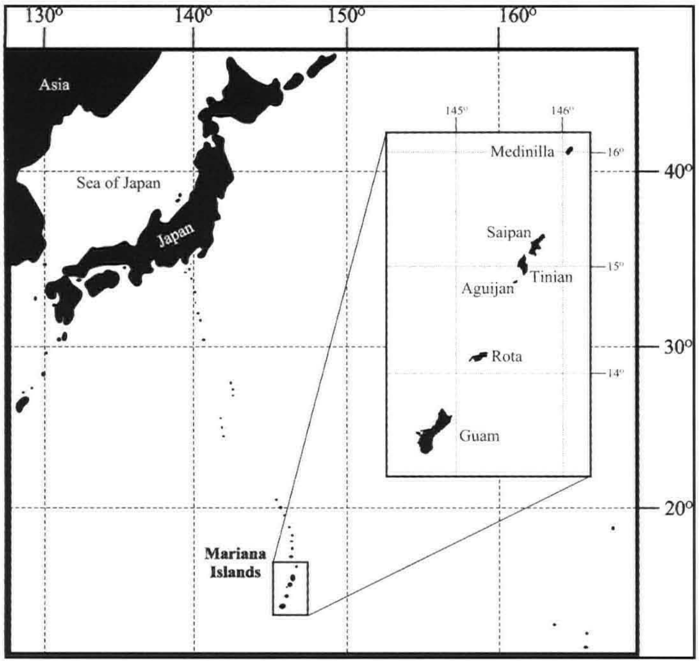

Figure 1. Location of study area, with carbonate islands of the Marianas shown in expanded view.

its close proximity to Tinian, Rota and Saipan suggests a similar geological history. Thus, the island probably consists of an Eocene volcanic edifice mantled by Miocene and Plio–Pleistocene coral-algal limestone. It is covered with dense tropical vegetation and has a distinct wet-dry climate, with a rainy season from July–September and dry season from February–March. Temperature ranges from 20° to 32°C with 2000mm average annual rainfall (Gingerich and Yeatts, 2000; Tracey *et al.*, 1964; Doan *et al.*, 1960).

Aguijan contains no beaches, but rather a coastline of scarps and cliffs. The general geomorphology of the island is similar to Carolina's ridge on Tinian and Tapingot peninsula on Rota, with three distinct terrace levels that occupy elevations of approximately 50, 100, and 150m. These have been defined by Stafford *et al.* (2002) as Lower Terrace, Middle Terrace, and Upper Terrace respectively (Fig.2). Although no volcanic rocks crop out on Aguijan, it is likely that the island has a basement of Eocene volcanic tuff and breccia covered by younger limestone units, based on the elevation of the island and its similarity to terraced regions on nearby islands. Limestone units on Aguijan are composed of algal and coralliferous facies that appear identical to the Plio-Pleistocene Mariana Limestone on Tinian (Doan *et al.*, 1960; Tayama, 1936). Limestone rocks exhibit high primary porosities and do not appear to have undergone extensive burial and diagenesis that would have induced greater compaction and cementation.

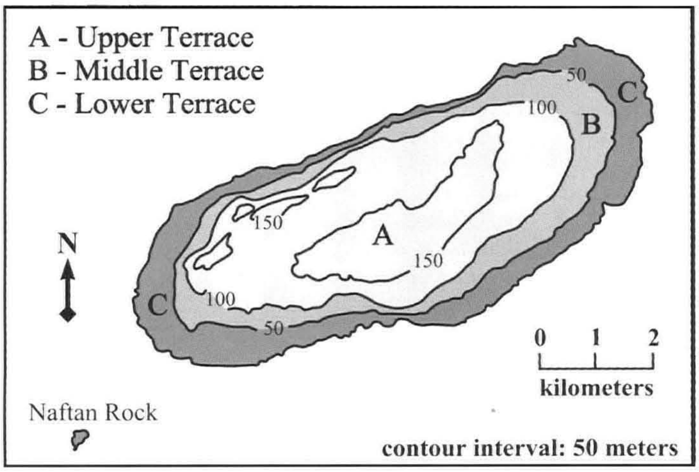

Figure 2. Map of Aguijan showing terrace levels (Stafford et al., 2002).

Terrace levels and coastlines on Aguijan are controlled by three factors: 1) original volcanic deposition, 2) original carbonate deposition and 3) structural deformation, primarily brittle failure. With no beaches, littoral erosion forming scarped coastlines is strongly controlled by structural deformation. Island uplift in the Marianas combined with coastal processes has produced three types of brittle failure: 1) regional faulting associated with island arc tectonism, 2) brittle failure parallel to scarps and cliffs associated with margin failures (i.e. unloading joints) and 3) brittle failure near-perpendicular to scarps and cliffs, associated with tension release structures that form in relation to margin failures (i.e. conjugate joints) (Stafford *et al.*, 2005; Stafford, 2003; Tracey *et al.*, 1964; Doan *et al.*, 1960). Additional deformation may occur from passive, isostatic subsidence, although that phenomenon is minor in the Marianas (Dickinson, 2000).

EOGENETIC ISLAND KARST

Karst forming on small carbonate islands and coastlines containing rocks that have not been buried beyond the range of meteoric diagenesis (i.e. eogenetic rocks) is unique from karst forming on large carbonate islands and in continental settings (Mylroie and Jenson, 2002; Vacher and Mylroie, 2002; Mylroie and Vacher, 1999). On carbonate islands, a freshwater lens forms in the aquifer on top of the denser seawater, extending about forty units below sea level for every one unit of hydraulic head above sea level (Mink and Vacher, 1997; Raeisi and Mylroie, 1995).

Eogenetic carbonate rocks have not been extensively cemented or compacted and retain much of their primary depositional porosity. Vacher and Mylroie (2002, p.183) define eogenetic karst as *"the land surface evolving on, and the pore system developing in, rocks undergoing eogenetic, meteoric diagenesis."* True island karst develops only in young rocks on small islands and coastlines that are affected by glacio-eustatic sea-level fluctuations, but which have not been buried beyond the range of meteoric diagenesis. Island karst is distinct from karst on continents and in the interior of larger carbonate islands, such as Puerto Rico, where karst development mimics continental settings and should thus be called *"karst on islands"* as opposed to *"island karst"* (Vacher and Mylroie, 2002, 183–184). True island karst is defined by the current hydrological model for small carbonate islands and coastlines, the Carbonate Island Karst Model (CIKM) (Vacher and Mylroie, 2002; Mylroie and Vacher, 1999).

The Carbonate Island Karst Model was developed to explain karst development in island and coastal settings where diagenetically immature rocks interact with fresh and saline groundwater that is affected by changes in sea level induced by glacio-eustacy and tectonic uplift (Stafford *et al.*, 2003; Jenson *et al.*, 2002; Mylroie amd Jenson, 2002; Mylroie and Jenson 2001). The main aspects of the model include (Fig.3):

1. The karst is eogenetic.
2. The freshwater / saltwater boundary creates mixing dissolution and organic trapping horizons.
3. Glacio-eustacy has moved the freshwater lens up and down during the Quaternary.
4. Local tectonics can overprint the glacio-eustatic sea-level events.
5. Carbonate islands can be divided into four categories based on basement / sea-level relationships:
   a. Simple Carbonate Islands (e.g. Bahamas)
   b. Carbonate Cover Islands (e.g. Bermuda during glacio-eustatic sea-level lowstands)
   c. Composite Islands (e.g. Barbados and commonly in the Marianas)
   d. Complex Islands (e.g. Saipan).

Simple carbonate islands (Fig.3a) contain no non-carbonate rocks interfering with the freshwater lens morphology and groundwater recharge is completely autogenic. Carbonate cover islands (Fig.3b) contain subsurface, impermeable, non-carbonate rocks that interrupt the freshwater lens and shunt percolating vadose water along the contact, but groundwater recharge remains entirely autogenic. Composite islands (Fig.3c) contain non-carbonate rocks that crop out at the surface and partition the freshwater lens in the subsurface, with both allogenic and autogenic groundwater recharge. Complex islands (Fig.3d) exhibit interfingering of carbonate / non-carbonate facies and faulting, which brings rocks of different lithologies into contact when they where not before, partitioning the lens and providing both allogenic and autogenic recharge.

AGUIJAN KARST DEVELOPMENT

Karst features on Aguijan can be subdivided into two categories: epikarst and caves. Caves can be subdivided into two classes based on developmental controls: fissure caves and mixing zone caves. On larger carbonate islands in the Marianas, additional karst landforms are observed, but the lack of non-carbonate outcrops on Aguijan precludes development of dissolutional closed depressions and stream caves along carbonate / non-carbonate contacts. No active freshwater discharge features were observed on Aguijan because coastlines were not thoroughly investigated due to heavy surf conditions, high-angle cliffs, and access limitations. However, it is likely that small freshwater discharge features exist at sea level on coastlines, similar to those seen on scarped coastlines on other carbonate islands in the Marianas. For a thorough description of Aguijan karst development, the reader is directed to Stafford (2003), a Master's thesis that includes detailed maps of the caves surveyed on Aguijan.

Epikarst

Epikarst is the most extensive karst landform on Aguijan, with karren morphology varying with coastline proximity. Proximal to coastlines, in areas where limestone is constantly wetted by sea-spray, centimetre- to metre-scale pinnacles are common and have been termed phytokarst (Folk *et al.*, 1973), biokarst (Viles, 1988), or littoral eogenetic karren (Taboroši *et al.*, 2005). This unique karren form is polygenetic, originating from the complex interaction of meteoric water with salt spray, dissolution by meteoric waters, salt weathering, and biological weathering (Taboroši *et al.*, 2005). The presence of joints and fractures near coastlines results in enlarged planar features (vertical and horizontal) and kamenitzas (i.e. shallow solution pans).

Epikarst in the interior, where the limestone is not directly wetted by sea spray, forms karren that is more subdued. Where soil is present, karren generally expresses little surface relief, but can form closely spaced, metre-scale canyons in regions of fractured bedrock. Where the soil has been mostly removed by erosion, inland karren is less extensive than in coastal areas where the soil cover has been stripped away by littoral processes. This suggests that salt

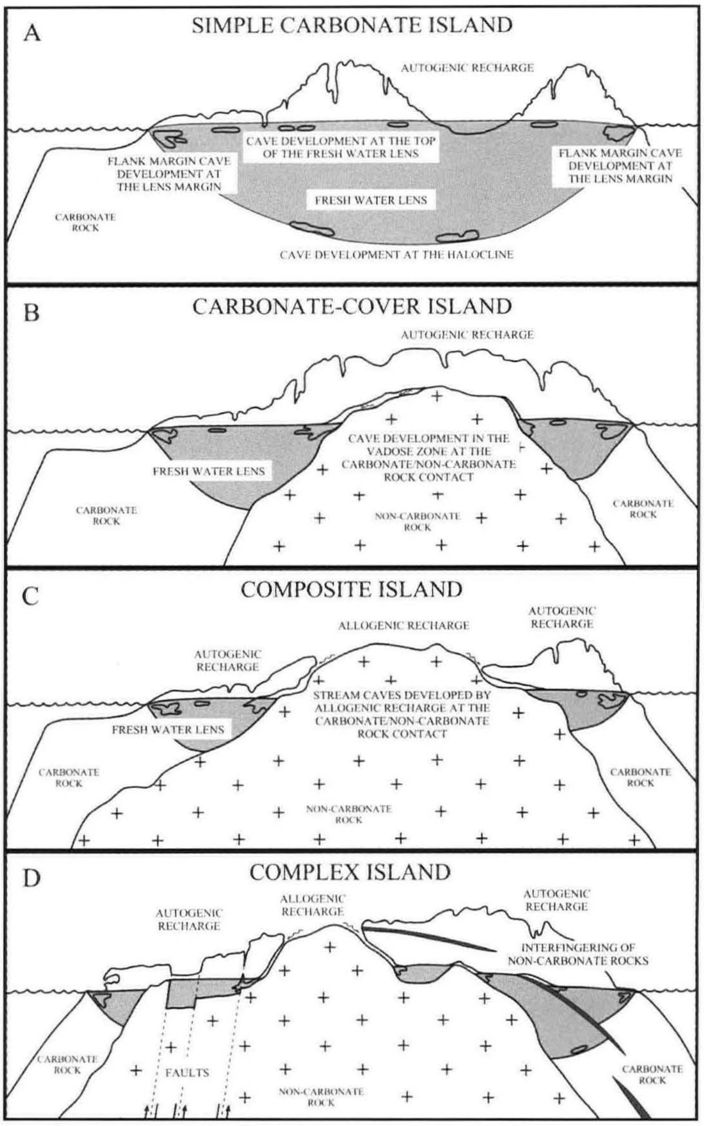

Figure 3. *Carbonate Island Karst Model illustrating the 4 types of carbonate islands that exist, based on variations in basement / sea-level relationships (adapted from Mylroie et al., 2001).*

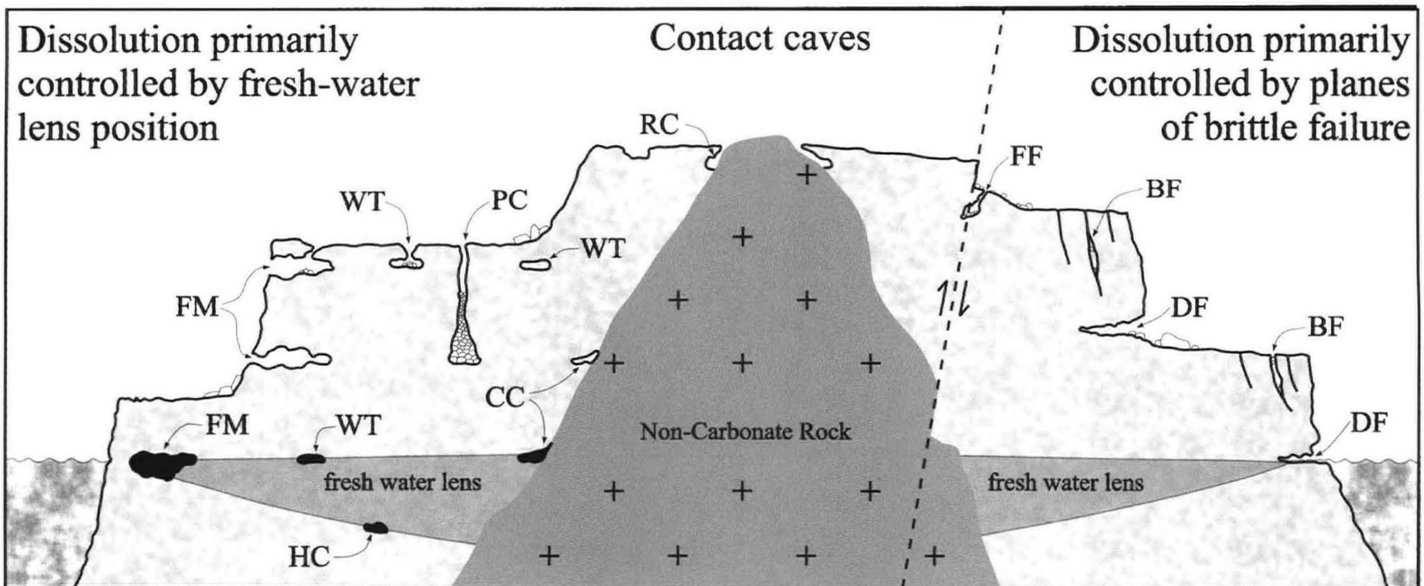

Figure 4. *Schematic diagram illustrating the types of subsurface karst development on carbonate islands. Note that not all cave types occur on all carbonate islands.*

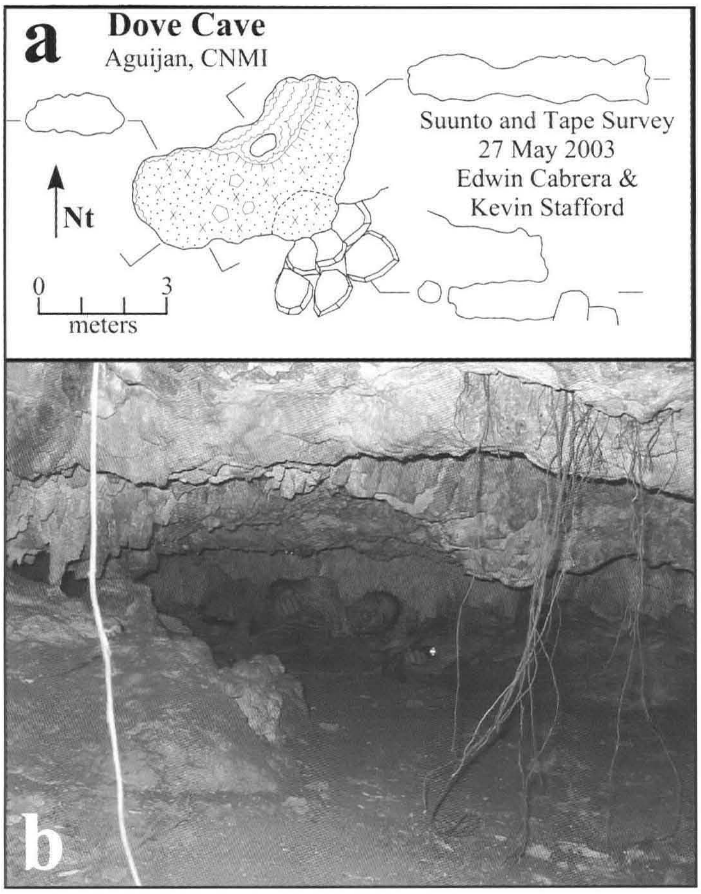

__Figure 5.__ Banana holes (breached water table caves) are generally small features that have been breached by collapse. a.) Dove Cave is a typical water table cave forming a small, globular chamber. b.) Water table caves exhibit little vertical component and roots often penetrate the ceiling because of proximity to the land surface.

weathering and the interaction of salt spray and meteoric water in coastal areas is largely responsible for the unique characteristics of littoral eogenetic karren, although some of the variation seen in inland karren is likely the result of soil processes. The recent work of Taboroši *et al.* (2005) provides a detailed discussion of epikarst and karren forms on tropical carbonate islands.

Caves

Caves on Aguijan occupy two morphologically distinct classes: mixing zone caves and fissure caves. An inventory of cave and karst features on Aguijan identified 26 caves or cave complexes, including 20 mixing zone caves, 5 fissure caves and Liyang Atkiya, a cave that does not conveniently fit current models for island karst development. Local guides report that the inventory includes the majority of the known caves on Aguijan, excluding a few sites high in cliffs or along coastlines that could not be accessed because of the difficulty of working on an uninhabited island with sheer coastlines and heavy surf. There is no doubt that some explorational bias exists in the inventory due to lack of entrances (unbreached caves), dense vegetation obscuring entrances, safety concerns, and time constraints, etc.

The majority of caves on Aguijan are mixing zone caves (Fig.4), which reflect the position of the extant freshwater lens (Mylroie and Carew, 1995; Mylroie *et al.,* 1995a). Mixing zone caves are hypogenic (Palmer, 1991) and form interconnected, globular chambers. They occur as three morphologically similar subcategories that include water table caves, halocline caves, and flank margin caves, which develop in relation to the freshwater lens contacts, that include the vadose / phreatic contact, freshwater / saltwater contact, and the margin of the freshwater lens, respectively (Mylroie *et al.,* 1995a). Because they form in relation to the position of the freshwater lens, mixing zone caves provide excellent indicators of changes in relative sea level resulting from island uplift and/or glacio-eustacy (Carew and Mylroie, 1995; Mylroie *et al.,* 1995a,b).

Water table caves (Fig.4) occur at the top of the freshwater lens where organic detritus accumulating at the vadose / phreatic contact decomposes and enhances dissolution, forming small, shallow chambers that are characterized by a length to depth ratio greater than one (Fig.5a,b). When breached at the land surface, water table caves are commonly termed "banana holes" after features first reported in the Bahamas, in which banana trees and other crops are grown (Harris *et al.,* 1995). Halocline caves (Fig.4) are thought to be similar to water table caves in size and shape, but develop at the bottom of the freshwater lens at the freshwater / saltwater contact, where the density horizon between fresh and saline water traps organics and the mixing of freshwater and saltwater produces aggressive waters that are undersaturated with respect to calcite. Halocline caves have never been proven to exist, and modern caves currently at the halocline may merely represent the distortion of the halocline into the high transmissivity pathway that pre-existing caves provide. Breached water table caves and halocline caves cannot be easily distinguished in the field because of their morphological similarity. However, the location of water table cave development with respect to the freshwater lens makes them more likely to be breached by surface denudation. Only two features have been identified on Aguijan that appear to represent water table caves, although they may actually represent either halocline caves or small flank margin caves. Although only two features have been identified, it is likely that more exist that have not been breached at the land surface. On carbonate islands that are not tectonically active (e.g, Bahamas) banana holes (i.e. breached water table caves) are frequently reported. However, on these islands the land surface is

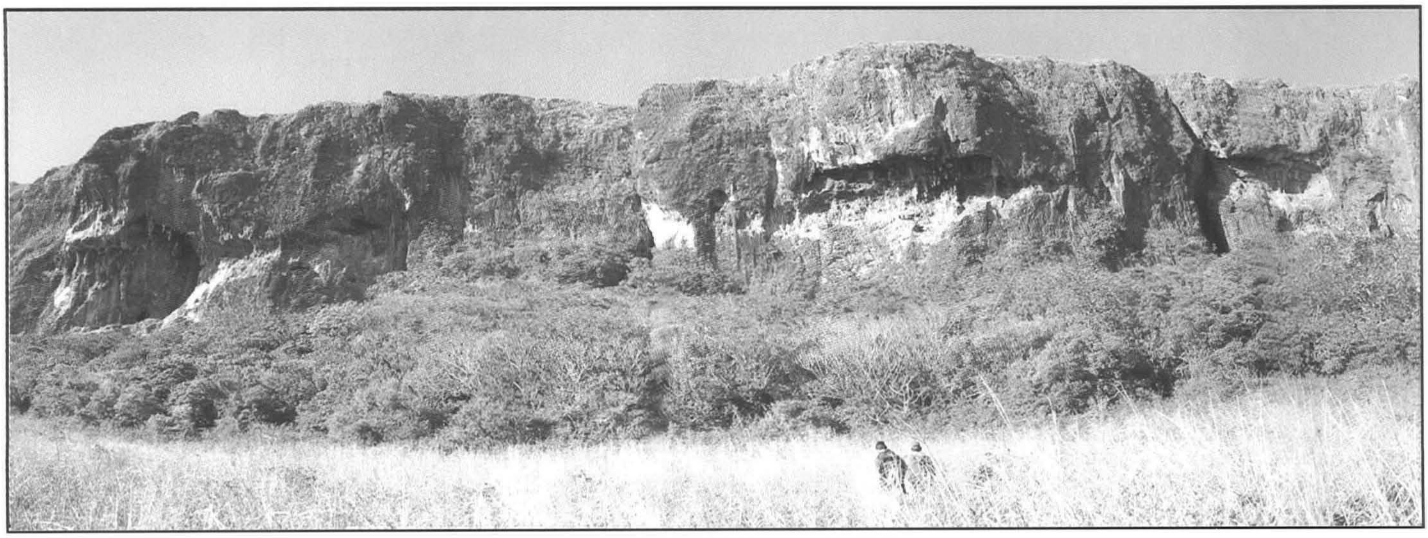

__Figure 6.__ The Middle Terrace of Aguijan contains extensive horizons of remnant flank margin caves that delineate previous freshwater lens positions. Note people in foreground for scale.

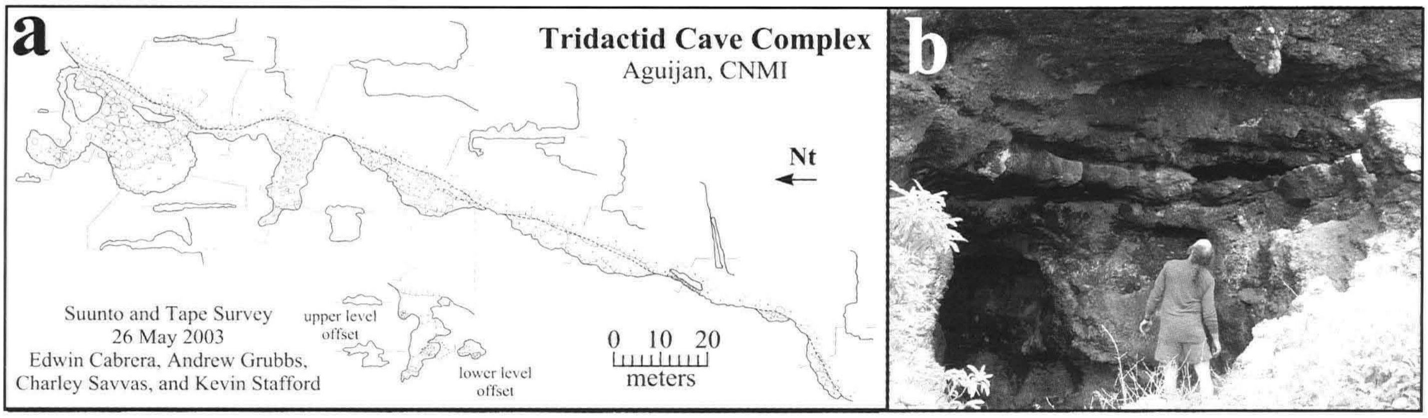

Figure 7. *Flank margin cave development produces horizons of mixing zone caves. a.) Tridactid Cave Complex illustrates well the poorly interconnected, small chambers observed in horizons of flank margin cave development on Aguijan. b.) Most flank margin caves are located in cliffs and are breached by scarp retreat.*

generally less than ten metres above sea level and only minor surface denudation is required to breach them (Harris *et al.,* 1995). Aguijan has a maximum elevation of 157m, which may account for the limited number of water table caves identified, because it is likely that significant surface denudation is required to breach caves formed at the top of a previous freshwater lens position.

Flank margin caves (Fig.4) are the most common cave type on Aguijan, with 19 caves or cave complexes identified. They form at the margin of the freshwater lens where organic-trapping horizons at the vadose / phreatic and freshwater / saltwater contact are in close proximity to freshwater / saltwater mixing at the bottom and edge of the freshwater lens as the lens thins towards the margin of the island (Mylroie *et al.,* 1995a). Flank margin caves are globular and range greatly in size, forming large central chambers with small alcoves interconnected with smaller passages. These caves are commonly found at consistent horizons along scarps and cliffs (Fig.6) because their development at the edge of the previous freshwater lens positions makes them highly susceptible to breaching by scarp retreat (Mylroie *et al.,* 1999). On Aguijan, horizons of flank margin cave development were observed on each terrace level, suggesting at least three previous freshwater lens positions have existed on Aguijan in association with previous relative sea level stillstands. However, the horizons of cave development generally contain small caves that are poorly interconnected (Fig.7a,b), as opposed to the large, extensively interconnected flank margin caves seen on other carbonate islands such as Isla de Mona (Frank *et al.,* 1998). This suggests that sea level stillstands were relatively brief in the Marianas and did not provide sufficient time for larger caves to develop. Rather, continual uplift reduced the residence time of relative stillstands induced by glacio-eustacy.

Fissure caves on Aguijan are linear features that develop in relation to planes of brittle failure associated with geological structure (Fig.4) (Stafford *et al.,* 2003). The brittle failure surfaces provide routes for increased groundwater flow that results in preferential dissolution along faults, fractures and joints. The planar surfaces can locally distort the freshwater lens morphology and can provide vadose fast-flow routes that enable meteoric recharge to effectively bypass the vadose zone (Mylroie *et al.,* 1995c; Aby, 1994). Three distinct types of fissure cave development occur on Aguijan, which represent three different types of brittle failure: faults, margin failures and tension-release features associated with margin failures.

Although no detailed geologic mapping has been conducted on Aguijan to identify faults, one cave complex, Orphan Kids Cave Complex, was identified in a region of highly fractured bedrock that appears similar to fault-controlled fissure caves identified on Tinian. Fault-controlled caves on carbonate islands have been generally characterized as linear features that descend at moderate to steep angles and show horizontal widening as a result of dissolution of collapse material originating from the hanging wall (Stafford *et al.,* 2003). Orphan Kids Cave Complex consists of three caves in close proximity that align along a dipping planar failure (Fig.8a). They descend at moderately steep slopes and show minor horizontal widening. However, no offset could be observed in the caves, possibly because of calcite precipitates coating the walls and extensive breakdown obscuring any offset (Fig.8b).

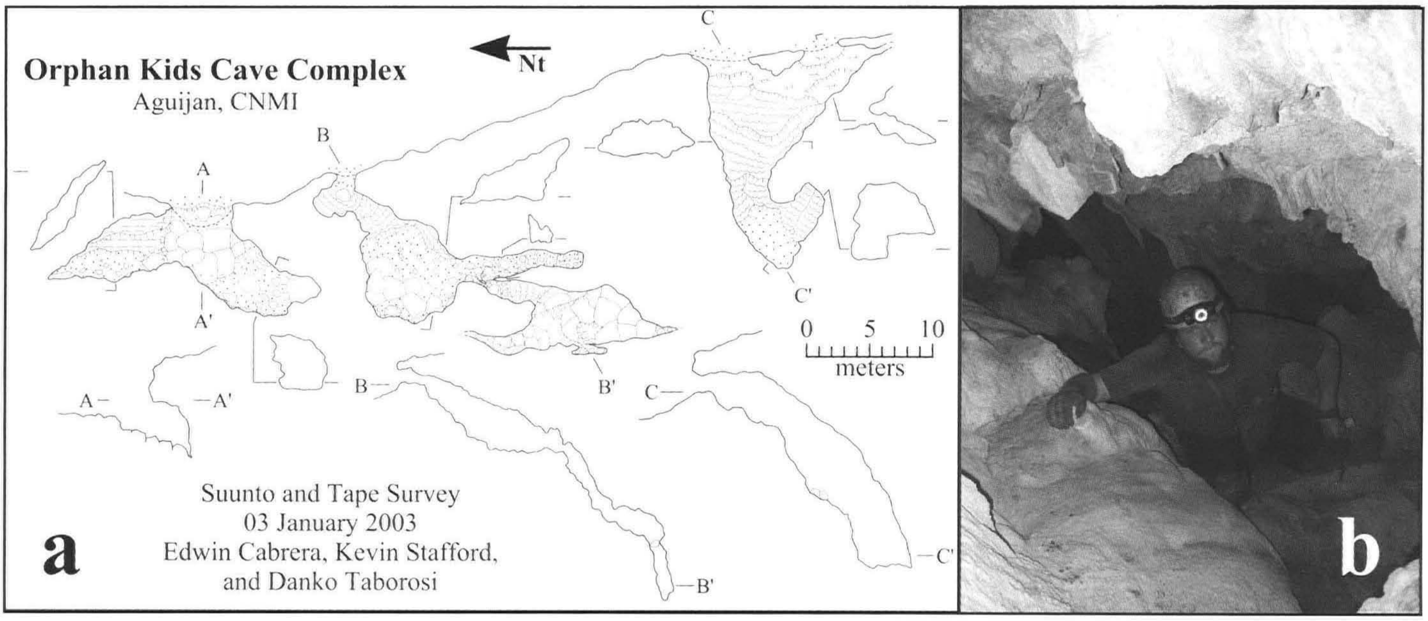

Figure 8. *Fissure cave development along faults. a.) Orphan Kids Cave Complex consists of three caves in close proximity aligned along a brittle failure feature parallel to the bank margin. b.) Calcite precipitates and breakdown prevent the observation of possible fault offset in the cave.*

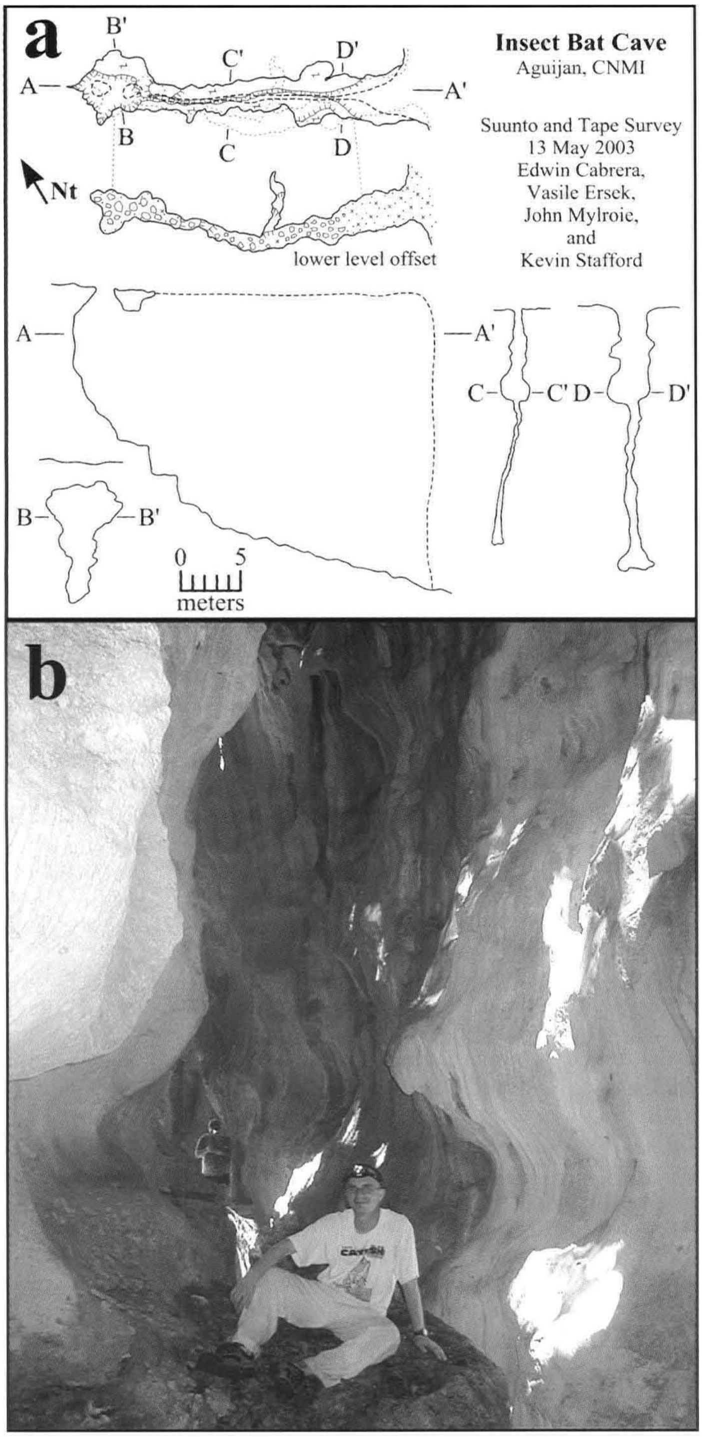

Figure 9. Fissure cave development along tension-release failures. a.) Insect Bat Cave extends inland 30m along a brittle failure plane nearly perpendicular to the scarp wall. b.) Horizontal widening from mixing zone dissolution suggests that Insect Bat Cave discharged freshwater at sea level in the past and represents a palaeo-discharge feature.

Fissure cave development parallel to scarps and cliffs is generally associated with margin failures, while fissure cave development near-perpendicular to scarps and cliffs is generally associated with tension-release fractures. Island topography suggests several significant margin failures exist on Aguijan, but only one fissure cave, Anvil Cave, was identified in association with margin failure. Anvil cave is a linear feature that descends near-vertically along a planar surface and contains extensive breakdown, which forms the majority of the ceiling and floor. Although the feature exhibits some horizontal widening from wall collapse, it appears similar to more extensive fissure caves associated with margin failures observed on Tinian (Stafford *et al.,* 2005; Stafford, 2003). Associated with margin failures, three fissure caves nearly perpendicular to scarps were identified along tension-release failures. All three caves are located in the scarp separating the Lower Terrace and the Middle Terrace and extend inland for more than 30m (Fig.9a). They show horizontal widening from mixing zone dissolution (Fig.9b) with morphology reminiscent of fissure caves observed on carbonate islands that discharge freshwater at sea level. The morphology of the caves and their location above sea level suggests that these sites discharged freshwater at some time in the past and represent palaeo-discharge features. It is likely that similar active discharge features exist at sea level on Aguijan, but coastal conditions prevented detailed studies of coastlines.

Liyang Atkiya (Fig.10a) is the largest single cave on Aguijan and does not conveniently fit any current models for island karst. The cave consists of a large entrance chamber that descends over a breakdown floor from a small, breached entrance at the base of the scarp separating the Lower Terrace and Middle Terrace. At the base of the main chamber, which is over 80m inland from the scarp wall, the cave reduces to a narrow opening less than one metre in diameter. Inland from the main chamber, a linear passage extends northeastwards for 75m before bifurcating into two passages. One passage continues northeastwards for 40m, whereas the second passage trends westnorthwestwards for more than 60m. In the inland portions of the second passage, the cave splits into many small passages, reminiscent of boneyard in continental settings (Fig.10b). Throughout the linear passages, the floor is composed mostly of breakdown, but the ceiling is primarily dissolutional. In places scallops are present on the ceiling and walls (Fig.10c) providing evidence for previous conduit flow upgradient, towards the entrance.

Scallops have been observed in a lift tube in Kalabera Cave on Saipan, where water rose along a lithological barrier between carbonate and non-carbonate rocks (Jenson *et al.,* 2002); however, this model cannot easily be applied to Liyang Atkiya because no non-carbonate rocks were observed in the cave. The cave appears to be strongly controlled by geological structure, as is evident from the linear nature of the cave, but the main entrance chamber appears similar to the central chamber of some larger flank margin caves, except for the absence of numerous smaller passages and alcoves. However, breakdown is abundant in this portion of the cave, and the original dissolutional surface is gone. The current theory of speleogenesis suggests that Liyang Atkiya probably contains non-carbonate rocks beneath the breakdown floors, providing a lithological barrier that forced freshwater to flow up-gradient towards the cave entrance and the palaeo-coastline represented by the scarp. The ascending water flowed along a plane of brittle failure producing the linear passages now marked by scallops, and mixed with saltwater near the palaeo-coastline, forming the broad entrance chamber. As relative sea level lowered, buoyant support was lost and regions of the cave collapsed, and the entrance was breached by scarp retreat, producing the cave as seen today.

CONCLUSIONS

Eogenetic karst on Aguijan appears similar to that seen on larger carbonate islands in the Marianas, reflecting a polygenetic origin both in epikarst and cave development. Epikarst development in coastal regions is strongly influenced by salt weathering and mixing of salt spray and meteoric water, whereas inland karren in regions containing soil is more subdued. However, the influences of geological structure result in enlarged joints and fractures that can produce metre-scale canyons. Cave development is primarily controlled by dissolution associated with previous freshwater lens positions and brittle failure features. Fissure caves develop along faults, margin failures and tension-release fractures associated with margin failures. Fissure caves sub-perpendicular to scarps show horizontal widening from dissolution by freshwater flowing through them during sea level stillstands that represent palaeo-discharge features. Flank margin caves, formed by mixing zone dissolution at the lens margin dominate all terrace levels, commonly forming distinct horizons. The presence of three distinct terrace levels, and cave development associated with each, indicates at least three previous sea-level stillstands of sufficient duration to create both flank margin caves and the depositional terraces that lie seaward of them. More horizons may exist because differential rates of uplift may have raised portions of the island differing amounts. Although mixing zone dissolution dominates on Aguijan, geological structure

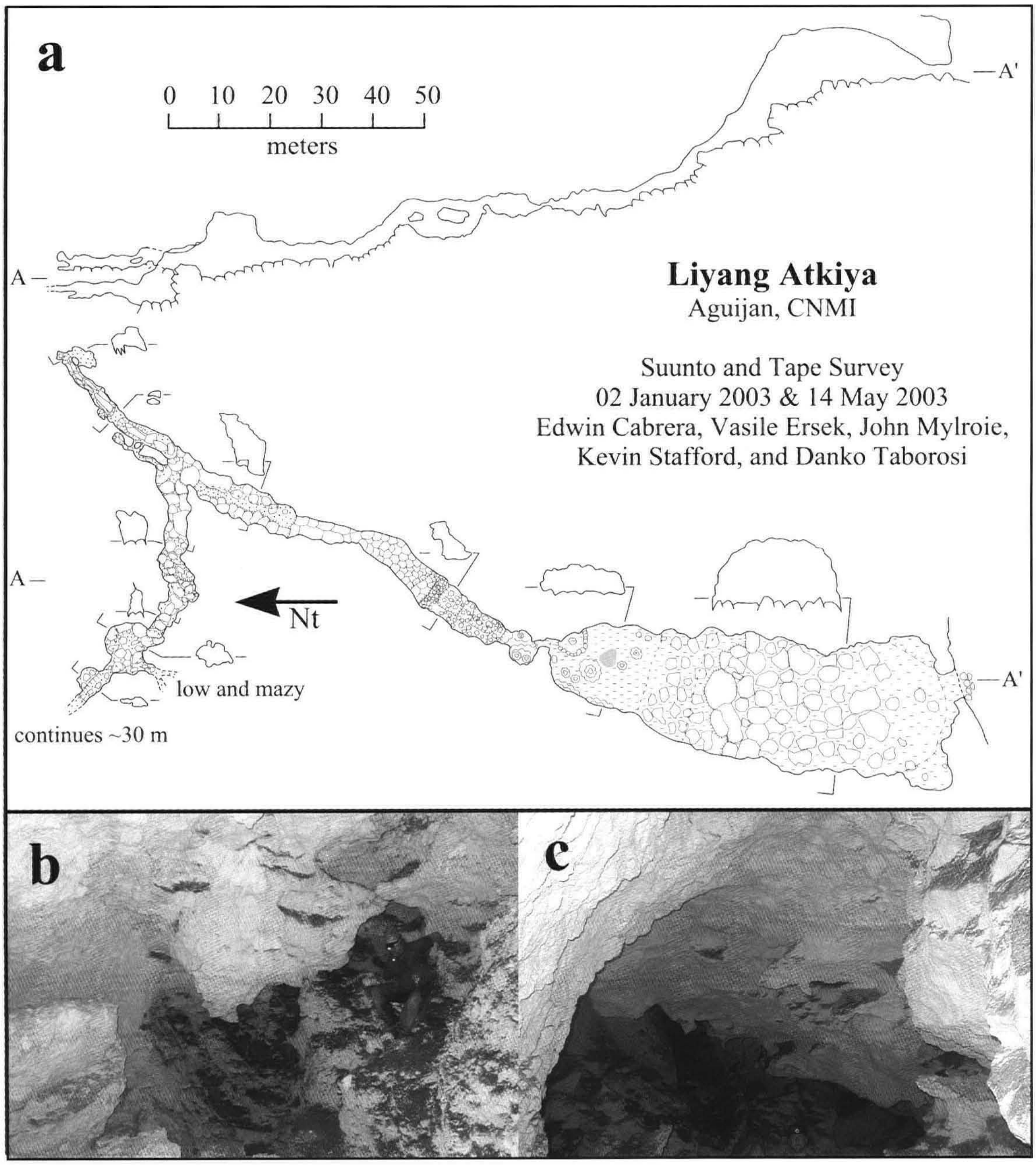

Figure 10. *Liyang Atkiya. a.) The largest cave on Aguijan, Liyang Atkiya, exhibits a morphology that is distinct from other known caves in the region. b.) Regions of the cave contain floors composed of large breakdown, while the ceiling and walls contain large scallops indicating flow upgradient, towards the cave entrance. c.) Inland portions appear similar to "boneyard" observed in continental hypogenic caves.*

not only controls fissure cave development but also influences mixing zone cave development.

The elevation of the island and its geomorphic similarity to larger islands in the Marianas, suggest that Aguijan may be a carbonate-cover island, although no outcrops or contacts with non-carbonate rock have been observed. Eogenetic karst development on Aguijan demonstrates well the utility of the Carbonate Island Karst Model for describing and explaining the caves and karst features on small, tectonically active, carbonate islands. More detailed investigations, including basic geological mapping, of the island are still needed to further unravel the hydrological complexities, such as Liyang Atkiya.

ACKNOWLEDGEMENTS

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Koru Polje and karst landform evolution in the middle part of the Kure Mountains, Northern Anatolia, Turkey.

Ali UZUN

Geography Department, Faculty of Arts and Sciences, Ondokuz Mayis University, 55139 Samsun, Turkey

Abstract: Koru Polje and its close surroundings lie at an elevation of about 1450 to 2000m in the middle part of the Kure Mountains (the western part of the Northern Anatolia Orogenic Belt). Various karst landforms characteristic of the temperate climatic zone can be seen in this area, which is generally rainy throughout the year, with an annual precipitation of more than 1600mm, cool winter and mild summer temperatures, and an average annual temperature below 7°C. The study area is entirely within the forest zone and its karstic landforms are developed under soil and plant cover. Large closed depressions like Koru Polje and the Subatanyaylasi Depression are shaped by fluviokarstic processes. Quaternary climate changes affected the evolution of large karstic landforms in the study area. Periglacial conditions prevailed during Quaternary cold periods and development of surface karst landforms was interrupted at these times. In warm periods after the release of permafrost, surface water sank into reactivated swallow holes. Thus, karst landform evolution in the study area accelerated during the warmer periods of the Quaternary, and during recent times.

Keywords: Kure Mountains; karst landforms; polje; Turkey

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INTRODUCTION

The investigation area is within the northern mountainous zone of Turkey (Fig.1). Much of Turkey displays lithological, climatic and topographical conditions that support karstification, so karstic features are found all around the country. Karstic landforms can be seen in the southern parts of Anatolia, and landscapes with transitional characteristics can be seen in the inland regions of the country. It is generally believed that karstification processes are unimportant or can be ignored in the north, the east, and the northwest, including Thrace (Alagöz, 1944; Erinç, 1960; Sür, 1994) but, as in the Kure Mountains, well-developed karstic features can also be seen in the northern part of Turkey.

The aim of this study is to investigate the karst forms progress of the research area. Regarding this aim, climatic changes in the Quaternary and the effects of recent climatic conditions on the development of the karstic forms in the study area are discussed.

During this study, topographic maps (1/25,000, 1/50,000, 1/100,000) aerial photos (1/40,000), geologic maps in associated literature, and data from meteorologic stations around the region are used.

STUDY AREA

Koru Polje and its close surroundings lie at an altitude of about 1450 – 2000m in the middle of the Kure Mountains (the western part of the Northern Anatolia Orogenic Belt) (Fig.1). Koru Polje is the largest karst depression in the research area, and it has two large neighbouring depressions (Subatanyaylasi and Handeresi depressions), which were investigated in the study.

Lithology and soil

The karstic forms in the research area are generally developed on the Inalti Limestone (Upper Jurassic to Lower Cretaceous) (Fig.2). Detailed information on this limestone is provided by Blumenthal (1942), Ketin (1983), Gedik and Korkmaz (1984) and Deveciler *et al.* (1989). For example, Blumenthal (1942) notes that the limestone has a red polygenetic conglomerate at its base and has a microbreccia structure with oncolites in its matrix. Additionally, Gedik and Korkmaz (1984) note that the limestone is massive and reaches 1000m in thickness in some areas. Studies of aerial photographs and on the ground in the research area show that the Inalti Limestone has joint systems crossing one another, and it has thick strata with variable dip directions. Older geological formations (Akgöl and Bürnük formations) in the study area were deposited during the Jurassic Period. The Akgöl Formation consists of shale, sandstone and limestone, and the Bürnük Formation comprises conglomerate, sandstone, and mudstone (Fig.2). Additionally, the limestone samples analyzed in the laboratory have a $CaCO_3$ content between 80% (Akgöl Formation) and 97% (Inalti Formation).

Cambisols (brown forest soils) are widespread in the investigation area, and these soils are rich in organic material and $CaCO_3$ (Anon, 1972). They can be 40 to 50cm thick, but more generally they are thin and stony. Nevertheless, when melting snow and rainwater infiltrate into the soil, they absorb CO_2 and humic acid, becoming more effective in dissolving limestone.

Climate and hydrology

Koru Polje is about 20km from the Black Sea, and its floor lies at 1460m above sea level (ASL). There is no meteorological station in the study area, so the precipitation data were inferred through interpretation of data from Bozkurt and other coastal town meteorological stations (Bozkurt 167m, Çatalzeytin 4m, Ayancik 4m ASL). Annual precipitation is over 1600mm (Bozkurt 1214.8mm, Catalzeytin 967.3mm, Ayancik 1003.1mm), and the annual mean temperature is lower than 6 to 7°C (Bozkurt 13.7°C). Mean winter temperatures are below 0°C, with 45 to 60 days of snow cover

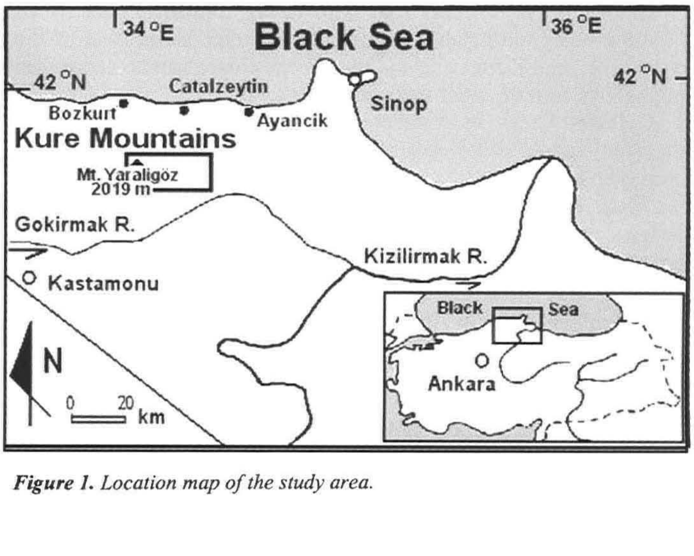

Figure 1. Location map of the study area.

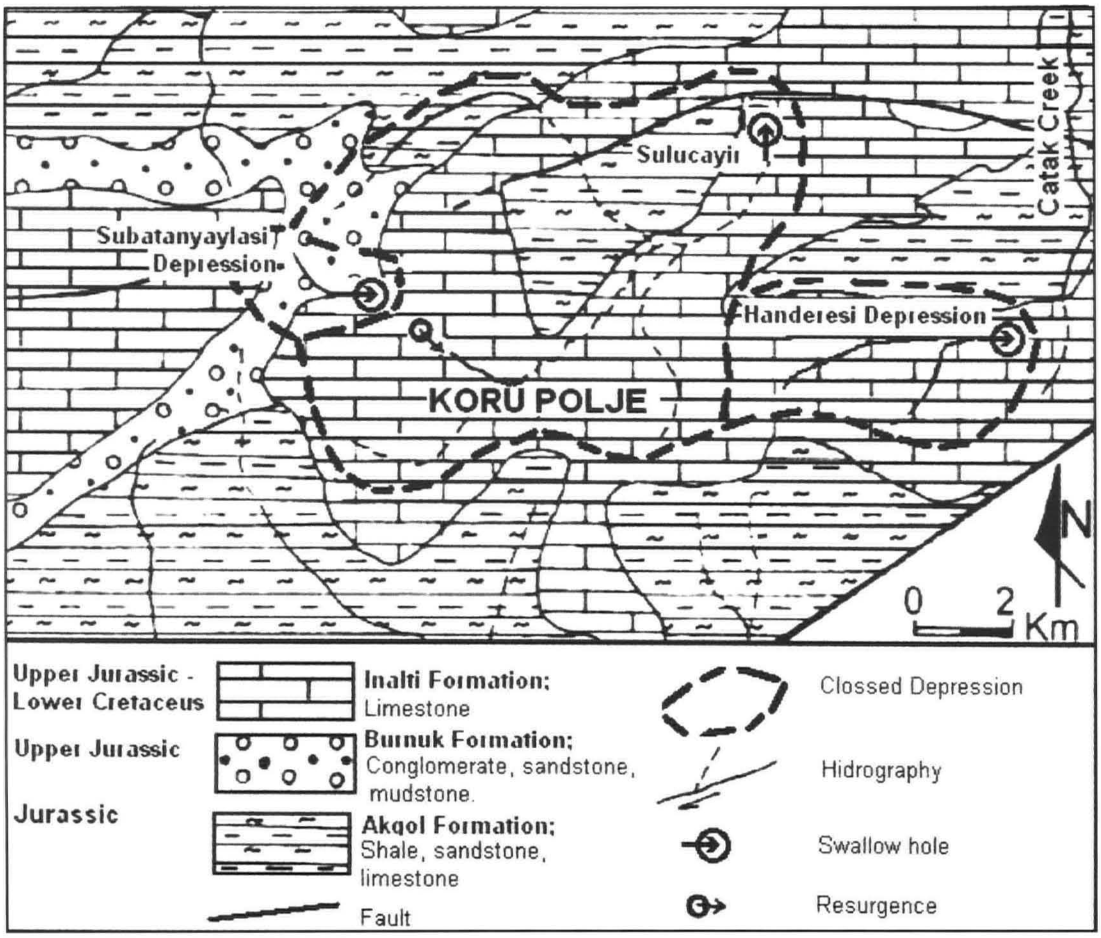

Figure 2. *Geological map of Koru Polje and its surroundings (partly modified after Deveciler et al., 1989).*

(Onur, 1964). According to these climatic data the investigation area is comparable to the karst of Georgia, characterized by humid climate and heavy snowfalls in winter (Maruashvili, 1982). Cold water derived from the melting of the snow cover as temperatures increase after April, and which is rich in CO_2, causes an increase in the karstic processes affecting the limestone. On the other hand, the study area had a cooler climate during the cold periods of the Pleistocene and a permafrost zone might have formed in the area. Characteristic periglacial deposits and landforms have not yet been found, but the actual climatic conditions and the elevation of the study area suggest that it was possibly a permafrost zone during the cooler periods of the Quaternary. Soil and frozen water plugged cracks in the bedrock during these cooler episodes, causing surface runoff and fluvial valley development in the area. On the other hand, it is clear that unfrozen aquifers exist beneath the permafrost zone in periglacial areas, and water circulates along fissures and faults in karst rocks (Demek, 1989). Demek (1989) called such water **taliks.** Taliks are commonly located under valley bottoms. According to this explanation, underflow between the Subatanyaylası depression and Koru Polje may provide further evidence of former periglacial conditions. Surface creeks sank into newly formed or reactivated swallow holes during the warmer periods after the release of the permafrost, and Koru Polje and other large closed karstic depression might have formed under these conditions.

Derekoru Creek and Handeresi Creek drain the surface water of the study area. The hydrological characteristics of the area are closely related to the topography, bedrock and climate, as well as to the soil and vegetation cover. Of these factors the climatic influences, particularly the amount and kind of precipitation and the temperature regime, are very important in defining hydrological characteristics in the field. For instance, winter snow fills and plugs the swallow holes of Koru Polje. This snow cover remains until the spring months, starting to melt by March, due to the increasing temperature and rainfall. Occasionally this melting process occurs rapidly and causes a temporary lake to form in the bottom of Koru Polje. Then the swallow holes are suddenly unplugged by water pressure, and the water surges out from a resurgence in the Catak Creek's valley (Fig.2), flooding the valley beyond. This phenomenon is called "Koru patladi" (Koru has burst) by the villagers in the region.

Vegetation cover

The study area is totally within the forest zone. Fir (*Abies nordmanniana* ssp. *bornmülleriana*) and pine (*Pinus sylvestris*) forest covers a large area in this region. However, the forest on the floor of Koru Polje has been destroyed (Fig.3), apparently mainly by the deforestation effects related to temporary settlements. Deforestation occurred because the people living in these settlements used the forest as their wood supply. As a result of this, the anthropogenic features of the area developed. But the slopes of the large karstic depressions are covered by forest, because the anthropogenic disturbance is less there. Even here the forest is destroyed on some slopes, but junipers (*Juniperus alpina* ssp. *alpina*) replace pine and fir, and they protect the soil from erosional effects.

LARGE KARSTIC DEPRESSIONS

There are many closed karstic depressions in the study area, the largest of which is Koru Polje. Two other large closed depressions in this area are known as the Subatanyaylasi and Handeresi depressions. According to Bonacci (2004) poljes are generally elliptical, with floors that slope relatively gently from the inflow (spring) zone to the outflow (commonly swallow hole) zone. They vary in size from less than $0.5km^2$ to more than $500km^2$ in area.

Study of aerial photos, and observations in the field, show that karstic depressions tend to be elongated in the same direction as tectonic lines, generally trending about easterly or northeasterly (Fig.3). The streams of this region flow in the same direction. Finally, the surface water sinks into swallow holes that generally lie along these same tectonic lines and cracks. Likewise, many closed depressions follow tectonic lines and cracks in the southern part of Mount Yaraligöz on the western side of the study area (Uzun, 2004). For that reason, it can be said that fluviokarstic processes being suitable for tectonic directions in the investigation area have formed these large karstic depressions.

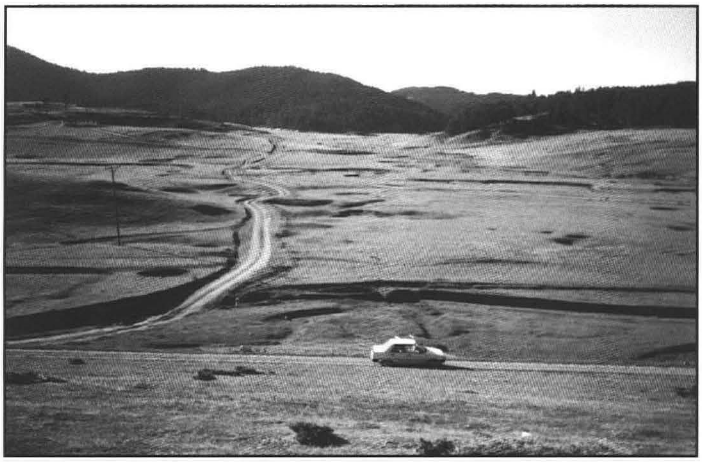

Figure 3. The bottom of the Derekoru Valley has a plain shape at the south of the forestry management's buildings in Koru Polje, and the forest has been destroyed in this area.

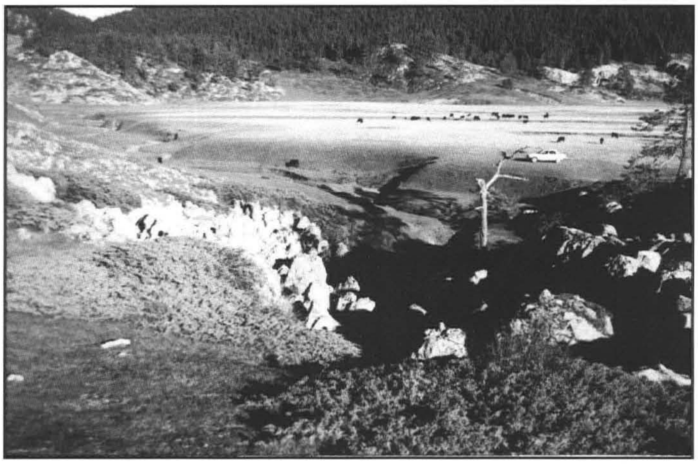

Figure 4. Derekoru Creek sinks in swallow holes near Sulucayir on the northeast margin of Koru Polje, where the floor is plain-like, and its slopes are covered in pine and fir forest.

Koru Polje

Koru Polje is the largest karstic depression in the study area. Its floor area is 19.2km^2, in the shape of a parallelogram. Koru Polje is shaped like a large valley, with a plain-like floor of alluvial material in the Sulucayir area and south of the forestry management's buildings (Figs 3 and 4).

Derekoru Creek resurges from a spring in the northwestern part of the polje, runs on the surface for about 1.5km, and then it disappears, infiltrating into the alluvial material at the bottom of the polje (Fig.3). However, it has only a seasonal runoff, related to the rain and melting snow. Derekoru Creek sinks in swallow holes near Sulucayir at the northeastern margin of the polje (Fig.4). One of the important tributaries of this stream is Kabalakli Creek, which joins Derekoru Creek to the south of the forestry management's buildings. This creek also has only a seasonal runoff, which drains the northern part of polje, and it disappears near Kiziltuzla, infiltrating into alluvial material.

Koru Polje is surrounded by Dibekkorukayasi Hill (1860m) to the west, Kirkdilim Hill (1916m), Soyuk Hill (1908m), Karakuz Hill (1752m) and Yelbeyi Hill (1640m) to the north, Cikrincak Hill (1709m), Eger Hill (1676m), Cikrikkapi Hill (1669m) and Tana Hill (1828m) in the south, and Kilickaya Hill (1706m) to the east. The relative altitude difference is about 450m, between Kirkdilim Hill (1916m) and the Sulucayir area (1460m) in the polje. The polje has an alluvial floor to the south of the forestry management's buildings and near the swallow holes in the Sulucayir area (Fig.4). The general inclination at the polje floor is about 1% along the course of Derekoru Creek, whereas slope inclinations are particularly high on the southern slopes of the polje (48% on the north slope of Cikrikkapi Hill and 54% on the north slope of Tana Hill).

Subatanyaylasi Depression

This depression lies to the west of Koru Polje (Fig.2). It is elongated west–east and is about 2km long, with an area of about 2km^2. The main stream in the depression is Üçgöller Creek, which collects and carries all of the depression's water. This depression was formed as a fluvial valley by Üçgöller Creek during cold periods of the Pleistocene when permafrost and soil plugged the cracks of the bedrock, enforcing surface runoff. At that stage it had closed-depression characteristics in the form of a blind valley, because in warm periods after the end of the permafrost Üçgöller Creek sank in a newly-formed or reactivated swallow hole along a fault at the southeast corner of the depression (Fig.5) (Demek, 1989). The creek flows underground for about 400m, and reappears from a resurgence spring in Koru Polje, where it is called "Derekoru Creek". Thus, a short part of the old valley's floor is dry between Koru Polje and Subatanyaylasi Depression (Fig.6).

The Subatanyaylasi Depression is developed in an area of contact between the Upper Jurassic to Lower Cretaceous limestone Inalti Limestone and the underlying Upper Jurassic conglomerate, sandstone, and mudstone of the Bürnük Formation (Fig.2). Southern and northern walls of the depression have different inclination values (the southern slopes 50%, the northern slopes 20%), and it appears that the most important reason for this asymmetric shape is the lithological difference (Fig.2). There is widespread forest cover on the slopes of Subatanyaylası, and thus it appears that bioactivity is not a very important influence on the asymmetric shape of the slopes. On the other hand, actual data do not yield enough information about mechanical weathering during the cold periods of the Quaternary. Subatanyaylasi Depression is surrounded by Sarayoluğu Hill (1906m) in the west, Çatalkaya Hill (1872m) in the north, Soyuk Hill (1903m) in the east, and Kirkdilim Hill (1915m) in the south. The relative altitude difference in this depression is over 300m between Kirkdilim Hill (1915m) and the entrance of the swallow hole (1605m).

Handeresi Depression

Like the Subatanyaylasi Depression, Handeresi Depression, another neighbour of Koru Polje, was formed by dissolutional and fluviokarstic processes. The depression is surrounded by Eğer Hill (1677m) in the west, Karşi Ridge to the north, Kavakliyalak Ridge in the east and Kuzucal Hill (1624m) in the south. Handeresi Depression is developed within the Upper Jurassic to Lower Cretaceous Inalti Limestone.

Handeresi Depression is a blind valley, and its drainage basin covers about 3.6km^2. The main stream in the depression is 2.5km-long Handeresi Creek, which sinks in a swallow hole at the eastern end of the depression. This swallow hole is called "Han Cave" (Fig.7), and has two entrances at the same altitude (1335m). Additionally there is another, crack-like swallow hole in the northern

Figure 5. Üçgöller Creek sinks in a swallet in the southeastern corner of Subatanyaylasi Depression, and a short part of the old valley's bottom is dry.

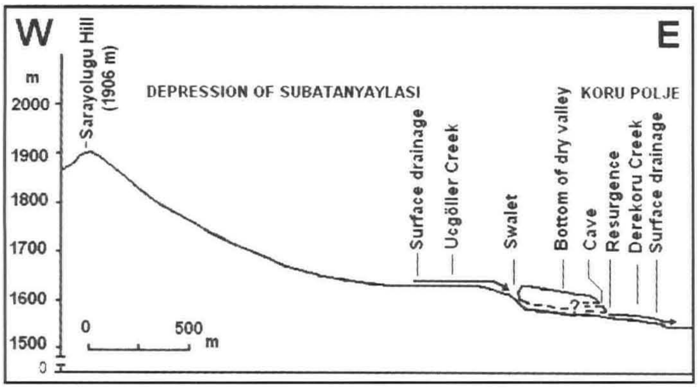

Figure 6. Longitudinal profile of Üçgöller Creek and its dry valley, between Subatanyaylasi Depression and Koru Polje.

Figure 7. Han Cave. Handeresi Creek sinks in swallow holes at the eastern end of Handeresi Depression.

slope 10m above, and 50m away from the Han Cave entrance, and this probably coalesces with Han Cave below ground.

Handeresi Depression developed as a tributary of the Çatak Creek valley during the cold periods of the Pleistocene. After formation of the Han Cave swallow hole, a short part of the valley between Çatak Valley and Han Cave became dry, and its floor remained about 30m above the entrance of Han Cave, in much the same way as the Ücgöller Creek dry valley between Subatanyaylasi and Koru Polje (Fig.6).

RESULTS AND DISCUSSION

All of the study area presented an appropriate environment for mantle karst, except for some karren types that developed on bare rock, most recently under modern climatic conditions. But, it is not possible to explain the formation of all the karst features in the area in terms of today's climatic conditions. For this reason the climatic changes of the Pleistocene must be taken into consideration, because periglacial conditions prevailed in the higher parts of the area during the cold periods of the Pleistocene, and permafrost must have been established there. Thus, rainwater and meltwater ran off in streams, and the streams formed valleys. Then these streams sank into swallow holes during interglacial periods and under modern conditions, forming blind and dry valleys.

Essentially, when the dimensions and characteristics of the larger karst landforms, and the amount of dissolution and landscape lowering per year are taken into consideration, it can be said that these features have formed over a long time period. For example, Bradshaw *et al.* (1979) said that the rates of dissolution ranged from 18mm/1000 years in South Wales, 50mm/1000 years in northwest Yorkshire, 72mm/1000 years in Jamaica and 300mm/1000 years in the Southern Alps, due to the varying types of limestone, relief and climate. In addition, Pulina (1999) said that the dissolution rate is intermediate (23mm/1000 years) in the lower karst area in Dobruca (Bulgaria and Romania), and is strong (56mm/1000 years) in intermediate elevation areas and 114-139mm/1000 years in high mountain area in the west Caucasus.

As a result, Koru Polje, Subatanyaylasi Depression and Handeresi Depression have vertical intervals of 25m, 30m and 30m respectively between the entrances of their swallow holes and the bottoms of the dry valleys behind them. According to the data presented above, it can be deduced that these swallow holes have been forming for many ten of thousands of years, and the large karstic depressions have been forming since the at least the beginning of the Quaternary Period, or perhaps even from the Late Tertiary.

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A brief history of stalagmite growth measurements at Ingleborough Cave, Yorkshire, United Kingdom.

Donald A McFARLANE [1], Joyce LUNDBERG [2] and John CORDINGLEY [3]

[1] W. M. Keck Science Center, The Claremont Colleges, Claremont CA 91711 USA.
dmcfarla@jsd.claremont.edu
[2] Department of Geography and Environmental Studies, Carleton University, Ottawa ON K1S 5B6 CANADA.
[3] Northern Pennine Club, Greenclose House, Clapham, via Lancaster, UK.

Abstract: Early (pre-radiometric-dating) measures of growth rates of the Jockey Cap stalagmite, Ingleborough Cave, Yorkshire have been augmented by recent laser range-finder measurements. This yields a growth rate of 0.147mm/yr. Propagation of this rate yields a basal date of 4469 yr BP. C-14 dating gives a basal age (after correction for dead carbon content and carbon flux) of 3477 – 3794 yr BP and a growth rate of 0.18mm/yr, comparing reasonably well with the historical estimates. This date for speleothem initiation correlates with several indices of environmental change in the region: a change to colder, wetter conditions and the beginning of significant forest clearance. U-Th data indicate a change in the type of detrital material introduced to the cave that may correlate with increased agricultural activity at ~1350 yr BP.

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INTRODUCTION

The early nineteenth Century in Britain saw the development of the first truly scientific explorations of caves and their contents. Dean William Buckland's influential work, *"Reliquiae Diluvianae, or, observations on the organic remains contained in caves, fissures, and diluvial gravel and on other geological phenomena attesting to the action of an Universal Deluge"* (1823) probably marks the beginning of scientific speleology in Britain. At this time, caves and their contents were generally perceived to be of great antiquity, but no means for quantifying their age existed. Buckland recognized that flowstone deposits overlying the bones of extinct mammals, as for example at Kirkdale Cave in Yorkshire, may represent long intervals of time, but he could go no further. A method of estimating growth rates of calcite deposits would thus be of great interest. This is the background for the discovery and subsequent measurement of the Jockey Cap, a stalagmite from Ingleborough Cave.

HISTORICAL BACKGROUND

In September 1837 heavy flooding around the flanks of Ingleborough, Yorkshire, resulted in a significant outpouring of water from beneath scree, 20m up-valley from Beck Head, the normal resurgence for Fell Beck. Presuming the water to come from a hidden cave, Mr J Anson Farrer, the landowner, ordered excavations to be made. These were unsuccessful, but served to focus attention on nearby Clapdale Great Cave, where the effective limit of exploration was a flowstone dam holding back a substantial accumulation of water. On September 23rd, the dam was breached, and after draining the "lake", two labourers penetrated some 70m into the cave (Beck, 1984). Subsequent explorations over the next 150 years extended the known cave – now known as Ingleborough Cave – to 4.2km, and in 1983 connected the cave to the 11.6km of the Gaping Gill system via sumped passages (Beck, 1984).

Soon after the opening-up of the cave, James Anson Farrer took a series of measurements of a distinctive stalagmite known as "The Jockey Cap" (Fig.1). Farrer recorded his observations in the "Cave Book", a leather-bound notebook that has survived in the care of the Farrer family to the present day and has been summarized in some detail by Craven (2004). In March 1839, Farrer recorded:

> *"Measured from the roof by the side of the stalactite to the rim of the hole into which the water falls is 7ft 1¼ inches"* [Farrer, ms "Cave Book"].

On October 30th 1845, Farrer made a second set of measurements, and a third on March 30th 1853:

> *"Circumference at base ten feet seven inches. Height from roof to the rim of the hole in the centre of the Jockey Cap seven feet two and a half inches"* [Farrer, ms "Cave Book"].

These observations were quoted in print for the first time by John Phillips (1853), Professor of Geology at Cambridge, and in due course came to the attention of Phillips' protégé, William Boyd Dawkins.

Dawkins was born on 26 December 1837, just three months after the exploration of Ingleborough Cave. Dawkins attended Jesus College, Cambridge, graduating in 1860, having developed an interest in the relationship of geology to history (Jackson, 1966). Inspired by work at Kent's Cavern by the Reverend William Pengelly, Dawkins focused on caves and began excavations at the Hyaena Den, in the Wookey Hole ravine, in December 1859 (Dawkins, 1862). This life-long interest in caves ultimately led to his famous work, *"Cave Hunting, researches on the evidence of caves respecting the early inhabitants of Europe"* (1874), in which Appendix II reprints his 1873 publication, *"Observations on the rate at which stalagmite is being accumulated in the Ingleborough Cave"* (1873).

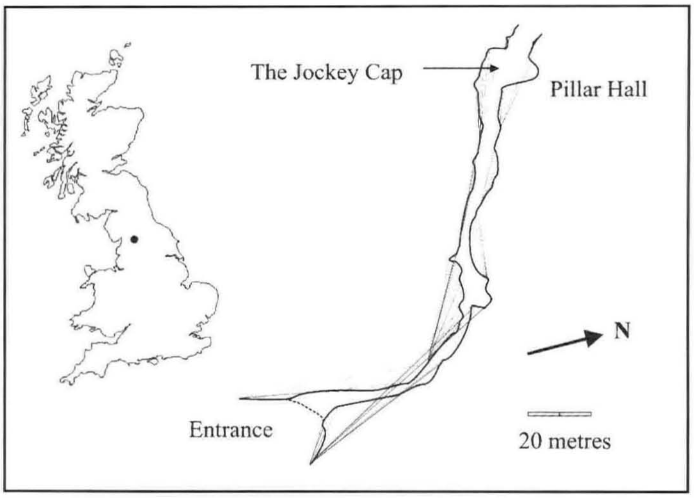

Figure 1. *Plan view of part of Ingleborough Cave, showing the location of the Jockey Cap.*

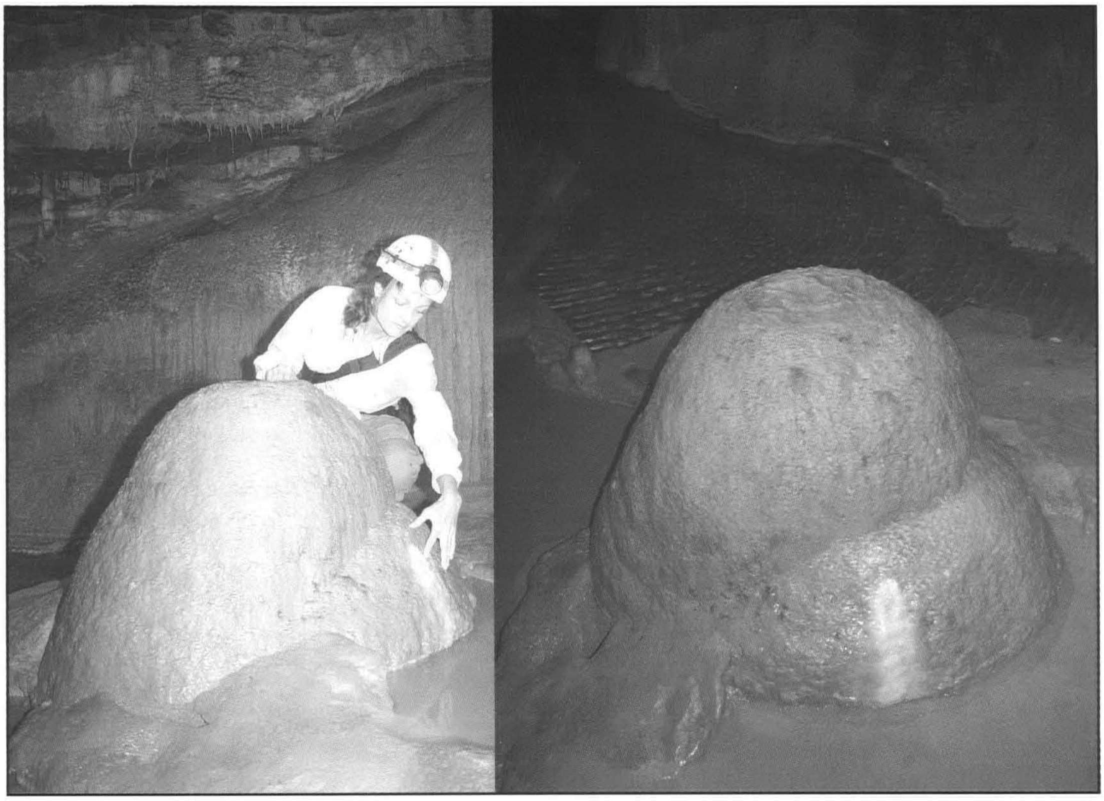

Figure 2. The Jockey Cap, 29th July 2002.

Dawkins had visited Ingleborough Cave on March 13th, 1873, and completed a fourth set of measurements. Dawkins recognized that his measurements were not directly comparable with Farrer's because Farrer's measurement points could not be relocated with sufficiently accuracy. Hence, *"For the sake of ensuring accuracy in future observations"*, Dawkins drilled three holes around the basal circumference of the Jockey Cap, inserted "gauges" of brass wire and measured the curvilinear dimensions of the stalagmite using lengths of iron wire that were subsequently deposited in the Manchester Museum. The only measurement in which Dawkins had confidence in reproducing was *"roof to apex of Jockey Cap"*, from which he recorded an apparent growth increment of 8.25 inches (209.5mm) between October 1845 and March 1873, equivalent to *"0.2946 inches"* or 7.48mm/yr. At this rate, and neglecting the growth of a small corresponding stalactite broken off on March 30th 1853, the Jockey Cap was apparently destined to form a continuous column with the roof in 295 years, and more dramatically still, could be extrapolated to be only 100 years old in 1839.

The rapid growth rate that Dawkins was obliged to infer from the available data presented him with a quandary: if he presumed an approximately constant rate of accumulation – in keeping with Charles Lyell's Principle of Uniformitarianism (Lyell, 1830) – then the Jockey Cap was astonishingly young. This would have been quite out of keeping with the developing consensus that stalagmitic coverings over the bones of extinct mammals were indicative of great antiquity. As Coneybeare (1822) had quipped, mocking Buckland's pioneering work at Kirkdale Cave, Yorkshire (McFarlane and Ford, 1998):

> *"By the crust of thy Stalactite floor,*
> *The post-Adamite ages I've reckoned,*
> *Summed their years, days & hours and more,*
> *And I find it comes right to the second"*

It is curious that Dawkins, beyond a brief comment that the *".. Jockey Cap may be the result not of continuous but of the intermittent drip of water..."*, chose not to discuss the significance of his young age for the stalagmite, although it may be that the care that Dawkins applied to taking his 1873 measurements reflected his concerns about variable growth rates. In 1914, aged 77, Dawkins wrote:

> *"There are no chronometers in nature that can be used to measure time past. All attempts to measure it by appeal to the rate of erosion of the land, or the thickness of the deposits from floods, or the amount of salt in the sea, are idle speculation founded on the false assumption that there was no variation in these things in the past"* (Dawkins, 1914, p.4).

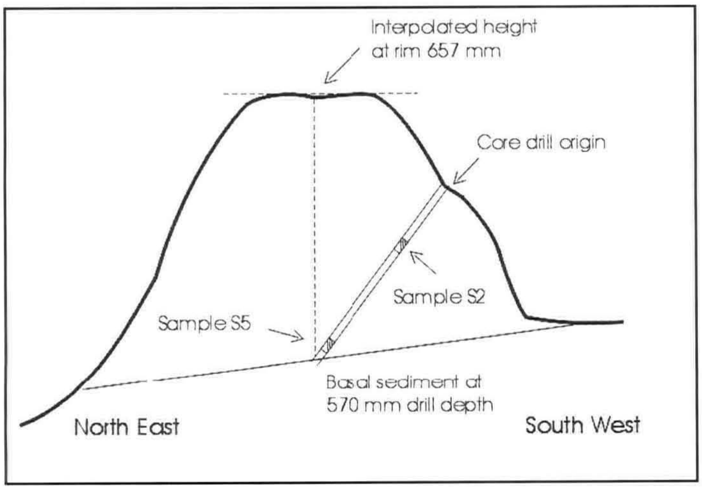

Figure 2b. The Jockey Cap - sample sites.

Date of measurement	Apex-roof height (cms)
1845	241.935*
1873	220.98*
1892	218.44*
1904	218.44*
1967	217.18*
2002	217.00

Table 1. *Historical measurements of the Jockey Cap apex to roof height. [* indicates data from Ford, 1975.]*

Sample	Age (ka)	Corrected Age (ka)	^{238}U ppm	^{232}Th ppm	230/234 act. rat.	234/238 act. rat.	230/232 act. rat	234/238 Init. act. rat.
5 495-530mm	63 ±6	8	0.103	3.6	0.44±0.03	1.062±0.003	1.7	1.074±0.0027
2 180-215mm	27 ±2	-118	0.104	7.4	0.22±0.02	1.043±0.002	1.5	1.047±0.0022

***Table 2.** U-Th data. [Corrected Age assumes an initial $^{230}Th/^{232}Th$ activity ratio of 1.5.]*

It is of interest that Herbert Balch, in his 1914 monograph on the excavations and geology of Wookey Hole, Somerset, was equally circumspect:

> *"A further point of importance is the antiquity of the stalagmite pillars of the upper new chambers ... I have no desire to calculate how long in years these columns have occupied in building, but this I do say ... if we admit that the great chambers are the work of untold thousands of years, then we must conclude that these pillars are monuments of equal antiquity"* (Balch, 1914, p.255).

One year earlier, Arthur Holmes had summarized the potential of the newly developing field of radiometric dating in his ground breaking *The age of the Earth* (Holmes, 1913). However, it would be a further 52 years before radiometric dating, in the form of uranium-thorium disequilibrium dating, would yield the first reliable absolute age on a speleothem from Akhshtyr Cave, Krasnodar (Cherdyntsev *et al.*, 1965) and relegate direct growth measurements to the realm of strictly local and historical interest.

RECENT ADVANCES

Additional measurements of the Jockey Cap (Table 1) were made in 1892, 1904 and 1967 (quoted in Ford, 1975). The roof-to-apex measurement was repeated in July 2002 by laser rangefinder (accuracy ± 3mm). The apex of the formation (Fig.2) has a concave cupola within it, the edge of which formed the measurement point for both Farrer and Dawkins. This edge is not perfectly horizontal however, yielding slightly different apex-to-roof measurements depending on instrument orientation. The weighted mean of 3 measurements of the apex-to-roof distance on July 29th 2002, incorporating instrument accuracy, was 2.1700 ± 0.0017m (1 sigma).

Taken at face value, these results imply a very rapid rate of growth of the Jockey Cap in the mid 19th Century (7.5mm/yr, 1845–1873), dropping to a very slow rate in the late 19th and through the 20th centuries (0.147mm/yr, 1873–2002, Fig.3). There is some anecdotal evidence (Jarman, pers.comm, 2002) that the position of the drip that feeds the Jockey Cap has shifted since the early Farrer measurements, lowering the growth rate. However, the magnitude of the apparent change is largely dependent on the accuracy of Farrer's 1845 measurement. If this measurement is discarded, the variability of the growth rate is substantially reduced. By way of comparison, a length of telephone wire (Fig.5) placed in the Ingleborough Cave (Inauguration Series) in 1971 (Platts, 1971) had accumulated a deposit of calcite averaging 1.6mm in thickness by the time of its removal in 2002, a growth rate of 0.05mm/yr.

At the apparent growth rate of 0.147mm/yr calculated from 1892–2002 measurements (Fig.3), and a thickness of 657mm (from measurements of total height done in 2004, Fig.2), the simplistic age calculation for the base would be 4469 years. The next obvious step is to check this date by an alternative dating technique.

Hitherto, it has been supposed that the historical significance of the Jockey Cap, and the destructive nature of radiometric dating would preclude direct measurement of the formation's age. However, in 2003, under permit from English Nature, the authors were able to obtain calcite samples from the interior of the Jockey Cap by the conservative drilling of a narrow-diameter sample hole from the periphery of the formation to its presumptive centre-base (Cordingley, 2004). Table 2 presents TIMS ^{230}Th / ^{234}U dates on 2 calcite sub-samples from the Jockey Cap (S5 is close to the base and S2 closer to the outer margin). However, the very high levels of ^{232}Th (3.6 and 7.4 ppm respectively) indicate significant contamination by detrital thorium, creating difficulties in the interpretation of these ages. Table 2 also shows the "corrected" age using an assumed initial ^{230}Th / ^{232}Th activity ratio of 1.5 (the standard correction for cave muds, taken from Schwarcz, 1980). The basal date comes down to ~ 8ka but the outer sample is an impossible -118ka. If, instead, a much lower (but arbitrary) initial ^{230}Th / ^{232}Th activity ratio of 0.4 is assumed, then the "corrected" basal age becomes ~51ka and the outer sample a reasonable ~3ka. There is no basis by which to know which initial activity ratio is applicable, nor is there a way to know if the same correction should be applied to both dates (indeed the obvious difference in ^{232}Th concentration of the two samples might suggest a shift in conditions). Thus it must be concluded that the ^{230}Th / ^{234}U dates cannot adequately constrain the date.

Therefore, an AMS radiocarbon analysis of subsample 5 was undertaken, yielding an uncalibrated ^{14}C age of 4800 ± 40 rcybp (5660 – 5510 cal yrs BP, 2σ range). Presuming that the outer edge has an age of 0 years and that the growth rate has been constant, then the basal age is 5344 ± 40 rcybp. This date is in approximate agreement with the simplistic date calculated from the historical measurement and obviously quite different from the U-Th dates. However, radiocarbon dates on speleothems are typically too old, relative to the true age of the deposit, because speleothems incorporate "live" ^{14}C from atmospheric and soil carbon dioxide, along with "dead" carbon derived from dissolution of the limestone bedrock. The difference between the apparent radiocarbon age and the true radiocarbon age is dependent solely on the dead carbon percentage (DCP) and is independent of sample age (Geyh and Schleicher, 1990);

$$\Delta t = (\tau / \ln 2) \, . \, \ln(1 - (k/100))$$

where τ is the half life of ^{14}C and k is the DCP. Genty *et al.* (2001) found a relationship of mean annual temperature with proportion of dead carbon for 10 speleothem samples from northern Europe. Using this relationship and the mean annual cave temperature for Ingleborough Cave of 9°C the dead carbon proportion applicable to this sample would be 19.5% (an age difference of -1793 years). The uncorrected carbon date on subsample 5 of 4800 ±40 rcybp thus becomes 3007 rcybp or 3123 – 3403 cal yrs BP. The age on the base would then be 3477 – 3794 cal BP. The estimate for basal age propagated from the historical measurements is roughly 1000 years older than this (4469 years BP). In view of the presumed inaccuracy

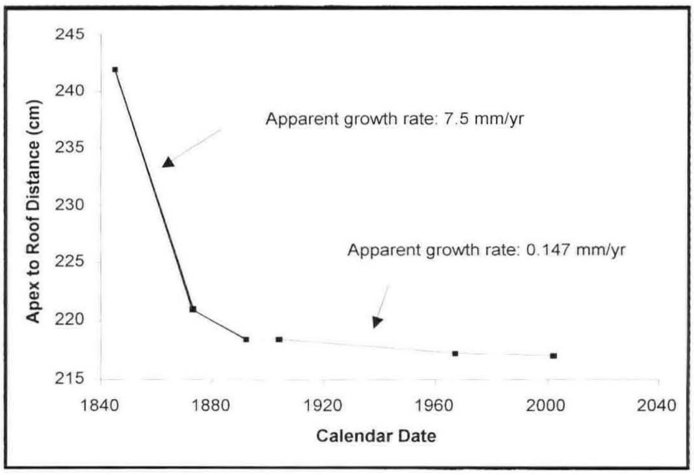

***Figure 3.** Apparent growth rate of the Jockey Cap, Ingleborough Cave, from historical data. (Measurements not precisely located on the speleothem are not included in this graph.). The value from 1845 is probably a measurement error.*

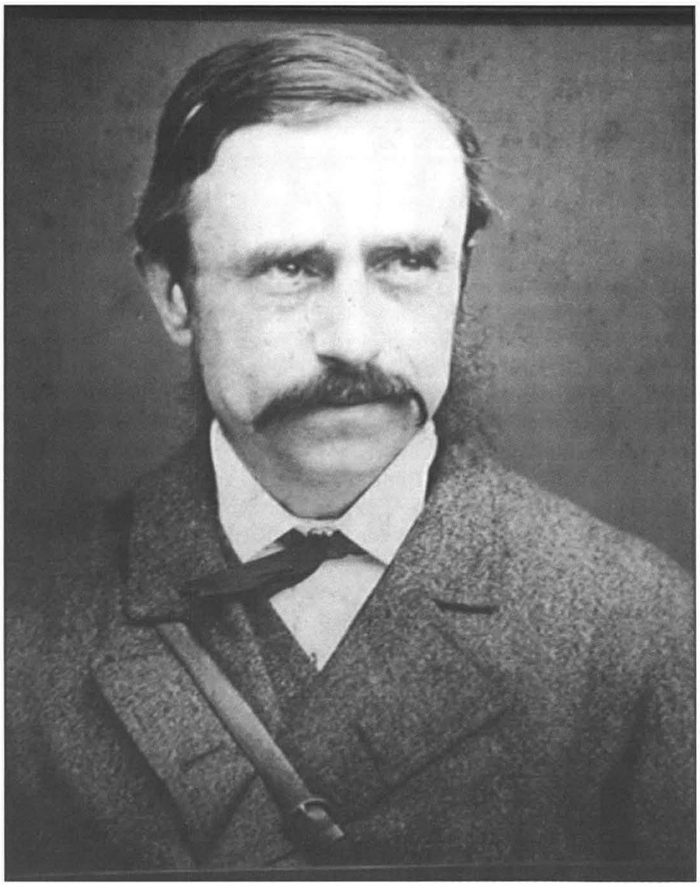

Figure 4. Portrait of William Boyd Dawkins, 1870s (courtesy of the Buxton Museum, Derbyshire).

of the measurement techniques available in the past, it is perhaps remarkable that the estimates are so close. This implies that the growth rate was relatively constant, suggesting that, in this case, Dawkins' (1914) caution was unwarranted. It also suggests that simple historical geometrical growth measurements may, in some cases, be surprisingly useful.

GROWTH RATES AND DRIP WATER CHEMISTRY

Using the ^{14}C date, the growth rate for the Jockey Cap is estimated at ~0.18mm/yr. Growth rates measured from Holocene speleothems in European caves vary widely from 0.01 to 0.93mm/yr (Hill and Forti, 1997), although 0.02 – 0.11mm/yr seems to be the more common range for much of the Holocene. Baker and Smart (1995) tried to compare actual growth rates with modelled growth rates (based on work by Dreybrodt, 1988) over well-constrained historical times for speleothem of southern England. Typical growth rates were only 0.009 – 0.050mm/yr. However one exceptional site in Kent's Cavern, Devon, with a low slope angle, grew at a rate comparable with that of the Jockey Cap: 0.130 – 0.261mm/yr. They found that growth in their seven samples was more closely related to Ca^{++} ion concentration than to other parameters such as temperature, water film thickness or discharge. The Ca^{++} ion concentration for the Kent's Cavern sample was 2.64 mmol/litre, which should give a growth rate of 0.05 – 0.10mm/yr, considerably below the measured rate of 0.130 – 0.261mm/yr. They speculate that the low slope angle causes increased residence time of waters and a significantly thicker water film. Baker *et al.* (1998) report additional comparisons of theoretical and measured growth rates. Using Baker and Smart's (1995) graph of Ca^{++} concentration against growth rate, and Pitty's (1974) measure of the Jockey Cap drip Ca^{++} concentration (85.6 ppm or 2.14 mmol Ca^{++}/litre) yields an expected growth rate of ~0.035mm/yr for the Jockey Cap, also considerably below the measured rate. The wide, boss-shape of the Jockey Cap gives a relatively low slope angle at the apex and at the sides. It also has an obvious slight depression at the top, providing the potential for delayed water discharge and thus increased time for deposition. If Baker and Smart's (1995) speculations are correct, then the high growth rate of the Jockey Cap is not unreasonable.

PALAEOENVIRONMENTAL COINCIDENCES

It is of interest to speculate on what triggered the initiation of speleothem growth at this time. Several studies indicate that the period of the beginning of the Jockey Cap's growth (~4ka) coincides with regional environmental changes. Palynological records from the British Isles demonstrate the *"Pine Decline"* (Pilcher *et al.*, 1995): pines that had colonized the area between 9.5 and 8ka had died out in almost all areas by 4ka. Tufa deposits from England also show the climatic optimum ending around 4.5ka (Andrews *et al.,* 1994). Peat records in Scotland show a major shift to a cool, wet climate at around 4.0ka (Chambers *et al.,* 1997). At Hockham Mere (East Anglia) spread of grasses occurred at about 4400 BP (Godwin, 1975). Human activity also became significant at roughly this time: the clearance of British forests began about 5000 BP and lasted 3000 years (Yalden, 1999); the earliest record of farming in northwest England is 5110 BP (Ammerman and Cavalli-Sforza, 1971); and the Peak District saw deforestation and the rapid spread of peat bog in the interval 5500 – 5000 BP (Yalden, 1999). Howard *et al.* (1999) note several other coincidences for the Yorkshire Dales region: palaeobotanical work indicates that significant clearance and agricultural activity began around 4.5ka; a raised bog in Yorkshire indicates a shift to wetter conditions around 4.2 ka; and U-Th dates on tufas overlying river terraces suggest that the phase of deposition on the uppermost terrace had ceased by 4.5 – 4.2ka and given way to renewed erosion. The coincidence of all these proxies suggests that an increase in rainfall and the spread of peat bogs combined with the initiation of widespread forest clearance in the region was probably the trigger that started the Jockey Cap's growth, although we cannot exclude the possible contribution of changes in the hydrological geometry of the system due to dissolution or infilling.

It is also of interest to speculate on the environmental changes indicated in the U-Th data. If the basal carbon date is taken as "true" and the initial ^{230}Th / ^{232}Th activity ratios required to bring the ^{230}Th / ^{234}U dates into line are calculated (1.57 and 0.42 respectively for the basal and outer samples), then it is apparent that the detrital contamination of the two samples is not of the same type, and that there must have been a fundamental change in the type of material being introduced to the cave. Thus the ^{230}Th / ^{234}U dates seem to indicate a shift in conditions of growth. Howard *et al* (1999) observe an interesting shift in the materials of the river terraces in Wharfedale, Yorkshire Dales: agricultural expansion around 1350 years ago is suggested as the source of notably different sediment supply for the third terrace. It is possible that this change could also have affected Ingleborough Cave.

CONCLUSION

Historical measurements of the Jockey Cap since 1873 yield a growth rate of 0.147mm/yr. Assuming constant growth rate, propagation of this rate yields a basal date of 4469 yr BP. Carbon-14 dating, corrected for an assumed dead carbon content and for carbon flux yields a basal date of 3477 – 3794 yr BP and a growth rate of ~0.18mm/yr. This suggests that the historical measurements were surprisingly accurate. The rather fast growth rate is consistent with other measures of gently sloping, wide, boss-shaped speleothem and is probably caused by slow flow rates of drip waters over the formation.

This date for speleothem initiation correlates with several indices of environmental change in the region: a change to colder, wetter conditions and the beginning of significant forest clearance. U-Th data indicate a change in the type of detrital material introduced to the cave between the early growth and the more recent. This may correlate with changes in sedimentary material of river terraces in the area in response to increased agricultural activity.

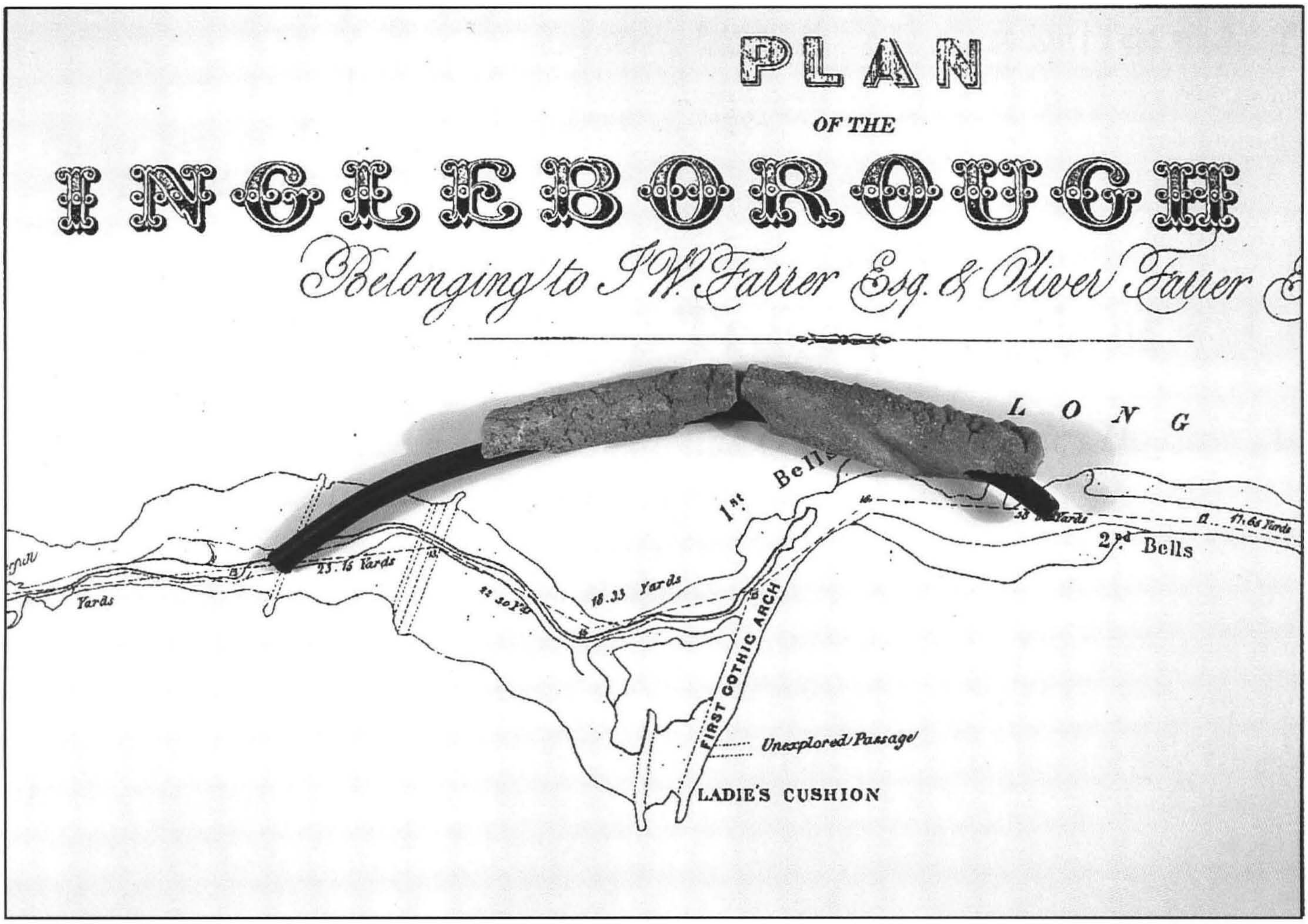

Figure 5. Calcite accumulation on telephone wire, 1971 – 2002. The wire is 2.38mm in diameter.

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A note on the distribution of plants in Scoska Cave, North Yorkshire, United Kingdom, and their relationship to light intensity

Allan PENTECOST and ZHANG Zhaohui

School of Health and Life Sciences, King's College London, Franklin-Wilkins Building, 150 Stamford Street, London SE1 9 NH.
e-mail allan.pentecost@kcl.ac.uk

Abstract: The flora of a small limestone cave was investigated. A total of 59 species was recorded (4 algae, 3 lichens, 47 bryophytes, 4 ferns and 1 angiosperm) making it bryologically the richest cave in Britain and one of the richest in Europe. All but nine of the species had been recorded from other European caves. Species-richness declined irregularly from the entrance (relative irradiance with respect to open sky 12%) to 34m depth (rel. irradiance 0.004%). Bryophytes were found at 0 to 16m depth, where relative irradiance declined to 0.2%. Only algae were encountered at 34m depth. Whereas irradiance, which declined exponentially, was the major factor controlling plant distribution, substratum characteristics and surface moisture were also important.
Key words: caves, flora, bryophytes, light.

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INTRODUCTION

Remarkably little has been published on the flora of British caves, despite the popularity of caving as a British sport. While cave surveys have been numerous, there has been little effort to examine caves systematically for their flora. This contrasts with continental Europe where the cave flora is better known, e.g. Maheu (1906), Lämmermayer (1916) and Dobat (1966; 1970; 1998a,b). In Britain, Mason-Williams and Benson-Evans (1958, 1967), Mason-Williams (1962; 1966) and Cubbon (1970; 1976) provide lists of bacteria, algae, bryophytes and angiosperms from several South Wales caves, including some information on substratum pH, light and humidity. Dalby (1966) investigated the growth of a moss, *Eucladium verticillatum* in an English mine and found interesting adaptations to light, while Zhang and Pentecost (1999) published a short list of cave bryophytes from Yorkshire. Some British cave algae have also been noted by Claus (1967) and Carter (1971) but, apart from this, there are only isolated references to the British cave flora in more general works such as Hill *et al.* (1994).

The largest concentration of limestone caves in Britain is to be found in the Craven district of North Yorkshire. Surprisingly, this area is also one of the least well known for its cave flora. The senior author recognized Scoska Cave as a good site for the investigation of plant threshold communities some years ago. The entrance is 70m above the River Skirfare on a northeast-facing steep scarp below Scoska Moor in Littondale (British National Grid Reference 34/915724, altitude 285m). It is the source of a small stream, Gildersbank Sike. Scoska Cave is noted for its moderately wide (3 to 4m) and straight entrance passage, which follows a sub-horizontal bedding plane in Dinantian limestone close to the top of the Gordale Limestone Member (Malham Formation, Great Scar Limestone Group). Light can penetrate at least 40m into the passage and is gradually attenuated by the influence of the simple cave geometry. The roof is about 2m high, following a higher bedding plane (Fig.1a).

This paper reports on the flora of the cave and its relationships with light intensity, with particular reference to biodiversity (as species-richness).

METHODS

The cave was examined on two dates April 1st 2000 and July 15th 2000. In addition to collecting small samples of cave flora at regular intervals from the entrance, cave dimensions were measured together with air temperature, relative and absolute humidity and irradiance. Humidity was measured with a hand-held psychrometer and irradiance with a Licor 185B quantum meter, the sensor of which was placed directly toward the cave entrance. Absolute and relative photosynthetically available radiation (PAR) was obtained by comparison with the open, unobstructed sky. Critical plant groups were identified using standard British floras. Bryophytes were conspicuous, but lichens, ferns, spermatophytes and, in less detail, the algae were also examined. Lichen, bryophyte and pteridophyte nomenclature follows Purvis *et al.* (1992), Blockeel and Long (1998) and Stace (1991) respectively.

RESULTS

Cave substrata

At the entrance, angular blocks of limestone cover the floor for a distance of about 10m within (Figure 1a). Thereafter a brown cave earth is exposed in places with scattered limestone blocks. The cave walls are steep, largely devoid of crevices and mostly dry with a little speleothem development about 30 to 40m from the entrance. Gildersbank Sike breaks out from the floor 24m within the cave but disappears under rocks after a short distance, reappearing at the entrance. Its discharge was low, about 1 l/sec when visited. The water had pH 8.3, Ca 62 ppm, Mg 0.5 ppm, Na 2.5 ppm, SO_4 9 ppm and alkalinity 2.3 mEq/L (140 ppm).

Microclimate

Climatic data are shown in Fig.1. Irradiance (Figure 1b) becomes attenuated approximately logarithmically from the entrance to a depth of 30m. Beyond 40m the passage turns to the left and light is abruptly diminished. No plants were observed beyond this point. The decline in intensity followed closely the exponential Bouguer-Lambert Law (regression Anova $p<0.001$) and provided a mean 'extinction coefficient' of $0.24m^{-1}$. Absolute light intensity was higher during April than in July, as the April measurements were made on a brighter day with threshold irradiances averaging 5.5 and 2.2 Klx respectively. Only diffuse light enters the cave as the passage orientation precludes direct sunlight. Light levels (as relative irradiance, RI) at the entrance were 12% and 11% of the open sky during the April and July visits owing to shading by trees (ash and sycamore). For the entrance measurements the sensor was directed horizontally out of the cave toward hillsides and trees and not towards the sky above. Absolute light levels in this cave would be expected to be at a maximum just before tree leaf expansion (April–May).

Temperature and humidity profiles were obtained at 10.30h on the July sampling date and are shown in Figure 1c. Air temperature underwent a linear decline from the entrance to a depth of 20m, where it stabilized at around 9.5°C. In contrast the relative humidity rose from about 80% at the entrance to 95% at 15m depth. Deeper in the cave this high humidity was maintained. The air showed little apparent movement within this part of the cave. The water vapour pressure, obtained from psychrometric tables, remained approximately constant, ranging from 11.3–11.9mb (mean 11.4mb).

Flora

A total of 59 taxa were recorded, consisting of four algae, three lichens, 47 bryophytes, four ferns and one flowering plant. The flora was dominated by bryophytes in terms of species-richness and cover (Table 1). Bryophytes grew only on the lower walls and floor of the cave and not

Phylum/Genus	species	authority	0-2m	2-4m	4-6m	6-8m	8-10m	10-12m	12-15m	15-20m	20-40m	other caves[1]
Cyanobacteria												
Gloeocapsa	punctata	Naeg.									X	E
Phormidium	ambiguum	Gom.								X		E
Schizothrix	perforans	(Ercegovic) Geitler									X	B
Chlorophyta												
Gongrosira	sp.									X		E
Lichenes												
Lepraria	incana	(L.) Ach.	X	X	X	X	X	X	X	X		B
Lepraria	nivalis	Laundon	X	X								B
Leproplaca	chrysodeta	(Vain.ex Raes.) Laundon	X	X	X					X		B
Musci												
Amblystegium	serpens	(Hedw.)Br. Eur.						X				B,E
A.	tenax	(Hedw.) C. Jens				X						
Brachythecium	rutabulum	(Hedw.) Br. Eur.			X							E
Bryum	cf. pallens	Sw.			X	X						E
Bryum	pseudotriquetrum	(Hedw.) Schwaegr.		X								B
Cratoneuron	filicinum	(Hedw.) Spruce		X	X							B,E
Dichodontium	pellucidum	(Hedw.) Schimp.				X						
Didymodon	fallax	(Hedw.) R.H. Zander	X									E
Encalypta	streptocarpa	Hedw.			X							B,E
Eucladium	verticillatum	(Brid.) Br. Eur.	X	X								B,E
Eurhynchium	hians	(Hedw.) Sande Lac		X								B,E
E.	pumilum	(Wils.) Schimp.			X	X	X		X			E
E.	speciosum	(Brid.) Jur.				X						B,E
Fissidens	adianthoides	Hedw.					X					E
Fissidens	cristatus	Wils. Ex Mitt.		X						X		B,E
Fissidens	taxifolius ssp. pallidus	Hedw.		X	X							B,E
Gymnostomum	aeruginosum	Sm.	X	X								B
Heterocladium	heteropterum	(Bruch. Ex Schwaegr.) Br. Eur		X						B,E		
Hymenostylium	recurvirostrum	(Hedw.) Dixon		X								E
Hypnum	resupinatum	Taylor							X			
Isopterygiopsis	pulchella	(Hedw.) Z. Iwats				X						E
Leptodontium	flexifolium	(With.) Hampe	X			X						
Mnium	stellare	Hedw.		X					X			E
Neckera	complanata	(Hedw.) Hub.					X					E
Orthothecium	intricatum	(Hartm.) Br. Eur.			X				X	X		
Palustriella	commutata var. commutata	(Hedw.) Ochyra	X	X								B,E
Plagiomnium	undulatum	(Hedw.) Kop.	X									B,E
Platydictya	confervoides	(Brid.) Crum.					X		X	X		E
Pseudotaxiphyllum	elegans	(Brid.) Z. Iwats				X		X		X		E
Rhynchostegiella	teesdalei	(Br. Eur.) Limpr.							X	X		E
Rhynchostegiella	tenella	Dicks.) Limpr.						X		X		E
Rhynchostegium	riparioides	Hedw.) C. Jens			X							B,E
Tortella	tortuosa	(Hedw.) Limpr.		X	X		X		X			E
Weissia	cf perssonii	Kindb.							X			

Table 1. *Scoska Cave flora*

Hepaticae												
Conocephalum	conicum	(L.) Underw.	X						X			B,E
Jungermannia	atrovirens	Dum.				X						E
Jungermannia	exsertifolia	Steph.				X						E
Leiocolea	badensis	(Gott.) Joerg.				X						
Leiocolea	bantriensis	(Hook.) Joerg.	X			X						
Lophocolea	bidentata	(L.) Dum.	X			X						E
Metzgeria	conjugata	Lindb.							X			E
Pellia	endiviifolia	(Dicks.) Dum.	X					X				B,E
Plagiochila	britannica	Paton	X	X								
Plagiochila	porelloides	(Torr. Ex Nees) Lindenb.		X							B,E	
Preissia	quadrata	(Scop.) Nees			X							E
Pteridophyta												
Asplenium	adiantum-nigrum	L.							X			E
Asplenium	trichomanes	L.							X			B,E
Asplenium	trichomanes-ramosum	L.							X			B,E
Dryopteris	filix-mas	(L.) Schott							X			B,E
Spermatophyta												
Chrysosplenium	oppositifolium	L.					X	X				B,E
Mid-point relative irradiance %		8.24	5.03	3.08	1.88	1.15	0.71	0.38	0.15	0.007		
Species-richness		16	16	13	15	7	6	15	11	2		
[1]B : Recorded from other British caves; E, other European caves.												

***Table 1**, continued.*

the upper walls or roof, which may have been too dry. The total species richness peaked at 0 to 4m and 10 to 15m from the entrance where 16 and 15 species were recorded respectively. Beyond 15m the species richness declined rapidly and beyond 20m only two species, both algae, were recorded. Common threshold bryophytes that were absent from the interior included *Eucladium verticillatum, Gymnostomum aeruginosum* and *Palustriella commutata* var. *commutata.* These grew on moist walls of the cave where there was a small seepage, depositing small amounts of travertine. At the threshold, 0 to 4m from the entrance, the relative irradiance (RI) ranged from 5 to 10%. Many species penetrated further. For example, frequent bryophytes in the region 6 to 10m with RI 1 to 2% were *Eurhynchium pumilum, Fissidens adianthoides* and *Pseudotaxiphyllum (Isopterygium) elegans.* Deeper still were *Amblystegium serpens, Fissidens cristatus* and *Thamnobryum alopecurum.* The latter was the most frequently encountered bryophyte in the cave and also occurred at the threshold. *Orthothecium intricatum, Pseudotaxiphyllum elegans, Rhynchostegiella teesdalei* and *Platydictya confervoides* (15.9m, RI 0.23%) were found further into the cave. Bryophytes penetrating to the greatest depth were *Fissidens cristatus* and *Thamnium alopecurum* (both to16.2m with RI 0.20%). Liverworts were much less common, with large thallose species abundant only at the moist threshold. Within the cave conditions were probably too dry to support luxuriant liverwort growth, but a few species such as *Conocephalum conicum* and *Metzgeria conjugata* penetrated to 12m. Four ferns, *Asplenium adiantum-nigrum, A. tichomanes, A. trichomanes-ramosum* and *Dryopteris filix-mas* were noted up to 12m from the entrance but none was common. Three species of leprose lichens were conspicuous on threshold walls where they formed diffuse yellow and white patches. *Lepraria incana* was the commonest and was found to a depth of 17m.

Only a few algae were collected. Sparse populations of the cyanobacteria *Gloeocapsa* and *Schizothrix* were recovered from damp speleothem at depths of 34m and 27m respectively and no algae were evident visually beyond 34m. Light levels were extremely low at these points, with RI values of approximately 0.004% and 0.014% respectively. An unidentified coccoid green alga was associated with the *Gloeocapsa.*

DISCUSSION

Measurements of irradiance in Scoska Cave demonstrate an exponential decline in light with distance from the entrance. This is no doubt the result of the straight tube-like form of the passage and would also be expected in artificial excavations such as mine adits. Other caves may show a similar relationship for part of their length (Dobat, 1998a) but presumably only where the cave geometry is favourable. In Skoska, air temperature fell to about 9.5°C within the cave, which is close to, though slightly higher than, the predicted mean air temperature at the site (8.5°C). Ground air temperature is usually close to mean air temperature in Britain though minor differences often occur as discussed by Wigley and Brown (1976). Relative humidity was high, which is to be expected for a cave with a moist floor and stream running through it. The humidity profile is similar to that of the Scheunenhöhle, Germany (Dobat, 1998a).

With a total of 59 plant species in five phyla the flora of this cave must be considered both rich and diverse. This is surprising considering its small size. However, comparable species richness has been reported for several caves in Germany and France (Maheu, 1906; Lämmermeyer, 1912; Dobat, 1998b). In the Scoska Cave site the richest area was at the threshold where 16 species were recorded over a length of 2m. Further into the cave species richness declined irregularly (Fig.1d). This is partly the result of the rocky nature of the floor at the cave entrance, which gave way to clay within. The wet clay supported several species of fern, a flowering plant and several bryophytes. This must be one reason why the 6 to 8m and 10 to 12m sections had a species-richness approaching that at the threshold. Richness declined rapidly once the RI fell below 0.5% (Table 1). A similar decline has been found at increasing distances from artificial cave lighting (Dobat, 1998b). Among bryophytes the moss *Thamnobryum alopecurum* penetrated to the greatest depth within Scoska Cave. In artificial 'Lampenfloras', Dobat (1998b) found that *Fissidens*

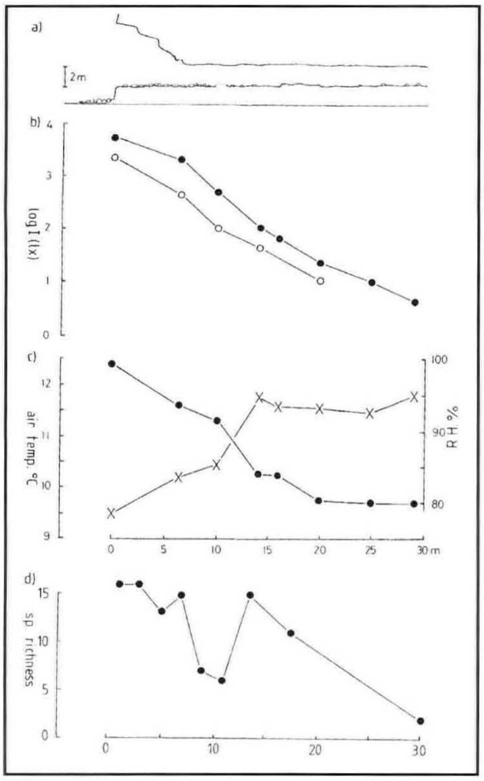

Figure 1. *Morphometric and climatic data for the entrance passage of Scoska Cave, North Yorkshire.*

a) Cave profile showing rock-strewn passage and flat cave roof.
b) Photosynthetically available radiation (PAR) in Scoska Cave (lx). Closed circles April 2000; open circles July 2000. Note logarithmic scale for PAR.
c) Air temperature, °C (closed circles) and % relative humidity (crosses).
d) Species richness vs. distance from cave entrance

species could tolerate a low irradiance of 80 to 90 lux, which corresponds to the depth where *Thamnobryum* was found in Scoska. *Thamnobryum* was also abundant in Sleets Gill Cave nearby. It is one of the best-known cave mosses in Britain and Europe. In South Wales it has also been found in low light regimes (Mason-Williams and Benson-Evans, 1958) and it is common in shady British woodlands and ravines (Hill *et al.,* 1994). According to Chapman (1993) the fern flora of Scoska is typical of British cave thresholds and the same species are encountered in caves of the adjacent continent. Only one flowering plant, *Chrysosplenium oppositifolium* was recorded. In South Wales, the same species was the most frequently recorded flowering plant in the caves investigated by Mason-Williams and Benson-Evans (1958), where it occurred at light intensities of 18 to 24 lux, much lower than the intensities recorded at Scoska.

Little attention was paid to the algae of Scoska Cave but, judging from previous studies (e.g. Claus 1962; Carter, 1971), a thorough investigation would probably yield many species. It was clear that some algae tolerate lower irradiances than the bryophytes and vascular plants. Coccoid cyanobacteria such as *Gloeocapsa* are known to occur at low irradiances in other caves (Cox *et al.,* 1971). Some cyanobacteria can grow heterotrophically and this might explain their occurrence at such low light levels. However, their absence from the darkest recesses and a tendency for them to occur only on parts of speleothem facing the entrance of Scoska Cave suggest that they are in fact growing autotrophically. Algae are known to occur through much of the 35m section of cave that was investigated, since lichens growing to a depth of 17m contained the symbiotic green algae *Chlorella* and *Stichococcus*. Little is known of the ecology of lichens in caves but Jaros (1964) found that *Lepraria nivalis* occurred in relative light intensities ranging from 93 to 0.5% in a Hungarian cave. In Scoska Cave this species was only found close to the entrance and exposed to an RI of 5 to 10%.

Among the plants recorded at Scoska, nine have not previously been recorded from caves as far as the authors are aware, and all were bryophytes. Of these, six did not penetrate further than 8m from the entrance and the remaining three, *Hypnum resupinatum, Orthothecium intricatum,* and *Weissia* cf. *personnii* penetrated regions where the RI fell to about 0.4%. Most of the cave bryophytes are typical of limestone and base-rich waters such as those of Gildersbank Sike. Many of the species encountered in the cave also grew on sheltered cliffs nearby. A few, such as *Dichodontium pellucidum,* grew only on clay soil, demonstrating the importance of suitable substrata for colonization in caves.

As other studies have demonstrated (see review of Dobat, 1998a), light was clearly the most important factor controlling plant distribution. However, the irregular decline in species-richness points to other important factors, namely substratum type and moisture. Skoska Cave has few roof seepages in the illuminated zone and the bare limestone surface can only be wetted by condensation. Whereas condensation undoubtedly occurs near the cave entrance due to temperature and humidity change, this lack of moisture places a stress on many hygrophilous bryophytes, which would only find sufficient moisture on or near the cave floor where moisture can be gained through capillarity. The occurrence of large limestone blocks up to 50cm across prevents this near the entrance and largely explains the variation in species-richness. Water relations and substratum type are therefore important factors for distribution and biodiversity.

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Hydraulic and geological factors influencing conduit flow depth.

Stephen R H WORTHINGTON

Worthington Groundwater, 55 Mayfair Avenue, Dundas, Ontario, L9H 3K9, Canada.
sw@worthingtongroundwater.com

Abstract: There has much been speculation as to whether cave formation should occur at, above, or below the water table, but a satisfactory explanation has been lacking until recently. The last 50 years has seen extensive mapping of caves both above and, more recently, below the water table. It is now becoming apparent that there are systematic differences in depth of flow between different areas and that conduit flow to depths >100m below the water table is not uncommon. Such deep flow is facilitated by the lower viscosity of geothermally heated water at depth. Analysis of data from caves shows that depth of flow is primarily a function of flow path length, stratal dip and fracture anisotropy. This explains why conduits form at shallow depths in platform settings such as in Kentucky, at moderate depths (10–100m) in folded strata such as in England and in the Appalachian Mountains, and at depths of several hundred metres in exceptional settings where there are very long flow paths.

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INTRODUCTION

The nature and extent of cave development with respect to the water table has received much attention, especially in the first half of the Twentieth Century (Lowe, 2000a). Early theories were largely speculative because few caves above the water table and none below the water table had been accurately mapped. For instance, in 1950 there were only seven caves with mapped lengths greater than 10km. In the last 50 years, however, this number has grown rapidly, reaching 125 in 1977 and 350 in 2000 (Chabert, 1977; Madelaine, 2001). The growth of mapped cave passages below the water table is even more marked. In 1950 underwater exploration in caves had barely commenced, but by 2000 there were 14 caves explored to depths of at least 150m below the water table (Farr, 2000). This impressive dataset of mapped caves provides an invaluable empirical database for ideas on cave development.

Conduit development results from the interplay between hydraulic, chemical and geological factors. Early calculations on conduit enlargement were disappointing as they showed that infiltrating water would quickly become saturated with respect to calcite, that no further dissolution would then take place, and thus caves could not be formed (Weyl, 1958). Caves clearly do exist, and so some alternative explanations were proposed, such as the presence of sulphides (Howard, 1964) or the occurrence of mixing corrosion (Bögli, 1964). At the time it thus appeared that caves might only form in some special situations and so be rare. However, this concept was overturned in the 1970s when lab experiments showed that the dissolution rate of calcite and of dolomite is non-linear and that there is a large reduction in the rate as chemical equilibrium is approached (Berner and Morse, 1974; Plummer and Wigley, 1976; Herman and White, 1985). These results were in turn incorporated into numerical models, which showed that caves form in all unconfined carbonate aquifers (Dreybrodt, 1990; Palmer, 1991). Furthermore, this process occurs not only where there is sinking stream recharge but also where there is percolation recharge (Dreybrodt, 1996).

Early studies on the depth of cave development with respect to the water table focussed largely on hydraulic factors. For instance, Davis (1930) noted that some flow lines from recharge areas to discharge areas describe arcs deep below the water table during the initial pre-karstification stage of flow through an aquifer, and he suggested that cave development could occur along such deep flow paths. Swinnerton (1932) suggested that the greatest flow and thus the greatest dissolution would occur along the shortest flow path, that shallow flow paths are the shortest, and consequently that conduit formation close to the water table is favoured. Thrailkill (1968) analysed flow through shallow and deep flow paths and his findings supported Swinnerton (1932). The concept of cave development close to the water table attracted widespread support and the occurrence of deep phreatic flow presented a challenge because there was no known process that explained it. Ford and

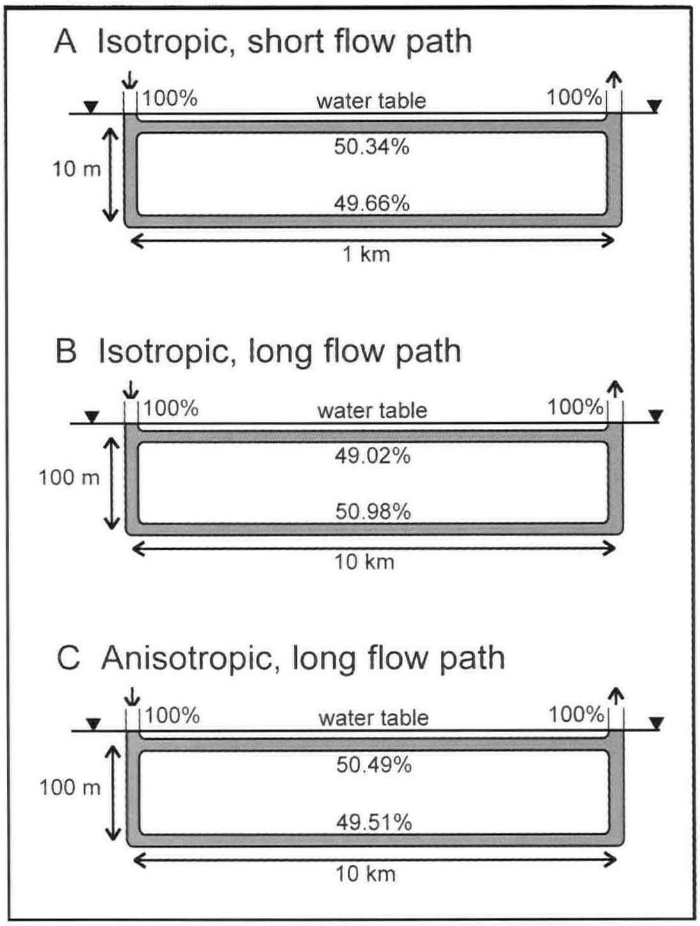

Figure 1. *Relative flow in shallow and deep conduits in flat-bedded limestone where the length/depth ratio is 100. A) Greater flow in the shallow conduit where the flow path is 1km long due to the shorter flow path in the shallow conduit. B) Greater flow in the deep conduit where the flow path is 10km long, due to the lesser viscosity at depth. C) Greater flow in the shallower conduit where initial apertures in the horizontal fractures are twice the apertures in the vertical fractures.*

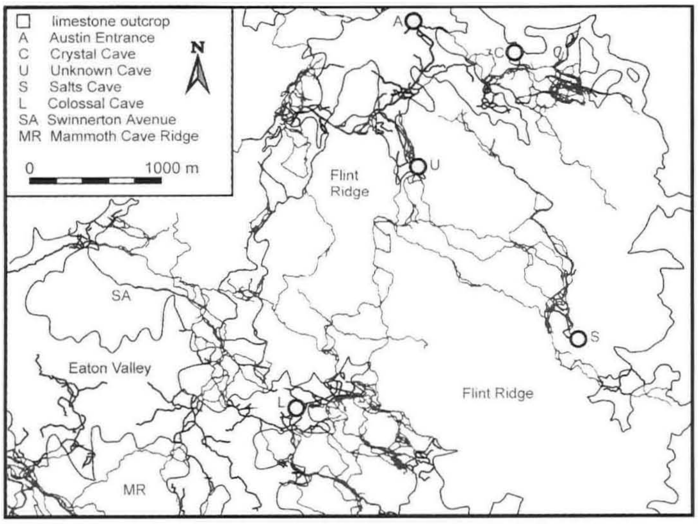

Figure 2. *Relationship of cave passages in part of the Mammoth Cave System to the surface outcrops of limestone along valleys (after cave map by Cave Research Foundation and geology map by U.S. Geological Survey).*

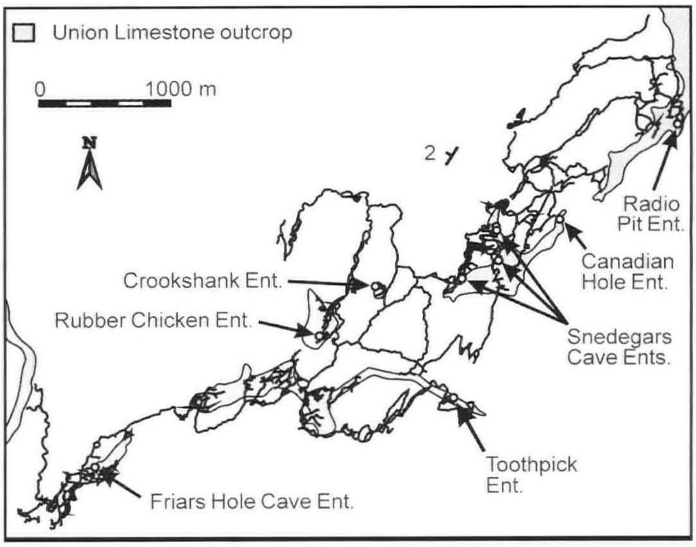

Figure 4. *Map of Friars Hole System, showing limestone inliers where recharge to the cave occurs (based on map compiled by D Medville).*

Ewers (1978) proposed that deep flow only occurs where there are a limited number of open fractures and that it is solely the presence of these open fractures that facilitates conduit development deep below the water table. However, Worthington (2001) carried out a comprehensive analysis of the equation for laminar flow through fractures and showed that the effect of geothermal heating results in increased flow for deep flow paths. Consequently, the presence of random large open fractures at depth is not required to explain deep flow.

The most widely quoted model in recent years has been that of Ford and Ewers (1978), which appeared to provide a comprehensive explanation of the occurrence of deep phreatic, shallow phreatic and water table caves. However, there has been a general failure to find examples that fit the model, and Ford (2000) stated that the model *"...does not attempt to predict what will be the effective fissure frequency and aperture in any particular topographic or geologic setting"*. This raises the spectre that cave development might occur at unpredictable depths below the water table, being related only to randomly located open fractures.

This pessimistic view of cave formation appears to be contradicted by the growing evidence from cave exploration and mapping that there are systematic differences between different areas in the depth of flow. For instance, cave diving in the Mendips, the Peak District and in the Yorkshire Dales has shown that these three areas in England have sumps that descend to as much as several tens of metres below the water table (Farr, 2000). Geomorphological studies in English caves have demonstrated that some fossil conduits had similar depths of flow (Ford, 1968; Waltham, 1974). In contrast, extensive cave exploration in Kentucky indicates that few conduits were formed more than a few metres below the water table (Palmer, 1987), whereas in some mountainous areas there are examples of conduits formed at depths >100m below the water table (Waltham and Brook, 1980; Smart, 1984; Farr, 2000, Jeannin *et al.*, 2000; Yonge, 2001).

The systematic differences between England, Kentucky and mountainous areas suggest that depth of flow is likely to be a function of one or more parameters that vary between these three settings. Worthington (2001) found that depth of flow was a function of stratal dip and flow path length, but only a limited number of parameters was considered in that study. The discussion below considers a larger number of parameters that might influence the depth of conduit flow, including hydraulic factors, fracture permeability, fracture geometry, spacing of bedding planes, and topography.

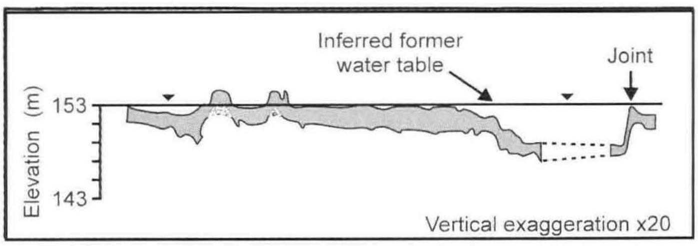

Figure 3. *Profile of part of Swinnerton Avenue in the Mammoth Cave System (after Palmer, 1989a).*

HYDRAULIC FACTORS

Flow along fractures in the early stages of karstification is in the laminar regime, and can be described by the Hagen-Poiseuille equation (White, 1988, p.162). This describes head loss (h) through a circular pipe as

$$h = 8\,\eta\, v\, L\, /\, (\rho\, g\, r^2) \qquad (1)$$

where η is dynamic viscosity, ρ is the density of water, v is velocity, L is conduit length, r is conduit radius, and g is the acceleration due to gravity.

Thrailkill (1968) calculated the differences between shallow and deep flow paths in horizontally-bedded strata by using Equation 1. His results showed that shallow flow is slightly greater than deep flow, implying that conduits should develop close to the water table. However, Thrailkill used the simplifying assumption of constant temperature and constant viscosity in his calculations.

The average global geothermal gradient is about 25°C/km, so that water following a deep flow path in a limestone aquifer will be slightly warmer than water following a shallower flow path. The density and dynamic viscosity of water both vary as a function of temperature, and can be combined to give the kinematic viscosity, which decreases by 50% between 10°C and 40°C. This results in increased flow in fractures at depth, increased dissolution, and an environment for preferential formation of conduits deep below the water table.

Figure 1 shows a comparison of flow through shallow and deep flow paths, where the temperature at the water table is 20°C and the geothermal gradients is 25°C/km. A single input and single output are modelled, with flow through a shallow and a deep conduit. This is similar to the model of Thrailkill (1968), except that all terms in the Hagen Poiseuille equation are considered here. Three cases are examined in Figure 1 and in all cases the deep flow path is 2% longer than the shallow flow path. Figures 1a and 1b are for isotropic conditions, where the apertures of the horizontal and vertical pipes are the same.

For a short (1km) flow path the lower viscosity at depth does not compensate for the longer flow path, so flow through the shallow pipe is greater (Figure 1a). However, the opposite is true for the longer (10km) flow path in Figure 1b, with more flow passing

Cave	Length (m)	Maximum depth	Loop crest mean depth (m)	Loop base mean depth (m)	Loop crest/ base ratio	Number of loop crests and bases	Reference
Doux de Coly, France	5675	63	29	42	0.69	13	Figure 12e
Grotte de la Mescla, France	1510	95	30	59	0.51	18	Tardy, 1990a
Rinquelle, Germany	930	23	10.8	21.2	0.51	21	Farr, 2000
Grotte de Paques, France	810	50	4.8	19.6	0.24	11	Tardy, 1990b
Source du Lison, France	802	29	7.7	16.2	0.48	14	Isler, 1981
Joint Hole, England	700	19	3	12	0.21	11	Monico, 1995
Fontaine de Saint George, France	1520	76	5	15	0.33	15	Farr, 2000
Fontaine de Ressel, France	1865	81	19	37	0.56	12	Farr, 2000
Chaudanne Spring, Switzerland	608	140	43	59	0.69	17	Farr, 2000
Bätterich Spring, Switzerland	374	79	16	53	0.42	6	Farr, 2000
Blautopf, Germany	1250	24	10	17	0.53	25	Farr, 2000
Source de Bestouan	2955	29	5.6	18	0.31	14	Douchet, 1992

Table 1. *Depth of the crests and bases of phreatic loops in 12 sumps*

through the deeper conduit. Worthington (2001) calculated that a distance of 3300m is the critical flow path length threshold for more efficient flow path at depth, assuming a geothermal gradient of 25°C/km and that the strata are flat-lying. Figure 1c shows results for anisotropic conditions, where the initial apertures of the horizontal pipes are twice that of the vertical pipes. The anisotropy results in greater flow through the shallow pipe.

The hydraulic analysis shows that deep conduit development should be favoured in many settings, implying that the base of a limestone aquifer is the optimum location for conduits. In fact, such a location for conduits is rare (excepts for conduits formed in the vadose zone), implying that there must be other pertinent factors that favour shallow flow or inhibit deep flow. One possibility is anisotropy (Figure 1c), and the evidence for this is discussed next.

FRACTURE PERMEABILITY

Evidence of fracture permeability from cave maps and flow path analysis

Conduits developed in older (e.g. Palaeozoic) limestones are almost all oriented along bedding planes, joints, or faults, or along intersections of two of these fracture planes. Jameson (1985) found that the initial fracture guidance for a passage could best be inferred in caves where the fractures are prominent but widely spaced, bedding is massive, roof collapse is minimal, sedimentation is limited, and passage size is not so great that traces of the initial guiding fractures have been eroded away. Few caves fit all these conditions and so it is commonly difficult to identify the initial guiding fractures. Furthermore, few detailed studies of fracture guidance in caves have been made. One such study is by Jameson (1985), who found that all but 2% of the passage length in part of Friars Hole System, West Virginia, was formed along fractures.

Matrix permeability is higher in younger limestones and so fracture-guided conduits may be less important in some of these rocks. Nevertheless, in the limestones of Eocene to Miocene age at Mulu there is widespread passage development along bedding planes, joints and faults (Waltham and Brook, 1980). Furthermore, many cave passages in early Cainozoic limestones in Tonga and late Cainozoic limestones in the Bahamas are oriented along near-vertical fractures (Lowe and Gunn, 1986; Palmer, 1986).

The alignment of cave passages along bedding planes, joints and faults gives an indication of the relative permeability of these features. Mammoth Cave, Friars Hole System and Castleguard Cave provide examples of fracturing (Figures 2–5), and these caves have been widely cited in the literature (Gunn, 2004; Culver and White, 2005).

Mammoth Cave, Kentucky, is the world's longest cave and has figured prominently in discussions of cave formation. It is located in a low-dip mid-continent setting where there is little faulting or folding. Joints in the cave are sparse, individual joints have very limited vertical and horizontal extents, and few passages have clear joint orientation (Deike, 1989; Palmer, 1989a,b). In this situation, almost all passages follow bedding planes and in plan view have meandering paths (Figure 2). Swinnerton Avenue provides a typical example. All of the approximately 1000m of passage is aligned along bedding planes except for a 3m section where flow rose on a joint (Figure 3). Scuba diving in the Mammoth Cave area has shown that most active phreatic passages are located within a few metres of the water table. Likewise, studies of fossil passages indicate that most were within a few metres of the water table when they were active (Palmer, 1987, 1989a,b). The scarcity of clear passage guidance on either joints or faults and the frequent large width/height ratios of phreatic passages at Mammoth Cave indicate that the initial horizontal hydraulic conductivity (K_h) along bedding planes was much greater than the initial vertical hydraulic conductivity (K_z) along joints or faults.

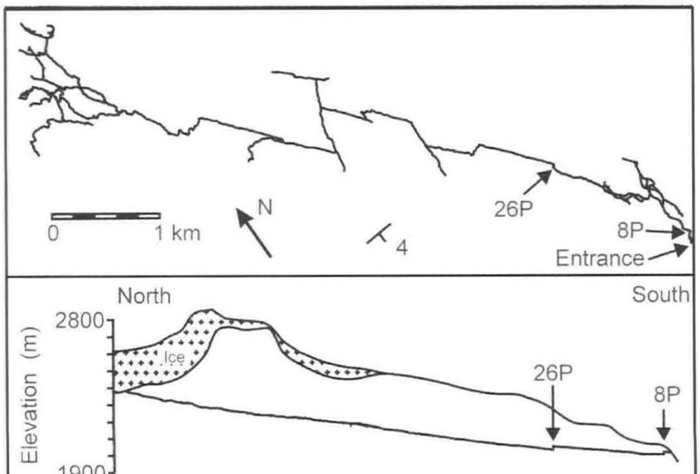

Figure 5. *Plan (top) and profile projected along the strike (bottom) of Castleguard Cave. The profile shows only the main passage (based on survey compiled by S. Worthington).*

Cave	Length (m)	Maximum depth	Loop crest mean depth (m)	Loop base mean depth (m)	Loop crest/ base ratio	Number of loop crests and bases	Reference
Roller Coaster, Yorkshire Pot,	522	58	33	42	0.78	12	Figure 12d
Grotte Annette - Trou de Glaz, France	1600	79	27	60	0.45	18	Figure 9a
Ogof Hesp Alyn, Wales	1100	59	6	28	0.21	12	Appleton, 1989
Réseau de Foussoubie, France	9000	130	68	77	0.89	80	Le Roux, 1989
Wookey Hole, England	1300	95	21	37	0.65	34	Farr, 2000
Rats Nest Cave, Canada	900	136	57	82	0.69	16	Yonge, 2001
Grand Circle - Bowling Alley, Cueva del Agua, Spain	1400	206	72	106	0.78	20	Smart, 1984
Big Rift - Hole in the Wall, Cueva del Agua, Spain	1200	104	65	83	0.77	27	Smart, 1984

Table 2. *Depth of the crests and bases of phreatic loops for 8 former conduit flow paths.*

Friars Hole System, West Virginia, provides a second example (Figure 4). The cave is the longest in the Appalachian Mountains. It lies close to the boundary between the Appalachian Plateau and Valley and Ridge Provinces, and the structure shows features of both geological provinces. The entrances to the cave lie along a valley, Friars Hole, where a series of limestone inliers have been exposed. Sinking streams typically descend downdip to the northwest through the vadose zone in the upper 50m of limestone, and then along

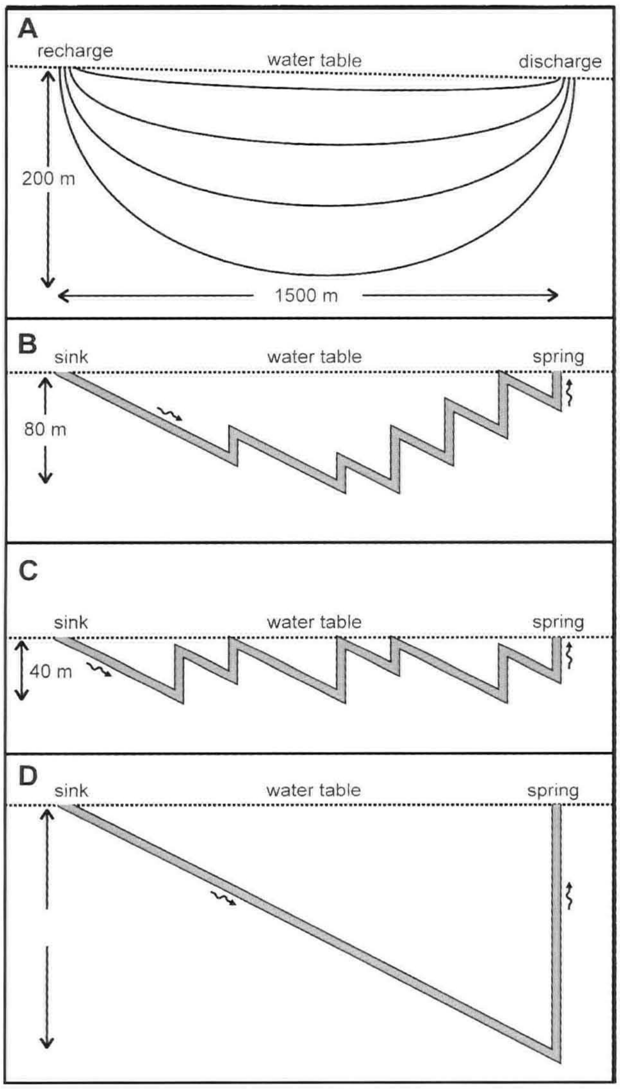

Figure 6. *Potential flow paths where the flow path from a sink to a spring is downdip. A) Initial flow field; B) – D) Possible flow paths. The three flow paths in B–D have identical lengths.*

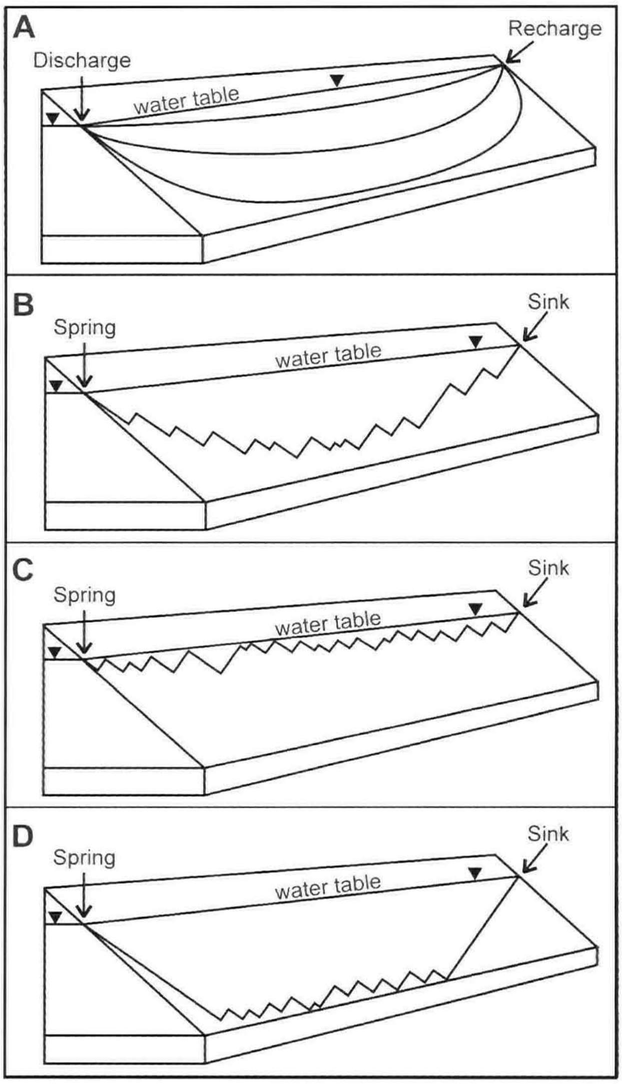

Figure 7. *Potential flow paths where the flow path from a sink to a spring is along the strike and where conduits form at the intersection of joints and a single bedding plane. A) Initial flow field; B) – D) Possible flow paths. The three flow paths in B–D have identical lengths. The dipping bedding plane is assumed to extend to much greater depths than is shown.*

No.	Cave	Geological age	Flow path length (m)	Stratal dip (degrees)	Range of elevation (m)	Mean flow depth (m)
1	Jordtulla, Norway	Palaeozoic	520	25	30	9
2	Otter Hole, Wales	Palaeozoic	3500	6	140	10
3	Friars Hole System, West Virginia	Palaeozoic	11000	2.2	200	17
4	Ogof Ffynnon Ddu, Wales	Palaeozoic	3100	12	350	35
5	Doux de Coly, France	Mesozoic	13700	6	200	43
6	Hölloch, Switzerland	Mesozoic	11000	16	1670	100
7	Nettlebed, New Zealand	Palaeozoic	7000	50	1200	120
8	Lubang Benarat, Malaysia	Cainozoic	7000	45	1600	150
9	Siebenhengste, Switzerland	Mesozoic	12000	13	1630	230
10	Mammoth Cave, Kentucky	Palaeozoic	2200	0.6	155	2
11	Horseshoe Bay Cave, Wisconsin	Palaeozoic	3000	2	30	6
12	West Kingsdale System, England	Palaeozoic	2700	3	130	35
13	Rio Encantado, Puerto Rico	Cainozoic	9500	4	260	15
14	Ogof Hesp Alyn, Wales	Palaeozoic	2000	14	80	24
15	Guanyan, China	Palaeozoic	6500	7	130	25
16	Swildons-Wookey, England	Palaeozoic	3500	15	176	40
17	Trou de Glaz, France	Mesozoic	1500	17	730	67
18	Peña Colorada, Mexico	Mesozoic	12000	40	1760	120
19	Nelfastla de Nieva, Mexico	Mesozoic	7400	70	1000	240
20	Edwards Aquifer, Texas	Mesozoic	180000	1.3	160	600

Table 3 *Structural and flow characteristics for 20 conduit flow paths (partly after Worthington, 2001)*

almost horizontal base-level passages along the strike to the southwest. Many of these base-level passages are formed at the intersection of low-angle thrust faults and the contact between the Union Limestone and the underlying Pickaway Limestone (Worthington, 1984; Worthington and Medville, 2005). The detailed study by Jameson (1985) of 429m of passage in Snedegars Cave showed that 37% of the passage was oriented along bedding planes, 30% on joints, 20% on bed/joint intersections, 7% on faults, 4% on fault/joint intersections, and the remaining 2% had no guiding fracture. From a geomorphological study, Worthington (2001) inferred that the mean depth of flow in fossil conduits was 17m below the water table. The roughly equal proportions of bedding plane guidance and joint or fault guidance for passages at Friars Hole System (Jameson, 1985), as well as the elongation of phreatic passage cross-sections along either bedding planes or on faults or joints, indicates that the initial pre-dissolution apertures f bedding planes were similar to those of faults and major joints. Consequently, the initial vertical and horizontal fracture permeabilities were of similar magnitude ($K_h = K_z$).

The third example is Castleguard Cave, which is the longest cave in Canada and is located in the Rocky Mountains. The cave's topographical and geological situations are described by Ford *et al.* (2000). Figure 5 shows the plan and profile of the cave. The main passage extends updip for 8921m from its entrance at 2010m above sea level to a termination where it is blocked by glacier ice that has intruded from the overlying Columbia Icefield. The plan shows that the main passage is oriented along a series of northwest-trending joints. However, the profile shows that the cave was almost all developed on three bedding planes (Figure 5, profile). The lowest of these is followed by the main passage for 7045m. The two pitches are developed on joints or faults, and the remainder of the main passage is developed along bedding planes (40% of the total length) or bed-joint intersections (60%). The longest distance that a passage follows a single bed-joint intersection is 650m. There has been minor movement, possibly of just a few centimetres, on both joint and bedding plane fractures (Ford *et al.*, 2000). The geomorphology of the cave suggests that it was enlarged up to a cross-section of about $3m^2$ while it was below the water table, indicating that the present entrance was more than 370m below the water table at that time. Passage cross-sections and fracture guidance suggest that $K_h = K_z$.

In Britain there have been many studies that have described the major guiding fractures in caves, such as in South Wales (e.g. Coase and Judson, 1977), the Forest of Dean (e.g. Elliott *et al.*, 1979), the Mendip Hills (e.g. Drew, 1975), Derbyshire (e.g. Ford, 1977) and Yorkshire (e.g. Waltham, 1974). There are many cave passages oriented along joints or faults close to sections of cave where faults and joints have much less importance than bedding planes in guiding cave passages. Leck Fell provides a notable example. The stream in Short Drop Cave flows down the axis of a plunging syncline and is perched 100m above the water table, indicating narrow joints apertures in this area. However, just 200m to the north the deep shafts of Death's Head Hole, Rumbling Hole and Big Meanie are aligned on a single vertical fault (Waltham, 1974; Waltham and Hatherley, 1983), and this demonstrates the local-scale variability in K_h / K_z. None of the above studies were carried out to the level of detail of Jameson (1985), and so there are no statistics on the relative importance of the various types of fracture or fracture intersections in providing guiding pathways for passages.

Bedding planes are used extensively in all the caves described above. However, joint and fault guidance is extremely variable between caves. In most cases bedding plane and joint or fault apertures appear to be similar, giving an isotropic fracture network ($K_h = K_z$). Less commonly the fracture network may be anisotropic, with $K_h > K_z$ or $K_h < K_z$. Mammoth Cave is an example of the former, where $K_h > K_z$, and this inhibits deep flow. Death's Head Hole is an example of the latter, with $K_h < K_z$, and this promotes deep flow.

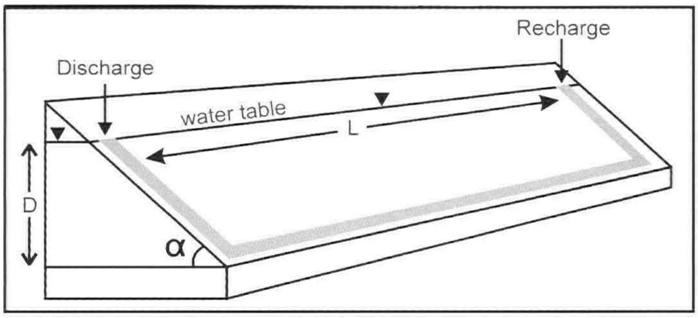

Figure 8. A simple rectilinear flow path on a dipping bedding plane.

Stress-release fracturing

Sasowsky and White (1994) found that many long caves in Tennessee closely paralleled the sides of deep valleys, and suggested that this is due to stress-release fracturing. However, the reasons are unclear why stress-release fracturing should be important in this setting and of lesser importance in other caves in North America such as Mammoth Cave, Friars Hole System, and Castleguard Cave. Much of the passage of Mammoth Cave is found close to the centre of ridges capped by clastic rocks rather than at the flanks of these ridges where stress-release fracturing should be more important (Figure 2). Similarly, at Friars Hole System and at Castleguard Cave there is no tendency for passages to be located where the rock overburden in minimised (Figures 4 and 5).

Stress-release fracturing is more important close to the surface and decreases sharply with depth. Therefore it will promote shallow conduit development in those cases where it is important.

FRACTURE GEOMETRY

Fracture geometry can have a significant influence on the depth of conduits below the water table. Two common situations are discussed below, with the flow direction either aligned in the same direction as the stratal dip or normal to the dip. In both cases steeper dips facilitate flow to greater depths below the water table (Ford, 1971). Conversely, deep flow is likely to be inhibited in low-dip strata unless open fractures facilitate vertical flow, as in Yorkshire, as noted above.

Figure 6 depicts an aquifer where flow from a recharge area to a discharge area is in the same direction as the stratal dip. Figure 6a shows a simple initial flow field before the start of dissolution. A single source of recharge is shown, such as occurs where a sinking stream develops. Initially, there are a series of flow lines from the area of recharge to the area of discharge. The following three figures

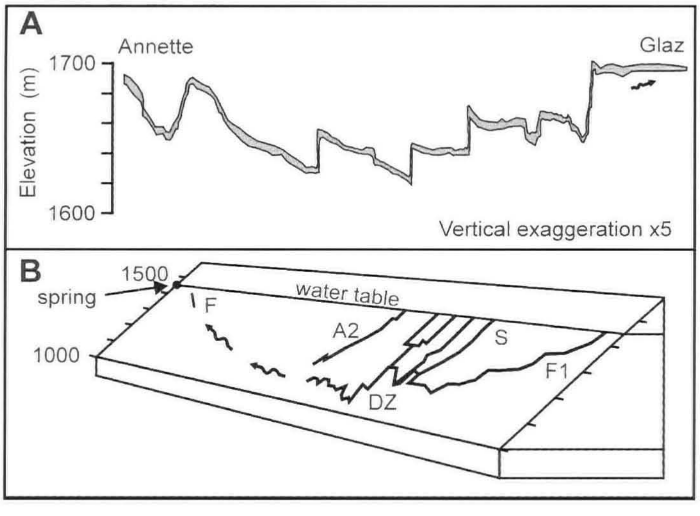

Figure 9. Major conduit flow paths that exhibit a single curving loop below a former water table. A) Profile of downdip flow in Dent de Crolles, France (adapted from Lismonde, 1997); B) Perspective view of 12km flow path on strike at Siebenhengste (S), Fitzlischacht (F) and the caves A2 and F1, Switzerland (adapted from Jeannin et al., 2000). Note: DZ = Deep Zone.

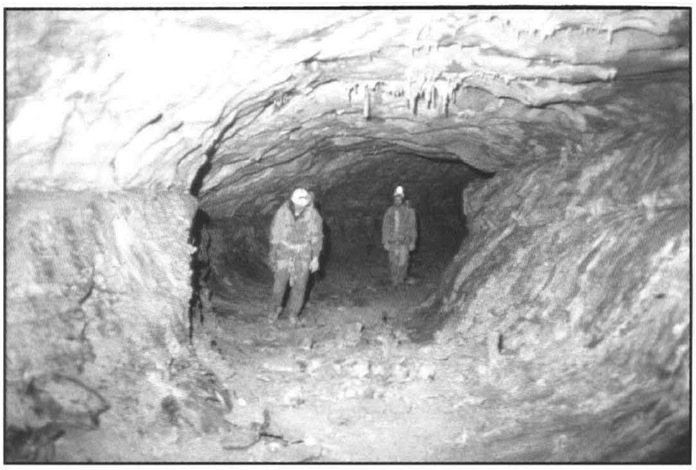

Figure 10. Bedding plane guided phreatic tube in Trou de Glaz. The passage was formed at least 50m below the water table.

(6b,c,d) show three possibilities for where conduit enlargement might occur. Figure 6b shows a cave with six phreatic loops and a flow path that follows a generally curving pattern below the water table. Figure 6c also shows six phreatic loops, but the conduit is in general closer to the water table than in 6b. Figure 6d shows a single phreatic loop. All three flow paths have identical lengths, with the conduit following a bedding plane for a horizontal distance of 1500m and following one or more joints vertically for a total of 180m.

Given the equal length of the flow paths in Figures 6b, 6c and 6d, it might be considered that there are equal probabilities of a conduit forming along any one of them. However, there are reasons why each one of these flow paths might be favoured. The flow path in Figure 6b might be favoured if the early conduit dissolution was along a flow path similar to that in a porous medium and if there is a balance between the two competing factors of decreasing fracture aperture with depth (which promotes shallow flow) and decreasing viscosity with depth (which promotes deep flow). The flow path in Figure 6c might be favoured if factors such as greater fracture apertures at shallow depth or mixing corrosion between conduit water and percolation were the most important factors. The flow path in Figure 6d is favoured if the fracture network is isotropic as in Figure 1b.

Figure 7 shows the equivalent situation where flow is along the strike. Figure 7a shows flow lines along a single bedding plane from a recharge area to a discharge area and Figures 7b, 7c, and 7d show three possibilities of where a conduit might form. It is assumed that there are two major perpendicular joint sets and that conduits form at the intersection of joints with the bedding plane. The flow paths in Figures 7b, 7c and 7d have identical lengths. The reasons why one of these three might be favoured for conduit development are the same as with the downdip case (Figure 6).

Figure 8 shows a simplified rectilinear flow system that is similar to Figure 1 but has flow along a dipping bedding plane rather than a vertical fracture. The length of the flow path P is

$$P = L + 2D/(\sin \alpha) \qquad (2)$$

where L is the horizontal distance of the flow path, D is the depth of the conduit and α is the stratal dip in degrees. Shallow dips have increasingly long flow paths and thus there is a lower probability that the more efficient flow at depth (q.v. Equation 1) will be associated with low dips. If the depth of flow is inversely proportional to the increasing length of the flow path then the depth of flow will be proportional to the sine of the dip.

Figure 9 shows two caves with flow paths that are similar to Figures 6b and 7b, respectively. The flow path between Grotte Annette and Trou de Glaz is primarily downdip (Figure 9a), and is one of the major flow paths in this 50km-long cave (Lismonde, 1997; Audra, 2004). It was used as the basis for Figure 6, and the flow pattern is clearly very similar to Figure 6b. As discussed earlier, this suggests that the pattern of preferential solution was influenced principally by the initial flow field in combination with decreasing fracture apertures with depth. However, the geology also plays an important role. The section of cave shown is developed in 190m of Cretaceous limestones. Lismonde and Marchand (1997) identified just five bedding planes within this 190m section that are preferentially used for conduit development, and most of the cave shown in Figure 8a is aligned along one of these bedding planes (Figure 10). A relatively minor fraction of the passages has vertical flow along joints or faults (Figure 11).

Figure 9b shows the caves of the Siebenhengste area in Switzerland that developed when the water table was at 1440m asl. Most of the passages are developed at the base of the Schrattenkalk Formation, a pure limestone that is 150–200m thick and that overlies a marly limestone. The limestones dip to the southeast at about 13°, though the dip steepens near the several faults that are present. Flow was on the strike to the southwest. There is a major strike-oriented passage that descends from F1 to the Deep Zone, which is up to 415m below the former water table, and then rises to Fitzlischacht, which is close to the former spring (Jeannin *et al.*, 2000). Four passages in Siebenhengste Cave descend downdip to depths of 200–300m below the former water table where they join the main strike-aligned conduit. The nearby cave A2 has a similar pathway.

The two flow paths shown in Figure 9 are close to the ideal situation of a single loop below the water table, as shown in Figures 6b and 7b. However, these two examples may not be representative, and further examples are given below.

Six cave profiles are shown in Figure 12. These examples were chosen because they all have substantial maximum depths of flow below the water table. This makes comparison to the examples in Figures 6 and 7 simpler than for caves developed closer to the water table. In explaining the section of cave shown in Figure 12a, Waltham and Brook (1980) wrote:

> *"If the horizontality of the trunk passage was due to the influence of the original water table, there seems no reason why the cave should have developed 50 metres below water level"* (Waltham and Brook, 1980, p.131).

Waltham and Brook made similar comments on Benarat Walk (Figure 12b), and concluded:

> *"it is clear that the caves of Mulu must contribute data to any thoughts on cave genesis..... The great horizontal or sub-horizontal phreatic tubes mostly have an uncertain relationship to their contemporary water table, and raise questions on the distinction between shallow and deep phreatic cave development"* (Waltham and Brook, 1980, p.138).

The same occurrence of horizontal passages deep below the water table is seen in Nettlebed Cave (Figures 12c and 13) and Yorkshire Pot (Figure 12d), both of which, like the Mulu examples, have flow along the strike in steeply dipping carbonates. At Nettlebed, flow in the Oubliette was along the strike of steeply-dipping fractures in marble (Figure 13). At the Meltdown, the flow rose up at least 70m in an almost circular phreatic tube (Figure 12c). In Yorkshire Pot, both the Roller Coaster and its tributary, Alberta Avenue, were formed along the strike of a steeply-dipping bedding plane in limestone.

The situations at Doux de Coly and West Kingsdale are somewhat different because the conduits have formed along a number of bedding planes. Flow at Doux de Coly is along the strike of the limestone, which has a dip of 6° (Figure 12e). Flow below the water table in the West Kingsdale System is updip (Figure 12f). The conduit may have been formed up to 60m below the water table (Waltham, 1974) or at only 20m below the water table (Brook, 1974). Deep flow along horizontal passages 60m or more below the water table in Yorkshire has also been described for Duke Street in Ireby Fell Cavern (Waltham, 1974) and for Sleets Gill Cave (Waltham *et al.*, 1997).

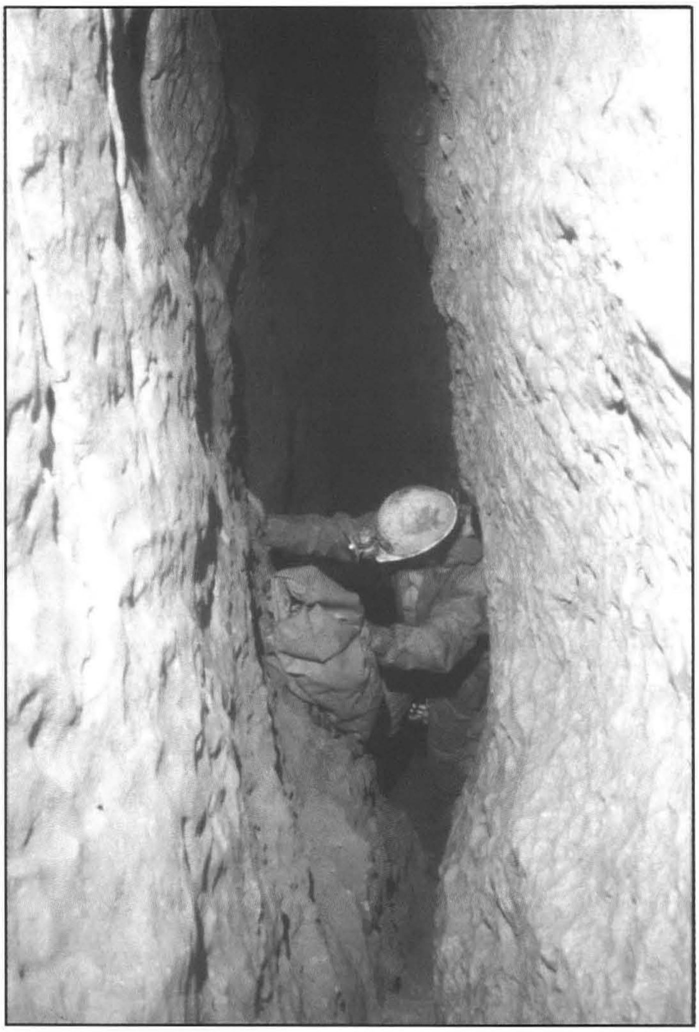

Figure 11. *Joint-guided rift in Trou de Glaz that was formed by upward flow at least 60m below the water table.*

The *"uncertain relationship to the contemporary water table"* noted by Waltham and Brook (1980, p.138) for the Mulu phreatic tubes also applies to the other caves in Figure 12. These phreatic tubes most closely resemble the situation in Figures 6b and 7b, though not as well as Dent de Crolles and Siebenhengste (Figure 9). This suggests that the initial flow field has had a powerful influence on subsequent cave formation in all these examples.

Data on phreatic looping below the water table may also be assessed by measuring the ratio of the depth of the crests to the depth of the bases of phreatic loops (i.e. D_c/D_b in Figure 14). For instance, the mean depth below the water table of loop crests and loop bases is 35m and 58m, respectively for the conduit in Figure 14a, and so the crest/base ratio (D_c/D_b) is 0.60. For the similarly curving flow paths in Figures 6b, 7b, 9a and 9b the crest/base ratios are 0.52, 0.82, 0.45 and 0.77, respectively. On the other hand, the crest/base ratios are much smaller where the loop crests are close to the water table: 0.18 in Figure 14b, 0.21 in Figure 6c, 0.36 in Figure 7c, and 0.28 in Figure 9 of Ford and Ewers (1978).

Loop crest/base ratios for 12 sumps and for 8 fossil passages are given in Tables 1 and 2, respectively. The mean ratio of these twenty examples is 0.48. This high value is similar to the examples in Figures 9 and 12, and suggests that there is a tendency for the depth of phreatic conduits to be strongly influenced by hydraulic factors that cause loop crests to be well below the water table.

SPACING OF CONDUIT-GUIDING BEDDING PLANES

Frequently, cave development occurs preferentially on a limited number of bedding planes, as noted above for the Friars Hole System, Castleguard Cave and the Dent de Crolles System. Lowe (2000b) described the preferential cave development in the

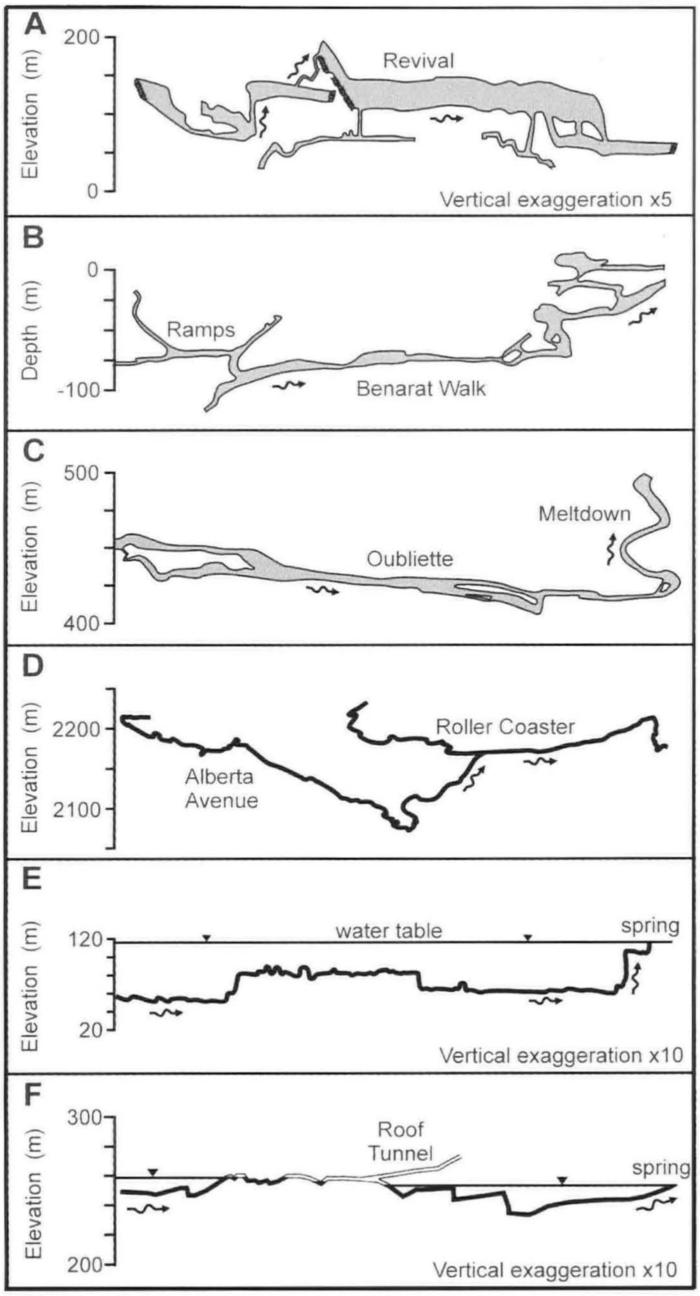

Figure 12. *Profiles of conduits formed well below the water table. A) Clearwater Cave, Malaysia; B) Tiger Foot Cave, Malaysia; C) Nettlebed Cave, New Zealand; D) Yorkshire Pot, Canada; E) Doux de Coly, France; F) West Kingsdale System, England. (A and B after Waltham and Brook, 1980; C after Pugsley, 1979; D after Worthington, 1991; E after EKPP, 2004; F adapted from Brook and Brook, 1976 and Monico, 1995).*

Yorkshire Dales along just a few bedding planes, which he called inception horizons, and he discussed possible reasons why just a few bedding planes in a sequence are favoured for cave development.

It is likely that the presence of a limited number of inception horizons in an aquifer has only a marginal influence on the depth of flow. For instance, there are five major cave-guiding bedding planes in the 190m section of limestone in which the predominantly downdip Grotte Annette to Trou de Glaz passage is formed (Figure 9a). If there were fewer or more major cave-guiding bedding planes in this section then the magnitude of the phreatic lifts would change, but the cave would still be able to follow a looping flow path that descends some 80m below the water table.

The number of cave-guiding bedding planes is also likely to have little influence on the depth of flow where flow is on the strike, such as at Friars Hole System (Figure 4), Siebenhengste (Figure 9b), or Mulu (Figure 12a, 12b). In each case many bedding planes in the dipping limestone intersect the water table and cave passages are able to follow a single favourable bedding plane for substantial distances. On a particular bedding plane, the conduit is formed at a hydraulically favourable location. This may be just below the water table (e.g. Cleaveland Avenue, Mammoth Cave: Palmer, 1981), 10m below the water table (e.g. Friars Hole System: Figure 4), 100m below the water table (e.g. Mulu: Figure 12a,b) or hundreds of metres below the water table (e.g. Siebenhengste: Figure 9b).

TOPOGRAPHY

Caves in mountainous areas tend to have deep flow paths, and several examples were noted above. These areas also tend to have steep stratal dips and large vertical ranges between the highest recharge points and spring elevations. The reasons why steep dips are associated with deep flow have been explained earlier. But the extent to which flow paths deep below the water table might be associated with mountainous topography is less clear. This is because the increase in fracture apertures in the early stages of karstification results in a large drop in hydraulic gradients and a vadose zone that may be more than 2000m thick, as at Krubera Cave in Georgia (Klimchouk *et al.*, 2004). If flow depth below the water table is a function of pre-karstification hydraulic gradients, then mountainous topography could be an important factor in promoting deep flow. On the other hand, depth of flow may be related more to the low and stable hydraulic gradients that exist following the early stage of karstification. Numerical modelling has demonstrated the rapid decline in hydraulic gradients in the early stages of karstification and so the steep early gradients may have little effect on later conduit development (Gabrovšek and Dreybrodt, 2001; Kaufmann, 2002). These ideas are tested using empirical data in the next section.

DISCUSSION AND CONCLUSIONS

Discussion above of the factors influencing depth of flow suggests that deep flow is associated with longer flow paths, steeper dips, the presence of open joints and faults, and possibly with a large range in elevation in an aquifer. The four variables, depth of flow, flow path length, stratal dip and the range in elevation, can reasonably be estimated for a number of aquifers (Table 3). Worthington (2001) listed the first 19 examples shown in Table 3 and the remaining example is the aquifer associated with Comal Spring in Texas, which is the largest spring in the southwest USA. A recent numerical model of the aquifer feeding this spring includes a 140km-long conduit that is up to 1200m below the potentiometric surface (Lindgren *et al.*, 2004).

Whereas it is straightforward in many cases to evaluate flow path length, stratal dip and the range in elevation for a karst drainage basin, there is no simple way to evaluate fracture anisotropy. Conduits are developed on joints or at bed/joint intersections in most structural settings, with platform carbonates such as at Mammoth Cave being a notable exception. The latter also have low dips, and so stratal dip may act as a proxy measure of fracture anisotropy. Figure 15 shows the relationship between depth of flow and flow path length, stratal dip and the range in elevation for the examples in Table 3. Regression of mean depth of flow against the different parameters in Figure 15 gives:

$$D = 0.053\ L^{0.77} \tag{3}$$

$$D = 120\ \theta^{0.56} \tag{4}$$

$$D = 0.60\ E^{0.74} \tag{5}$$

$$D = 0.061\ L^{0.91}\ \theta^{0.72} \tag{6}$$

$$D = 0.016\ L^{054}\ E^{0.56} \tag{7}$$

$$D = 1.6\ E^{0.64}\ \theta^{0.72} \tag{8}$$

$$D = 0.047\ L^{0.85}\ \theta^{0.64}\ E^{0.11} \tag{9}$$

where D is the mean conduit depth in metres below the water table, L is the flow path length in metres, θ is the dimensionless stratal dip (equal to the sine of the dip in degrees), and E is the elevation difference in metres between the lowest spring and the highest recharge point to the aquifer. The correlation coefficients of the above seven equations are 0.64, 0.50, 0.68, 0.90, 0.80, 0.70 and 0.90, respectively. Equation 6, which uses length and dip, gives the best correlation. The addition of elevation as a dependent variable (Equation 9) does not improve the correlation. The correlation using length and dip can also be expressed as

$$D = 0.18\,(L\ \theta)^{0.81} \qquad (10)$$

This equation has a lower correlation (0.79) than Equation 6 but is simpler to express graphically with a best-fit line added (Figure 15d). These results show that the two parameters of stratal dip and flow path length explain most of the variability in conduit flow depth.

The relationships that are apparent in Figure 15 can be further tested by comparing pairs of caves from one area where the dip or flow path length varies between the two caves. The caves of the Alyn Gorge in Wales provide one such pair. Ogof Hen Ffynhonau and Ogof Hesp Alyn are adjacent caves with parallel flow routes. The latter lies further from the adjacent valley floor and has a deeper phreatic origin (Waltham *et al.,* 1997). The deeper flow in Ogof Hesp Alyn is explained by the longer flow path (Equations 6 and 10).

The model presented above differs significantly from the Ford and Ewers (1978) model, which relates depth of flow to "fissure frequency". The fissure frequency model attributes the occurrence of shallow or deep phreatic cave formation solely to the degree of fracturing. The model has been widely quoted in the literature, but suffers from three major problems. First, the model is based on the premise that shallow flow is the hydraulically most favoured pathway for conduit development, but Worthington (2001) showed that hydraulic factors favour deep flow in most karst aquifers (see Figure 1). The second problem is the lack of examples that fit the model and the many examples that contradict the model. For instance, mountainous areas typically have both substantial fracturing and deep flow, which is the opposite of the prediction of the model (Rossi *et al.,* 1997; Jeannin *et al.,* 2000). Conversely, limestones with little fracturing such as at Mammoth Cave and elsewhere in Kentucky have shallow flow, which again is the opposite of the model prediction. The third problem is that it appears that the hypothesis cannot be tested because Ford (2000) noted that the model does not provide predictions. If a model cannot provide predictions then it cannot be shown to have any applicability.

Figure 16 gives a summary of how hydraulic and geological factors may interact. Figure 16a shows a limestone aquifer with a caprock such as shale. A simplifying assumption is made that the caprock has recently been eroded away from the limestone. Recharge is from a stream flowing off the caprock as well as from precipitation onto the limestone itself. The horizontal distance in the figure is in the range of several to several tens of kilometres. The vertical distance is in the range of several tens to several hundreds of metres, so there is substantial vertical exaggeration in the figure.

Figure 16b shows flow lines in the limestone immediately after the removal of the caprock. If the limestone aquifer is of Palaeozoic age, then it is well-lithified, the porosity is up to a few percent, and most of the permeability is due to flow along bedding planes, joints and faults. The combined matrix and fracture hydraulic conductivity in such an aquifer is typically 10^{-6} – 10^{-5} m/s (Worthington *et al.,* 2000). Most of the recharge to the aquifer is assumed to be from the sinking stream, and so most of the flow lines emanate from the stream reach where it is sinking. Discharge from the aquifer occurs as a seepage zone in a valley.

The duration of the phase shown in Figure 16b is extremely short (a few thousand years) because dissolution of bedrock fractures results in the formation of a conduit network that connects the recharge to the discharge area. The diagnostic features to differentiate the Figure 16c situation from that of Figure 16b in the field are the presence of discharge from discrete springs rather than from dispersed seepage, as well as the low hydraulic gradient. The low gradient is due to the increase in permeability, which is commonly two to three orders of magnitude (Worthington *et al.,* 2000). A series of simplified flow lines is shown in Figure 16b. The actual flow lines are less regular because they follow fractures, with the enlarged pathways being known as channels (Glennie, 1954) or primary tubes (Ford and Williams, 1989, p.253). Preferential enlargement of the channel that has the most favourable position and/or largest aperture results in the conduit shown schematically in Figure 16c. The most favourable depth for channel enlargement is a result of the balance between the competing factors of decreasing fracture aperture with depth and decreasing viscosity with depth; the former promotes shallow flow and the latter promotes deep flow. Equations 6 and 10 give approximations of the depth below the water table at which the conduit develops.

Figure 16d shows a simplified scheme of the actual conduit flow path along fractures. In reality, caves typically follow individual joints for a few metres to a few tens of metres, and follow individual bedding planes for a few metres up to a few thousand metres. Consequently, many more fractures could be utilised than are shown in the figure.

The question was posed earlier as to why there are systematic differences between the shallow phreatic caves that occur in Kentucky, deeper phreatic caves in England, and much deeper phreatic caves that are common in mountainous areas. Equations 6 and 9 provide the answers. The Kentucky aquifers have shallow flow because of the platform setting, resulting in low dips and low permeability along joints. This is demonstrated by the small amount

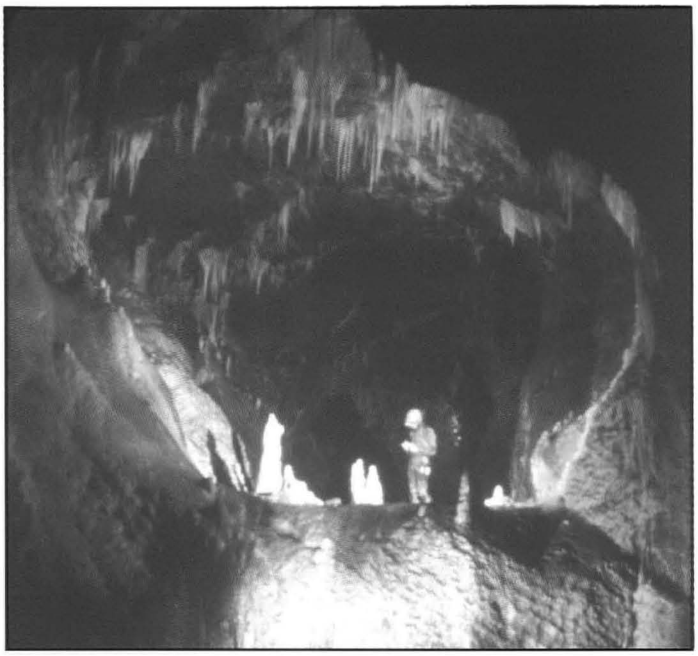

Figure 13. Large phreatic tube in Nettlebed Cave, New Zealand. The flow from this phreatic passage ascended more than 80m at the Meltdown (photo by C Pugsley).

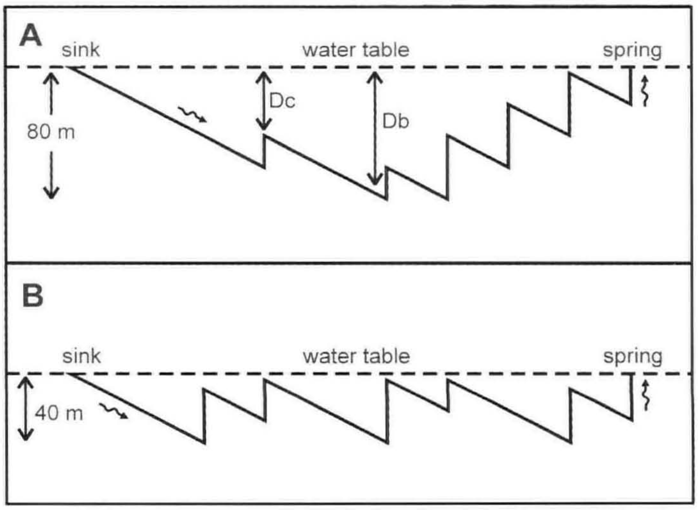

***Figure 14.** Phreatic flow paths with (A) a single loop deep below the water table and (B) with loop crests just below the water table.*

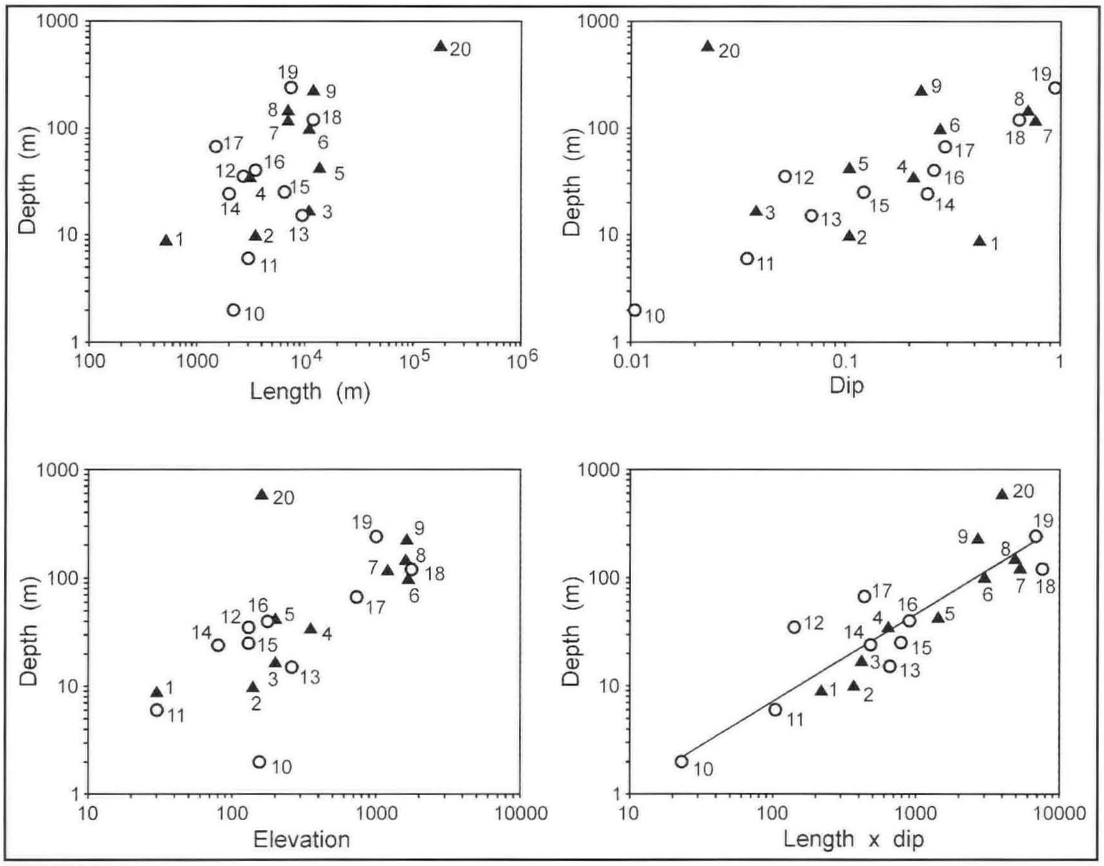

Figure 15. Correlation of conduit depth of flow below the water table with A) flow path length (top left); B) Stratal dip (top right); C) Range in elevation between recharge and spring (bottom left) and D) flow path length and dip (bottom right). Details of the 20 examples are given in Table 3.

of passage development along joints and faults. Limestone aquifers in England have deeper flow because of the structural setting, resulting in steeper dips, open joints, many faults, and the concomitant cave development along joints and faults as well as along bedding planes. Mountainous areas commonly have even deeper flow because of a combination of open joints, steep dips and long flow paths.

Most conduit development in England is limited to a depth of about 100m because most flow paths are generally only a few kilometres long. From Equation 6 or Equation 10, the deepest flow is predicted to occur where there are steep dips and long flow paths. The Mendip Hills have steep dips and the Cheddar and Wookey Hole catchments are the longest in the Mendips, and so should have the deepest flow. The conduits feeding these spring are likely to descend to depths greater than 100m below the water table. Scuba diving has so far reached a depth of -58m at Cheddar and -70m at Wookey Hole and both conduits continue at depth beyond the limit of exploration (Farr, 2000). Similar conduit depths could occur along mineralised faults in Derbyshire such as on New Rake between P8 and Speedwell or on Faucet Rake between P9 and Speedwell (Gunn, 1991). Even deeper conduits may have formed in the Peak District along long regional flow paths which emerge at thermal springs (Worthington and Ford, 1995).

The model predicts that very deep flow is likely at major springs, which typically have long groundwater catchments. Mante Spring (Mexico) and Vaucluse Spring (France) are two prominent examples. These springs have been explored by scuba diving or submersible vehicles to depths in excess of 250m below the water table. Fish (1977) concluded that the flow path to Mante Spring is some 200km long and has a maximum depth of flow in excess of 1500m. The depth and length of the flow system feeding Comal Spring in Texas, which was described above, are of similar magnitude to those of the flow system feeding Mante Spring. Vaucluse Spring is the largest spring in France and its groundwater catchment is more than 60km long.

The model is applicable to most unconfined limestone aquifers and thus to most known caves and most limestone aquifers used for water supply. Its applicability in confined aquifers is limited because the depth of flow may be constrained by the structure. For instance, Bath Hot Springs are thought to be fed by geothermally-heated water flowing through a deep syncline (Waltham *et al.*, 1997, p.267). The model also does not apply to caves formed in special situations such as hypogene caves and sea coast mixing zone caves (Ford and Williams, 1989, 282–291).

The combination of flow path length and stratal dip (Equations 6 and 10) together with fracture anisotropy provide a satisfactory approximation that explains the depth of conduit flow in areas where the flow is at shallow depths below the water table (e.g. Kentucky), at moderate depths (e.g. England, Appalachian Mountains), or at great depths (e.g. many mountainous areas and major springs).

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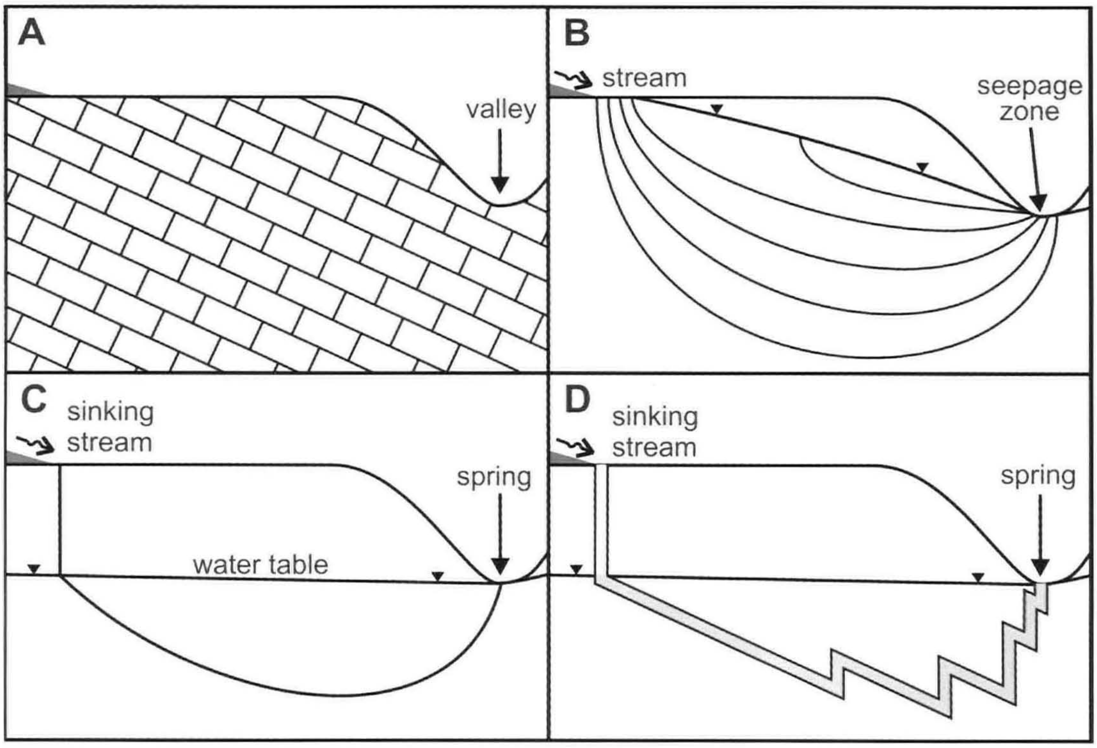

Figure 16. Factors influencing the initial conduit flow path in a limestone aquifer: A) geological contacts and location of valleys; B) initial flow field; C) theoretical flow path; D) actual flow path, following open fractures downdip and up joints.

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Vested interests at Cango Cave, South Africa, in the Nineteenth Century.

Stephen A CRAVEN

7 Amhurst Avenue, Newlands 7700, South Africa.

Abstract: Various vested Nineteenth Century interests are described, relating to the profitable and State owned Cango Cave, viz. the local Field Cornet, the civil service, the surrounding landowner and other adjacent farmers, and the Oudtshoorn Divisional Council. Although it is the stated policy of successive political masters of the Cape Colony that the Cave is a national asset that shall be conserved, the management structure was not conducive to the enforcement of that policy.

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The legal owner of the commercial Cango Cave, situated in the Swartberg foothills 27km north of Oudtshoorn in the Western Cape Province of South Africa is, and always has been, the State. When in 1820 the surrounding farm Kombuis was sold by the Crown to the tenant farmer, Pieter van der Westhuizen, the Cave was reserved for the State in perpetuity[1]. The local Field Cornet was appointed ex-officio caretaker of the Cave, in consideration of which he was permitted to charge visitors 10 rix dollars for his own account in lieu of salary. This was probably equivalent to about £50 in today's devalued currency. Provision was made for Cave vandals to be fined 50 rix dollars, but there is no record that anyone was so penalised. For 47 years successive Field Cornets Louis Johannes Botha Senior and Junior lived three hours ride and 25km to the west at Vinknestrivier on the back road to Calitzdorp[2] (Table 1). They were therefore unable to supervise the Cave. The Field Cornet was required to keep a visitors' book, and to record therein the names of all the visitors. Such a visitors' book was kept[3], but has not survived. That part-time minor Government official had a vested interest in under-reporting the visitors' numbers. If he were known to be earning a large income from the Cave, the Government might have appointed a salaried manager and kept the income for itself.

Date	Name	Farm
1811 – 1837	Louis Johannes Botha Senior	Vinknestrivier[4]
1837 – 1858	Louis Johannes Botha Junior	Vinknestrivier[5]
1858 – 1864	Coenraad Josephus Strydom Senior[6]	Kruis Rivier
1864 – 1891	Coenraad Josephus Strydom Junior[7]	Kruis Rivier[8]

Table 1. Cango Field Cornets, 1811 – 1891.

These arrangements were agreeable to the Field Cornets, who had acquired a potentially valuable monopoly, and to the civil servants who were not required to audit the Cave accounts. They were not good for the Cave. There was no provision for the accumulation of a capital fund from which the expense of a gate and other essential improvements might be paid. The Field Cornet, even if he had the necessary financial resources, would have been unwilling to spend money on the Cave because he enjoyed no security of tenure. The surrounding landowner was unwilling to spend money on the Cave because he received no guaranteed income therefrom.

Despite the poor access road, which involved crossing the Grobbelaar's River in Schoemanspoort thirty-two times in each direction[9], and the expense of travelling on horseback and by ox wagon, visitors did come to see the Cave. Their animals ate the landowner's grass and trampled his veld, for which he received no official compensation. Intermittent conflict between the Field Cornet and the landowner was inevitable.

On 4 July 1823 George Thompson was taken into the Cave by Farmer Botha who lived "a few miles" away[10], which is incompatible with the 25km from Vinknestrivier. That farmer may have been Philip Rudolph Botha of the adjacent farm Groenfontein "agter die Druip Kelder"[11], of which family there were three generations of the same name[12]. It therefore appears that there was a tripartite arrangement between Field Cornet Botha, a farmer of the same surname, and the landowner van der Westhuizen.

In 1827 the farm Kombuis was subdivided. That portion surrounding the Cave, Grootkraal, was sold to van der Westhuizen's son-in-law Johannes Petrus Maree (alias Marais) and "Petrus Jacobus" van der Westhuizen[13], who may have been his son Pieter Jacobus[14]. The new landowners could come to no initial agreement with the Field Cornet. In an attempt to obtain redress, on 23 July 1828 Marais complained to the Colonial Secretary about the "nuisances" committed by Field Cornet Botha[15]. Not having received a reply[16], Maree sent a reminder seven years later![17] There is no record that any reply from the Colonial Secretary was ever received by Maree[18].

Two years later there appears to have been an agreement. On 3 April 1829 James Holman confirmed that the Cave was on land owned by "John" Maree, and that permission to enter had to be obtained from the Field Cornet who lived three hours ride away. Holman did not enter the Cave[19] and we therefore do not know the name of the local caretaker. On 6 December 1830 William Harrison stayed with the adjacent farmer Botha, but had to await the arrival of unnamed "gentlemen" before being allowed into the Cave[20]. Botha's farmhouse was said to be 40 minutes ride away from the Cave[21], compatible with the 4km distance over rough country[22]. It seems that the farmhouse at Grootkraal was too small to accommodate visitors.

In 1839 equal shares in Grootkraal were sold for £210 each to Daniel Jacobus du Plessis and Petrus Jacobus Terblans[23]. Comparison of the subsequent increases in selling prices of these two shares (Tables 2 and 3) strongly suggests that only one shareholder had an agreement with the Field Cornet to conduct visitors into the Cave[24].

In 1840 Walter Sherwill recorded that Field Cornet Botha accompanies most parties into the Cave[25]. It is unlikely that the Field Cornet would be prepared to ride for 6 hours in one day on a regular basis, and that he would know in advance who intended to visit the Cave. It therefore appears that Sherwill had confused that official with one of the innumerable Bothas living in the Cango Valley.

In 1848 Petrus Johannes Botha, son of Field Cornet Louis Johannes Botha Junior[26], bought a half share in Grootkraal at the inflated price of £650[27] compared with £300 for the other half share the previous year[28]. This high price indicates that Petrus Johannes Botha had come to a profitable agreement with his father, a good example of nepotism that was, nevertheless, perfectly legal. In 1849 John Freeman confirmed that, "Mr Botha, a farmer ... has lately purchased the property, including the caverns"[29]. It is important to

Purchaser	Transfer number and date	Amount
Daniel Jacobus du Plessis	141 of 21 June 1839	£210
John O'Connel	60 of 18 January 1847	£300
Petrus Jacobus Botha	99 of 14 December 1848	£650
Petrus Jacubus Nicolaas Botha	235 of 30 January 1868	£225

Table 2. *Grootkraal half-share transactions 1839 – 1868.*

realise that Botha had not bought the Cave; he had come to an agreement with the Field Cornet.

Not every visitor stayed with Farmer Botha at Groenfontein. Others camped, the land near the entrance to the Cave having become an informal outspan. Perhaps in consideration of this nuisance, the annual quitrent was reduced in 1832 from £5-15-1½ to £3-15-0[30]. On the other hand an adjacent farm had its quitrent reduced at the same time[31], so the reductions may have been prompted by poor economic conditions in the Colony. In October 1856 the landowner, in reply to an official enquiry, was informed by the Civil Commissioner that the outspan was an informal one[32]. This was good financial news for the landowner. An official outspan provided free camping at the landowner's expense[33]. An informal one would enable the owner to charge fees.

In 1858 Field Cornet Botha Junior was replaced by Coenraad Josephus Strydom Senior (Table 1), who resigned in 1864 in favour of his son Coenraad Josephus Strydom Junior[34]. The Strydoms lived at Kruis Rivier, 12km west of Vinknestrivier and about 4½ hours ride from the Cave. They would therefore have had even less direct control of the Cave than did the Bothas.

In 1866 there was another disagreement. On 26 July that year the partner with the less expensive (£650) half-share, Petrus Jacobus Botha, complained to the Oudtshoorn Civil Commissioner that the visitors were grazing their horses on his land and damaging the Cave[35]. This suggests that Field Cornet Louis Johannes Botha Junior, had a disagreement with his son. The Field Cornet thereafter had contracted with Wynand Petrus du Plessis who, in consequence thereof, in 1853, had bought his half share for £850. The sale in 1868 of the Field Cornet's son's half share for a mere £225 supports this theory. In his 1866 letter the complainant added that he had provided at his own expense a fixed iron ladder for the descent into Van Zyl's Hall. He continued that the Field Cornet lived 32km from the Cave, and was therefore unable to exercise proper supervision. In due course the Colonial Secretary on 11 October 1866 unhelpfully instructed the Civil Commissioner to inform Mr Botha that, *"the terms of the title to the farm do not allow the proprietor to place any restrictions upon visitors to the Caverns, which are under the protection of the Field Cornet. If the ladder placed within the entrance is his own property, he is of course at liberty to remove it; and he has the right, should he choose, to exercise it, of impounding the horses or cattle of visitors if found straying on his land."*[36] The bureaucrats in Cape Town were clearly indifferent to the legitimate complaint of the joint landowner, and had ignored the gubernatorial Cave conservation policy.

The Oudtshoorn Divisional Council, founded in 1858, was responsible for the maintenance and improvement of the Divisional roads[37]. The road to the Cave extends for 1½km off that to the Swartberg Pass. That bad road required improvement and maintenance, as did the road north from Oudtshoorn through Schoemanspoort[38]. The Council was reluctant to spend money on these roads because it derived no income from the Cave. Indeed, before 1899 when it was declared a Divisional road[39], the Council was legally precluded from spending money on the road from Grootkraal. After a delay of three decades the Divisional Councillors decided on 14 May 1886 to apply to the Government for control of the Cave, and if successful, to install a gate, build a "substantial" access road and appoint a responsible caretaker[40]. The application was unsuccessful.

The opening of the Swartberg Pass from Prince Albert on 10 January 1888[41] reduced the travelling time between Cape Town and Oudtshoorn to 48 hours. Because the road passed within 2km of the Cave, the opening of the Pass would have increased the numbers of Cave visitors. On 3 February 1890 Bernardus Johannes Keyter, a prominent Oudtshoorn resident, wrote to the Colonial Secretary pointing out that the Cave was being vandalised, and that a "guard" should be located near the Cave. His expenses could be recovered from the 15 shilling admission fees. On this occasion the civil servants in Cape Town and Oudtshoorn were not unsympathetic to the need for conservation of the Cave. The Oudtshoorn Civil Commissioner, J F Webb, was well aware of, *"the necessity for arresting the disgraceful destruction which has been for so many years allowed to proceed unchecked despite the constant outcry from distinguished foreign and other visitors"*. He estimated that a gate could be fitted for £20, and a caretaker employed for £18 per annum. This no doubt prompted the Divisional Council on 8 August 1890 again to apply for control of the Cave[42], a request that was again refused. After the usual inter-departmental consultations, in February 1891 the Assistant Commissioner for Crown Lands and Public Works approved the expenditure of £20 on the sturdy gate, which is still in use. At the same time he terminated the 70-year arrangement with successive Field Cornets, and appointed caretaker the surrounding landowner, Herman Wilhelm Johannes van der Veen (son of Herman), who could be expected to maintain much better supervision of the Cave than did his predecessors. He was voted no salary, but was allowed to charge visitors between 1 and 5 shillings each, depending on the size of the party[43]. Van der Veen kept his appointment until his death on 3 March 1925[44]. This substantial reduction in the entrance fees gives a good indication of the previous profitability of the Cave to the Field Cornets, surrounding landowner and neighbouring farmers.

These new arrangements reduced vandalism and prevented unauthorized entry, and eliminated the squabbles between the

Purchaser	Transfer number and date	Amount
Petrus Jacobus Terblans	141 of 21 June 1839	£210
Theunis Jacobus Botha	85 of 25 May 1846	£262½
Jacobus Johannes Schoeman	1 of 04 January 1847	£300
Wynand Petrus du Plessis	189 of 25 January 1853	£850
Louis Jacobus Kleynhans	319 of 25 July 1868	£1625
Herman van der Veen	320 of 25 July 1868	£1125

Table 3. *Grootkraal half-share transactions 1839 – 1868.*

previous vested interested parties. Unfortunately the bureaucrats in Cape Town had again taken the line of least resistance. By refusing the caretaker a salary they continued to be spared the necessity of auditing the Cave accounts.

In January 1897 the Cave was extended as far as the Banqueting Hall[45,46], thus creating more work for the guides who were paid out of Van der Veen's unchanged admission fees. Using these discoveries as an excuse, the Town Clerk, Peter T Blant, submitted a petition signed by 58 Oudtshoorn residents calling on the Speaker of the House of Assembly to raise an additional fee of 6d for each visitor to the New Chambers. The Speaker, Mr G C Olivier, was the Member for Oudtshoorn and a member of the Oudtshoorn Town and Divisional Councils, and Mayor of Oudtshoorn. These extra fees would be paid into a special fund from which could be financed the necessary structural alterations to facilitate access to the New Chambers. The Under Secretary for Agriculture approved this on 20 May 1897, and voted £100 for the necessary *"opening up and improving the approaches to"* the Cave[47]. Unfortunately there was still no dedicated Cango Cave fund. The extra 6d fees were credited to *Revenue Agricultural Miscellaneous Reimbursements*. This modest extra income for the Government, amounting to £30-17-9 by 10 July 1899[48], prompted the Divisional Council again to seek control and management of the Cave, a request that was supported by the Oudtshoorn Civil Commissioner. The application was refused because, *"it would be foolish ever to entrust a world wonder like this to the care of a local authority. It should be national property."*[49] At least one Divisional Councillor was displeased that the Government would again not transfer the entrance fees to his Council[50].

The failure to establish a capital fund from which the necessary improvements could be financed required that every item of desired expenditure had to be motivated to the civil servants in Cape Town. This continued until control and management were in 1921 transferred to the Oudtshoorn Town Council[51]. But that is another, much longer, and ongoing story[52].

ENDNOTES

[1] Cape Deeds Office, George Quitrents Vol.3(1) No.24.
[2] 1:50000 Trigonometrical Survey Sheet 3321BD Kruisrivier.
[3] Craven, S A, 2002. Alexander Lawrence's visit to Cango Cave – August 1849. *Bulletin of the South African Spelaeological Association*, Vol.37, 15–18.
[4] Cape Archives Depot CO 5700 d. 23 August 1811.
[5] Cape Archives Depot CO 2770 No.33.
[6] Cape Archives Depot CO 3068 No.50.
[7] Cape Archives Depot 1/OHN 5/1/1/1/1 Nos 42 and 56.
[8] Cape Archives Depot MOOC 6/9/218 No.379.
[9] Letter d. 20 October 1855, Sophie Gray to her children (University of the Witwatersrand Library).
[10] Forbes, V S (Editor), 1967. Travels and Adventures in Southern Africa by George Thompson, Vol.1, footnote p.135. [Cape Town: Van Riebeeck Society.]
[11] Cape Archives Depot CO 2576 Folio 780 d. 29 March 1811.
[12] Pama, C, 1981. Genealogies of Old South African Families 1. p.79. [Cape Town: Balkema.]
[13] Cape Deeds Office, Transfer 160 of 02 March 1827.
[14] Pama, C, 1981. Genealogies of Old South African Families 2. p.1120. [Cape Town: Balkema.]
[15] Cape Archives Depot CO 2703 No.172.
[16] The incoming letter has been endorsed *"vide reply to the applicant 15 Aug 1828"*, but the reply is missing from Cape Archives Depot CO 4888 and 1/UIT 10/13 where it should have been filed.
[17] Cape Archives Depot CO 2755 No.5.
[18] No such letter is recorded in Cape Archives Depot CO 4950 Index of letters despatched.
[19] Holman, J, 1834. A Voyage around the World Vol.2 pp.318–319. [London: Smith Elder and Co.]
[20] National Library of South Africa, Cape Town, MSB 224 p.141.
[21] Anon, 1835. Itinerary of the Colony of the Cape of Good Hope p.13 [Cape Town: Robertson.]
[22] 1:50000 Trigonometrical Survey Sheet 3322AC Kangogrotte.
[23] Cape Deeds Office, Transfer 141 of 21 June 1839.
[24] Craven, S A, 1999. Land values around Cango Cave, South Africa, in the 19th century. *Cave and Karst Science,* Vol.26(3), 127–128.
[25] Sherwill, W S, 1842. A Passage ... Graham's Town Journal 20 October.
[26] Cape Archives Depot MOOC 6/9/224 No.1596.
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Forum

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

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BOOK REVIEWS

Beneath the Surface: A natural history of Australian caves. Edited by Brian Finlayson and Elery Hamilton-Smith. Published by University of New South Wales Press, Sydney. 2003. ISBN 0-86840-595-7. 182 + xviii pp. A$49.95.

I enjoyed first of all a glance through, and then a more detailed reading of this book, and some of my initial opinions evolved during the process. The early impression was that the book contains considerable nostalgia for, and related to the thinking of, Joe Jennings (to whom the book is dedicated) and also, though perhaps more subliminally, relating to the work of Marjory Sweeting. Having placed both of these two among the "greats" of karst research in a contribution to the *Encyclopedia of Caves and Karst Science* (see book reviews in Cave and Karst Science, Vol.31, No.1) I had no major problem with this, except that it did make me wonder how much new thinking would be visible "up front" in the book. Looking at the author list, which includes names well known outside Australia, such as David Gillieson, Ken Grimes, Julia James, Armstrong Osborne and John Webb, I was hopeful – but, equally, I was surprised to note that a number of "names" that might have been expected in a book of this type, and with this perspective, were absent.

Leaving the currency of the content aside for the moment, the structure of the book is interesting, especially if its subtitle is considered. Whereas "natural history" (a term that for me brings back distant schoolday memories of learning about science without realising it was science) does pervade much of the text and (especially) the coloured photographic illustrations, the book encompasses much more. There are six main chapters, plus various "bits and pieces", at least some of which should appeal to everybody with an interest in the wider fields of caves and karst.

The first main chapter deals with *"Black holes: caves in the Australian landscape"*, and it is a joint effort from John Webb, Ken Grimes and Armstrong Osborne. There is no value here in exploring the detail presented in the chapter, but its coverage is wide, taking in karst and groundwater issues as well as the caves of the title. As one whose pre-knowledge of Australian karst was limited, I found the chapter to be informative on several levels, being rather more than a simple Cook's Tour and yet (to me at least) touching upon the many high-spots that such a tour would have to take in. Lava tubes, fissure caves, piping caves and caves in sandstones and granite, as well as the more widely known carbonate caves, are mentioned in various degrees of detail, and overall this relatively short contribution presents a tantalizing overview of the variety of caves that are known in this (reportedly! – cf p.1 of this chapter) poorly cavernous country.

The next chapter, *"The crystal gallery"*, authored by Julia James, provides a useful background to the processes involved in cave mineral deposition and other issues relating to minerals in caves. Individual mineral types and speleothem forms are presented in enough detail to be both informative and interesting, and with applicability beyond the confines of Australia. A short contribution by John Webb at the end of the chapter describes the history of recognition of rare phosphate minerals from the Skipton Lava Cave in western Victoria.

Chapter 3, contributed by Liz Reed and Dave Gillieson, deals with *"Mud and bones: cave deposits and environmental history in Australia"*. It is an interesting and productive idea to bring together aspects of clastic sediment deposition alongside descriptions of the bones that they commonly contain and of palaeoenvironments. Equally interesting (to the non-specialist at least) are brief forays into aspects of taphonomy (processes of fossilization) and the related issues of chemical alteration of sediments. Most tantalising of all though, to anyone with an interest in the past and particularly in the near-unique evolutionary history of Australia's animals, are the brief descriptions of the cave bone deposits, including extinct and (now seeming) exotic marsupials, and the environments in which these animals lived.

In Chapter 4, Leslie Hall and Greg Richards discuss *"Flying around underground: cave bats"*. It is interesting to read that at least 29 species on bats, from an Australian total of 85 to 90 recorded species, roost in caves. Several of the book's generally excellent colour photographs illustrate individual bat species and some of their roosting sites. The chapter also presents a broad range of background information, including details of bat roosting behaviour and bat migrations, and gives brief mention of other creatures that choose to spend at least parts of their lives living or sheltering in caves.

The cave-life theme is extended in Chapter 5, *"The crawling and creeping and swimming life of caves"*, contributed by Stefan Eberhard and William Humphreys. Here we find history, explanation of concepts and classifications, descriptions of habitats and, in my opinion unfortunately, only brief but interesting descriptions of the various creatures found within the various habitats discussed. It must be difficult to decide how much specific detail can be accommodated in a publication of this kind and (yet again as a non-specialist) I even find myself leaning towards the view that it's useful to read the scene-setting information, even if this leaves the reader intrigued and "hungry" for more insight into the creatures themselves. In this respect I'm ashamed to add that generally I **do** find it preferable to read about and look at pictures of most of these "creepy-crawlies" than actually to encounter them *in situ*, but I have long been intrigued in particular by the true cave fishes, such as the blind gudgeon shown on colour photo 34, and would dearly love to see such creatures in their natural habitat.

The final main chapter is *"People and caves: changing perspectives"*, by Elery Hamilton-Smith. Here the author works chronologically through various aspects of the human use of Australian caves, dating back to the Pleistocene and reaching forward through early "European" explorations to the developments of organized speleology and the growth in the number of "commercial" caves (also discussed in Appendix 2).

Overall I found this to be an interesting book and I suspect that its interest will grow with further reading. It would be essential prior reading for anyone thinking of visiting Australia and making a whistle-stop tour of a selection of cave and karst sites. Even to those more firmly bound to the "armchair" it provides a mouth-watering introduction, hinting that much more fascinating information about Australian caves and karst and related topics is "out there somewhere". As to my initial impression that some of the ideas presented are "conservative"? Well, I still suspect that this is the case and believe that various intriguing issues of Australian karst development and related topics are simply awaiting the results of new, targeted research and the deployment of new ideas. But for all that, the book provides a fine background and a fitting tribute to the work of Joe Jennings and many other researchers before and since. What's more, it is a well-produced and well-presented volume that, by today's standards, provides extremely good value for money.

Dave Lowe
C/o BGS
Keyworth
Notts
NG12 5GG
UK

The Gypsum karst of Sorbas: A subterranean journey through the interior of the gypsum. [*El karst en yeso de Sorbas: Un recorrido subterráneo por el interior del yeso]* By José María Callaforra, with photographs by Jabier Les. Published by Publicaciones Calle Mayor S L [www.callemayor.es]. 2003. 86pp. "For free distribution" *[Ejemplar de diffusión gratuita]*.

Perhaps this is best described as a small, coffee-table book? It's about half the size of most of the monster volumes that it was once fashionable to leave strewn "casually" around the house as indicators of wide-ranging erudition and supposedly good taste. Maybe it's still fashionable, but even if not, there remain many eye-catching and worthy books that we can "thumb-through" and be amazed. Though giving the impression of being laid-back and understated, this is one of them.

I hope that I don't do the book a disservice by referring to it as a coffee-table book. It certainly contains a wealth of eye-catching, informative and well-reproduced coloured images, taken both underground and on the surface. But it's more than just a gasp-producer. Nor is it a "heavy" and jargon-ridden scientific tome. Yet it does set out to describe and explain the underground and surface features, processes and terminology of gypsum karst, along with emphasizing the value of this now-protected environment. And it succeeds – in my opinion – admirably and in two languages. In fact, after working through the book I was simply amazed at how much really helpful and "idiot-proof" information can be squeezed into so few pages in so few words, thanks to the wealth of illustrations. That this information is provided side-by-side both in the original Spanish and in creditably well-translated English makes it all the more remarkable.

The author and photographer work logically through a series of major chapters dealing with *Karstification in gypsum; The gypsum karst landscape; Karstic springs; The caves; Speleothems, Speleogenesis of the Sorbas gypsum karst; The Sorbas karst and its environmental protection,* rounding off with a useful bibliography. Each chapter is subdivided into "bite-sized chunks", each with its own short subtitle and, where appropriate, a well-chosen phrase or rhetorical statement to amplify the subtitle and grab the interest of the reader. There will be some who would complain that some of these secondary statements – in English translation at least – sound a little bit "quaint" or "affected", perhaps owing more to the art of the advertising copywriter than to the scientist. But maybe that was the intention, as this book certainly "sells" the Sorbas karst.

The text throughout, even in translation, is easy to follow and informative, without being in the least bit patronising – a balance that is hard to manage and an achievement upon which the author should be congratulated. What's more, in addition to the very many excellent photographs, the text is broken up by equally clear and informative maps, cross-sections, block diagrams and other illustrations, all produced in good, clear colour, all with Spanish and English labels and all kept simple enough to be understood while not totally dumbing-down the underlying science. Most of the block diagrams are particularly excellent as a means of getting across what's going on, but the other, less striking, illustrations are no less useful. Just as much as the author and photographer then, the "originator" of the illustrations deserves credit for the quality and usefulness of these creations. Finally of course the photographer, the award winning Jabier Les, has put together a superb collection of underground and surface shots, ranging from wide panoramas to detailed macro-close-ups, which contribute significantly to the eye-catching appeal and effectiveness of the volume.

In a book such as this, it's really impossible to pick and justify anything as a "best" or "worst" aspect. As a scientist perhaps my main criticism would be that some of the photographs are more concerned with "spectacle" and the "wow-factor" than with "science" – but then the book doesn't set itself up as a seminal science text anyway, and even scientists like to be "impressed" from time to time. Overall though the book is intended to be an awareness raiser, and it certainly raised my awareness! Previously having seen gypsum karst only in passing and from the surface I was amazed to see the full scope and scale of the spectacular underground and surface karst in this area. Despite my previous reading of classic works on gypsum karst by various leading authors, describing many areas, I still tended to think of gypsum caves as being relict, dry and dusty, generally rather angular and littered with breakdown. Indeed such caves do exist, even at Sorbas, but so too do "classic" tubular passages, relict and active, with fascinating wall/ceiling structures and with a variety of crystalline and speleothem deposits, including the intriguing "gypsum balls", described as "cave perspiration"! What's more, even the big, dry caves with breakdown look "clean", impressive and generally welcoming.

I received my copy of the book quite a while ago and assumed simply that this was a "review copy" provided free of charge. Only when putting together the header information for the review did I spot the (strangely untranslated) note *"Ejemplar de diffusión gratuita"* – which I am reliably informed means that this book is intended for free distribution. Well you can't say fairer than that. It would be a bargain at any sensible price. If stocks remain and if it's still being distributed free of charge, it really is an amazing bargain for anybody wishing to see what gypsum karst really looks like, and for those keen to find out painlessly and enjoyably how it all develops.

Dave Lowe
C/o BGS
Keyworth
Notts
NG12 5GG
UK

Encyclopedia of Caves. Edited by David C Culver and William B White. Published by Elsevier Academic (Amsterdam, Boston and London). 2005. ISBN 0-12-406061-7. 654pp. £65.

Following hot in the footsteps of John Gunn's encyclopedia (reviewed in CaKS, Vol.31, No.1), this is another massive tome containing wide-ranging overviews and essays on many aspects of caves (but only incidentally on surface karst).

Overview of the geo-sciences within this volume was evidently the task of the second editor, Will White, already well known for his many papers and books on cave geology and hydrology. There are 39 entries that cover the main components of cave geo-science, and these vary from exciting and up-to-date syntheses to rather mundane reviews that have largely been seen before. One entry describes the multiple aspects of solution caves, and another provides the best available review of cave development by sulphuric acid; both are by Art Palmer and both are excellent. Entries on cave passages, passage development and underground karren features further explore cave genesis. Processes of stalagmite deposition are described by Wolfgang Dreybrodt, in an entry that is happily more readable than some of his erudite classics. There are then more entries that overview stalactites, stalagmites, helictites and gypsum deposits, with another very readable item on saltpetre mining – though all its data refer to historical sites in American caves, with no mention of ongoing activity in China's caves. An all-too-common failing of

American publications is their parochialism; this tome is no exception, as too many examples, concepts and terms lack true internationalism. Karst hydrogeology, water tracing, coastal caves, epikarst, closed depressions and subsidence sinkholes each have their own good reviews that stand out from the crowd; surface karst has no entries of its own.

Among the entries are 15 that describe "exceptional caves", all with names that international cavers will recognise. This could have been where parochialism paid off with some good overviews of American caves, but it doesn't. Too much caving, too little caves; though there are some useful descriptions. Friar's Hole is a classic of upland karst evolution well described by ex-Brit Steve Worthington. The nearby Burnsville Cove caves have little more than their exploration related, though there are some great photos. The entry on Mammoth Cave is surprisingly sparse, with no photos and no mention of the exciting ^{26}Al/^{10}Be dating that showed how very old are its clastic sediments. The Wakulla Spring caves have a welcome entry, but there is no scale on the maps. Lechuguilla is well reviewed and has an incredible survey but none of the fabulous photos for which this cave is famous, while Kazumura Cave has a better illustrated overview of its unbroken lava tube that is 41km long within a system of 65km of passages.

Outside USA, the overviews of important caves such as Siebenhengste and Castleguard are right to have been included, but offer little that is new. An entry on Krubera is included, but of course lacks its recent explorations to -2080m (which made the Encyclopedia join the honourable list of cave books that are instantly out-of-date). The Huautla caves have a welcome overview, but the area line map is confused by leaving the surface survey traverse on the computer output. Numerous Brit cavers will be horrified by the entry on Mulu, with its American bias, no photos, an appalling out-of-date and inaccurate travesty of a map, and nothing on the geomorphological evolution. There is a useful overview of the Nullarbor caves, but neither China nor New Guinea even appear in the index.

The Encyclopedia's first author is a biologist, and nearly half the pages are devoted to cave biology (with numerous splendid colour photos of cave life), which remains outside the knowledge base of the reviewer and therefore outside this review. A few entries also cover caving techniques, though this is always difficult to put to paper. An entry on camping in caves provides amusing reading of accounts of the various attempts at underground camping in USA mainly in the 1950s to 1970s, but could have improved by including note of more recent Soviet experience in their cold caves.

Undoubtedly, many cavers and cave scientists will find this volume to be a useful resource. It does contain a lot of information, including a few entries that are really valuable contributions to cave literature. Most illustrations are sound, but some have notable failings; there is a scatter of good photos (including an amazing image of a hydromagnesite balloon on page 313). The index is large, but (as with many an index compiled by publishers' specialists who lack real knowledge of the subject matter) is questionably complete (Sinkholes should refer the reader to many entries other than the Sinkhole entry, notably to the entire entry on Closed Depressions and to the Sinkhole Plain within the Mammoth Cave entry).

It is inevitable that comparisons are made with the Gunn Encyclopedia, and, for the cave geo-scientist, it is also useful to compare it with the Speleogenesis volume, edited by Alexander Klimchouk and friends, which appeared a few years ago. Table 1 reveals the numerical comparisons, mainly with reference to the geo-sciences. Culver and White has the better presentation, and has more of the longer entries, but (except for a few absolute gems) these still lack depth (no pun intended). Gunn is more encyclopedic, with much the widest coverage, which also includes surface karst. Klimchouk provides the deeper science, but can make heavy reading, and is underground geo-science only, with no mention of cave biology. Your reviewer has all three on his shelves, and uses them all; as he contributed to the Gunn tome and not to the others, it would be inappropriate to state his personal preferences. Cavers will find their own favourite, but will like features of all three.

Editor	Gunn	Culver and White	Klimchouk *et al*
Year	2004	2005	2000
Title	**Encyclopedia of Caves and Karst Science**	**Encyclopedia of Caves**	**Speleogenesis...**
ISBN	1 57958 399 7	0 12 406061 7	1 879961 09 1
Publisher	Fitzroy Dearborn	Elsevier	National Speleo. Soc.
List price (January 2005)	£95	£65	£67
pages (main text only)	788	618	484
price per text page	12p	11p	14p
price per geoscience page	21p	22p	14p
geoscience pages	445	295	483
diagrams/maps	174	155	305
photos colour	33	79	1
photos b/w	192	59	85
entries - geomorphology	76	39	48
entries - caves / karst areas	100	15	17
biology and archaeo pages	193	268	–
Caving, etc. pages	127	41	24
total contributors	203	106	36
total entries	351	107	62
total pages	902	654	507

***Table 1.** Encyclopediae compared.*

Tony Waltham
Nottingham
tony@geophotos.co.uk
February 2005

Atlas do Janelão by André Prous, Ezio Rubbioli, Claude Chabert, Luís Piló, Ana Brina and Lília Horta (Au Pré de Madame Carle, France). 2003. ISBN 2-912402-07-7. 55 pages, €178 (£120).

In fact this not a book; it is a work of art. And it could perhaps only have been produced by a Frenchman who has a passion for caves, has true style, and is just a little bit mad. Such is Claude Chabert (the drive behind this project), who obviously revelled in seven summer visits to Brazil's superb Janelão Cave, each year adding just a bit more to his beloved survey.

The result is a huge, A3-size, boxed file containing 55 loose folded sheets on cartridge paper; it weighs in at 3kg. The main passage of Janelão is 3km of continuous very large streamway (perhaps second in size only to Mulu's Deer Cave). Seen in its entirety, laid out on the lounge floor, the survey is 4.5m long – and is a delight of hand-painted, watercolour artistry. This is a cave map like no other. The cave name translates to "Cave of the Big Windows", in recognition of its series of skylights whose soft illumination renders the giant passage so visible. Janelão offers the most beautiful of underground scenery, and the publication is adorned with a selection of splendid photographs, and also lovely paintings and drawings, which combine to convey the atmosphere of this remarkable cave. All the text is in both Portuguese and French, with sections describing the cave paintings, flora, fauna, karst and exploration.

This is a publication for the serious collector, and not for the club library. Only 300 numbered copies have been produced, and they will be traded at ever-higher prices once they are sold out. The Atlas do Janelão is destined to become, and remain, a classic of cave "literature".

Tony Waltham
Nottingham
tony@geophotos.co.uk
April 2005

Sinkholes and Subsidence: Karst and Cavernous Rocks in Engineering and Construction. Tony Waltham, Fred Bell and Martin Culshaw. Springer Verlag, Berlin, Heidelberg, New York, and Praxis Publishing Ltd., Chichester. [Springer-Praxis books in geophysical sciences.] ISBN 3-540-20725-2. Published price £100.00 sterling.

At last – a book about engineering geology (and related topics) that is dedicated to karst and karst-related issues, written by a team that knows about and appreciates karst. The author team is strong and knowledgeable, to say the least, but there is also a list of additional contributors drawn from the worlds of engineering geology, karst geology/geomorphology, and beyond.

This review does not set out to examine and debate the detailed ins and outs of the recommended engineering practices that form the bulk of this 382-page book. Such reviews will appear elsewhere (if they have not appeared already). However, the novelty of the book is such that it is worthy of examination purely from the viewpoint of its potential place in karst – rather than engineering geology – literature. Before embarking upon an appreciation of the "karst" content of the book, it is as well to list the spectrum of topics that it covers. There are 12 descriptive chapters, plus chapter 13, which provides a number of pertinent and informative case studies, and it is here that the depth of knowledge provided by the team of additional contributors comes into its own.

The first twelve chapters are entitled:

- Rocks, dissolution and karst;
- Sinkhole classification and nomenclature;
- Rock failure in collapse and caprock sinkholes;
- Soil failure in subsidence sinkholes;
- Buried sinkholes and rockhead features;
- Sinkholes in insoluble rocks;
- Rock failure under imposed load over caves;
- Sinkholes induced by engineering works;
- Ground investigation in sinkhole terrains;
- Hazard and risk assessment of sinkholes;
- Prevention and remediation of sinkholes;
- Construction in sinkhole terrains.

Inevitably, many interesting aspects of karst science (and pseudokarst science) crop up throughout all of these chapters but, from a purely karst viewpoint, the first and second chapters contain the most concentrated interest.

Chapter 1, *"Rocks, dissolution and karst"*, needs less than 23 pages to provide a sound introduction to the major aspects of karst science, interwoven with appropriate "hooks" to the engineering topics that are covered in more detail in the cross-referenced chapters later in the book. Fundamental karst topics such as limestone lithologies and dissolutional processes are neatly covered, along with aspects relating to dolomitic rocks, evaporite rocks and chalk, as well as a short section touching upon the wide and ever more visible topic of anthropogenic influences on karst. The long and cosmopolitan experience of the first named author in the actual study of caves and karst and, more importantly, in getting across the important aspects of this knowledge to a mixed-experience readership, is immediately obvious. This chapter contains all that is needed to provide a basic understanding of the fundamentals of cave and karst development. Clearly there is more (much more) to karst science as a whole, but this chapter is exactly what it sets out to be – fit for purpose and up to date. What's more, the chapter, like the others in the book, is supported by a series of pertinent and informative figures and photographs.

Chapter 2 moves from the general to the specific, looking at dolines or, as many English-speaking engineers prefer to call them, sinkholes, features that maintain a high profile throughout much of the book. Whereas several pages could be written on the use, abuse, misuse and implications of the terms sink, sinkhole, swallow, swallet, swallow hole and doline (in several flavours) over the years, and the potential that remains for confusion in archival documents, the decision of the authors to adopt and "go with" the term sinkhole is sensible in context. A little of the history of the terminology is provided and discussed – objectively – leading to the conclusion that the terms sinkhole and doline are effectively the same but, for consistency, the former term is used throughout the remainder of the book. This chapter deals generically, and in terms that are easy to understand, with sinkhole classifications, sinkhole development and evolution and – importantly – with sinkholes in karstic rocks other than carbonates. It also introduces the vital topic of the interface between sinkholes and engineering practices. Once again this chapter is carried forward on a raft of fine photographs and line illustrations, and I can think of no better illustrated or more clearly written English language introduction to sinkholes, whether in specific engineering texts or in more general karst textbooks.

From my own layman geologist's point of view the specialized engineering geology discussed in chapters 3 to 12 seems more than sound. Some might argue that detailed study of each chapter's central topic could fill a textbook on its own, but these chapters seem comprehensive in width of coverage, and bang up to date. They are also well illustrated throughout with appropriate, in some cases spectacular, photographs and a plethora of line illustrations, some based on diagrams seen before, some original.

Chapter 3 includes considerations of the manifestations of "collapse", in a variety of rock types, rounding off with a brief consideration of the hazards that collapse presents. A similar pattern is followed in chapter 4, which examines the mechanisms and effects of subsidence and the various subtypes of subsidence sinkholes. In chapter 5 the important issues of buried sinkholes and related irregular rockhead features (such as pinnacles and unroofed caves) are considered. Chapter 6 is dedicated to sinkholes in insoluble rocks –dwelling mainly on those related to lava tubes, but with a brief consideration of other pseudokarst situations including piping effects in unconsolidated materials. Moving more deeply into practical engineering, chapter 7 examines the effects of loading the surface above karstic voids, and chapter 8 looks at other important engineering issues such as reservoir construction and groundwater abstraction. The remaining chapters (9 to 12) delve still more deeply into engineering practices, covering the major topics of ground investigation methods, hazard/risk assessment, prevention and remediation strategies and construction methods. There are fewer photographs overall throughout these last few chapters, but there are many clearly drawn line figures and tables. Those photographs that are used are appropriate to the topics and in many cases they make a telling impression.

Chapter 13 comprises 16 case studies that cover a spectrum of karst-related "problems" in a variety of geographical and geological situations, all documented by acknowledged experts in the fields being considered. Here again the photographic coverage is excellent, as too are the many line figures including clear and informative site plans and schematic cross sections.

Scattered through the first half of the book are a number of "boxes" containing short discussions of well illustrated and self-supporting examples of the features or issues being presented in the adjacent pages. These "boxes" add a specific level of reality to the theoretical considerations that would not be provided even by passing, in-text, references to named examples. Of course the latter are also plentiful throughout the book, and they are immensely useful in their own right.

At the front of the book a short but interesting Preface, plus lists of contributors, figures, tables and boxes, are augmented by a brief but useful glossary of "sinkhole terminology". The book is completed by an extensive and up to date, but obviously not exhaustive, reference list, a locational index and a subject index, with both of the latter seeming fairly well and accurately populated, and hence really helpful.

To me this seems to be a useful, user-friendly and well-written reference text that carries significant interest for lay readers (whether or not they be geologists), even those who might just start by glancing at the illustrations before being drawn into the related discussions. It will inevitably also provide an accessible way into the intricacies of karst and its related issues for those wishing to gain a deeper knowledge. Mainly, however, it is designed to educate all those – engineers or otherwise – who might need to plan for, or deal with, the many unique problems and hazards associated with karst landscapes (and buried karst landscapes). The only negative comment has to relate to the published price. Whereas at £100 per copy the book will probably attract an initial bulk sale to libraries and a few corporate organizations, it seems unlikely that it will find much of a market among the general public, even among karst researchers and those interested in the exploration and study of caves. This is a shame and a seeming waste of the work that went into the book and the thought that must have underlain the authors' choice of illustrations.

In closing I cannot resist quoting verbatim from a postscript to the book's Preface. After brief discussion of a recent karst-related incident in Florida, USA, the authors note:

> Press comments that *"A sinkhole as deep as this is undetectable"*, *"It was just a bizarre event"*, *"A small problem with the soil, something 1–6m across, is easy to miss; if you try to find every one, you could not afford the project"*, and *"It was an act of God"* showed a complete lack of understanding of the karst. The authors hope that this book will improve understanding in the future.

Amen to that.

Dave Lowe
C/o BGS
Keyworth
Nottingham
NG12 1AQ
UK.

THESIS ABSTRACT

Effects of Exposure to Continuous Low Doses of Ionising Radiation.

Kathleen Meehan
Doctor Technologiae; January 2005
Cape Technikon (now Cape Peninsula University of Technology)

Abstract

Ionising radiation has the ability to induce, *inter alia*, DNA damage and is well established as a causative agent of carcinogenesis and mutagenesis. Whereas the effects of high doses of radiation of short duration have been well documented, the biological effects of long-term exposure to low doses is not as clearly understood and current risk estimates are largely extrapolated from high-dose data of atomic bomb survivors. This study evaluated the clastogenic effects of low dose ionising radiation on a population of bats (*Chiroptera*) residing in an abandoned monazite mine. Bats were sampled from two areas in the mine, with external radiation levels measuring around 20 µSv/hr (low dose) and 100 µSv/hr (high dose). A control group of bats was sampled from a cave with no detectable radiation above normal background levels.

Although experimental studies have shown that exposure to radiation may lead to the onset of fibrosis and an inflammatory response in the lung and other tissue, the magnitude of the dose exposure was not comparable to this study and histological examination of bat lung and liver tissues showed no morphological changes in radiation exposed bats when compared to the control group.

The most frequently encountered genetic event in human malignancy is the alteration of the p53 gene, which regulates cell division by arresting cells in the G_1 phase of the cell cycle to allow for DNA repair. Mutant p53 proteins have a longer half-life than wild-type and accumulate to high levels in the nucleus of tumour cells.

The micronucleus assay used to evaluate residual radiation damage in binucleated lymphocytes showed that the micronucleus frequency was higher in the test group than the control group. This study showed that bats exposed to radiation also presented with an increased number of micronuclei in reticulocytes compared to the control group. The Single Cell Gel (Comet) assay is a means of evaluating clastogenecity of exposure to environmental agents including radiation at the level of individual cells. Bats exposed to radiation showed increased DNA damage as shown by the length of the comet tails. The results of the micronucleus and the comet assays showed not only a statistically significant difference between test and control groups, but indicated a dose dependent increase in DNA damage. These assays may thus be useful in evaluating the potential clastogenecity of exposure to continuous low doses of ionising radiation.

Chronic radiation exposures may give rise to a number of specific haematological defects, which are collectively termed "preleukemia" or myelodysplastic syndrome. This study evaluated the haematopoeitic effects of continuous low dose ionising radiation on a population of bats (Chiroptera) residing in an abandoned monazite mine. Bats were sampled from two areas in the mine, with external radiation levels measuring around 20 µSv/hr (low dose) and 100 µSv/hr (high dose). A control group of bats was sampled from a cave with no detectable radiation above normal background levels. Whole blood was collected into EDTA and full blood counts were performed. A significant decrease in the MCV indicated that erythrocytes from the radiation exposed bats were microcytic. Differential counts were performed on the peripheral blood of the bats and statistical analysis showed a highly significant decrease in the neutrophil count in all but one group, and a significant increase in the lymphocyte count in all but the same group. Absolute counts were calculated and although some lymphocyte counts from exposed bats differed significantly from the control group ($p<0.05$), all neutrophil counts in exposed bats showed a highly significant decrease ($p<0.001$). Neutrophils showed marked dysplasia in radiation-exposed bats and pseudo-Pelger Huet cells, common in radiation-exposed individuals, were observed and enumerated. All radiation-exposed groups differed significantly from the control group. Cytochemical analysis using DAB myeloperoxidase showed that control bats had hypogranular neutrophils and radiation-exposed bats had largely agranular neutrophils. Bone marrow biopsies were taken both from control and from radiation-exposed bats and evaluated for cellularity, granulocyte: lymphocyte: erythrocyte (GLE) ratio and megakaryocyte morphology. A hypocellular bone marrow, a decreased granulocytic haematopoeisis and dysplastic megakaryocyte morphology were observed in radiation-exposed bats. As the morphology of the bone in radiation-exposed bats appeared abnormal, mineralization of bone was determined using image analysis and compared to the control bats. Analysis showed a highly significant decrease in the percentage mineralization of the bone from radiation-exposed bats. All features observed are congruent with current literature describing secondary (radiation-induced) myelodysplastic syndrome. As there is considerable debate as to what dose radiation exposure is harmful, the results of these findings may prove significant in establishing haematopoeitic effects of continuous low dose exposure to ionising radiation.

RESEARCH FUNDS AND GRANTS

The BCRA Research Fund

The British Cave Research Association has established the BCRA Research Fund to promote research into all aspects of speleology in Britain and abroad. A total of £2000 per year is currently available. The aims of the scheme are primarily:

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

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

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

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

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

Ghar Parau Foundation Expedition Awards

An award, or awards, with a minimum of around £1000 available annually, to overseas caving expeditions originating from within the United Kingdom. Grants are normally given to those expeditions with an emphasis on a scientific approach and/or pure exploration in remote or little known areas. Application forms are available from the GPF Secretary, David Judson, Hurst Barn, Castlemorton, Malvern, Worcestershire, WR13 6LS, e-mail: d.judson@bcra.org.uk. Closing dates for applications are: 31August and 31 January.

The E K Tratman Award

An annual award is 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 (see above for contact details), not later than 31 January each year.

BRITISH CAVE RESEARCH ASSOCIATION PUBLICATIONS

Cave and Karst Science – published three times annually, a scientific journal comprising original research papers, reports, reviews and discussion forum, on all aspects of speleological investigation, geology and geomorphology related to karst and caves, archaeology, biospeleology, exploration and expedition reports.

Editors: Dr D J Lowe, c/o British Geological Survey, Keyworth, Nottingham, NG12 5GG, UK, (e-mail d.lowe@bcra.org.uk) and Professor J Gunn, Limestone Research Group, University of Huddersfield, Queensgate, Huddersfield, HDl 3DH, UK (e-mail j.gunn@bcra.org.uk).

Speleology - published three times annually and replacing BCRA's bulletin *'Caves & Caving'*. A magazine promoting the scientific study of caves, caving technology, and the activity of cave exploration. The magazine also acts as a forum for BCRA's special interest groups and includes book reviews and reports of caving events.

Editor: David Gibson, 12 Well house Drive, Leeds, LS8 4BX, (e-mail: speleology@bcra.org.uk).

Cave Studies Series - occasional series of booklets on various speleological or karst subjects.

No. 1 *Caves and Karst of the Yorkshire Dales*; by Tony Waltham and Martin Davies, 1987. Reprinted 1991.
No. 3 *Caves and Karst of the Peak District*; by Trevor Ford and John Gunn, 1990. Reprinted with corrections 1992.
No. 4 *An Introduction to Cave Photography*; by Sheena Stoddard, 1994.
No. 5 *An Introduction to British Limestone Karst Environments*; edited by John Gunn, 1994.
No. 7 *Caves and Karst of the Brecon Beacons National Park*; by Mike Simms, 1998.
No. 8 *Walks around the Caves and Karst of the Mendip Hills*; by Andy Farrant, 1999.
No. 9 *Sediments in Caves*; by Trevor Ford, 2001
No. 10 *Dictionary of Karst and Caves*; by D J Lowe and A C Waltham, 2002.
No. 11 *Cave Surveying*; by A J Day, 2002.
No.12 *Underground Britain-Legal + Insurance Issues*; (2nd extended/revised edition) by David Judson, 2005.
No 13 *Exploring the Limestone Landscapes of Upper Wharfedale*; by Phillip Murphy, 2003.
No.14 *Swildon's Two and Three*; by Dave Irwin, 2004.
No.15 *Exploring the Limestone Landscapes of The Three Peaks + Malham*; by P Murphy, 2005.

Numbers 2 and 6 are out of print, but have been updated by numbers 11 and 10 respectively.

Speleohistory Series – an occasional series.

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

BCRA SPECIAL INTEREST GROUPS

Special Interest Groups are organised groups within the BCRA that issue their own publications and hold symposia, field meetings, etc.

Cave Radio and Electronics Group promotes the theoretical and practical study of cave radio and the uses of electronics in cave-related projects. The Group publishes a quarterly technical journal (c.32pp A4) and organises twice-yearly field meetings. Occasional publications include the Bibliography of Underground Communications (2nd edition, 36pp A4).

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

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

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

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

Copies of BCRA Publications are obtainable from: Ernie Shield, Publication Sales, Village Farm, Great Thirkleby, Thirsk, North Yorkshire, Y07 2AT, UK.

BCRA Research Fund application forms and information about BCRA Special Interest Groups can be obtained from the BCRA Honorary Secretary: John Wilcock, 22 Kingsley Close, Stafford, STl7 9BT, UK.