Cave and Karst Science

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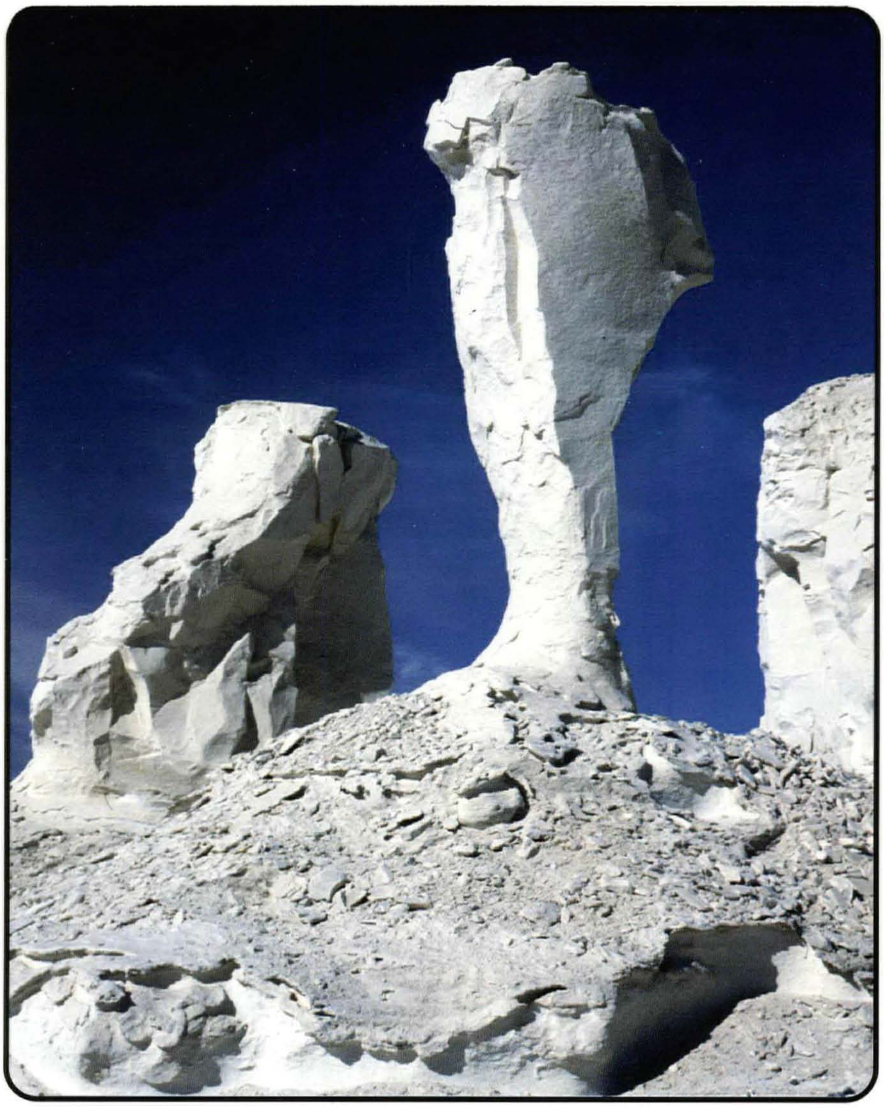

De Hoop karst, Western Cape, South Africa
Geology and archaeology in Mongolia
Djara Cave, Western Desert, Egypt
Peak Cavern, Derbyshire, UK
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Symposium abstracts
Forum

Cave and Karst Science

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Cave and Karst Science

TRANSACTIONS OF THE BRITISH CAVE RESEARCH ASSOCIATION

Volume 29, Number 2, 2002

Contents

Papers

Reports

Symposium Abstracts

Forum

Cover photo:

The White Desert of Farafra, in the same part of the Egyptian Western Desert as Djara Cave (see Paper in this Issue), displays spectacular karst landforms in pure white chalk. The features shown here are up to about 15m tall and are fine examples of relict towers, formed during past wetter climatic conditions, now degraded in the modern desert

Photo by Tony Waltham

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

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The karst of the De Hoop Nature Reserve, Western Cape, South Africa

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Abstract: The De Hoop Vlei Reserve and adjacent areas, only 150km east of Cape Town, support an important coastal karst, which is developed on Tertiary dune limestones. A high density of enclosed hollows with some dry valleys constitute the surface karst. Shallow caves are localised. The complexity of enclosed hollow plan-form increases with altitude and therefore with the age of the limestone surface. A pitting index is given as a measure of difference between areas of differing karst age. There is also evidence for syngenetic karst development of both valleys and hollows.

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INTRODUCTION

Some of the most spectacular surface karst and caves in South Africa are accorded conservation status by virtue of falling within the De Hoop Nature Reserve. This reserve, set up originally to preserve and breed endangered animals, is located on the coast of the Western Province, east of Cape Agulhas (34° 50'S: 20° 00'E), some 150km east of Cape Town (33° 55'S: 18° 28'E) (Fig.1). De Hoop Vlei, an important RAMSA bird locality, divides the karst area (Butcher, 1983). Most of the reserve lies east of the Vlei but, as a large area outside the Reserve on the west is held by the Defence Force, it has *de facto* conservation status. This karst area is developed on Cenozoic Bredasdorp Group limestones (formerly known as the Coastal Limestones).

GEOLOGY

To help understand the karst geomorphology mention must be made of the structural context. The Reserve lies within the Cape Mountain belt. Cape Supergroup Peninsula Formation quartzites and sandstones form the mountain ranges, and Bokkeveld shales (also Cape Supergroup) underlie the intervening valleys and plains. North of Cape Town the alignment is north-south whereas eastwards the alignment swings west-east. The Reserve lies south of the orogenic node where the alignment changes (Fig.2). The change in direction can be recognised in the Bredasdorp Range, in the planed and buried ridges that crop out at Struis Bay and Arniston (34° 35'S: 20° 14'E) and in the Potberg, which rises to a maximum altitude of 370m, jutting into the ocean at Cape Infanta (34° 29'S: 21° 51'E) (Fig.2).

The resistant Cape fold ranges have assisted preservation of the limestone between the Bredasdorp and Potberg ranges. Following the break-up of Gondwana (the southern hemisphere supercontinent) a series of fault troughs developed along the coast extending off-shore, in which sediments of Cretaceous and later age have been preserved (Dingle *et al.*, 1983). The Reserve overlies the inner margin of one such half-graben (Fig.3). Two major Tertiary tectonic uplifts account for the present altitude of the limestone. Faulting that resulted is most easily recognised in the Peninsula Formation quartzites, but has also been important in directing dissolution within the limestone. The basic geology of the Reserve is shown on Figure 3.

Cenozoic near-shore limestones occur sporadically along the South African coast from Saldanha (33° 03'S: 17° 51'E) in the west, to northern KwaZulu-Natal in the east. The southern Cape outcrop between Cape Agulhas (34° 50'S: 20° 02'E) and Mossel Bay (34° 11'S; 22° 08'E), of which the De Hoop area forms a part, and that of the Eastern Cape between Woody Cape and Great Fish River (33° 29'S: 27° 16'E) have the highest density and diversity of karst. The limestones

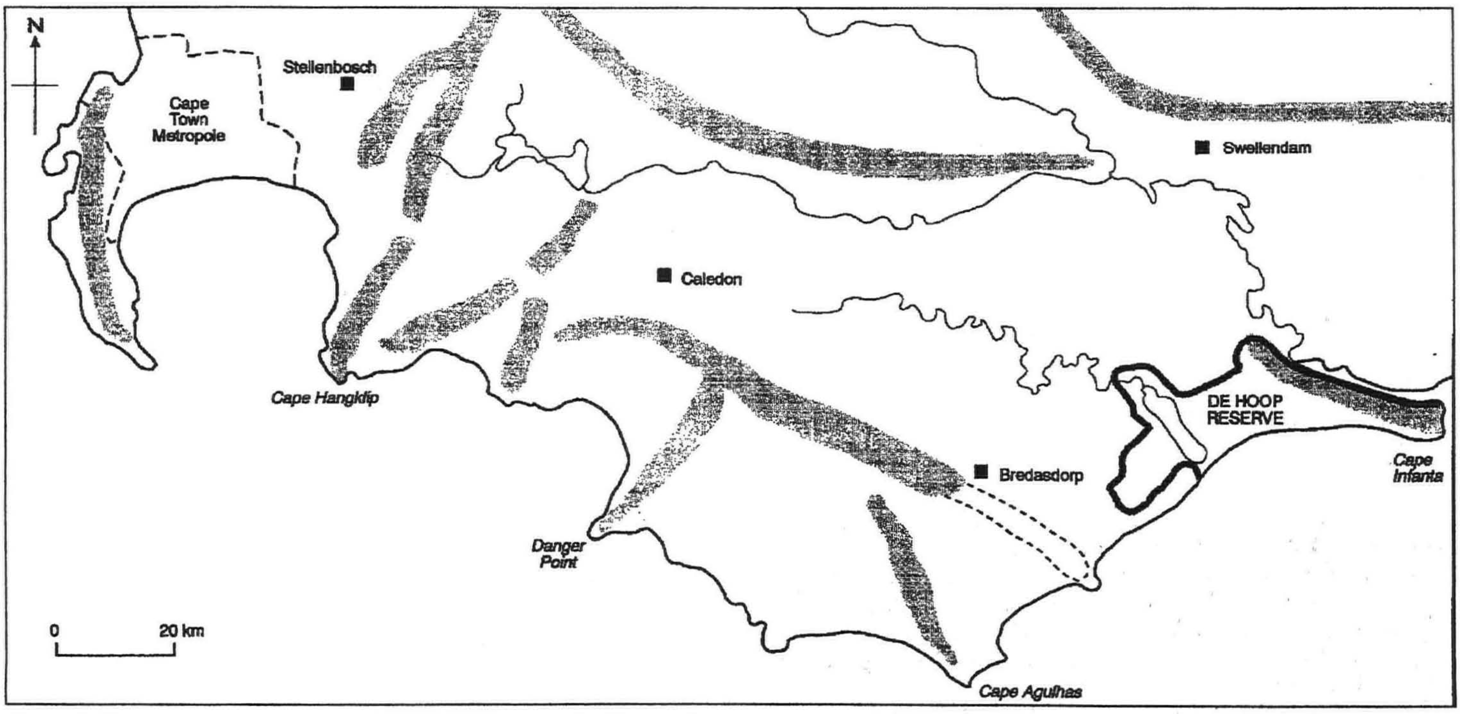

Figure 1: The location of the De Hoop Nature Reserve within the Western Cape fold belt. Note the change of trend in the ranges from north–south in the west to dominantly west–east.

Formation	Description	Age
Strandveld	Unconsolidated wind-blown dunes	Holocene
Waenhuiskrans	Semi-consolidated aeolianite	Pleistocene
Klein Brak	Shelly quartzose sand and conglomerate	Pleistocene
Wankoe	Consolidated aeolianite	Pliocene
De Hoopvlei	Shelly quartzose sand and oyster-bearing conglomerate	Pliocene

Table 1: Subdivision of Bredasdorp Group (after Malan, 1990)

that crop out in the Reserve and host its karst are Cenozoic in age and can be subdivided into 2 groups. Both groups of limestones in the Reserve have a basal marine component overlain by a much thicker aeolianite of beach and dune origin (Malan & Viljoen, 1990) (Table 1). These extend throughout the southern Cape (Table 1). The marine De Hoopvlei Formation consists of shelly quartzose sand with oyster-bearing conglomerate, and is overlain by consolidated aeolianite of the Wankoe Formation. These formations are believed to be Pliocene in age (Malan 1990). The moderately lithified Wankoe Formation is undoubtedly the main karst host rock.

Early Pleistocene deposits comprise the marine quartzose sands and conglomerate of the Klein Brak Formation and an overlying beach and dune aeolianite, the Waenhuiskrans Formation. These formations occur closer to the coast and is less well consolidated than the older limestones. Over most of the De Hoop Reserve, the Wankoe limestones actually underlie the Waenhuiskrans deposits. Mobile sand dunes of the Strandveld Group are the youngest stratigraphical element in the area, and they are well developed along the coast (Fig.2).

KARST

The main topographical components of the De Hoop Reserve and adjacent areas constitute belts sub-parallel to the coast (Fig.2). Section A–B illustrates the topography of the Reserve immediately east of the Vlei (Fig.4). The section also illustrates the area (developed on Cape Supergroup Bokkeveld shales) north of the Reserve, which has rolling topography with scattered tabular hills rising to almost 300m (Fig.4a). The tabular hills, capped by silcrete overlying white saprolite, represent remnants of the Tertiary African Surface. With destruction of the caprock, rolling topography develops.

The remnant African land surface is separated from the limestone outcrop by a narrow valley. The settlement of Wydgeleë is sited in this border depression, drained by the intermittent Potberg River. Farther east this depression has broadened into a rand polje. Adjacent to Bredasdorp and east of the Breë River, the border depression has opened into plains. Residual lumps of conglomerate indicate that the border depression and the plains were formerly covered by limestone. The nearshore limestone then abutted directly on the African land surface.

The Die Duine (hard dunes) ridge, averaging 180 to 200m altitude, reaches a maximum altitude of 274m near the Potberg Range, but is lower to the west. It rises steeply from the border depression. Die Duine has well-developed surface karst but few known caves. The steep 10° to 12° slopes on either side are scarred by rocky gorge-like dry valleys, which run out onto a low angle basal foot slope that supports little or no karst.

From the base of the footslope to the coast the terrain is level and stepped. It is the product of marine planation when sea level stood progressively at 90m, 60m, 30 to 40m and just below 20m elevation above present sea level. This karst is dominated by enclosed hollows of progressively smaller dimensions and more regular outline with lower altitude.

Much of the seaward margin of the 20m surface is concealed by Strandveld Formation dunes, which separate the planed area from the shore, and cut off De Hoop Vlei from the sea. De Hoop Vlei is incised almost to sea level, so is bordered by rock cliffs inland. Dry valleys feed from Die Duine, with springs emerging near the Vlei. The Sout River drains from the African Surface into the De Hoop Vlei and maintains the water level (Butcher, 1983). The intermittent Potberg River is a main eastern tributary. In times of drought the Vlei can become dry.

The eastern section (C–D) across Potberg shows that there only Die Duine and the 90m and 60m benches are present (Fig.4b). Marine erosion has truncated the seaward extension of the limestone, which now abuts the coast in cliffs. In these cliffs a number of vadose caves have developed above the contact with Cape Supergroup rocks.

The De Hoop karst has high karst density and moderate diversity. The permeability of the limestone ensures that all water goes underground, leaving dry valleys on the surface and springs that emerge at the base of kloofs. All limestone landscapes are dry environments. The aridity is enhanced here by the low annual rainfall, only 350mm per annum, falling chiefly in winter. Being near the sea the environment is windy and this also increases evaporation.

This karst, like that of the coastal karst areas farther east, is dominated by enclosed hollows ranging through shallow pan dolines, deep funnel-shape dolines and cenotes, to uvalas and poljes. Dry valleys and caves are also important. Adjacent to the Potberg Range, the border depression has broadened into a rand polje almost 5km long and 2_km wide. Its depth is shallow, only 19m lower than the valley floor. It is located along the sandstone / limestone contact at the intersection of two faults (Fig.3). The development of a polje at this site can be explained in terms of increased acid run-off from the sandstone ridge, with accentuated water penetration along the faults. However, another polje, Ou Werf, west of the Reserve on the summit of Die Duine, cannot be explained in those terms (Fig.2). The summit plateau surface is case-hardened, calcretised limestone with traces of micro-karren features. Poorly defined former valleys are interrupted by rocky uvalas of oval plan, 500m – 100m in length and up to 500m wide. The largest of these is Ou Werf. All have been left abandoned by a progressive drop in water table following sea level regression.

On Dronkvlei, most caves are adjacent to large irregular uvalas (apparently let down from the 30 to 40m surface, but with floor altitude at 15 to 20m) and several of the entrances resemble cenotes. Such specific doline forms are characteristic of development in areas with a high water table, with pronounced conduit flow along joints in porous, relatively easily dissolved limestones (Marker, 1976). Cenotes are rare in South Africa and the development of Onmeetbare Diepgat has been facilitated by its location on the fault that bounds the buried Cretaceous outcrop.

Detailed mapping from air photographs of the negative relief of the karst shows considerable variation with altitude (Russell, 1989) (Figs 5a and 5b). On the basis of this variability, Russell (1989) felt able to subdivide the karst area into distinct regions, each with its own characteristics (Tables 2 and 3). She also determined a pitting index, which

1	Border depression / karst plain
2	Summit plateau of Die Duine bevelled at 180 to 200m, deep rocky dolines and uvalas aligned along former valleys
3	12-13° slopes from Die Duine incised by steep dry valleys in which springs emerge at vlei level
4	15-20m surface with small circular pans only
5	Marine benches at 30 – 40m and 60m with more complex surface karst
6	90m marine bench
7	Syngenetic karst developed on Waenhuiskrans Formation
8	No karst development, as limestone is thin or absent

Table 2: Karst types of the De Hoop area

distinguished clearly between the higher karst areas on the basis of age (Table 4).

In summary, Die Duine at 180m to 200m summit altitude has a rock surface, case-hardened by calcrete, almost comprising a form of pavement. Into this surface deep, rock-rimmed uvalas are aligned preferentially along disrupted east to west shallow dry valleys. The steep slopes are cut by dry gorges which, to the south, run out onto a low angle rock foot-slope that merges with the highest of the marine planation levels. This slope carries no karst.

The marine planed benches at 90m, 60m and 30m support similar shallow uvalas of irregular outline. Their present plan form is attributed to complex coalescence of adjacent hollows. Only narrow ridges of the original surface remain (Fig.5). Variable depths of sand infill these hollows and occur as patches elsewhere. The concentration of caves in the vicinity of Dronkvlei and the localised cenotes are associated with the 30m surface where it is underlain by the fault basin. The 15m to 20m planed surface close to the vlei and inland of the coast is characterised only by shallow circular pan dolines (Fig.5b).

The different characteristics of the karst at different altitudes were attributed to the variables acting on the karst over time (Russell, 1989). These variables are discussed as follows:

Geology and lithology

As the Wankoe limestone is relatively uniform, being a lithified silicious beach aeolianite, the only major geological differences are in the thickness of limestone above an impermeable substrate or the piezometric surface. Where only thin limestone remains, as on the 15m to 20m bench, vertical infiltration is inhibited and lateral widening occurs. Only shallow pan dolines can develop. Where limestone thickness is greater, deep hollows can form. The less lithified Waenhuiskrans Formation supports only relatively simple karst forms. Blown sand and less lithified limestone govern the gradient of individual landforms as well as their maximum size.

Surface altitude	Limestone thickness	Hollow depth
200+	<200	<120
200+	<100	98
90 - 100	>80	<10
30 - 50	>50	<10
20	10 - 20	4

Table 3: Limestone thickness and depression depth (after Russell, 1989)

Syngenetic karst

This Tertiary limestone retains topographic form from its dune origin. This has controlled the location of dolines. Both the Waenhuiskrans Formation and the Wankoe limestone host a South African example of syngenetic karst development. Hollow initiation was constrained by the dune topography and is aligned along inter-dune corridors. Ultimately the dune ridges become debased and only the alignment of depressions indicates the syngenetic nature of the karst (Marker, 1993). Jennings (1968) argued (for Tertiary coastal limestones in Australia) that syngenetic development implied simultaneous karst development and lithification of the dune sands. Lithification begins by case-hardening, with the formation of calcrete in the zone of aeration, and this preserved the dune topography. Karst develops on the case-hardened surface, even above unconsolidated sands. The De Hoop Vlei karst is hosted by Tertiary limestone. It also lies adjacent to the present coast and the different topographic belts are located parallel to the coast. The alignment of karst hollows on the harder Wankoe Formation, particularly on Die Duine where the shallow dry valleys are also parallel to the coast, indicates that it too was syngenetic in origin. This supposition is confirmed in the karst east of Cape Infanta, where the evidence is clearer.

Eustatic sea level changes

A series of transgressive / regressive marine events during the Tertiary and Quaternary periods affected the Cape coast. The Tertiary transgressions cut broad wave platforms in the Cape Supergroup and Cretaceous sediments, on which the limestone was deposited. The

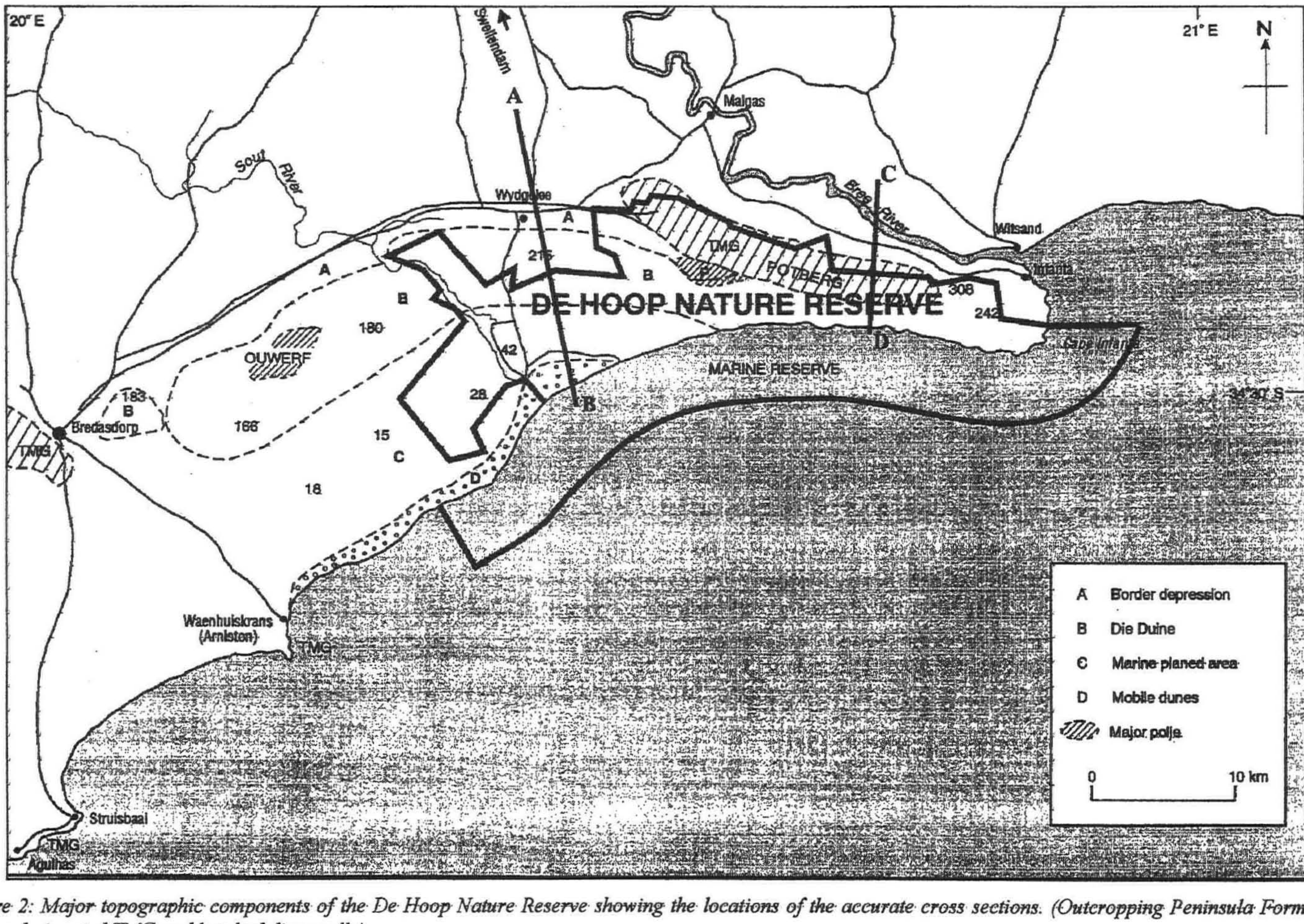

Figure 2: Major topographic components of the De Hoop Nature Reserve showing the locations of the accurate cross sections. (Outcropping Peninsula Formation ranges designated TMG and hatched diagonally).

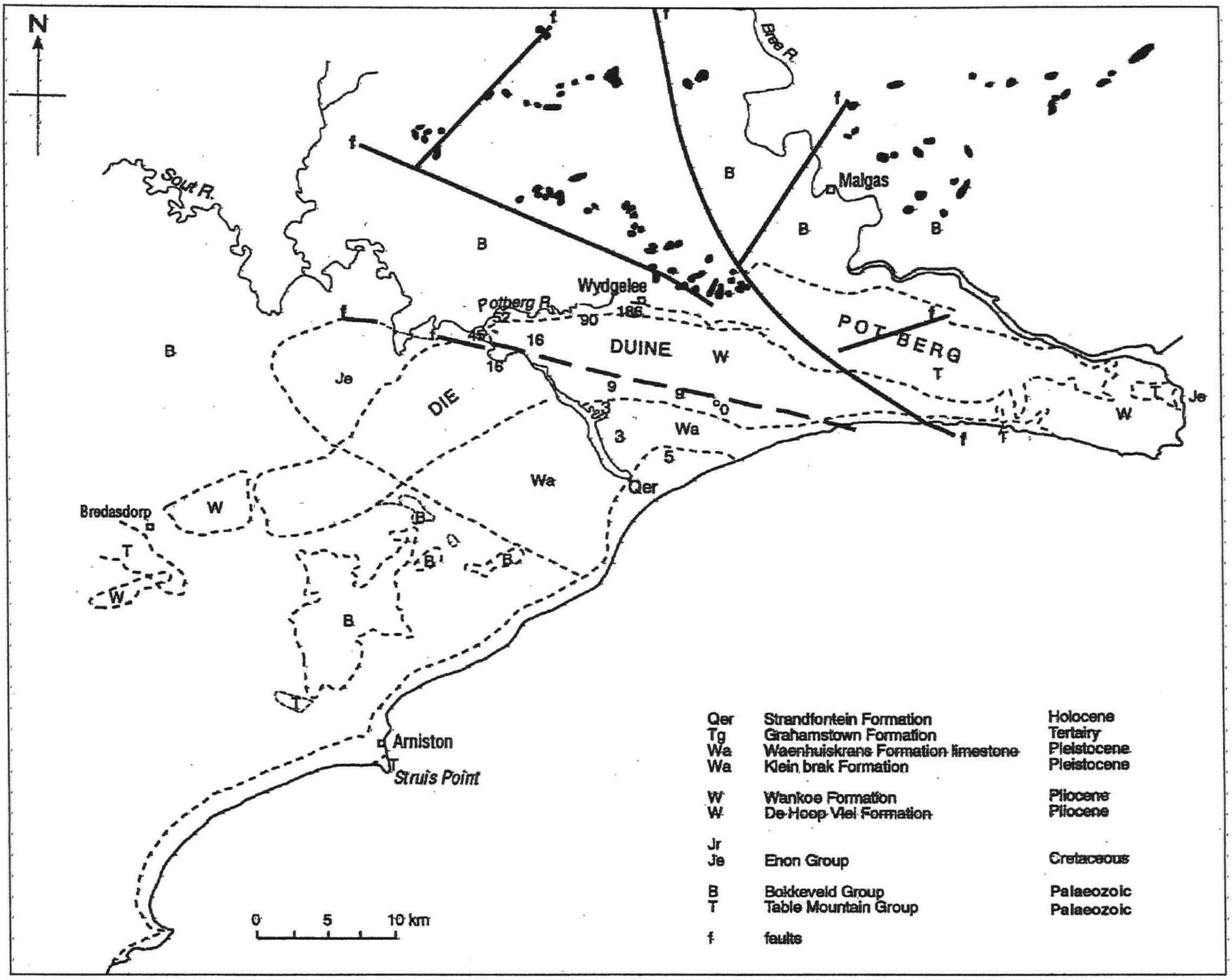

Figure 3: The geology of the De Hoop Nature Reserve and adjacent areas. Note the buried Cretaceous trough and the faults (based on Malan & Viljoen, 1990 and Geological Survey).

existence of marine benches at 90m, 60m, 30m and 15m altitude, incised into the Wankoe Formation, reflect the effect of glacio-eustatic marine incursions. These benches demonstrate that the combined effect of differing thickness of limestone left after planation, and the progressively younger time span available for karst evolution, have left their mark on the landscape (Russell, 1989) (Tables 3 and 4). The higher the platform the older and better developed is the surface karst, and the lower the percentage of the original surface remaining. Highly complex uvalas, the product of coalescence, dominate on the higher benches.

Sea level changes must also have affected the altitude of the piezometric surface and therefore the depth to which vadose water could penetrate. The present piezometric surface drops abruptly from Die Duine, where evidence suggests it is at 90m altitude and thus 90m beneath the summit, to the coast. The average altitude of the present piezometric surface is 9m beneath the Dronkvlei area east of the fault, and at 3m and –5m within the trough. The deep uvalas of Die Duine can be attributed to a progressively deeper vadose zone as well as to a longer time span for development. The pan doline karst close to the present coast at altitudes below 20m is a function of weakly lithified thin limestone with a restricted vadose zone as well as a shorter time for karst development.

The glacio-eustatic sea level changes also facilitated sand pulses onto the limestone. The sandy soils within the uvalas on Dronkvlei at 30m, and those inland on the higher benches, show greater soil development than those adjacent to the white Strandveld Formation current dunes. Elsewhere in the southern Cape karst belt, red dunes are the older form. They overlie and abut low cliffs above the 20m level. Pinkish sand deposits on the 90m bench may be relics from such red dunes. Texturally the Wankoe Formation weathered material, the red dunes and the pinkish-brown soils are virtually identical with the current dunes. They are all aeolian near-shore deposits. The presence of so much sand means that the true depths of the larger hollows are rarely known.

The time factor

The oldest limestones are Pliocene in age, so the time span available for development of the De Hoop karst is restricted. Die Duine stands at an altitude adjacent to the African Surface remnants. The limestone was formed as the shore deposit for that African coast and subsequently lithified. Its karst is older than any other in the Reserve. The marine benches, cut across Wankoe limestones below Die Duine, are progressively younger with lower altitude and towards the coast. The pan

Surface altitude	% Depression area/total area	Pitting Index
90m	57	1.7
60m	50	2
30 - 40m	25	4

Table 4: Degree of karst hollow development on different surfaces (after Russell, 1989). Pitting index may be defined as depression area to total area.

doline karst of the 15m to 20m surface is the youngest. However there is little distinction in characteristics of the uvalas on the three higher benches.

CAVES

The De Hoop Nature Reserve, situated some 50km ENE of Bredasdorp in the Overberg part of the southern Cape, is the best known site for caves in the Cape coastal limestones. Limited exploration, reflecting the 400km round trip from Cape Town and the flat, superficially featureless, veld make it fairly certain that there are more caves than the few that have been recorded. Indeed, the absence of landmarks made it very difficult to define the position of the entrances before the availability of GPS technology. In most places the veld is so dense that it is possible to walk within one metre of an entrance and not see it. Nevertheless, the members of the Cape Peninsula Speleological Society have a long-term project to survey and record the caves.

The De Hoop Guano Cave

This cave is about 400m long, situated 2½km southeast of the Windhoek farm, above the eastern shore of the De Hoop Vlei (Craven, 1985). It was mined for guano in the 1940s (Anon., 1943), and achieved notoriety as the site of the Cape's second outbreak of acute benign pulmonary histoplasmosis (Craven & Benatar, 1978, 1979). This is the only cave in the area that is situated on the lower slopes of the Hardeduine, about 30m above the plain.

Windmill Pot

Windmill Pot used to be the easiest cave to find in the area because it was situated 2km southeast of Dronkvlei, immediately adjacent to a windpump at a boundary fence. The fence has long since been removed. Entrance is via a 17m drilled shaft above which the pump (now moved a few metres to the side) was originally placed. At the bottom of the shaft is a pool of water and a few, short, low passages (Macpherson, 1960).

Hot Pot

Hot Pot is situated about 1½km southeast of Dronkvlei in a shallow pan doline. It was first reported in 1960, and noted to have dry air and no draught – hence the name (Macpherson, 1960). An 8m pitch, well-guarded by vicious bees, leads to 710m of typical low crawls, hard rocky floors and no formations (Hitchcock, 1985). The cave deposits have revealed a useful collection of faunal remains (Gow, 1980).

Nikki's Pot

This is situated about 3½km southeast of the De Hoop farmhouse, at the side of the track to De Mond. It is a conspicuous 10m-deep shaft with a >1m-deep sandy floor (Craven, 1980).

Onmeetbare Diepgat (= Bottomless Deep Hole)

This is a conspicuous doline, about 20m deep by 20m in diameter, situated 2½km eastnortheast of the farm Dronkvlei. Entrance is gained by digging out a short crawl at the eastern end of the doline, which leads to a 300m more or less horizontal and walkable passage with two lakes and a stream (Walker, 1959; Blacquiere, 1965; Breedt, 1971). The presence of running water confirms, as local farmers have long known, that water can be found by drilling boreholes. Another interesting feature of this cave was the discovery therein, in total darkness, of a troop of baboons, which may have been attracted by the water (Jongens & Coley, 1964).

There are several short caves in the shallow pan doline southeast of Onmeetbare Diepgat:

Binocular Pot

Binocular Pot has two adjacent 8m-deep pitches leading to a 105m low crawl (Gartz, 1989a).

Keyhole Cave

Keyhole Cave is about 5½km north of the sea, in the veld southeast of Onmeetbare Diepgat. There is a 7½m pitch with a 27m crawl at the bottom (Gartz, 1989b).

Edward's Pot

Edward's Pot has a 16m pitch with a 10m crawl at the bottom (Truluck, 1991).

Danielskuil

Danielskuil, similarly in the veld southeast of Onmetbare Diepgat, has been lost for over 30 years (Blacquiere, 1962). Its situation remains unknown.

Scott Pot

This is situated in the Melkhoutkraal veld north of the access road to the De Hoop farmhouse – another 10m-deep pitch with a mere 25m of passage at the bottom (Gartz, 1989c).

CONCLUSION

The De Hoop Vlei Reserve and the adjacent military area together conserve a part of an important karst area developed on Tertiary limestones of aeolian origin. The karst is significant for its high karst density and a range of karst hollows. Cave development is localised and appears to have been facilitated by proximity to the underlying fault trough.

This karst is an example of syngenetic development. It developed on the back-shore dune series, which localised doline development within interdune swales. The topography of Die Duine reflects an initiation on Tertiary coastal dunes adjacent to the African land surface with its deeply weathered remnants and silcrete duricrusts. Subsequent transgressive / regressive sea level changes explain the karst of the progressively lower altitude benches seawards of Die Duine and the decreasing complexity of hollow form as a function of less time and limited depth of limestone to permit vadose infiltration.

The De Hoop area karst is important too, by comparison with other South African karst areas, for its high karst density. The density is also higher than in the eastern extension of the limestone belt. The reason may be attributed to the same Cretaceous fault trough, which enables more effective piezometric gradients to develop.

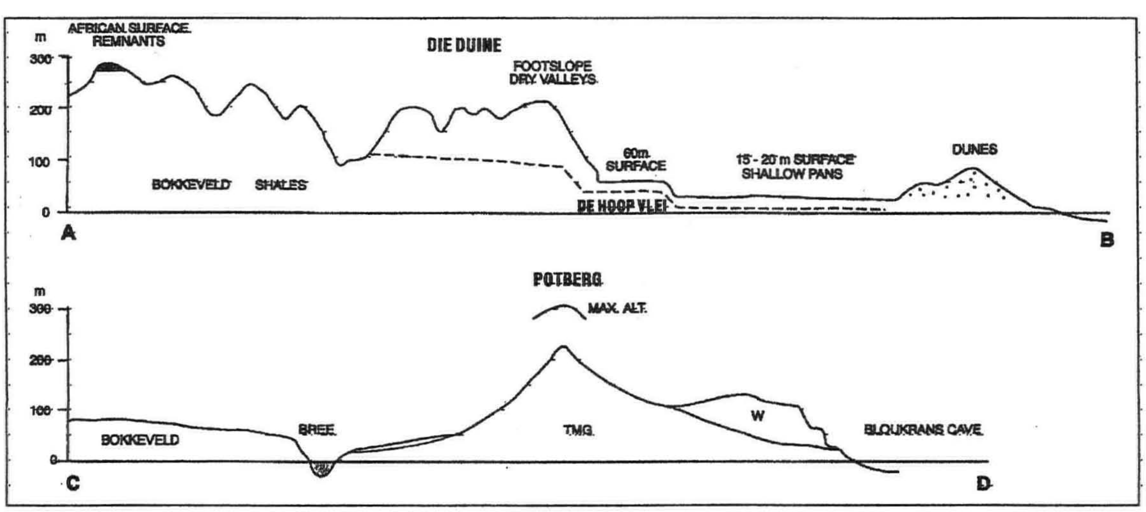

Figure 4: Topographic sections across the De Hoop Nature Reserve.

a) A–B along longitude 20° 25'E immediately east of De Hoop Vlei, which delimits the four major topographic components.

b) C–D along longitude 20° 45'E across Potberg to the coast (for position of sections, see Figure 2).

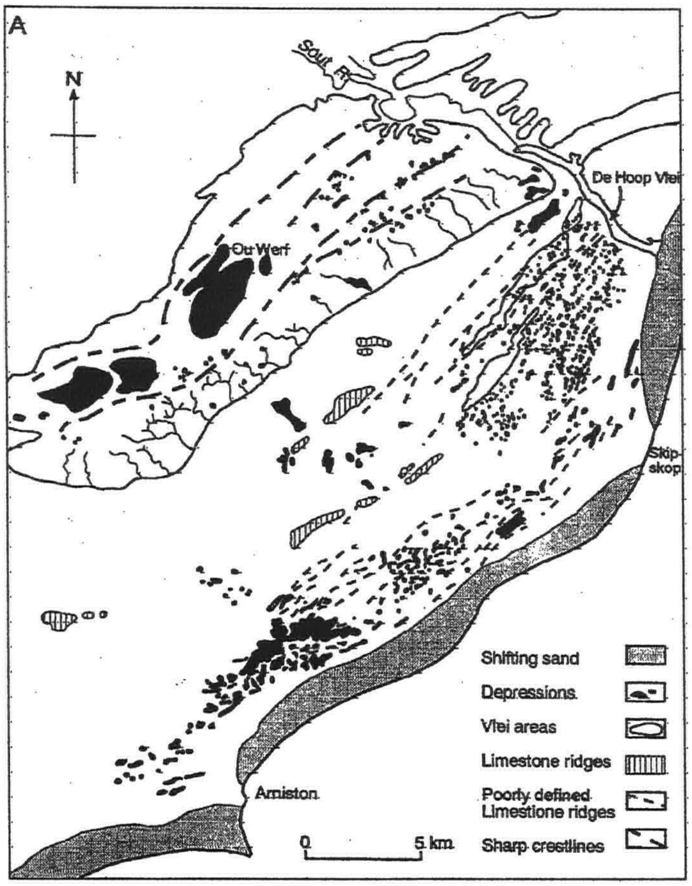

Figure 5: Detailed maps of the negative karst relief (shaded black) based on air photo analysis with ground control (from Russell, 1989).
a) West of De Hoop Vlei.

ACKNOWLEDGMENTS

The idea for this paper originated with a request for a scientific overview of the De Hoop Reserve. The draft was in preparation in South Africa when news was released of the tragic death of Lin Russell and her younger daughter. The geomorphology in this paper is based on research by Dr L Russell and was collated by MEM, who had supervised the research. The original dissertation (MSc) and thesis (DSc) are lodged in the library of the University of Fort Hare, Eastern Cape Province, South Africa, and one author also holds copies. The paper is dedicated to an excellent karst geomorphologist and her family. Her research was facilitated by support from staff of the De Hoop Vlei Reserve and funded through grants from the University of Fort Hare.

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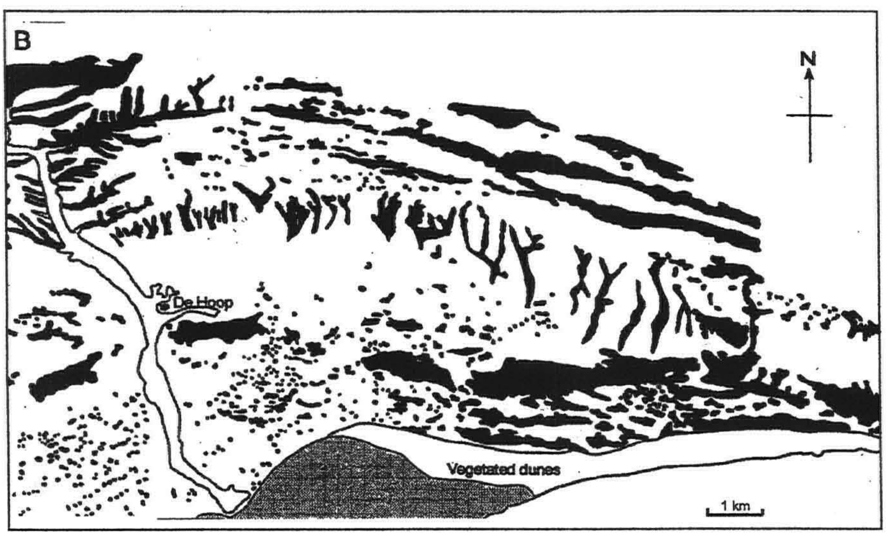

Figure 5b: East of De Hoop Vlei.

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Djara Cave in the Western Desert of Egypt: morphology and evidence of Quaternary climatic change

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Abstract: With stalactites, columns, stalagmites and flowstones up to 6m high and 1.5m in diameter, Djara Cave in the Western Desert is one of very few well-decorated caves in Egypt. U-series ages for four speleothems (140 ± 16, 201 ± 2/233 ± 24, 221 ± 34, and 283 ± 56ka) suggest humid intervals during marine isotope stages 5 and 7, and possibly also during stage 9. Importantly, none of the secondary carbonates date to the Holocene, despite archaeological evidence both in the cave, and on the ground surface above it, of visits to the site by ancient peoples, and of a more humid period of climate from about 11.5 to 6.5ka. $\delta^{18}O$ of speleothem carbonate averaged -12.1‰ PDB, indicating deposition by meteoric waters significantly depleted in ^{18}O. Using ^{18}O PDB of speleothem carbonate, and ^{18}O SMOW of ancient groundwater in the Nubian aquifer, the mean annual temperature at the time of speleothem deposition is estimated to have been 23.1°C, which is 1°C above the present mean annual temperature at the Farafra and Baharya oases. In Israel and Oman, modern speleothem carbonate is less depleted in ^{18}O than Holocene-age material, and this in turn is less depleted than carbonate deposited during isotope stage 5. This suggests that in these areas the Holocene was wetter than the present but not as wet as during marine isotope stage 5. At Djara Cave, the absence of speleothem deposits of Holocene age also suggests that this period was not as wet as during earlier interglacials. The ^{18}O-depleted waters from which the Djara speleothems were deposited appear to have originated in air masses that crossed North Africa from west to east at a time when there was a more southerly westerly airflow than now.

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INTRODUCTION

Large areas of the Western Desert of Egypt are underlain by soluble carbonate rocks, including limestone, marble, chalk, and dolomite. Caves are typical of such rock types in many areas of the world and in arid areas cave sediments, particularly speleothems, may provide significant information about past wetter climates (e.g. Brook, 1999). Unfortunately, in the Western Desert caves are extremely rare and only a few of those that are known contain speleothems. However, on December 24, 1873 a cave with extensive speleothem development, Djara (Rohlfs) Cave, was discovered by a German expedition led by Gerhard Rohlfs. As related by Kuper (1996), the expedition, which included 100 camels, set out from Assiut hoping to reach Kufra in Libya, and found the cave on the plateau between Assiut and Farafra (Rohlfs, 1875). On December 24, on their way from Assiut to Farafra, they set up camp near a place called "Djara", which Rohlfs (1875) describes as a spacious dripstone cave with beautiful stalactites. After this, Djara Cave was not visited again until 1989, when it was re-discovered by Dr Carlo Bergmann (using Rohlfs' map) while on a camel trek in the area. Bergmann reported rock art in the cave and rich prehistoric remains in its immediate vicinity. In November, 1990, the cave was visited by a small group of geographers and archaeologists from Berlin, Cologne and Cairo, together with Carlo Bergmann, and subsequent work was carried out in 1993 and 1996 (Kuper, 1996). These studies focused largely on the archaeology of the site and its surroundings. In December 1996 an expedition by geographers, geologists and archaeologists from Helsinki University, Finland, the University of Georgia, USA. and Ain Shams University, Egypt, along with members of the Egyptian Geological Survey and Survey equipment, traveled southwards from Bahariya to investigate the cave and its sediments. This paper reports on the findings of this latest work at Djara Cave.

DJARA CAVE

Djara Cave is located on the Eocene plateau between the Farafra depression and the Nile Valley, west of the Ghard Abu Muharik linear dune complex (Fig.1). There are two geological formations in the region of the cave, namely the Minia and Naqb formations, of Late Early Eocene to Middle Eocene age. The Minia Formation is mainly carbonate of different structures and textures, thick-bedded, white, and alveolinid. Near the Ghard Abu Moharik and the cave site, the Naqb Formation grades into the lower part of the Minia Formation. The Naqb is divided into two: a lower member, which is composed of dark grey to pink, non-fossiliferous dolomitic and siliceous limestone, and an upper member that is composed of fossiliferous limestone beds with minor clay and conglomeratic intercalations. Both formations are highly fractured, mainly by N–S and NE–SW trending faults and joints, and to a lesser extent by fractures trending NW–SE.

There are two small entrances to the cave, both of which lie in the centre of a broad, shallow depression from which rise several small hills (Fig.2). A compass and tape survey of the cave in December 1996, shows a single large chamber approximately 19 x 10m, which is typically 6m high. The larger of the two entrances, which are within 5m of one another, leads to a steep slope initially on rock, and past a series of wall flowstones, stalactites and columns, to a steep sand slope, similar in shape to a talus cone (Fig.3). This leads to the floor of the large chamber that makes up the accessible part of the cave (Fig.4). The second entrance also leads to sand deposits and the route to the floor of the large chamber follows a stream drainageway incised about 1m into the sands. It appears that a major collapse of the roof produced the breakdown cone beneath the entrances and that this eventually led to the opening of the cave to the surface. Speleothems grew on the breakdown blocks and some blocks and speleothems were wholly or partially

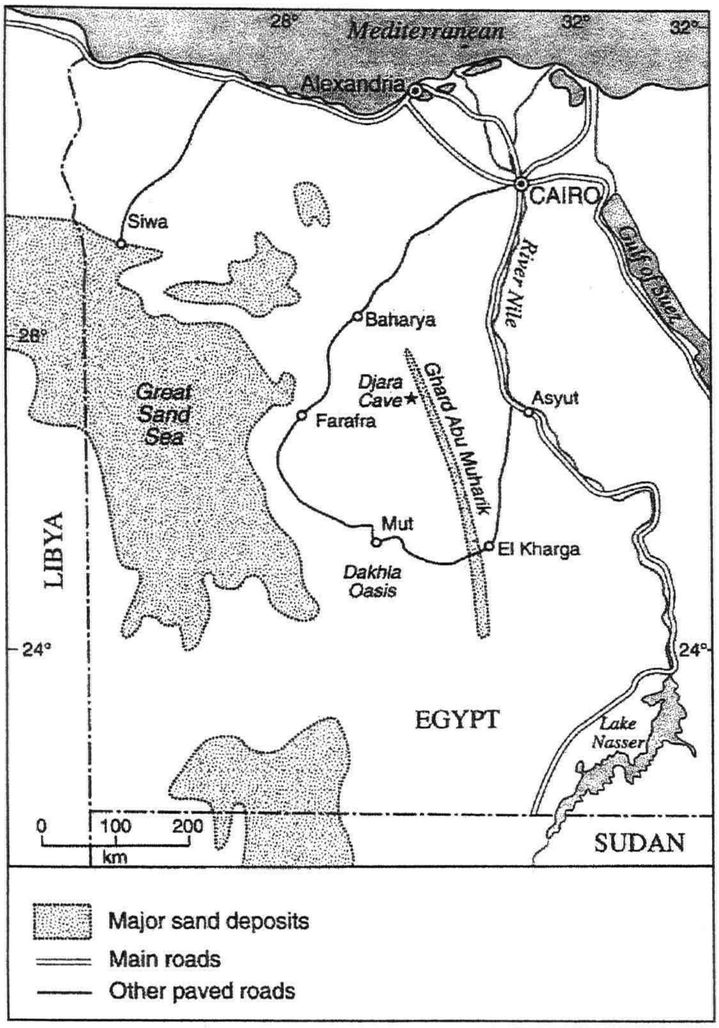

Figure 1. Location of Djara Cave in the Western Desert of Egypt.

buried by aeolian sand blown into the entrances. A striking characteristic of Djara Cave is its flat, sand-mantled floor, which, based on a ground-penetrating radar survey and coring by Kuper (1996), is a homogeneous deposit of sterile sand more than 6m deep in some places (Figs 3 and 4).

Significantly, Djara Cave contains numerous and sometimes large stalactites, columns, flowstones and sporadic stalagmites. These reach relatively large dimensions, being more than 1.5m in diameter in some cases and more than 6m high (Figs 4 and 5). Most are covered by a thin layer of dust, giving them a dull grey colour. However, a few are white and shiny and give the impression that they are relatively recent deposits. Helictites have grown from the ceiling and walls in several parts of the cave, and locally they are present as smaller deposits on larger stalactites and columns. Collapse blocks of limestone and broken formations are common near the two entrances, and may record the opening of the cave to the surface. Given the present rainfall of about 3mm/year, the large speleothems in the cave are clear evidence of past much wetter conditions in the area of the cave.

The present climate of this part of the Western Desert is hyper-arid. At Farafra, west of Djara Cave, rainfall from 1948–1982 totalled 4.0mm with rain in only 13 of the 35 years. At Bahariya to the north, rainfall totaled 4.3mm in the 30 years from 1931–1960, with rain in only 11 of these years. Mean annual temperatures at Farafra and Bahariya are 21.8 and 21.6°C, respectively. Mean maximum and mean minimum temperatures at Farafra are 30.2 and 29.6°C and at Bahariya they are 21.8 and 21.6°C (Egyptian Meteorological Authority, 1960).

At the time of the visit in 1996 the temperature at the back of the cave at 6:50 pm on December 1 was 23.8°C, and it was 15.5°C on the surface near the cave entrance at 6:56 pm. On December 2 the temperature was 6.3°C at the surface in the shade and by 9:00 am and 9:30 am it was 12.2 and 14.6°C respectively. By 10:05 am the temperature at the back of the cave was 22.9°C and this had risen to 23.4°C by 11:22 am. At 10:00 am it was noted that most of the cave floor was in daylight, suggesting that the heating effects of the sun may influence temperature variations in the cave for at least a short time each day. At 2:06 pm the surface temperature had risen to 23.1°C but by 3:05 pm, due to cloudy conditions, it had dropped slightly to 21.7°C. These data suggest that even in winter the cave temperature remains fairly constant at around 23°C, despite significant diurnal temperature variations at the surface. The cave temperature thus appears to stay very close to the mean annual temperature of the area (22°C at Farafra and Bahariya).

ARCHAEOLOGY

Scattered on the surface above the cave are numerous lithic artifacts and ostrich egg shell fragments particularly in an area 300x100m immediately north of the entrance. The entire area is widely deflated, but hearths are occasionally visible, as are areas where flint was worked intensively (Kuper, 1996). Kuper (1996) also reports undecorated ceramics, which strongly resemble the pottery from Fayum Neolithic settlements. In 1993 two small test pits were dug in the area, one immediately south of the cave entrance and the other about 100m farther south (Kuper, 1996). According to Kuper (1996) this latter site provided some radiocarbon ages around 7500 BP, whereas the oldest feature, a hearth, dated to 8600 BP. The excavation near the cave entrance measured 6x2m and uncovered two fireplaces extending about 20cm below the surface. Charcoal samples date the occupation to between 6800 to 6600 BP. The ages obtained place occupation in the Early and Middle Neolithic periods.

Donner *et al.* (1999) report ostrich egg shell ages from the surface above Djara Cave and from the nearby vicinity. In some cases the egg shell came from concentrations of fragments found together with artifacts. Three fragments from the limestone surface above the cave dated to 7410 ± 110, 7600 ± 100 and 7630 ± 110 BP; two fragments from a shallow stream channel nearby gave ages of 5450 ± 90 and 8730 ± 110 BP; and two samples from shallow playas not far from the cave dated to 7900 ± 110 and 9670 ± 110 BP. In addition, Kuper (1996) obtained ages on charcoal from excavations near Djara Cave ranging from 6500 to 8600 BP. Together, these data are evidence of wetter conditions in the vicinity of Djara Cave from about 11.4 to 6.4ka (9670 to 5450 BP). Also, Neolithic etchings on a carbonate column just inside the main entrance to Djara Cave, depict ostriches, Addax antelope and other bovids and goats (Kuper, 1996). As these animals are not present in the area today, because it is too dry, this is further evidence of increased wetness during the early to mid Holocene. The etchings are not covered by more recent secondary carbonate deposits indicating that there has been no flow of $CaCO_3$-saturated water over the column since the etchings were made in Neolithic times (Fig.6).

CLASTIC CAVE SEDIMENTS

At the entrances to the cave, in the upper metre or so of exposed limestone, a residual terra rossa soil is preserved in vertical joints widened by dissolution. This material is not forming under the present environmental conditions and was clearly produced under periods of past wetter climate. Terra rossa probably also mantled the surface near the cave at one time, but it has been deflated by the wind. This soil may give evidence about the origin of the cave and the wetter climate conditions that clearly produced it.

The dominant clastic sediment in the cave is aeolian sand in the entrance passages, and mantling the floor of the main chamber. This could only have entered the cave after it became open to the surface. Given the small size of the cave entrances, this may have been relatively recently. The sand in the cave has buried numerous stalagmites (Fig.7) that record several wetter periods in the past. Certainly, the rainfall of the area today is insufficient for significant speleothem formation.

Figure 2. The main entrance to Djara Cave showing sand accumulation in the entrance depression.

Despite the present meagre 3mm/yr rainfall, the aeolian sands in the cave show clear evidence of periodic reworking by water. Runoff into the cave has produced a 0.8m- to 1m-deep and 3.5m-wide channel in the bedded aeolian sands in the second entrance (Fig.3). This channel has exposed the upper 70cm of a stalagmite 28cm in diameter that had been buried by aeolian sand. The channel runs along the north wall of the cave to the southwest extremity, which is the lowest part of the main chamber. At the time of the visit in December, 1996, this and other low-lying areas of the cave floor were covered by up to 1.5cm of fine clay, obviously washed into the cave during floods. The clay had settled to the bottom of pools and as these dried out the clay contracted forming hexagonal mud curls up to 15cm in diameter. In the southwestern part of the cave there is a shallow scarp in the sands, marking the edge of the pool that formed here after the most recent rains. The depth of water in the pool could be gauged by clay and organic matter adhering to stalactites on the low ceiling of the cave at this point (Fig.8), which acted like dipsticks in the ponded water. It is estimated that the cave contained a pool 37cm deep at this point, and extending over an area of about $80m^2$. Given that the floor of the cave is mantled by up 6m of porous sand, this implies quite a substantial amount of water in the cave immediately after this major rainfall event. We also found animal faeces in the shallow stream channel near the north wall of the cave. Based on their size, these are probably from desert fox, and they suggest that animals entered the cave to drink from the pools created by the rare rains. It is highly likely that the extremely flat sand surface of the cave floor is due to periodic saturation of wind-deposited sands after rain. Periodic soaking of soft sands of uneven thickness would produce spatially-variable stresses that would result in an evening out of the surface creating the flat floor of the cave.

SPELEOTHEM AGES AND REGIONAL CONTEXT

In an attempt to determine when the climate of the Western Desert was wetter, samples of speleothem were collected from several locations for U-series dating. In addition, cores were drilled from four large speleothems in the hope of obtaining long, continuous records of past climates above the cave. Drilling was approximately horizontal into the formations producing radial cores of about 5cm diameter. A portable electric drilling rig powered by a generator provided by the Egyptian Geological Survey was used to obtain the cores. The steel drill stem, with its diamond-impregnated drill bit, was cooled and lubricated by water pumped along the drill stem using a garden pumping device. Water was obtained from a tank carried by a Geological Survey vehicle. Periodically during drilling the core broke, at which times drilling was halted and the broken segments of core were removed from the drill hole and the direction of drilling and the up direction were marked on each piece. Cores of 101, 47, 78 and 38cm were obtained from a stalagmite, wall flowstone, column, and second wall flowstone, respectively. Drilling penetrated all the way through the stalagmite and column giving information on diametrically opposite sides of these deposits, and penetrated to bedrock in the case of the wall flowstones.

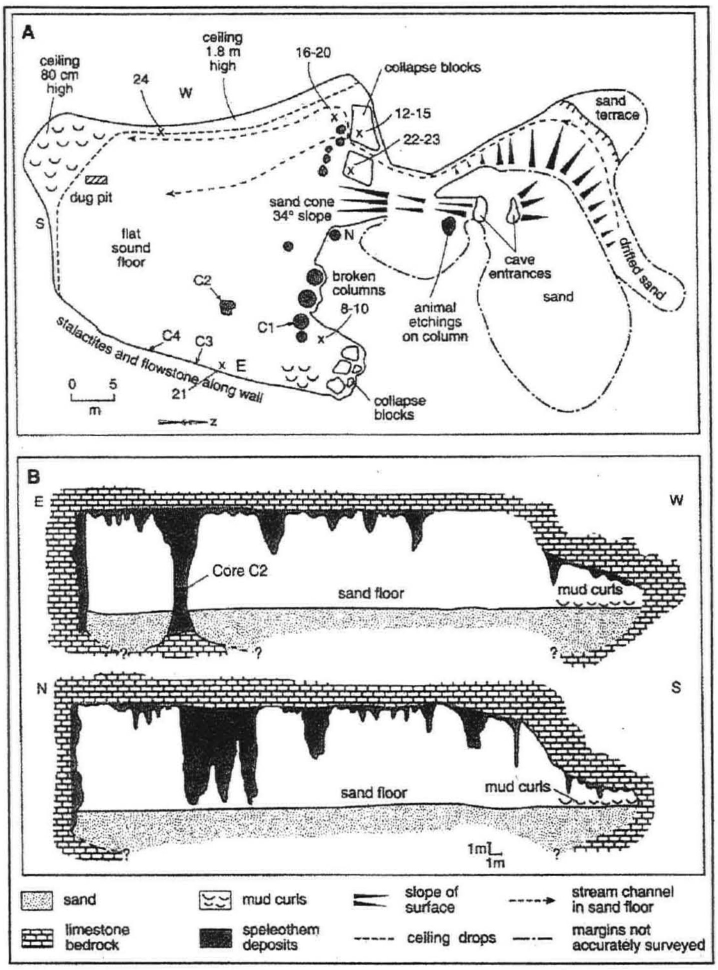

Figure 3. Plan and cross sections of Djara Cave showing speleothem sampling sites.

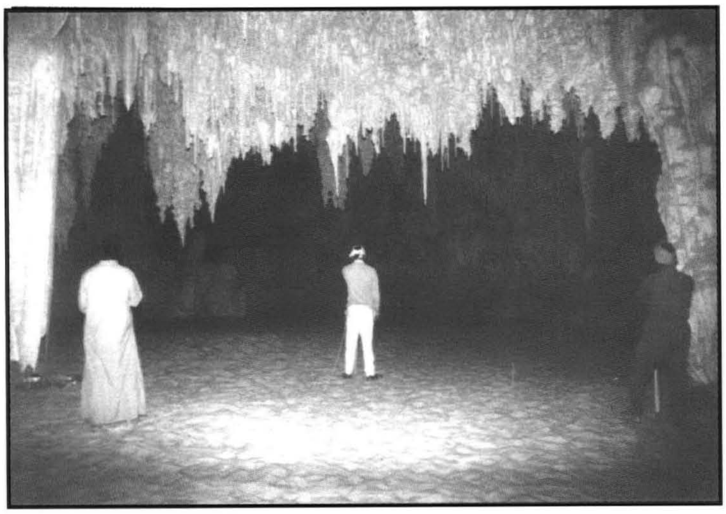

Figure 4. Large chamber with numerous stalactites in Djara Cave. Note the flat, sandy floor of the cave and that the base of the column in the right of the photograph is buried by this sand.

The bases of all four deposits are currently buried by the sand that forms the floor of the cave.

Twelve samples of about 20g were taken from the youngest parts of the three cores, and from other samples that were collected, for U-series dating by α-counting at Florida State University. In addition, nine samples (of 1 to 2g), were subjected to thermal ionization mass spectrometry (TIMS) or inductively coupled plasma mass spectrometry (ICPMS) U-series dating at the Minnesota Isotope Laboratory of the University of Minnesota. Samples of five speleothems were dated by both laboratories.

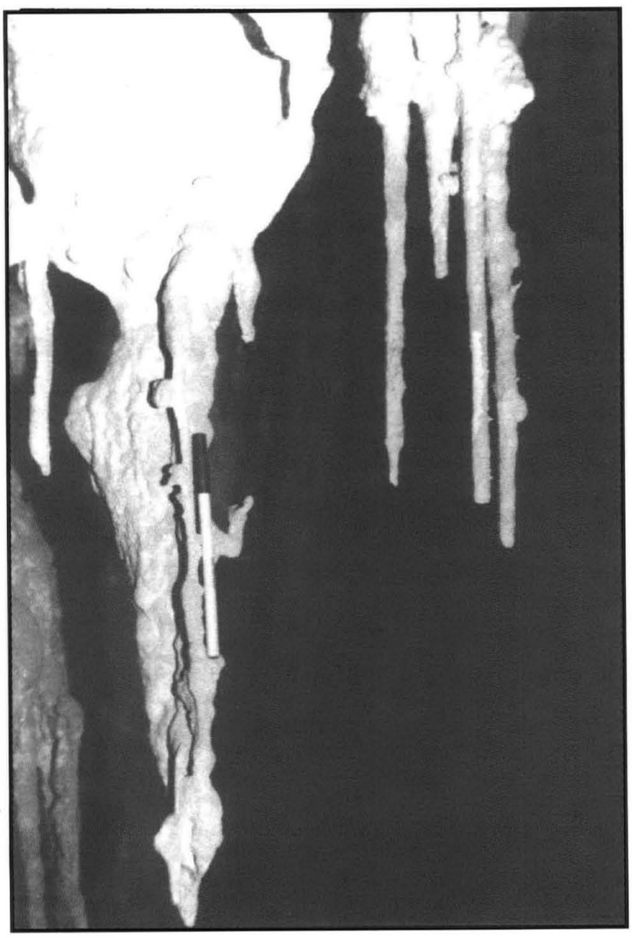

Figure 5. Stalactites and helictites in the main chamber of Djara Cave. Note the four straw stalactites in the right of the photograph.

Of the fifteen speleothems examined only four provided apparent finite ages of 140 ± 16, 201 ± 2 and 233 ± 24, 221 ± 34, and 283 ± 56ka (Table 1). Of the three samples dated by both TIMS and α-counting, only one produced apparent finite ages by both methods, namely EG96-25. The TIMS age of 201 ± 2ka for this sample is close to the 233 ± 24ka age determined by α-counting. In total, eleven samples were beyond the range of the dating methodologies (about 500ka) suggesting either that U has been leached from the speleothems, thus producing very old ages, or that the cave and the vast majority of its speleothems are extremely old.

Figure 9 summarizes U-series ages for cave speleothems and tufas in the Eastern and Western Deserts of Egypt, in northern Somalia, and in northern Oman. Rainfall in Egypt is affected by the African monsoon and in Oman and Somalia by the Indian monsoon. Past periods of significant speleothem and tufa growth in these areas are records of wetter climate conditions and stronger African and Indian monsoonal circulation. As northern Somalia is south of the other two areas, we might expect speleothems and tufas here to record modest increases in the northward penetration of the Indian monsoon and ITCZ, whereas speleothems and tufas in the other two areas will only record major increases in the penetration of the African and Indian monsoons, and the ITCZ.

Burns *et al.* (1998) have obtained 16 ages for a flowstone in Hoti Cave, northern Oman, and for older and younger stalagmites resting on it. These indicate wetter conditions due to greater southwest monsoon activity 125 to 120, 119 to 113, and 10 to 6ka. Speleothems from Haylaa and Gaalwyte Cave in northern Somalia, and tufas at Injeraley, Heneweine, and Hared, indicate greater summer monsoon rainfall in the Horn of Africa 260 to 250, 176 to 160, 116 to 113, 87 to 75, and 12 to 4ka (Brook *et al.,* 1997). At Kurkur Oasis in the Western Desert of Egypt, Crombie *et al.* (1997) report ages of 68 to 160ka for spring and lacustrine travertines exposed as 2m- to 3m-high terraces in Wadi Kurkur. However, they consider the two ages of 68 ± 2 and 160 ± 8ka to be unreliable, suggesting deposition of these particular travertines from 116 to 102ka. They also obtained ages of 191 to 220ka for spring mound travertines over fracture systems in ancient wadis, and ages of >260ka for paludal or lacustrine limestones on the surface above the Oasis. Sultan *et al.* (1997) provide 10 ages for tufa and cave deposits from the Kharga and Farafra depressions in the Western Desert of Egypt. These suggest deposition, and therefore wetter climates, at 338, 287 to 272, 255, 190 to 185, 157, and 45ka, assuming that none of the samples is re-crystallized. Eight stalagmites from Wadi Sannur Cave in the Eastern Desert of Egypt have been studied extensively by Dabous and Osmond (2000). Many samples were beyond the range of U-series dating and stratigraphical age reversals were common, indicating that there has been post-depositional leaching of uranium from the stalagmites or U migration within them. This would make some ages too young (where U had been added) but the majority too old (where U had been removed). Although apparent finite ages from Sannur Cave are included in Fig.9, for information, none is considered reliable.

Comparison of the age-frequency histogram in Fig.9 with the stacked and orbitally-tuned marine isotope record of Martinson *et al.* (1987) shows that many speleothems and tufas in Oman and Somalia were deposited during marine isotope stages 5 and 1, and that during Stage 5 deposition may have been greater in warm substages 5e, 5c and 5a. There also appears to have been significant travertine deposition at Kurkur Oasis in the Western Desert of Egypt during Stage 5, with 4 ages falling solidly in this period, and a fifth (68 ± 2ka) possibly indicating deposition during the later part of Substage 5a. At Djara Cave, one speleothem (140 ± 16ka) probably accumulated during Substage 5e. Apart from one age (45 ± 2ka) for a cave deposit from the Kharga Oasis (Sultan et al., 1997), there is no indication of tufa or speleothem deposition in the Western Desert of Egypt during marine isotope Stage 3, suggesting that this was a major dry interval. Three ages for Somalia speleothems (176 ± 27, 172 ± 24, and 160 ± 17ka), one for travertine at Kurkur Oasis (160 ± 8ka), and one for tufa in the Kharga Depression (157 ± 12ka), appear to date to Stage 6. Although

Figure 6. Etchings of animals on a column near the main entrance to Djara Cave. The etchings include ostrich and several species of antelope and are of possible Neolithic age. Note that flaking of the weathered surface of the speleothem has damaged some of the etchings, and that there is no evidence of carbonate deposition by running or trickling water on the etched surfaces. This suggests that there was no significant input of water to the speleothem after the etchings were created.

the error terms of two of these ages could place them at the very end of stage 7, the others appear firmly in Stage 6, suggesting a possible wetter period, perhaps during the Stage 6 interstadial from 180 to 160ka. In fact, the Nile Delta sapropel S6, which records increased rainfall in the Ethiopian Highlands, dates to about 176ka indicating that there was an interval of increased moisture during isotope Stage 6 (Rossignol-Strick, 1983). At Djara Cave, two speleothems appear to have been deposited during isotope Stage 7 (233 ± 24, 221 ± 34 and 201 ± 2ka), as were travertines at Kurkur Oasis (220 ± 25, 219 ± 13, and 191 ± 15ka) and possibly also tufas in the Kharga depression (190 ± 15 and 185 ± 15ka). One speleothem from Djara Cave, three speleothems from Somalia, and four tufas and one cave filling from the Western Desert, all appear to date to the glacial interval of isotope Stage 8 (Fig.9). However, error terms for the 9 ages average 44ka, and range from 27 to 67ka, making it difficult to know if deposition was during isotope stages 7, 8 or 9. Where ages are more reliable it appears that cave speleothem and tufa deposition was mainly during interglacial intervals (marine isotope stages 5 and 1), suggesting that older ages with large error terms may also record deposition during earlier interglacials.

U-series ages for lacustrine carbonates from Bir Tarfawi, Bir Sahara East, Wadi Hussein, Oyo Depression, and the Great Selima Sand Sheet indicate five palaeolake forming episodes at about 320 to 250, 240 to 190, 155 to 120, 90 to 65 and 10 to 5ka. This, and the absence of evidence for pluvial conditions between 60 to 30ka, has led Szabo *et al.* (1995) to suggest that past pluvial phases in North Africa correspond with interglacials (in this case isotope stages 9, 7, 5e, 5c or 5a, and 1). Szabo *et al.* also point out that the oldest lake- and groundwater-deposited carbonates are much more extensive than those of the younger period, suggesting that the earlier moist intervals were wetter than the later ones. Based on a variety of dating techniques (U-series, ESR, TL, OSL, amino acid epimerization), which did not always produce clear chronological records, Wendorf *et al.* (1993) suggest that permanent lakes existed at Bir Tarfawi and Bir Sahara East in southwestern Egypt during marine isotope stages 7 and 5, with individual lake stratigraphical units during stage 5 dating to the warmer sub-stages 5e, 5c and 5a. They believe that isotope stages 6 and 4/3 were hyper-arid in this area despite, some ages for lake deposits that fell into these time intervals. They also point out that the occurrence of permanent Holocene lakes in northern Sudan and their absence from southern Egypt indicate a rapid decline in rainfall north of 21°N suggesting a weaker monsoon during the Holocene than during the peaks of isotope stages 7 and 5.

Variability in monsoonal circulation over the last 464ka shows that the warm peaks of interglacials produced rich sapropel layers in the Nile Delta, indicating enhanced tropical rains over Ethiopia and East Africa (Rossignol-Strick, 1983). Petit-Maire (1994) has summarized the variability of the African monsoon over the last 130ka. She points out that marine isotope stage 3 is marked in Arabia by evidence of wet phases around 45ka and from 30 to 21ka, and then later by increased humidity from 9 to 6ka. In the Saharo-Sahelian belt isotope Stage 5 was humid, as indicated by the Shati palaeolake of central Libya at 27°N, which was 2,000 km^2 in area, and deepest at 130 to 125, 92, 89 and 77ka, and by a deep permanent lake in the Sbeita depression of northern Mali at 23°N from 133 to 123ka. From 70 to 45ka (isotope Stage 4) there is no evidence of humid conditions, but two humid periods characterize stage 3 at 46 to 40ka and 35 to 21ka. Petit-Maire notes that the development of this last episode matches the existence of the Aterian civilization (Tillet, 1989), human presence being unlikely without availability of surface water, vegetal food, and game. During the Holocene the Eastern Sahara remained a little drier than the Western Sahara, as it is today, but the entire region experienced generally wetter conditions from 10 to 4ka, peaking in wetness between 8.5 to 7ka. Petit-Maire's summary agrees well with the data in Fig.9. However, despite the widespread evidence for humid conditions during the Holocene, there is no evidence of cave speleothem or extensive tufa deposition in Egypt at this time. This suggests that conditions were not as wet during the Holocene as during earlier interglacials.

$\delta^{13}C$ AND $\delta^{18}O$ OF SPELEOTHEM CARBONATE AND COMPARISON WITH OTHER RECORDS

The mean $\delta^{13}C$ of 18 samples of 10 to 15 mg from Djara Cave speleothems is -3.8‰ PDB (σ = 3.11) and the mean $\delta^{18}O$ is -12.1‰ PDB (σ = 0.92)(Table 2). $\delta^{13}C$ ranged from -9.3 to 1.9‰ and $\delta^{18}O$ from -14.2 to -10.4‰ (Fig.10). In every sample the carbonate was highly depleted in ^{18}O suggesting a distant source for the waters that percolated through the roof of the cave and precipitated the speleothems.

Based on arguments presented in Brook (1999), under a C_3 biomass (soil $CO_2 \delta^{13}C$ = -22‰) the first speleothem calcite deposited in isotopic equilibrium from seepage waters is likely to have a $\delta^{13}C$ ranging from -12 to -9 ‰ PDB, depending on whether open or closed system conditions prevailed (with higher values being for more closed system conditions). By contrast, beneath a C_4 biomass (soil CO_2 $\delta^{13}C$ = -8.5‰), the first calcite deposited is likely to have a $\delta^{13}C$ in the range -2.3 to +1.5‰, again with higher values being for more closed system conditions. Under a C_3 or a C_4 cover, if there is significant degassing of CO_2 before water enters the bedrock isotopic values may be higher than those listed. Significantly, 9 of the 18 samples from Djara Cave have a $\delta^{13}C$ of less than -5.4 ‰, with the lightest sample having a value of -9.3‰ (Fig.10). This clearly suggests that the vegetation above the cave had a significant C_3 component when many of the speleothems were deposited, indicating a substantially moister environment than the hyper-arid environment of today with an almost total absence of vegetation.

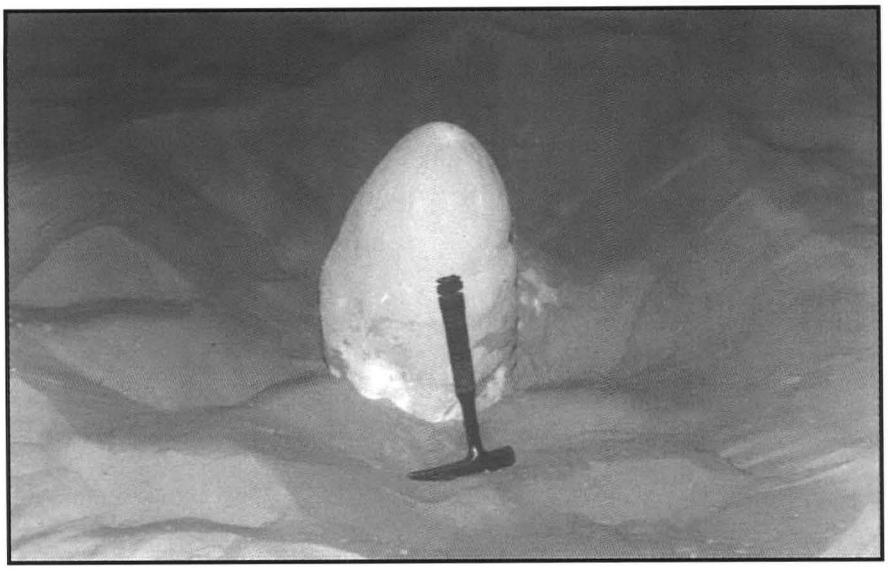

Figure 7. Large, buried stalagmite at the base of the sand cone leading from the main entrance into Djara Cave.

Studies of stable oxygen isotopes in secondary carbonates have been undertaken in Oman, Israel, Sudan and in Egypt. These serve for comparison with the Djara Cave results and help to determine the source of the water that produced the speleothems at Djara Cave and other secondary carbonates in the Western Desert. In Egypt, Sultan *et al.* (1997) report twelve $\delta^{18}O$ measurements on tufa and cave fillings from the Kharga and Farafra oases, which average -9.6 ‰ PDB and range from -13.3‰ to -4.8‰. Crombie *et al.* (1997) report an average $\delta^{18}O$ of -11.9‰ PDB for 14 travertine samples from the Kurkur Oasis, and a narrow range of -13.7 to -9.1‰. Average $\delta^{18}O$ in 103 samples of lacustrine carbonate from Bir Tarfawi and Bir Sahara East in southwestern Egypt, deposited 140 to130ka, is -6.60‰ PDB, with values ranging from -10.3 to -0.98‰ (McKenzie, 1993). Early to mid Holocene lacustrine carbonates from sites in northwestern Sudan show highly depleted ^{18}O of between -5.1 to -13.5‰ PDB. Increases in Mg/Ca and Sr/Ca mole ratios, as well as in $\delta^{18}O$, reveal a gradient of increasing humidity from north to south suggesting rainfall coming from the south (Abell *et al.*, 1996; Pachur and Hoelzmann, 2000). In all studies the $\delta^{18}O$ values are generally comparable with those quoted above for Djara Cave, and provide clear evidence that throughout the region speleothems, tufas and lacustrine carbonates of Holocene or greater age were precipitated by isotopically light meteoric water relative to present water in the region.

Crombie *et al.* (1997) note that today waters in Egypt fall into three distinct isotopic categories: modern meteoric water ($\delta^{18}O$ = -2.09 to + 3.9‰ SMOW), shallow, relatively young groundwater (< 20ka: $\delta^{18}O$ = -9 to -6‰ SMOW), and deep, old groundwater in the Nubian aquifer (> 20ka: $\delta^{18}O$ = -11.5 to -10.5‰ SMOW). By calculating deposition temperatures for the Kurkur travertines using each of these water types, Crombie *et al.* (1997) demonstrate that modern meteoric waters could not have produced them, and that they were most likely deposited by waters similar to the deep, old Nubian aquifer groundwater.

As the Djara Cave speleothems are clearly of at least last interglacial age, it is possible that they were deposited by meteoric waters with similar isotopic characteristics to the old groundwater of the Nubian aquifer. In such a situation cave dripwaters would have had δD = ~ -81.5‰ SMOW (Fig.2 of Sonntag *et al.*, 1978) and $\delta^{18}O$ = -10.8‰ SMOW (assuming the meteoric water line for the very old fossil groundwaters of North Africa was $\delta D = 8\ \delta^{18}O + 5$). If the spleleothems in Djara Cave were deposited in isotopic equilibrium with the precipitating waters, as seems likely given that the cave was closed to the surface when deposition occurred, then we can estimate the temperature of calcite deposition using the equation of O'Neil *et al.* (1969):

$$t = 16.9 - 4.38(\delta^{18}O_c - \delta^{18}O_w) + 0.1(\delta^{18}O_c - \delta^{18}O_w)^2$$

where t is temperature in °C and $\delta^{18}O_c$ and $\delta^{18}O_w$ are the oxygen isotopic characteristics of the speleothem and the water with respect to PDB and SMOW, respectively. The mean of 18 samples of speleothem from Djara is -12.1‰ PDB and this gives an estimated temperature in the cave at the time of speleothem deposition of 23.1°C. This temperature is 1°C higher than the mean annual temperature at Farafra and Bahariya today, and the same temperature that was measured during the visit to the cave in early December (noting that today the cave is open to the surface). The $\delta^{18}O$ values of the four dated speleothems (Table 2) suggest cave temperatures of 32.8°C at 140 ± 16ka, 19.4°C at 201 ± 2/233 ± 24ka, 25.8°C at 221 ± 34ka, and 27.1°C at 283 ± 56ka. The average estimated temperature for the two speleothems possibly deposited during marine isotope stage 7 (with ages of 201 ± 2/233 ± 24ka and 221 ± 34ka), using an average $\delta^{18}O$ of -12.05‰ PDB, is 22.5°C. As cave temperatures closely approximate mean annual temperatures at the ground surface, these calculations of cave temperatures at the time of speleothem deposition suggest strongly that deposition took place under conditions similar to, or warmer than, today. This implies deposition, and so wet climatic conditions, during past warm interglacials not during colder glacial intervals.

All of the temperature estimates above suppose that the speleothem-precipitating waters at Djara Cave were similar to the present ancient Nubian aquifer groundwaters, with an average $\delta^{18}O$ of -10.8‰ SMOW. However, if evaporation affected water percolating into Djara Cave more than the water recharging the Nubian aquifer, then the cave dripwaters may have been slightly enriched in ^{18}O compared to the ancient Nubian aquifer waters, although this appears unlikely. If the dripwaters were enriched by say 1.0‰ SMOW, that is $\delta^{18}O$ was -9.8‰ SMOW rather than -10.8‰ SMOW, then the estimated temperatures of deposition would be higher than those shown above. For example, for a spleothem $\delta^{18}O$ of -12.1‰ PDB and a water $\delta^{18}O$ of -9.8‰ SMOW the estimated temperature for carbonate deposition is 27.5°C, which is 4.4°C higher than for a water $\delta^{18}O$ of -10.8‰ SMOW. So, if evaporation did enrich the Djara dripwaters in ^{18}O temperatures in the area were even higher than those estimated above.

If the Djara Cave speleothems were deposited by isotopically-light waters similar to the ancient groundwater of the Nubian aquifer, where did this water originate? Sonntag *et al.* (1978) have documented a marked west to east depletion in deuterium in the fossil groundwaters of the northern Sahara, including the Nubian aquifer, with values ranging from -20‰ SMOW in Western Sahara and Mauritania to -83‰ SMOW in the Western Desert of Egypt. As this W–E depletion in δD closely parallels present groundwater characteristics in Western Europe, Sonntag *et al.* (1978) argue that the northern Sahara groundwaters originated from Atlantic airmasses transported eastwards across north Africa by a palaeo-westerly circulation that pushed south of its present limit. They also argue that this winter precipitation occurred during the last ice age and that the lower deuterium excess (where excess d = $\delta D - 8\delta^{18}O$) is due to a lower moisture deficit of the air over the colder ocean.

Other researchers have explored the possibility that the W–E depletion in δD and $\delta^{18}O$ is due to a stronger African summer monsoon. In fact, the GCM model of Prell and Kutzbach (1987), for July 126ka (when northern hemisphere insolation was 12% higher than now) produced intensified monsoonal circulation and an increase in SW wind speed over North Africa, bringing more moisture from the Atlantic Ocean and increasing precipitation over the Eastern Sahara. Crombie *et al.* (1997) infer that this intensified summer monsoonal circulation, with the ITCZ farther north than today, or during the early to mid Holocene, explains the W–E trend in ancient northern Sahara groundwater. Others are somewhat sceptical of this interpretation. For example, McKenzie (1993) argues that based on mean annual $\delta^{18}O$ for precipitation across North Africa (Yurtsever and Gat, 1981), simply shifting the current regional pattern of air masses northwards would not bring the required isotopically light rainfall to theWestern Desert. In fact, Joseph *et al.* (1992) have shown that modern rainfall and groundwater in the Sahelo-Sudanese zone becomes more depleted in ^{18}O from east to west due to transport of Indian Ocean water vapour by the East African and Tropical Easterly Jets and Easterly Waves. Even in the early to mid Holocene, lacustrine carbonates in northwestern Sudan, with $\delta^{18}O$ as low as -13.5‰, were derived from rainfall coming from the south. This isotopically depleted rainfall is believed to have originated as convective precipitation when exceptional events produced high altitude thunderheads along squall lines (Abell *et al.*, 1996).

There can be little doubt that the isotopically depleted, ancient north Sahara groundwater originated by progressive condensation of water vapor from palaeo-westerly wet Atlantic air masses that traveled eastwards across North Africa. However, it is still not clear if this flow resulted from a strengthened African monsoon circulation during the last interglacial, as suggested by Crombie *et al.* (1997), or if it resulted from the more southerly position of the belt of westerly circulation during a glacial, as postulated by Sonntag *et al.* (1978). One possibility is that the rainfall occurred at a time when the African monsoon was stronger and at the same time the belt of westerlies was south of its present position. This could have occurred during isotope substage 5e, when summer insolation in the northern hemisphere was 12% above the present value and when winter insolation was 12% below it. The significantly warmer summers would increase monsoonal activity and the colder winters might push the belt of westerlies south of its present location. Under such a scenario northern Africa would receive both summer and winter rainfall, which might explain the existence of permanent lakes at this time.

^{18}O-depleted speleothem carbonate of marine isotope Stage 5 age is also reported from Oman and Israel. At Hoti Cave in northern Oman, a flowstone (125 to 120ka) and the upper 84cm of a stalagmite resting on it (119 to 113ka) have $\delta^{18}O$ in the range -12 to -6‰ PDB (Burns *et al.*, 1998). $\delta^{18}O$ is significantly lower in these deposits than in a stalagmite deposited from 9.7 to 6.2ka (-4 to -6‰ PDB) or in modern stalagmites in the cave (-0.9 to -3.3‰ PDB). Burns *et al.* (1998) note that in areas receiving heavy, tropical rainfall, particularly in association with passage of the ITCZ, the $\delta^{18}O$ of rainfall is negatively correlated with rainfall amount (Dansgaard, 1964; Matsui *et al.*, 1983; Rozanski *et al.*, 1993, Gat, 1996). Bar-Matthews *et al.* (1997) have made the same observation about $\delta^{18}O$ of recent rainfall southwest of Jerusalem in Israel, which decreases as annual rainfall increases. On the basis of a rainfall amount–$\delta^{18}O$ correlation, Burns *et al.* (1998) argue that the ^{18}O-depleted Stage 5 deposits at Hoti Cave indicate a very heavy monsoon-type rainfall from 125 to 113ka, and the Holocene deposits a heavier rainfall than now, but with rains less intense than during marine isotope Stage 5. They suggest that periods of increased wetness in southern Arabia during the last 125ka were most likely caused by a northward shift of the convergence between northwesterly and southwesterly winds along the ITCZ during the Indian summer monsoon. At Jerusalem West Cave, in Jerusalem, Israel, the $\delta^{18}O$ of a stalagmite increased from -9 to -7‰ PDB from 135 to 115ka (Frumkin *et al.*, 1999). By contrast, from about 12 to 4ka $\delta^{18}O$ varied from about -7.4 to -5.5‰ PDB, and in modern calcite it is -5‰ PDB. Frumkin *et al.* (1999) argue that throughout the late Quaternary the most probable source of precipitation at the cave was the eastern Mediterranean.

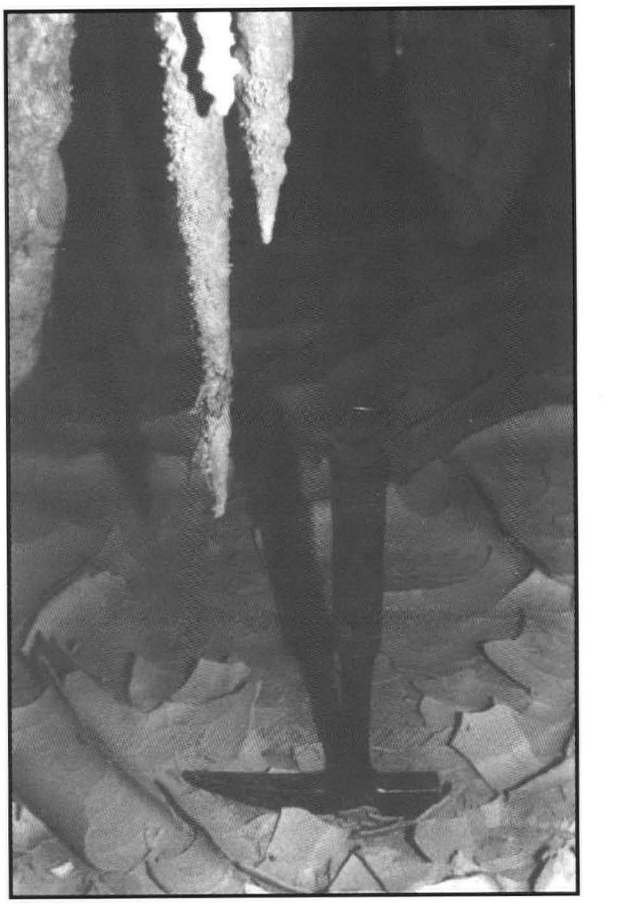

Figure 8. Mud curls in the lowest, southwestern part of Djara Cave. The mud is evidence of standing water in the cave at some time in the past. Organic debris clinging to the stalactite immediately left of the hammer handle is an indication of the depth of standing water after the most recent significant rains.

The above discussion shows clearly that cave speleothems deposited during marine isotope Stage 5, or earlier, are all depleted in ^{18}O relative to Holocene deposits, which are in turn depleted relative to modern calcite. High temperatures during isotope Stage 5, and to a lesser extent during the early Holocene, could be one explanation for this. However, two other factors may have had a greater influence on $\delta^{18}O$ values. The first is that rainfall amounts and intensities were probably much greater during the earlier period, leading to ^{18}O-depleted rainfall. The second is that during isotope Stage 5 distance from moisture source was apparently much greater than now or during the early Holocene. This may have been especially influential in the case of Egypt, where air masses may have crossed North Africa from west to east before depositing rainfall on the Western Desert.

DISCUSSION

Decorated caves are extremely rare in Egypt, despite much of the country being underlain by soluble carbonate rocks. Where large speleothems are present they record times of more humid conditions when the deserts of Egypt were very different from today. Djara Cave has provided some evidence about past climates in the Western Desert. The cave is clearly very old given that many of its large speleothems are beyond the range of U-series dating, which is about 500ka. The cave was formed by preferential dissolution by shallow groundwater at the intersection of major fractures in the limestone, and it enlarged along

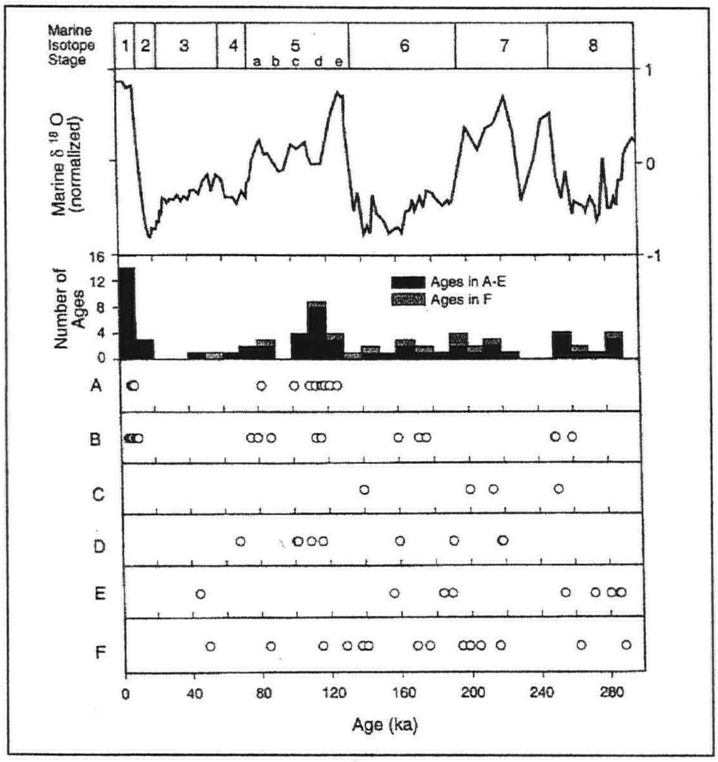

Figure 9. Speleothem and tufa ages for Egypt, Somalia and Oman compared with the orbitally tuned marine isotope record. A: Hoti Cave speleothems, Oman (Burns et al., 1998), B: northern Somalia speleothems and tufas (Brook et al., 1997), C: Djara Cave speleothems (this study), D: Kurkur Oasis travertines (Crombie et al., 1997), E: Western Desert speleothems and tufas (Sultan et al., 1997), F: Wadi Sannur Cave speleothems (Dabous and Osmond, 2000). The age-frequency histogram includes all ages shown in A-F. The marine isotope record is after Martinson et al. (1987).

prominent bedding planes. There was never a widespread groundwater body in the limestone but rather localized "pockets" of groundwater in cavities created by dissolution along major fractures and at fracture intersections. The cave remained closed to the surface for a considerable time and was probably filled with water after rain. During dry intervals the water level may have dropped so that the upper part of the cave may have filled with air. As a result, the cave is dominated by phreatic dissolution features that record the periods of complete flooding. Over time, the main chamber became more and more extensive, making the ceiling unstable and ultimately leading to collapse along dissolutionally-enlarged bedding planes. Certainly, there was a major collapse of the ceiling in the region of the present entrances to the cave, with the formation of a breakdown pile. However, this collapse did not initially open the cave to the surface. Over time the cave became more or less permanently air filled either because the groundwater was able to move deeper into the limestone as fractures were widened by dissolution, or, more likely, because the climate became more arid, reducing recharge to the limestone aquifer. After this, speleothems formed in the air-filled chambers during more humid phases of climate, as $CaCO_3$-charged water entered the cave. Deposits were laid down on the breakdown pile beneath the present entrance to the cave. After extreme rainfall events there can be no doubt that the cave contained standing water that submerged and partially re-dissolved some deposits of secondary carbonate. Eventually, further collapse of the roof opened the cave to the surface, allowing input of aeolian sand during arid intervals. This sand mantled the floor of the cave, burying collapse blocks and any stalagmites growing on them. Rare storms channeled water into the cave, saturating and leveling the sands of the cave floor.

The sands forming the floor of Djara Cave are probably, on average, 6m deep, and when saturated contain 25% water. This means that after the last extreme rain event, which ponded water in the cave, there must have been about 8500m^3 (8,500,000 litres) of water in the main chamber of the cave. At atmospheric CO_2 levels (i.e. assuming no enrichment by soil CO_2) this water could dissolve about 65mg/l or a

Sample ID	^{230}Th Age (ka) (corrected)*
1) Alpha-counting**	
EG96-C1A	221 ± 34.5
EG96-16	140 ± 15.9
EG96-18	283 ± 56
EG96-25	233 ± 24
2) TIMS***	
EG96-25	201,050 ± 2100

Table 1. Uranium-series ages of Djara Cave speleothems

* *Corrected ^{230}Th ages assume an initial ^{230}Th/^{232}Th atomic ratio of 4.4 ± 2.2 x 10^{-6}. This is the value for a material at secular equilibrium with the crustal value of 3.8. Errors are arbitrarily assumed to be 50%.*
** *Samples EG96-C3A; EG96-8; EG96-9; EG96-10; EG96-12; EG96-13; EG96-21; EG96-27were also examined but were beyond the range of α-counting (about 350 ka).*
*** *Samples EG96-C1A, EG96-C3A, EG96-14-1, EG96-14-2, EG96-16, EG96-21, EG96-21, EG96-22-2, EG96-23 were also examined but were beyond the range of TIMS (about 500 ka).*

total of 552,500g of calcium carbonate. If the average density of the limestone in the area is 2.6g/cc, this translates into 212,500cc of rock or 0.2m^3 of limestone dissolved during this single rainfall event. It is likely that some of this dissolution occurred at the surface before the waters entered the cave, and so a reasonable estimate of dissolution in the cave itself may be half of this amount or 0.1m^3 of limestone for the one storm. As the volume of the main chamber of the cave is about 1000m3, it would require 10,000 storms of the magnitude discussed to dissolve out a chamber of this size from the bedrock. Under the present climate the storm that caused the latest flooding of the cave probably has a recurrence interval of at least 50 years, suggesting a minimum time of 500ka to form this cave under present climatic conditions. As we have seen, speleothem ages indicate that the cave is considerably older than 500ka. The importance of the above calculation is that it suggests that the cave could have formed even under present conditions over a very long period of time. Increased rainfall, with soil development at the surface, and a denser vegetation cover, would have increased CO_2 in ground waters and would have speeded up the dissolution process allowing the cave to form more quickly. We know from the speleothem evidence that the cave was air filled prior to 500ka. If it took at least 500ka to create the dissolution cavity in which the speleothems were deposited then we have to assume that the cave itself began to form more than one million years ago.

U-series ages for four speleothems in Djara Cave (140 ± 16, 201 ± 2/233 ± 24, 221 ± 34, and 283 ± 56ka) suggest deposition during marine isotope stages 5 and 7 and possibly also during Stage 9. Despite comprehensive sampling of the carbonate deposits, none appears to be of early to mid Holocene age, even though there is archaeological evidence both in the cave (rock art) and on the ground surface above it (stone artifacts, ostrich eggshell, charcoal) of visitation by ancient peoples, and of a more humid climate at this time. Kuper (1996) obtained ages on charcoal from excavations of surface sites near Djara Cave ranging from 10.1 to 7.6ka (8600 to 6500 BP), while Donner *et al.* (1999) report ostrich egg shell ages from 11.4 to 6.4ka (9670 to 5450 BP). Also, possible Neolithic-age etchings on a carbonate column just inside the main entrance to Djara Cave, depict ostriches, Addax antelope, and other bovids and goats (Kuper, 1996). As these animals are not present in the area today because it is too dry, this may be further evidence of increased wetness during the early to mid Holocene. There is thorough documentation of increased wetness in the Western Desert during the early to mid Holocene (for summary see Embabi, 1999) but clearly the increased rainfall was not enough to deposit speleothems at Djara Cave and not as much as during previous interglacials when speleothems were deposited. The implication is that although the Holocene was substantially wetter than now it was not as wet as during, for example, marine isotope stages 5 and 7.

$\delta^{18}O$ of speleothem carbonate in Djara Cave averages -12.1‰ PDB indicating deposition by meteoric waters significantly depleted in ^{18}O. A deposition temperature of close to 23°C, only 1°C above the present mean annual temperature in the area, is indicated. In Israel and Oman, recently deposited speleothem carbonate is less depleted in ^{18}O than that deposited during the early and mid Holocene, and this in turn is less depleted than carbonate deposited during isotope Stage 5. Bar-Matthews *et al.* (1997) have shown that the $\delta^{18}O$ of water entering Soreq Cave, southwest of Jerusalem, Israel, increases with decreasing annual rainfall, implying that ^{18}O-depleted speleothem carbonate is an indication of increased annual rainfall and rainfall intensity. If this relationship also holds for the past, then in Israel and Oman the early to mid Holocene were wetter than now, and marine isotope Stage 5 was wetter still (Burns *et al.*, 1998; Frumkin *et al.*, 1999). At Djara Cave, the absence of speleothem deposits of Holocene age supports a similar conclusion. The ^{18}O-depleted waters from which the Djara speleothems were deposited appear to have originated in air masses that crossed North Africa from west to east at a time when westerly circulation was south of its present position, and when the African monsoon was stronger than now. At this time the Western Desert may have received rainfall in winter from the westerlies and monsoon rainfall in summer. Given the nature of ancient groundwater in the northern Sahara, the winter rains were responsible for most of the groundwater recharge. Despite the possibility of rainfall all year, the $\delta^{13}C$ of the Djara Cave speleothems suggests that the vegetation near the cave was composed predominantly of C_4 plants indicating that sub-arid or semi-arid conditions prevailed even when it was "wet".

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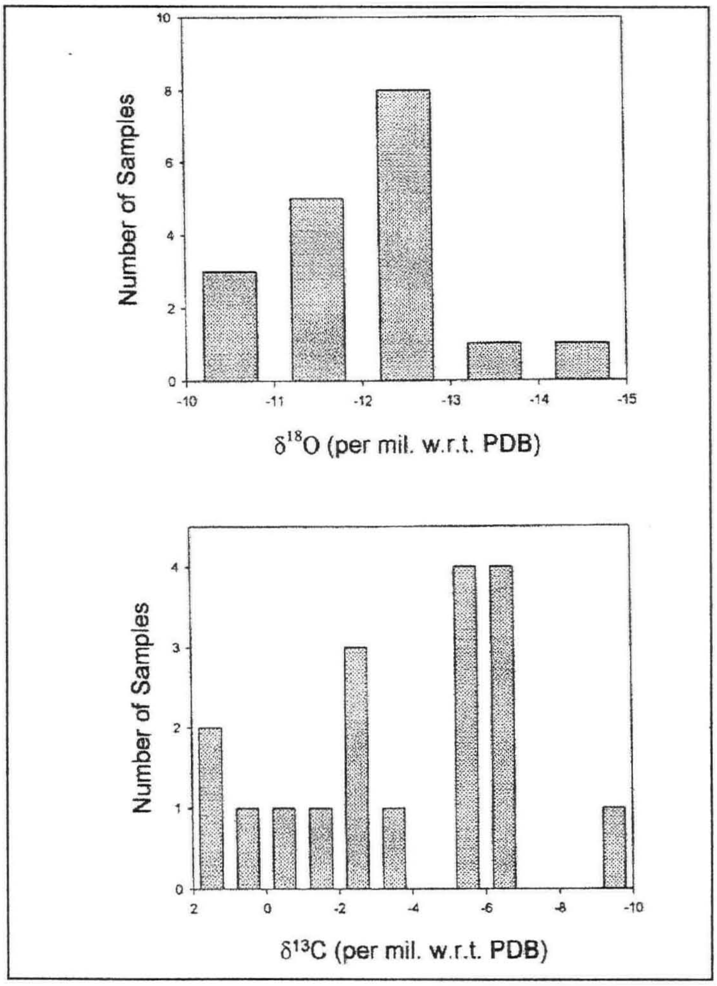

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Sample ID	Comments	$\delta^{13}C$ (‰ w.r.t. PDB)	$\delta^{18}O$ (‰ w.r.t. PDB)
EG96-C1A	Youngest part of core from broken column (age: 221 ± 34 ka)	-5.73	-12.74
EG96-C3A	Youngest part of core from wall flowstone	-6.32	-12.45
EG96-8	Flowstone curtain	1.86	-11.82
EG96-9	Small stalactite	-6.84	-12.7
EG96-10	Broken column.	-5.39	-12.77
EG96-12	Small stalactite	-6.61	-12.81
EG96-13	Flowstone curtain	-0.97	-12.27
EG96-14	Small stalagmite	-1.45	-10.87
EG96-15	Small stalagmite	1.5	-10.44
EG96-16	Stalactite on flowstone curtain (age: 140 ± 16 ka)	-6.07	-14.17
EG96-18	Flowstone curtain (age: 283 ± 56 ka)	-5.79	-13.01
EG96-21	Small stalactite	-5.39	-12.03
EG96-22	Oldest part of vertical stalactite on underside of fallen block that formed after block collapse	-2.86	-11.75
EG96-22-1	Youngest part of EG96-22	-2.37	-11.96
EG96-23	Tilted stalactite on underside of collapse block, so older than EG96-22and older than block collapse	-9.34	-12.22
EG96-24	Small stalactite	-3.38	-10.59
EG96-25	Small stalactite (two ages: 233 ± 24 and 201 ± 2 ka)	-2.6	-11.36
EG96-27	Small stalactite on flowstone curtain	0.04	-11.68
Mean (n = 18)		-3.76	-12.09
Standard deviation (σ)		3.11	0.92

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Investigating Peak Cavern, Castleton, Derbyshire, UK: integrating cave survey, geophysics, geology and archaeology to create a 3D digital CAD model.

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Abstract: Non-destructive geophysical imaging techniques have been applied to the sedimentary deposits within reputedly the largest cave entrance chamber in Western Europe. The Vestibule of Peak Cavern is thought to have been the site of human habitation since the Late Palaeolithic. However, the depth to the cave floor, the sedimentology and the archaeology of the cave fill were all uncertain. Ground Penetrating Radar (GPR) is shown to produce good quality images of dry cave deposits and underlying limestone cave floors. The GPR images show the sedimentological and archaeological distribution of the cave-fill, identify buried 'houses' and allow the mostly buried cave floor to be mapped. GPR and ground resistivity images combined with a Total Station survey of cave topography in a 3D Computer Aided Design (CAD) model. By combining the several independent lines of evidence within the model, the cave floor can be mapped. Further analysis of the CAD model has been used to address geological, speleological and archaeological issues. A follow-up data acquisition program could now be designed to improve the extent and quality of the GPR imagery in order to answer specific questions. Based upon this investigation and recent literature, the oldest deposits, within the Vestibule cave fill, are predicted to be located at the highest level. A 3D-GPR survey is recommended to define the stratigraphy of any lateral accretion surfaces within the cave fill and the effects of human activity in partially remodelling them.

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INTRODUCTION

The early Carboniferous Castleton Reef in Derbyshire, UK (Fig.1a) hosts an extensive network of linked cave systems, which the Technical Speleological Group has surveyed and continues to explore (Fig.1b). Peak Cavern is one of several access points near Castleton. The Peak Cavern entrance (or 'Vestibule') is unusually large, with considerable cave fill – the depth, sedimentology and archaeology of which were uncertain.

Ford (1999) recommended further investigation of the Vestibule, as it may have been a site of human habitation since the Late Palaeolithic. The Vestibule was first recorded in the Doomsday Book (Hancock, 1999), and there is evidence of rope making at Peak Cavern for the past four or five hundred years, on benches sculpted from the cave earth deposits (Fig.2). The present day Vestibule area has six terrace benches (Fig.3), upon which rope-making equipment is preserved for tour parties. There is also an ephemeral riverbed, which exposes the bedrock (Fig.3). Several 'houses', built or tunnelled into the terraces (Fig.4), and were once occupied by the rope makers.

In a larger context, Peak Cavern and several nearby show caves are formed within fore-reef facies, dipping at about 30° towards the north or northeast (Ford, 1999; Fig.1). To the south of the fore-reef facies are the sub-horizontal Carboniferous limestones of the Derbyshire White Peak area, which host lead-zinc-fluorspar mineralization and residual bituminous hydrocarbons. The reef is an exhumed fossil oilfield, suitable for petroleum reservoir outcrop analogue studies. To the north of the fore-reef facies, the anoxic, distal turbidite Edale Shale Formation

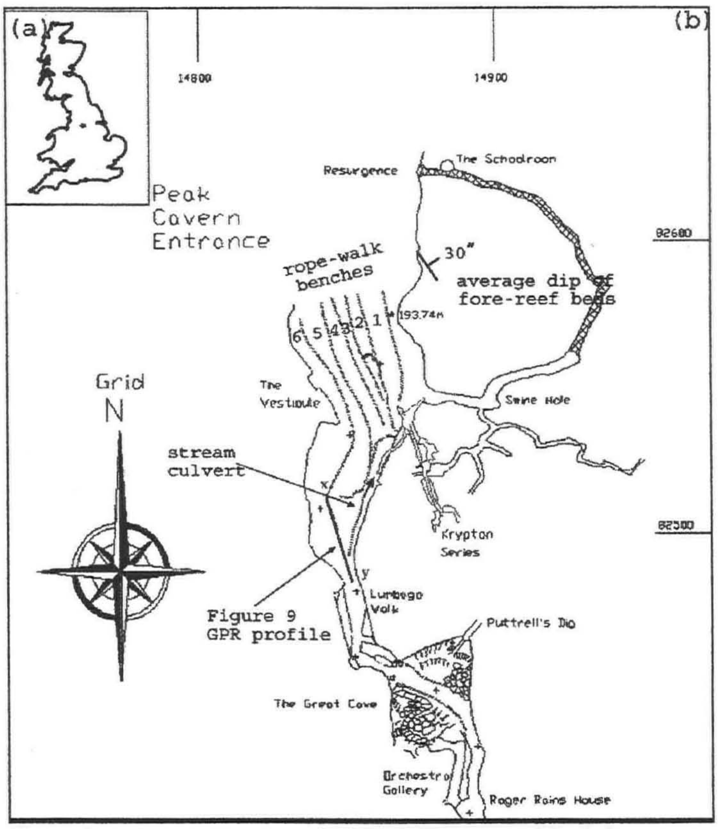


Figure 1. (a) Location map and (b) annotated segment of Peak Cavern cave survey, by the Technical Speleological Group, from an AutoCAD model by J Beck.

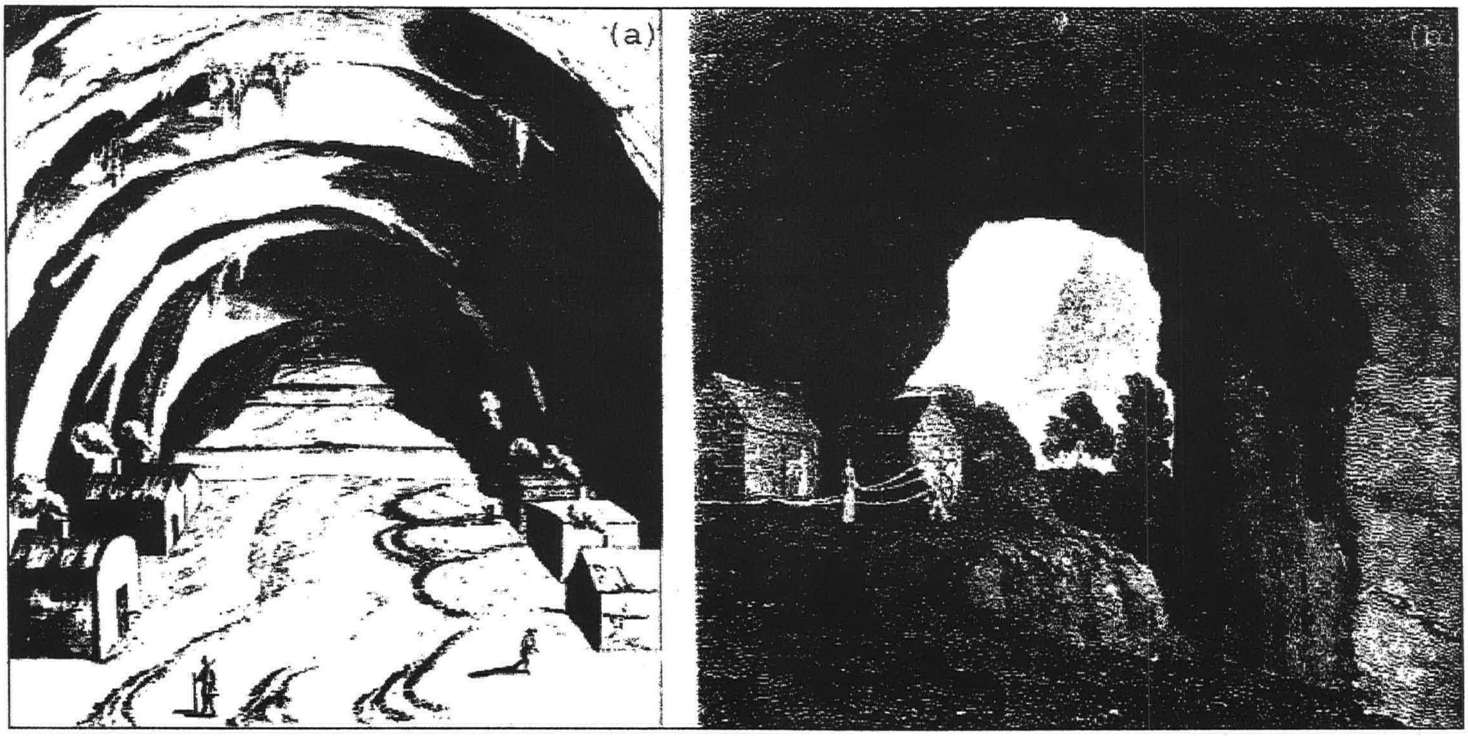


Figure 2. Engravings of the entrance (or Vestibule) of Peak Cavern, (a) by Leigh (circa 1700) and (b) by J Rose, from a drawing by E Dayes in 'The Beauties of England', 1803. From Woodall (1979).

floors the Hope and Edale valleys. Additional northerly-sourced turbidites subsequently covered the reef to provide a reservoir seal. The cap rock turbidites are exposed near Castleton at Mam Tor, and farther north in the Derbyshire Dark Peak area.

Hancock (1999) undertook a preliminary non-invasive, geophysical study. This provided useful background information. His ground resistivity profiles are discussed in the following section. Davis and Annan (1989) showed that GPR could be used to distinguish between soil and rock stratigraphy. Whereas there have been other GPR studies within cave systems (McMechan *et al.*, 1998, 2002; Beres *et al.*, 2001; Chamberlain *et al.*, 2000), these studies have focused on detecting cavities within the limestone, rather than on the cave sediments. GPR data were acquired within the cave during a half-day, opportunist visit in November 1999.

CAVE ENTRANCE SURVEY

The accurate relative positions of data are important for small-scale geophysical surveys. Typically, surveyors' tapes and compass bearings are used to position lines of profile and sample stations. Lehmann and Green (1999) integrated a geo-radar acquisition unit with a self-tracking laser theodolite with target recognition capabilities. In Peak Cavern, additional survey data were needed to position the geophysical images acquired within the cave entrance.

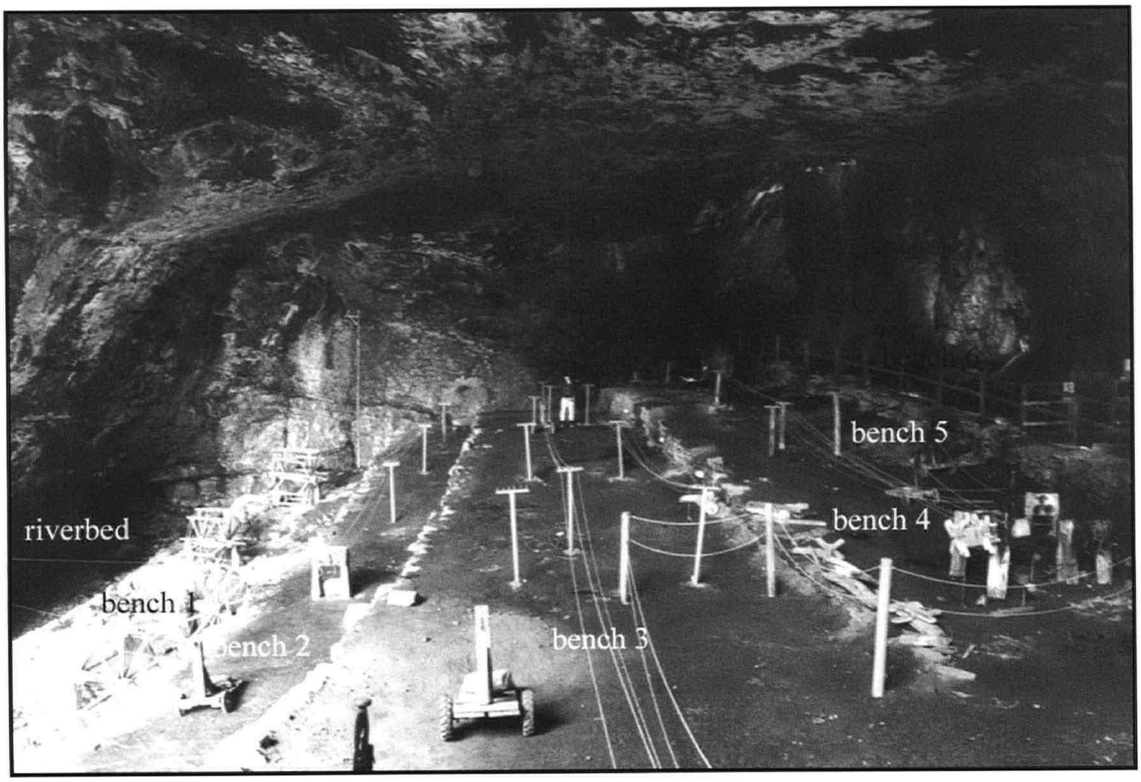
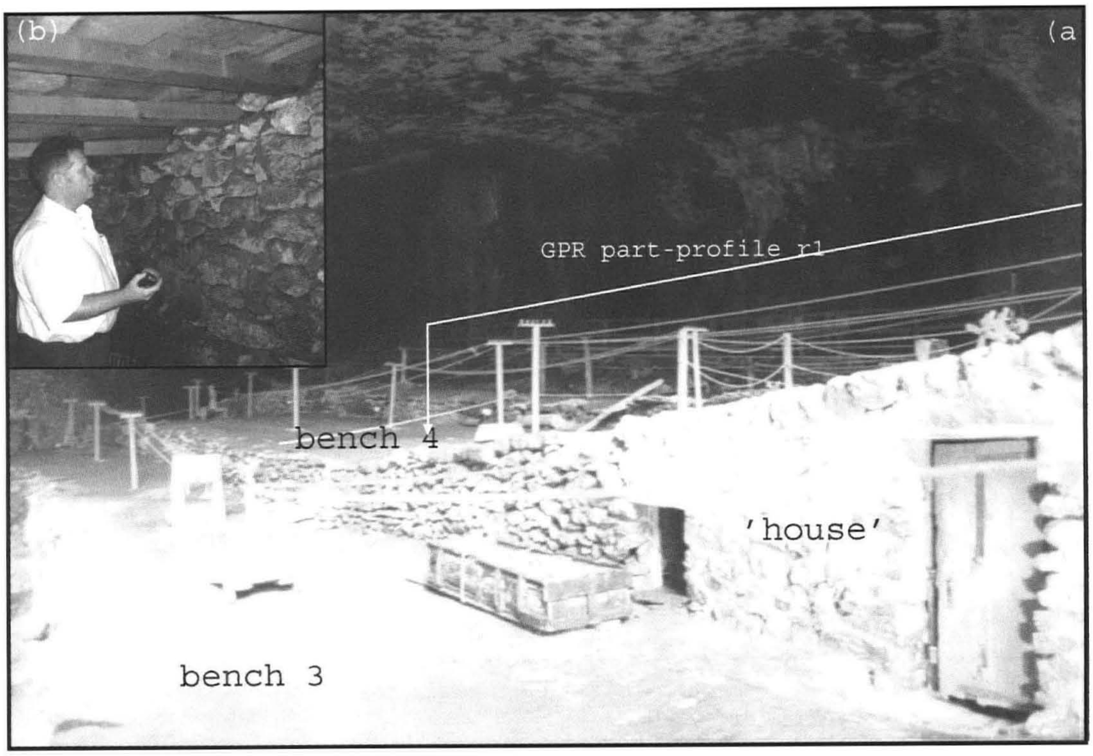


Figure 3. Photograph of the Vestibule (figure for scale). The six benches are marked, with the cave floor exposed in the dry streambed. Rope making equipment is still set up on the benches. There are only small amounts of metal above ground level, which did not noticeably affect GPR records.

Figure 4. Photographs of (a) outside and (b) inside a small 'house' under bench 4, used by rope-makers during the 17th to 19th centuries. Note that iron supports in the house roof are not exposed.

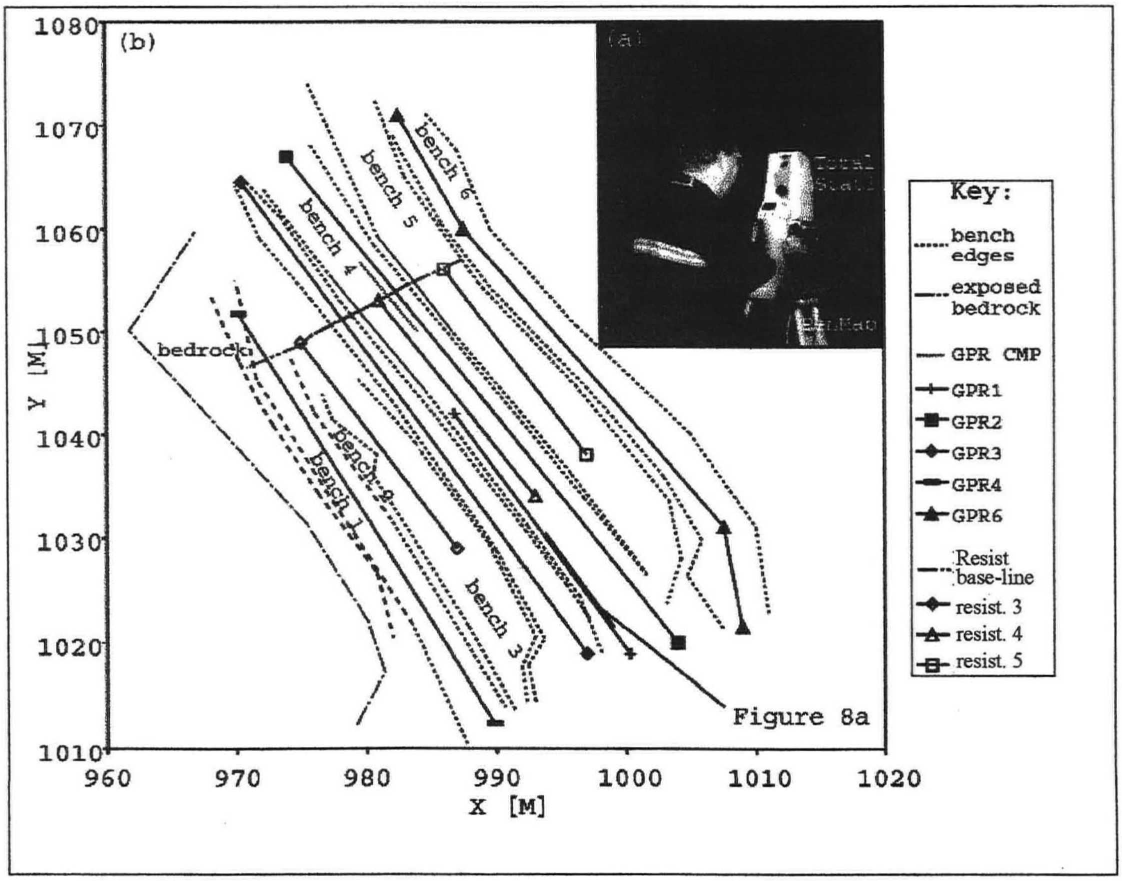


A Total Station theodolite and Penmap acquisition system were used for surveying. The theodolite base station was placed in a prominent position – overlooking the cave entrance by the kiosk, near the viewpoint for Figure 3. Around 450 surveyed points were acquired in reflectorless mode across the cave roof. Surveyors' tapes were laid out to mark the previously acquired geophysical survey lines and surveyed at the same time as the cave topography, particularly the six bench edges and the exposed bedrock in the dry riverbed (Fig.5). The cave benches and geologically significant locations were also surveyed (using around 100 location points) using a reflector on a pole of known height. Survey data were recorded by the Penmap acquisition system (Fig.5a), which provides immediate validation of the data points being acquired through a dynamic 3D display – a significant advantage over conventional surveying equipment. Single survey points and groups of points, or 'poly-lines', may be annotated and quality controlled as they are acquired.

RESISTIVITY PSEUDO-SECTIONS

Hancock (1999) used an expanding Wenner array to collect earth resistance data along transects on three benches. The electrode spacing was increased from 0.5m to 5m in steps of 0.5m. Results were plotted as apparent resistivity pseudo-sections. Pseudo-depth was defined as half

Figure 5. (a) Surveying the study site, using a Total Station theodolite, Sunscreen PC and PenMap acquisition software (right of tripod). (b) Plan view of the study site, see key for sub-divisions of surveyed bench edges, GPR and resistivity data.



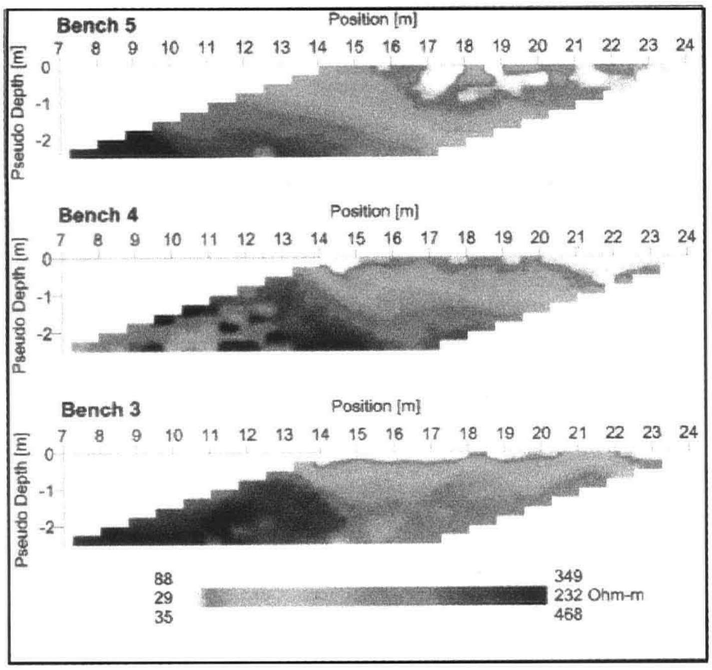


Figure 6. 2-D, resistivity pseudo-sections from Hancock (1999). See Figure 5 for location.

the electrode spacing and position measured from a baseline inside the Vestibule. In Figure 6, ground resistivity values are contoured, from high (black) to low (white).

Increased resistivities can be seen between 17m and 19m, at the bottom of the section on bench 4. The most striking feature in all three sections is the sloping apparent resistivity contrast seen from 12 to 18m. This was interpreted as an early surface of the alluvial deposits, with a later extension towards the cave's entrance (right side on figures). The more gradual increase found below bench 5 is attributed to its elevated level; benches 3 and 4 are on a similar, lower, level (compare Fig.3). The near-surface part of the sections shows several weak chevron, or inverted v-shaped, anomalies of intermediate resistivity. Man-made features may be the cause of these anomalies (Hancock, 1999).

GROUND PENETRATING RADAR (GPR) INVESTIGATIONS

GPR acquisition and processing

'Noise' test profiles were first acquired, testing several GPR antenna frequencies using the pulseEKKO™ PE100 system. The 110MHz dominant frequency antennae were chosen to ensure adequate penetration and imaging of the base of the cave beneath the cave fill. Next, a Common Mid-Point (CMP) gather was acquired, using 0.2m trace separation (Fig.5b for location). The CMP was used both to determine an optimum antenna separation for the subsequent constant offset profiles and for velocity analysis (Fig.7).

Figure 7 (left) shows two velocity values (0.13 and 0.15 m/ns), with relatively low velocity, multiple events between 50 and 80 ns Two-Way Travel-Time (TWT) and a single, higher velocity reflection event around 112 ns TWT. Both main primary events appear to be followed by multiple events at twice the TWT and at the same velocity as their parent primary events – i.e. directly beneath each primary event in the semblance plot. The two distinct velocity layers are attributed to a cave fill layer down to about 95 ns TWT, overlying Carboniferous Limestone, which forms the bedrock of the cave-floor. The limestone, being more compact and cemented than the overlying cave fill, results in a faster velocity than those measured in the cave fill sediments.

The initial test survey suggested strongly that the cave fill and cave floor could be distinguished using GPR equipment. The standard Normal Move-Out (NMO) method to obtain a velocity value from the CMP is detailed by Milsom (1996). An average velocity value of 0.28 m/ns was obtained from the CMP. This value was used to convert the subsequent fixed-offset profiles from time to depth. At the time of the survey, the manufacturer's recommended 1-metre antenna-separation for 110 MHz antennae was chosen. However, the CMP analysis showed that a smaller separation would produce better results for the shallowest, archaeological targets in any future GPR surveys. For deeper targets, such as within the rock head, a larger antenna separation would give better results.

The six benches that form the dominant topography within the cave entrance were profiled using the GPR fixed offset profile method (see Milsom, 1996). Figure 3 shows the labelled benches, with Figure 5 showing a plan-view of the profile locations. The antennae pair was moved at a constant 0.2m spacing between adjacent traces along each profile. The pulseEKKO™ acquisition software allows repeated pulses to be transmitted and recorded, which significantly improves image quality at greater penetration depths. Of course, it then takes longer to acquire, since the repeat traces are summed, incurring a computational time-penalty. It was found that a sum of 16 pulses-echoes produced good results at an acceptable time cost.

One problem encountered, when acquiring GPR data in the cave, was the dampness inherent in the study site. Whereas careful covering of delicate equipment was possible, the fixed-offset profile data acquired on the fifth bench were corrupted. This therefore prevented direct comparisons with the pseudo-resistivity section on this level.

After acquisition, the raw GPR data were processed to maximise the amount of information recoverable from the profiles. Variable time delays were subtracted to correct all traces to a common zero-time origin. A gain profile was applied to balance high-amplitude shallow events with relatively low amplitude deeper events. A Time-Variant Spectral Balance (TVSB) was used to improve frequency bandwidth. The average velocity from the CMP profile, discussed above, was used to convert the fixed-offset profiles from time to depth.

GPR results

The 2-D fixed-offset profiles along the benches show several anomalies, which correspond to exposed features, the most obvious of these being the small 'house' under bench 4 and seen in Figure 4. A segment of the GPR profile shows an anomalous absence of reflection events, corresponding to the space under the 'house' roof (Fig.8). Other interpreted features are listed in the Key to Radar Stratigraphy accompanying Figure 8. A previously unidentified void is clearly seen, which may be the site of another collapsed house. Between the 'house' and the void, a possible midden or spoil heap is expressed as dipping lateral accretion surfaces overlain by several domed layers. At either edge of the GPR profile segment in Figure 8, possibly undisturbed layers of planar horizontal cave fill are seen, similar to those overlying the cave floor. In the centre of the section, there appears to be a sharp-edged truncation of the deeper tabular cave fill layers, possibly by an excavation that preceded the construction of the 'house' and 'midden'. The increasing depth of cave fill, from the back of the cave towards the entrance, was seen on several lines. The increasing depth of fill from the back of the cave was consistent across the study site and recalls the high-resistivity wedge seen in all three resistivity pseudo-sections acquired by Hancock (1999). Several diffraction events are seen in disturbed ground, corresponding to the known locations of electrical cables and pipes, were observed on some GPR profiles, some pipes being observed emerging from a dry-stone retaining wall at the foot of benches 3 and 4.

The top bench (6) was profiled with fixed-offset GPR for 100m along the main tunnel of the Peak Cavern system, i.e. through 'Lumbago Walk' (Fig.1). The profile traverses over accumulated river deposits that locally formed at bends in the passageway. The GPR profile (Fig.9a) shows complicated stacking of bedforms above the interpreted cave floor reflection event (shown in Fig.5b). Interpreted inclined bedforms are seen to accrete laterally on either side of a domal feature, interpreted as being deposited on the channel bend during times of flood (see discussion).

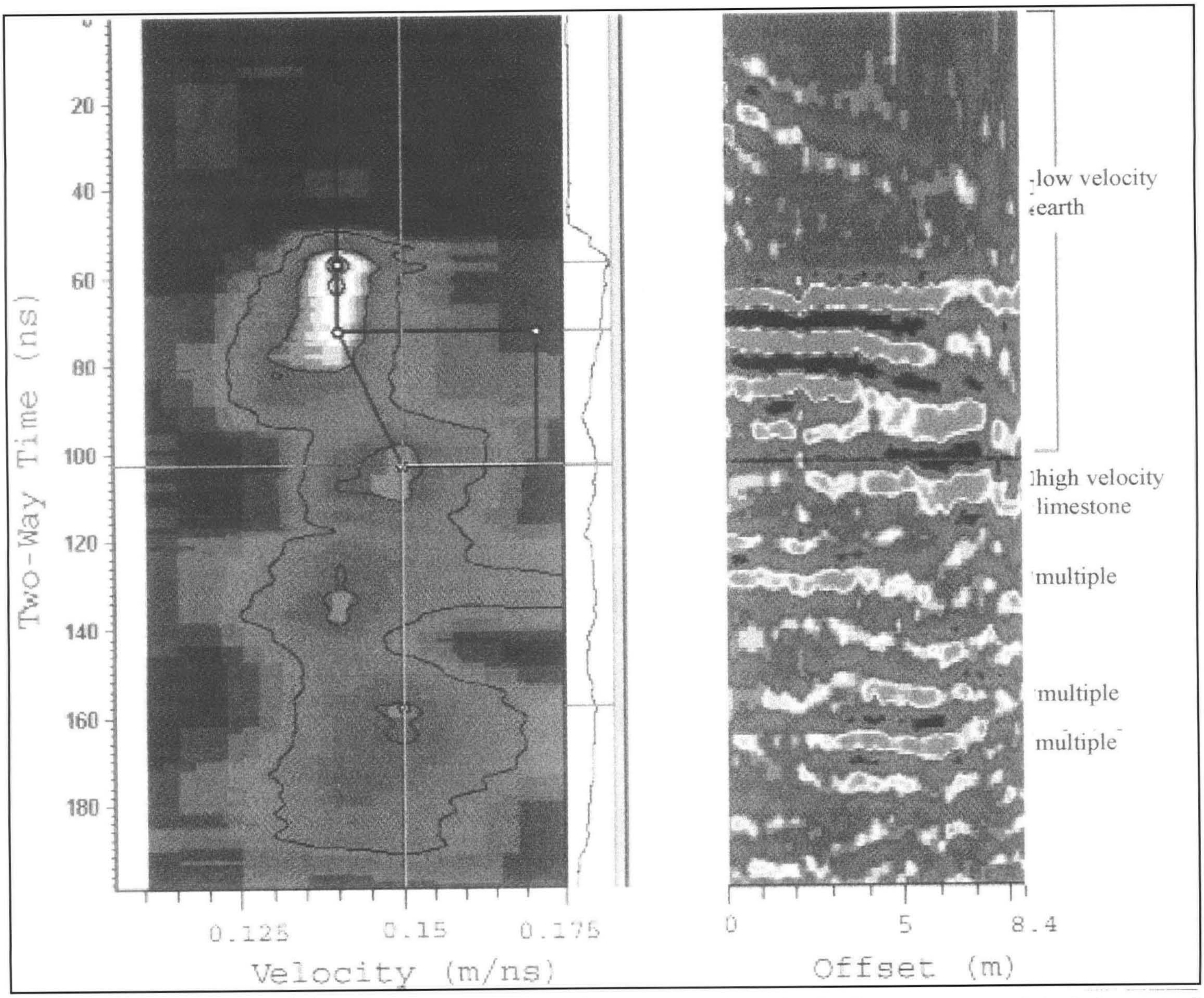


Figure 7. GPR Common Mid-Point (CMP) profile, acquired using 110MHz frequency antennae on bench 4 (see Figure 5 for location). Left side shows ratio of average energy : total energy of CMP traces. Bright areas indicate likely velocities (see text). Right side has Normal Move-Out (NMO) corrected gather, using velocity gather from left side. The marked velocity change is observed between 54 and 102 ns TWT. The average cave velocity was calculated to be 0.28 m/ns. attributed to the base of the cave – between the cave sediments and host limestone.

DATA INTEGRATION

There is currently no single software packages designed specifically to combine archaeological, geological, geophysical and survey data into one 'shared earth' model. 3D-CAD software was therefore used to integrate geophysical image data in a framework defined by Total Station survey points (see Pringle *et al.*, 2003). The survey data were partitioned into cave-fill topography, cave roof, streambed and cave entrance areas, then gridded and rendered, to produce an accurate, if partial, 3D view (Fig.10). The GPR images and the pseudo-resistivity sections were attached to vertical frames hung from their surveyed ground level positions.

The cave floor, or cave base target, was then interpreted as a single surface through all the relevant observations. These include the surveyed exposed bedrock in the stream, the small outcrops surveyed and 'PenMap' annotated at the foot of some benches, and the cave-floor picks in the GPR, CMP and fixed-offset profiles (Fig.10).

DISCUSSION

The results of the integrated survey and interpretation, shown in Figure 10, strongly suggest that:

1. The cave floor is broadly parallel to the cave roof. This is consistent with a cave developed in dipping strata and guided by the preferential dissolution of one bed, or a group of adjacent beds.

2. The cave fill rarely exceeds 6m in thickness (compare the depth scales in Figures 8 and 9), consistent with Dr T D Ford's expectation *(pers. comm.)*.

This has interesting implications for both cave formation and cave sedimentology. Related evidence and a proposed genetic link between cave formation and cave sediment deposition are presented below.

Cave formation

Osborne (2001) recognises "*structurally guided network caves*" in dipping beds as differing in plan and section from maze caves in sub-horizontal beds. In limestone beds dipping at 30° or more, cave architectures show *"large elongate cavities called halls, oriented along strike, and smaller, short cavities called narrows, oriented perpendicular to strike"*. Hall formation may be guided by the intersection of susceptible beds and fractures, where the process of mixing-corrosion can occur, as discussed in the next paragraph. The Peak Cavern Vestibule, unlike the rest of the Peak system, would qualify as a 'hall',

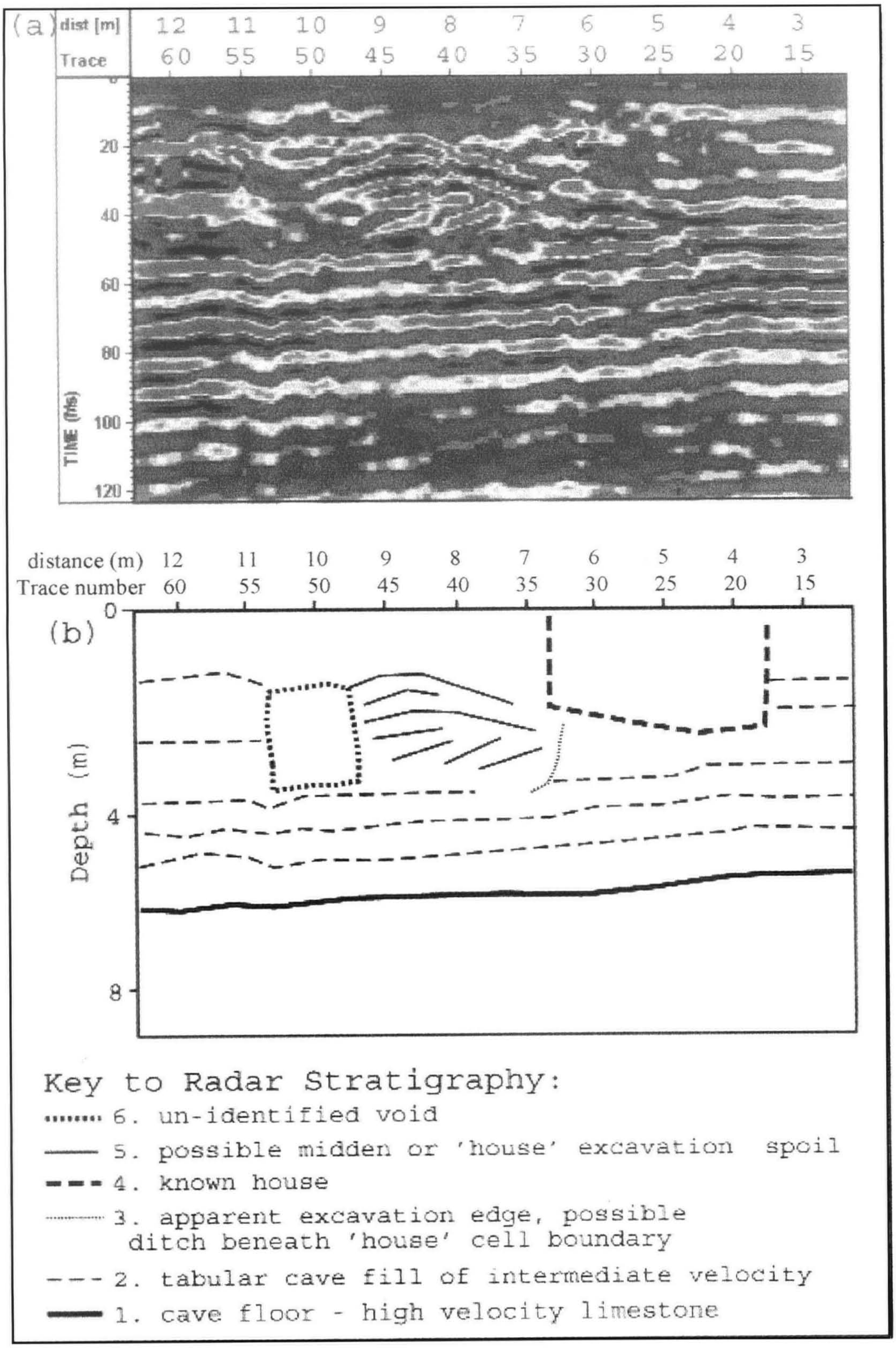


Figure 8. (a) GPR R1, fixed-offset, part-profile, with (b) interpreted line diagram. A radar stratigraphy is shown.

with visible fractures and several small avens and seepage from the roof with stalactites. However, the Swine Hole (Fig.1) qualifies as a 'narrow'. During periods of low flow, stream water travels through the Swine Hole through the 'resurgence' (Fig.1). In periods of high flood, excess water travels along the bare rock cave floor adjacent to bench 1. Once the Vestibule was open to the elements, additional erosional processes, such as freeze-thaw for example, could have further enlarged the 'hall'.

Westerman (1982) documented the nascent stages of karstification at joint/bedding plane intersections and developed a numerical model for groundwater flow through a fracture network, represented as pipes along the intersections. Sufficient computing power is now available to track solubility parameters (presented by Bögli, 1980) through a 'pipe-network' groundwater flow model. A realistic model of bedding planes and fractures on the scale of the Peak Cavern cave system could then be made. The 3D-CAD model presented in this paper illustrates the structural and stratigraphic detail that would be needed across the system before such a flow model could be built. Since Technical Speleological Group members have made an extensive survey of the Peak Cavern system, there is a framework in place to which the necessary geological detail could be added.

Cave sedimentology

The Vestibule deposits are the largest single cave fill accumulation within Peak Cavern, although sedimentary cave fill has been

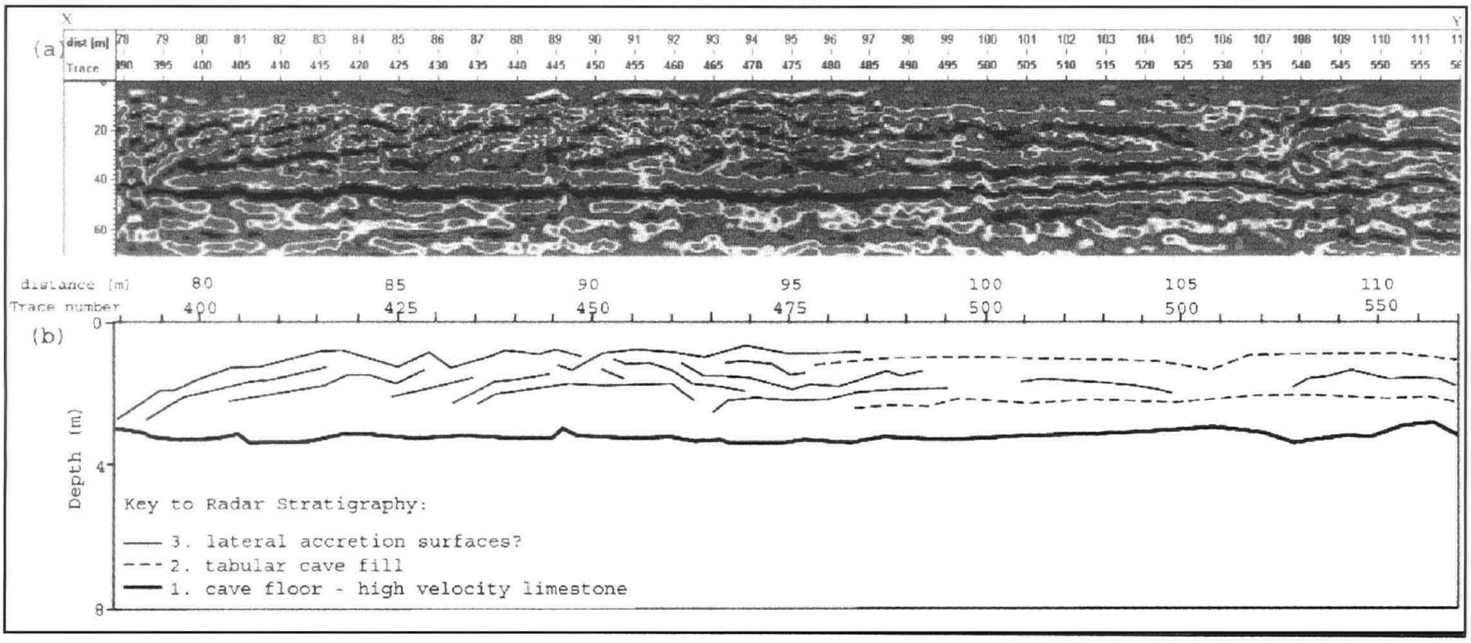


Figure 9. (a) GPR, 2-D fixed-offset part- profile R6, acquired using 110MHz frequency antennae (see Figure 1 for location), with (b) subsequent line interpretation. The section lies through the streambed fill at the back of the cave, the conical lateral accretion surfaces are attributed to sediment stacking during successive spring floods.

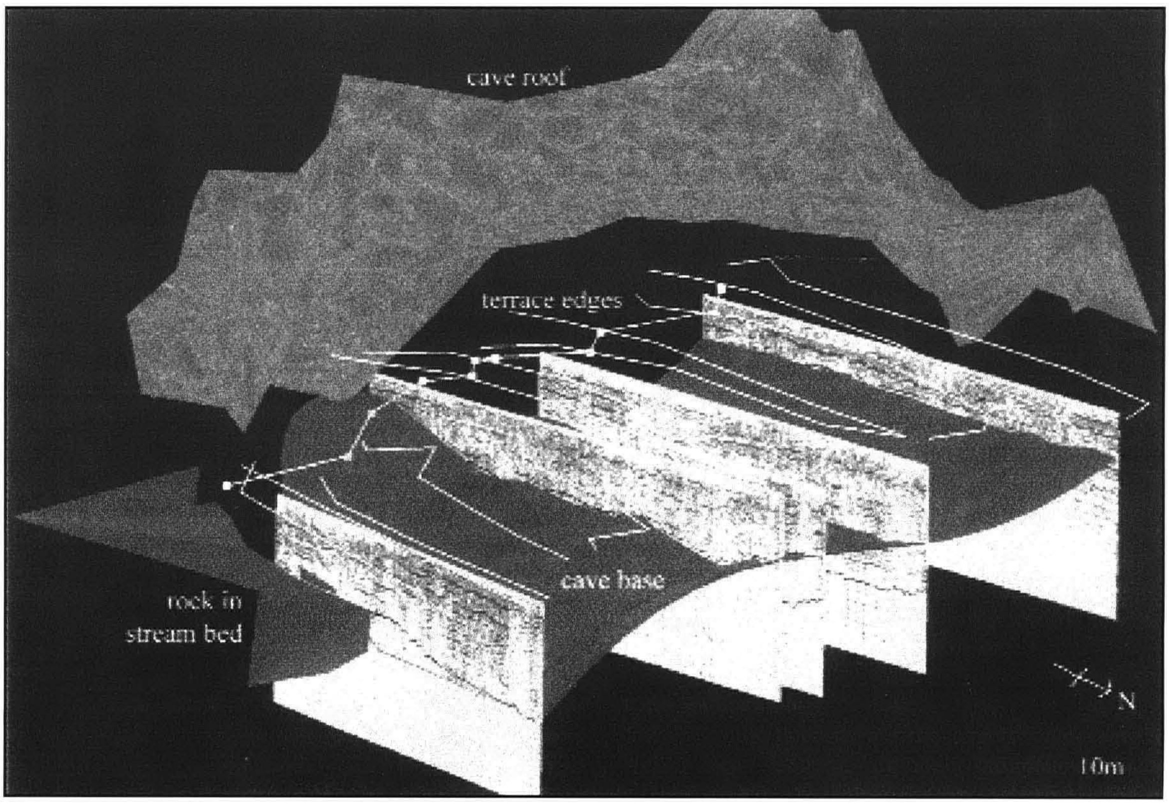
documented throughout the system by Thistlewood *et al.* (1989). The cave entrance developed in the Asbian fore-reef limestone beds with 30° bedding plane dips. The original cave stream, flowing through Lumbago Walk and along bench 6 (see Fig.1) is inferred to have migrated down dip (north-eastwards) as it eroded successive beds. It would therefore be expected that the upper levels of the developing cave would contain the oldest sediments, thus producing a reversed stratigraphical sequence. After a period of northeasterly migration, the stream switched position to flow down the narrower Swine Hole (Fig.1). At the present time, during normal rainfall, the Swine Hole 'narrow' is able to accommodate the flow and conduct it to a still lower level.

Inclined surfaces are imaged on GPR profiles (Fig.9) and these surfaces appear to have accumulated on the outside of a bend in the main streamway (see Fig.1 for location). Inclined surfaces are commonly observed in fluvial channels, especially in meandering systems, where they form on point bars, on the inside of channel bends. The point bars develop by erosion of the outer channel bank, accompanied by deposition of sediments on the inner channel bank. This produces a series of 'lateral accretion surfaces'. This process requires erodable banks, which is not the case in Peak Cavern, so the origin of the inclined surfaces are theorized as being deposited up the sides of the cave during times of flood.

Archaeological implications

Peak Cavern is believed to have a rich archaeological history (Ford, 1999) but, due to its size, importance and conservation provisions, excavation is inappropriate and, in fact, prohibited. However, the combined results of geophysical and topographical investigations have produced an interpreted cave floor base. The surface of sedimentary

Figure 10. Data integration in CAD (Bentley Microstation) software. Survey data, separated into cave floor, walls and roof, were separately gridded into a wire frame mesh. GPR and resistivity geophysical data were then integrated into the dataset, and the cave floor horizon was interpreted.



cave fill, prior to earthworks by a long line of human occupants, may be identified on ground resistivity and GPR images, although further work is needed to confirm and elaborate additional details. Geophysics can partially define the cave fill topography before human habitation, plus the extent to which human activity has altered the cave interior. Further analysis of results should permit targeted investigations to reveal the stratigraphy, chronology, archaeology and palaeontology of the cave fill, all of which have been uncertain.

OVERVIEW

The previous discussion on cave formation and sedimentology suggests that the oldest deposits in the cave should underlie the higher benches, 5 and 6. The youngest deposits should underlie the lower benches 1 and 2 (compare Fig.03). A case can be made that the Vestibule and Swine Hole sections of Peak Cavern are part of a 'hall and narrow', structurally-guided network cave in Asbian fore-reef limestone beds with an average 30° north-easterly dip. The stream appears to be following the strike and cutting down-dip along a susceptible limestone bed. It follows that the earliest part of the Vestibule and the earliest deposits therein are at the highest levels, near the southwestern wall and beneath the higher benches 5 and 6. Internal structure of the cave-fill deposits may be imaged by ground resistivity and, particularly well, by GPR. Geophysical contrasts across cave fill sediments might be imaged by ground resistivity and GPR, so that a stratigraphy could be defined by non-invasive means.

All the geophysical profiles acquired to date have been aligned parallel to the benches for ease of operation. In order to image putative lateral accretion surfaces parallel to the benches, geophysical cross-lines would be required perpendicular to the benches. This could be difficult with ground resistivity, but GPR is quite adaptable to that challenge (compare Pringle *et al.*, 2003, and Senechal *et al.*, 2001). It is proposed that a 3D-GPR survey be undertaken, to cover all the benches and tuned to image the internal structure of the cave fill. Several additional CMP surveys would be needed for antenna selection and velocity calibration.

CONCLUSIONS

Cave topographic survey, geophysical, geological and archaeological data have been acquired, processed and integrated to form a single, 3D digital model of the Peak Cavern cave entrance. Subsequent analysis of the data has shown that the cave floor slopes down from west to east, sub-parallel to the roof, consistent with cave erosion along bedding planes.

Geophysical investigations, especially GPR, are an appropriate non-invasive technique for shallow cave archaeological, sedimentological and stratigraphic investigations, but the acquisition parameters need to be refined for specific targets. Detailed surveying is considered critical to provide an accurate framework for the integration of geological, geophysical and archaeological data. 3D CAD software provides a suitable working environment for combining geometrical information from disparate datasets.

Based on the GPR observations, the earliest sedimentary deposits within the Peak Cavern Vestibule are predicted to be at the highest levels, beneath benches 5 and 6. The most recent deposits should be found under the lowest levels, i.e. beneath benches 1 and 2 and close to the modern stream when in flood, where active erosion is still taking place. A 3D GPR survey is recommended to image sedimentary lateral accretion surfaces within the cave fill that should align parallel to the benches. A radar-stratigraphical framework of the sedimentology and early archaeology of the Peak Cavern Vestibule deposits could then be established.

Further studies should be undertaken throughout the rest of the cave system – building upon the cave survey by the Technical Speleological Group. A comprehensive 3D-CAD model could combine geological and topographical information. A 3D-CAD based, hydraulic flow model could then be used to investigate a range of hypotheses for cave inception, development and evolution within the Castleton Reef.

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Geological and archaeological exploration of caves in Mongolia

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Abstract: Mongolia is a country with great cave potential. Carbonate rocks are widely distributed all over the country. With the advent of satellite remote sensing, their distribution can now be mapped in detail and access to the sites assessed before field investigations are initiated. Khovsgol aimag, one of Mongolia's northern provinces bordering Russia, has the most extensive carbonate outcrops. Many caves exist in these carbonate rocks but there are also caves in granitic intrusive rocks in this region. The majority of known caves in Khovsgol aimag are less than 10m long and 10m wide. The general absence of known large caves can be attributed to deformation of host rocks, blockage of passages and entrances by ice and/or water, burial, the reluctance of local residents to inform foreign visitors about caves, and the scarcity of speleologists in Mongolia. It is also rare for these caves to contain evidence of prehistoric and historic occupation by humans, despite the fact that there are many open-air Palaeolithic and Neolithic sites in the area. This is hypothesized as being due to caves' locations with respect to sources of high-quality raw materials for stone tools, and the general lack of access to water. Investigation of caves in Khovsgol aimag is in its infancy, and it is quite possible that large caves of scientific importance will be discovered in the future. The situation is very different with respect to caves in the Gobi-Altai ranges of southern Mongolia, where large caves containing rich archaeological assemblages are known. Among them, Tsagaan Agui and Chikhen Agui in Bayan Khongor aimag have been the most intensively studied, yielding evidence of human occupation at least as early as the Mid Palaeolithic. The palaeoenvironment of the Gobi-Altai region must have been ameliorated to have allowed occupation by human ancestors.

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INTRODUCTION

Recently Mongolian caves (Mongolian, *agui*) attracted increasing attention from the international caving community due to their great potential. Since the democratic revolution of Mongolia in 1990, there have been a number of reports on cave explorations undertaken by Western and Japanese explorers in the country (e.g., Holúbek, 1995; Birchall and Richardson, 1996; Aoki, 1996). These visits were restricted mostly to northern Mongolia (Khovsgol aimag; aimag being an administrative unit equivalent to a province), the Gobi-Altai (Bayan Khongor aimag), and western Mongolia (Khovd aimag) (Fig.1).

The scientific investigation of caves in Mongolia has been rather limited. However, cave environments have great potential for rich geological, biological, and archaeological research. Among these fields, archaeological investigation has been conducted most extensively in Mongolia. Cave sites preserve stratigraphical records of both cultural and sedimentological layers, and they are very important for understanding complex interactions between human occupations and environmental conditions in the region. The Joint Mongolian-Russian-American Archaeological Expedition (JMRAAE), initiated in 1995, is an important contributor to enhanced understanding of caves in Mongolia. For example, the JMRAAE examined in detail a cave (Tsagaan Agui) and a rockshelter (Chikhen Agui) in Bayan Khongor aimag between 1995-2000 (Derevianko *et al.*, 1996; 1998; 2000). The current paper presents the results of preliminary cave investigations carried out by the joint expedition in 2002, focusing on Khovsgol aimag. Archaeological findings from Tsagaan Agui and Chikhen Agui in the Gobi-Altai are also reported.

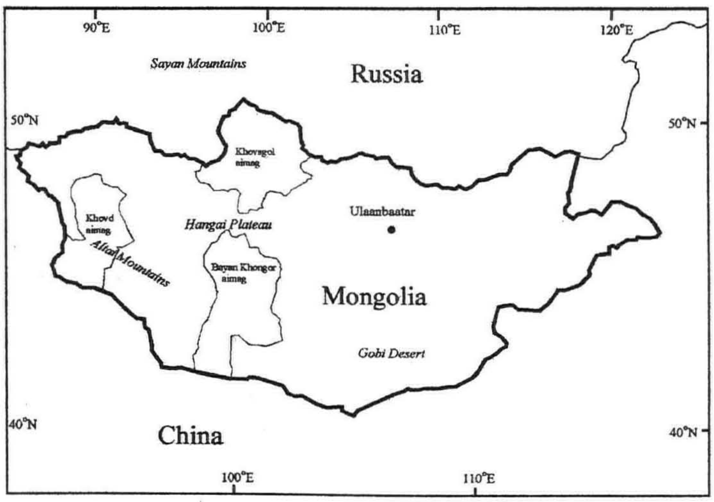


Figure 1. Location of Mongolia and the three provinces (aimags) discussed in the paper, Khovsgol, Bayan Khongor, and Khovd aimags.

GEOLOGY OF MONGOLIA AND REMOTE SENSING SURVEY OF CAVE AREAS

Mongolia is a vast landlocked country. It occupies a large part of northcentral Asia, with an area of over 1.5 million km^2. The average altitude of the country is about 1600m, with the Altai Mountains and Hangai Plateau dominating western and central Mongolia, and the Gobi Desert situated in the south. The geology of Mongolia reflects

Designation number (Cave name)	GPS coordinates	GPS altitude (not calibrated)	Rock type	Note
Alag Erdene 1	N50°03'41.3" E99°51'16.02"	2051m	Carbonate	Horizontal cave A few metres deep 2 horizontal caves
Alag Erdene 2	N49°59'09.2" E99°44'16.1"	1994m (Larger cave)	Granite	Extensive weathering Larger cave 7m deep Smaller cave 3m deep
Alag Erdene 3	N50°02'59.9" E99°51'40.0"	1990m	Carbonate	Small horizontal cave Entrance 0.5x1m
Alag Erdene 4	N50°01'49.1" E99°52'27.7"	1765m	Carbonate	Horizontal cave Entrance 1.5x1.5m 5m deep
Alag Erdene 5	N49°58'44.7" E99°46'58.9"	1883m (Upper cave)	Carbonate	3 horizontal caves Lower cave Middle cave Upper cave: Entrance 2.2x2.9m, 24.5m deep, ice pool, ice column, inside
Alag Erdene 5v (Khavtsgait Agui)	N49°58'47" E99°47'10"	Close to Alag Erdene 5	Carbonate	Near-vertical cave 60m deep, ice pool
Alag Erdene 6	N50°05'05.0" E99°53'03.4"	1851m	Carbonate	Horizontal cave Entrance 3.1x3.6m 9.5m deep
Alag Erdene 7 (Hurtsyin Agui)	N50°09'36.2" E99°48'24.6"	2092m	Carbonate	Horizontal cave Main entrance 6x3m 14m deep Tibetan script painted on the rock surface A 5m-deep cave nearby
Alag Erdene 8	N49°58'43.2" E99°47'28.8"	1850m	Carbonate	Horizontal cave Entrance 1.8x2.2m 3m deep
Alag Erdene 9	N50°04'12.8" E99°57'40.5"	1882m	Carbonate	Near vertical cave Entrance 0.5x0.5m
Egiin Gol 1	N50°14'35.9" E100°05'26.8"	1702m	Carbonate	Horizontal cave A few metres deep
Khatgal 1	N50°27'10.4" E100°06'46.2"	1653m	Carbonate	Small horizontal cave Entrance 1x1m
Sumber 1	N50°22'59.8" E99°19'52.4"	1917m	Carbonate	Horizontal cave Entrance 2x1m 3m deep
Tsagaannuur 1	N51°10'25.3" E99°22'15.7"	1541m	Carbonate	Horizontal cave Entrance 3x3m 4m deep

Table 1. List of studied major caves in Khovsgol aimag

continental formation processes based on complex interactions of cratons and arcs (Sengõr and Natal'in, 1996). The basement rocks comprise ancient passive and active margin terrains as old as the Proterozoic, which were accreted over successively forming foldbelts of sedimentary-volcanic formations. These formations are usually extensively folded and underpinned by a variety of granitic plutons (Traynor and Sladen, 1995). The extensive basin systems in Mongolia are filled with late Palaeozoic to Quaternary sediments (Sladen and Traynor, 2000), some of which are famous for hosting rich assemblages of dinosaur fossils. Carbonate rocks in the foldbelts have a sedimentary origin. The most extensive carbonate formations, mainly in the Late Proterozoic to Cambrian age range, occur in Khovsgol aimag. Carbonate formations in the Gobi and Altai regions range in age from Proterozoic to Devonian, or even younger. Karst geomorphology, including caves, is common in Mongolia, due to the widespread distribution of these old carbonate bedrocks.

Exploration of carbonate caves begins with assessment of geological maps. Russian geological maps of 1:500,000 scale are available for Mongolia. Remote sensing techniques are then employed to verify the geological maps, examine local topography, and assess road access to the caves. Field investigation relies heavily on the knowledge of local guides who are, in the case of Mongolia, mostly nomadic pastoral people.

Satellite remote sensing, which is a relatively new tool in the field of speleology, has been applied widely to the mapping of rocks and soils on Earth (Sabins, 1996) and other planets (Pieters and Englert, 1993). The study described here employed both SAR (Synthetic Aperture Radar) and visible-near infrared images, due to their availability and characteristic responses to major cave-hosting rock types such as limestone or dolomite, and the granite of northern Mongolia. Where high-resolution geological maps do not exist, remote sensing becomes a practical and useful approach. Plate 1 shows one example of how radar imagery is useful in detecting carbonate rocks. Radar signals are influenced strongly by two factors; surface roughness and dielectric constant (Sabins, 1996). The carbonate rock dielectric constant is not distinctive in comparison to other rock and soil types. However, carbonate rock outcrops tend to exhibit surface roughness at certain characteristic wavelengths because of their unique patterns of fracturing and weathering. Back-scattered radar signals are strong when the surface roughness is at the same or nearly the same scale as the radar wavelength. In the case of the RADARSAT images employed in Mongolia, the C-band wavelength is 5.66cm, which is close to the characteristic roughness scale of carbonate rock fragments in this region and, hence, parent outcrops. Obviously this is not a very sophisticated method for classifying carbonates in SAR images, but it provides a practical way to determine the approximate distribution of carbonates in the field.

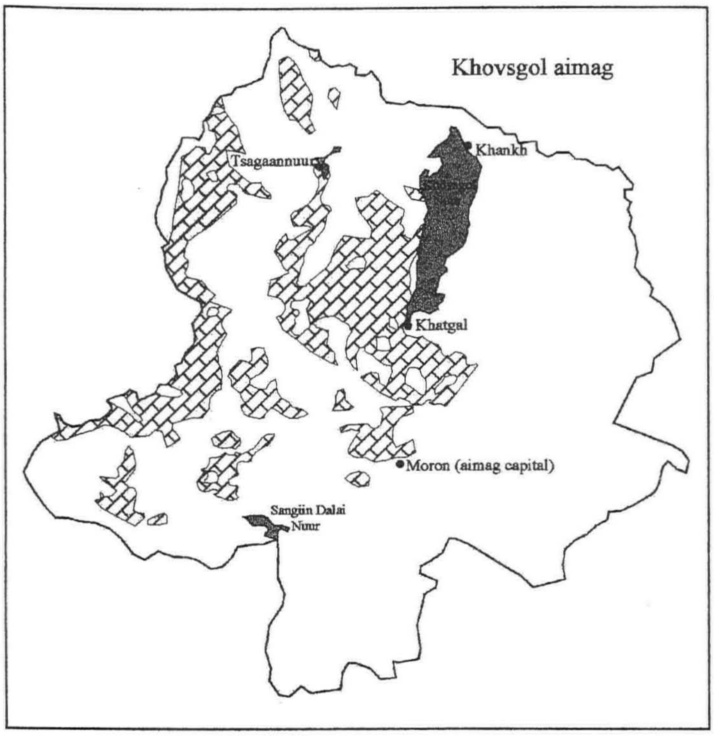


Figure 2. Distribution of major carbonate rock units in Khovsgol aimag. Modified from the simplified geological map in the Atlas of the Mongolian People's Republic (Ulaanbaatar, 1990). Although not mapped, other small carbonate units exist in this aimag.

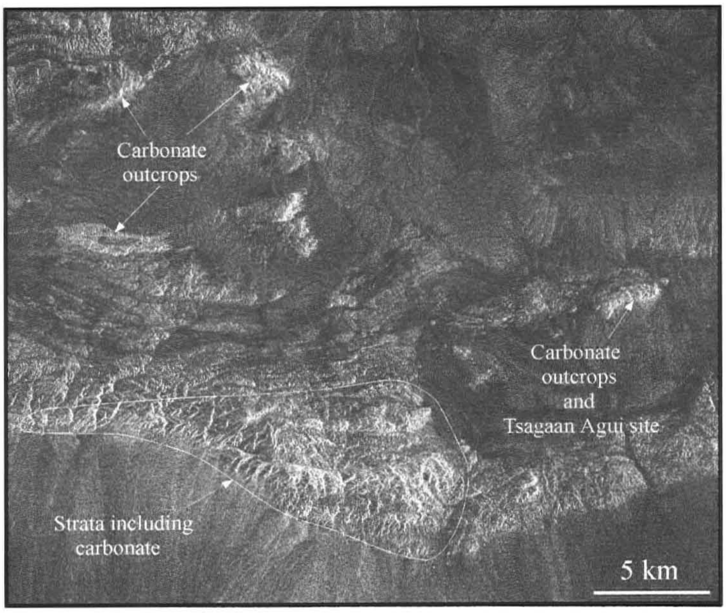


Plate 1. RADARSAT image (Standard mode, R107023338) of cave-hosting carbonate rock outcrops. Tsagaan Agui area, Bayan Khongor aimag in the Gobi-Altai. This example shows how carbonate rocks appear brighter than other geological units in SAR images. This is due to the fact that carbonate rocks in this region tend to fragment on a scale close to the 5.66cm radar wavelengths, (RADARSAT C-band).

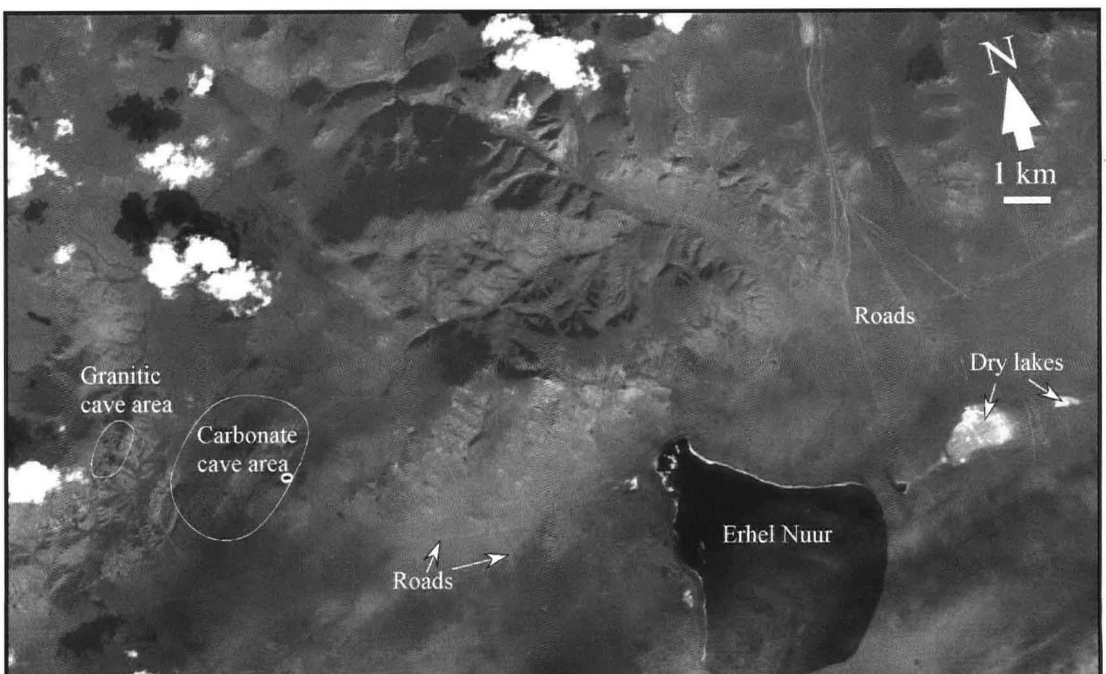
Visible near-infrared spectral data are also useful in detecting carbonate rocks, because carbonates have absorption features at wavelengths >1.6μm due to vibrational modes (Gaffey, 1987). Absorption bands can be used to map distribution of carbonate outcrops using, for example, ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) data. ASTER incorporates 14 spectral bands from visible to near-infrared and thermal infrared, which are useful for distinguishing various minerals and vegetation. The two classification methods described here require that the rock units are exposed and relatively free of vegetation. Therefore, their application is most effective in arid lands. The Gobi-Altai region presents an ideal environment for the application of these methods. In Khovsgol aimag, where exposed outcrops are limited, these techniques need to be employed with caution. ASTER images, with 15m spatial resolution (VNIR mode), are also useful for geomorphological examination of carbonate outcrops, as well as assessing roads and terrain conditions for visiting sites (Plate 2).

DESCRIPTIONS

Surveyed caves and areas with cave potential in Khovsgol aimag

Carbonate rocks are widely distributed in Khovsgol aimag (Fig.2), but the 2002 survey was focused on an area westsouthwest of the settlement of Alag Erdene (formerly Manhan), on the basis of logistical and other information gleaned from local herdsmen (Plates 3 and 4, Table 1). The carbonate rocks in this area are Late Proterozoic to Cambrian in age, with no visible signs of fossils. In general the host rocks are heavily deformed due to accretional processes and mountain building. Locally, however, beds are preserved in more or less their original state, and cave formation occurs along the bedding planes of these strata. Most of

Plate 2. ASTER image (VNIR mode, 2007147725) covering one study area near the town of Alag Erdene in Khovsgol aimag, northern Mongolia. High spatial resolution images (15m in this case) were used to assess carbonate and granitic outcrops and access to the sites.



	GPS coordinates	Rock type	Cave type	Archaeology
Tsagaan Agui	N44°42'32.6" E101°10'08.8"	Carbonate	Cave Main chamber height 4 to 5m 38m deep	The Middle Palaeolithic through the historic period
Chikhen Agui	N44°46'22.6" E99°04'06.4"	Carbonate	Rock shelter 6.4x2.3m 9m deep	Epipalaeolithic (the Upper Pleistocene through the Early Holocene) and possibly the Middle-Upper Palaeolithic transition

Table 2. Characteristics of Tsagaan Agui and Chikhen Agui Caves in Bayankhongor aimag.

the caves examined are dissolution cavities showing strong structural guidance. Occurrences of preserved speleothems are limited within the known cave systems. The caves appear to have been occupied by animals, both wild and domestic, judging from widespread faeces, fur and feathers on the ground. Also, sub-fossil bones of animals are reported in some caves. However, no clear traces of human occupation have yet been found in these caves, except for evidence of short-term visits by modern nomads. In addition to this principal area of investigation, sporadic visits were made to caves in other parts of Khovsgol aimag (e.g., Egiin Gol 1, Khatgal 1, Sumber 1, and Tsagaannuur 1). The main caves of interest are described below.

Alag Erdene 5 is a rocky hill containing three caves formed at different elevations (Plate 5). Among the three, the uppermost is the longest (approximately 24.5m), with both near-horizontal and near-vertical sections. Inside the cave, a frozen pool and water column are preserved (Plate 6). Water in the cave has a brownish-red color, possibly indicating contamination by soils or organic materials. Deeper in the cave, near-vertical sections continue (Plate 6). As is commonly the case in Mongolian caves, Alag Erdene's uppermost fissure contains wooden logs left behind by previous visitors to aid climbing (Plate 6).

Alag Erdene 7 (Hurtsyin Agui) is a large, complex chamber with multiple entrances (Plate 7) and with small holes in its ceiling. The cave system occupies a large part of the host hill. Tibetan script painted on the rock surface outside the cave's main entrance, although poorly preserved, is most likely the seven-character Chenrezig mantra, Om Mani Peme Hung, commonly seen in such circumstances.

Frequent, but presumably recent, use of Egiin Gol 1 cave by animals is evident (Plate 8), as animal faeces are scattered across the cave floor. This cave is located just below the ridge of a massif adjacent to the main Egiin Gol range and is near a mid Holocene Neolithic archaeological site (5340 ± 40 RCYBP, Beta - 170893) excavated during the 2002 expedition. Interestingly, no evidence of prehistoric human occupation was found during the preliminary inspection. This may be due to the fact that the cave entrance is approximately 100m above river level and not easily accessible.

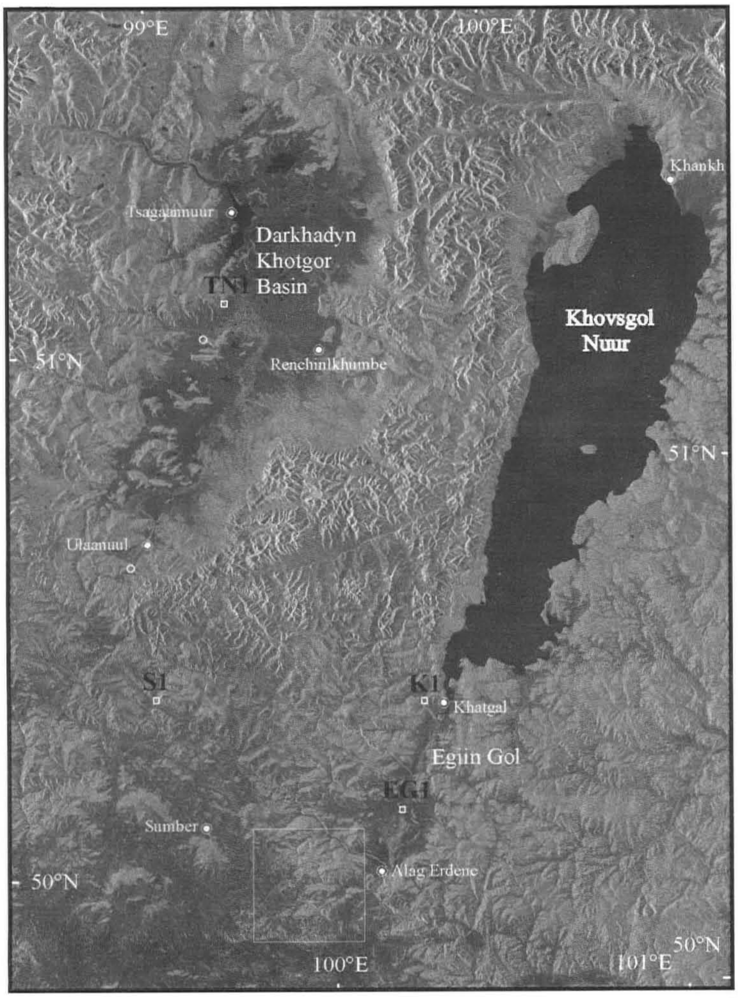


Plate 3. Northern Khovsgol aimag and areas investigated in 2002 (large open square: the main reconnaissance area near Alag Erdene – see Plate 4 for more details, open square: cave sites, open circle: not investigated in detail but with high cave potential). Khatgal (K), Egiin Gol (EG), Tsagaannuur (TN), Sumber (S). RADARSAT image, SCAN SAR R120050130.

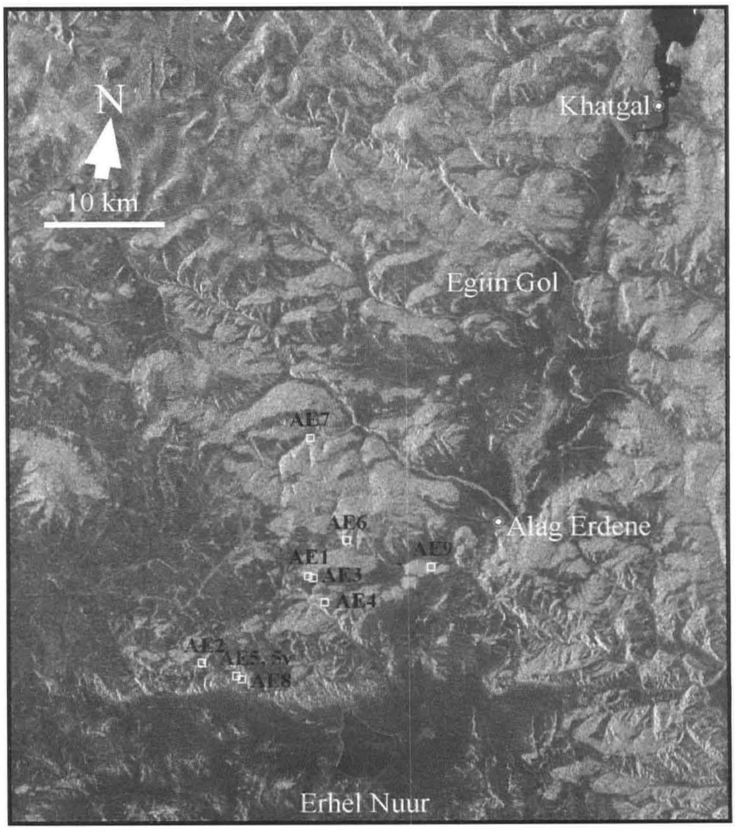


Plate 4. Location of caves investigated near Alag Erdene (AE). RADARSAT image, SCAN SAR R120050130.

Sample number	Material and horizon	Age
AA-23158	Wood charcoal from Quadrat A'23, top of Stratum 3, -355cm	33,840 ± 640 RCYBP
AA-23159	Wood charcoal from Quadrat A26, Stratum 4, -274cm	32,960 ± 670 RCYBP
AA-26586	Wood charcoal from Quadrat A22, Stratum 1, Horizon 3, -334cm	931 ± 65 RCYBP
AA-26587	Wood charcoal from gravel layer, Quadrat A21, lowest Stratum 2 just above Stratum 3, -430cm	33,777 ± 585 RCYBP
AA-26588	Wood charcoal from Quadrat A'21, surface of Stratum 3, -436cm	33,497 ± 600 RCYBP
AA-26589	Wood charcoal from Quadrat A'22, surface of Stratum 4; probably derived from Stratum 3, -390cm	30,942 ± 478 RCYBP

Table 3. Radiocarbon ages of samples from Tsagaan Agui Cave, Bayankhongor aimag.

Alag Erdene 5v (Khavtsgait Agui) is the deepest known near-vertical cave in Mongolia and is located near Alag Erdene 5. This cave was explored by a Japanese expedition in 1997 (M Kitamura, personal communication). It is about 60m deep (Plate 9) and divided in two parts, an initial steep section, and a second part at an angle of 45°. The deepest part has a frozen pool and ice columns, and flows of ice are also observed. The cave system would be even deeper if the water were absent.

Alag Erdene 2 lies in an area of granitic intrusive rocks (Plate 10). Khovsgol aimag has many granitic intrusive rock units, mostly of Palaeozoic age. Distinctive surfaces that exhibit numerous holes and a rough texture, which characterize the granitic rocks in the study area, are interpreted as being caused by weathering. Caves in these granitic rocks appear to have been formed by active weathering.

Although not yet surveyed extensively, many other areas in Khovsgol aimag appear to have a high cave potential. For example, the Darkhadyn Khotgor Basin, west of Lake Khovsgol Nuur (Plate 3), contains vast areas of carbonate rocks (Fig.2) ranging in age from Late Proterozoic to Cambrian. Some of these outcrops were visited in 2002 and this confirmed their potential for caves, as they are commonly dotted with numerous small holes (Plate 11). This basin is also known to have hosted large palaeo-lakes in the past (Plate 12). Tsagaannuur 1 is located near the site of a former shoreline and its altitude is at approximately the same level as the flat plain in front of the hill in Plate 12, implying that the cave was submerged when the lake was present.

One of the most extensive carbonate outcrops in Mongolia lies southwest of Lake Khovsgol Nuur (Fig.2), mostly in Cambrian carbonate rocks. Some outcrops extend to 3000m a.s.l. or even higher. Most of this vast carbonate region is within a "Strictly Protected Area" set up by the Mongolian government to conserve and protect its unique ecosystem. Thus access by motorized vehicles is limited. Horseback travel is likely to be the most effective approach for any further exploration of this region.

Perhaps the longest cave known in Khovsgol aimag is Dajan Derchen Agui, located near the Uur Gol River in eastern Khovsgol. This cave was visited by an international team of cave explorers in 1994 and it was measured as about 300m long (Holúbek, 1995). A few other, smaller caves were noted by the team in the same area. Dajan Derchen Agui appears to be one of exceptions in Khovsgol aimag in terms of its use by humans, and it seems to have been used for a religious purpose. There is a lamaist-shaman altar at the entrance and "*ovoos*" are present inside the cave [an *ovoo* or *obo* is a collection of stones, wooden pieces and other items piled up to make a mound for a shamanistic offering to the gods]. Eastern Khovsgol has no very large carbonate rock units, but small outcrops are widely scattered and so potential exists for the future discovery of many caves.

Caves in the Gobi-Altai

Caves in other aimags than Khovsgol have been studied for scientific reasons. For example, in Khovd aimag, the cave complex at Khoit Tsenker has been recorded as one of far western Mongolia's most important localities, preserving a sequence proving prehistoric, possibly Pleistocene, human occupation (Alekseev, 1990). However, caves in Bayan Khongor (Derevianko *et al.*, 1996 1998 2000) are the most extensively studied, because of their archaeological significance.

The Gobi-Altai region includes extensive areas of primarily Devonian carbonate rocks, but some rocks may be younger, and others may be as

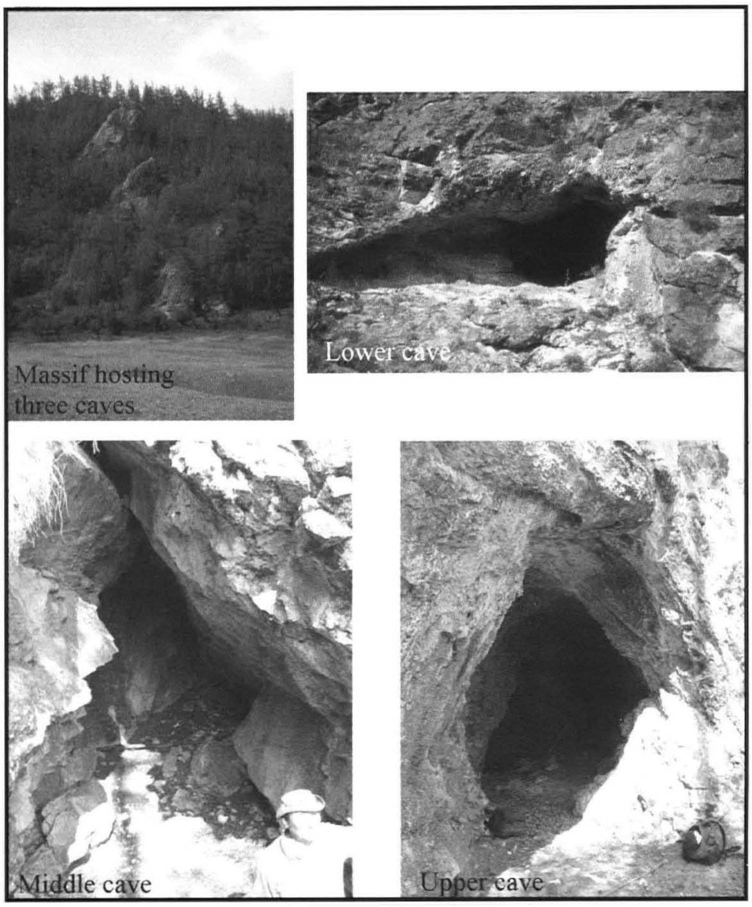


Plate 5. A carbonate hill hosting three caves, entrances of upper, middle and lower caves. Alag Erdene 5, Khovsgol aimag.

Sample number	Material and horizon	Age
AA-26580	Wood charcoal, Quadrat _/3, -112cm	27,432 ± 872 RCYBP
AA-26581	Wood charcoal, Quadrat E/3, -65cm	8,540 ± 95 RCYBP
AA-26582	Wood charcoal, Quadrat _/4, -84cm	8,847 ± 65 RCYBP
AA-26583	Wood charcoal, Quadrat _/2, -85cm	9,040 ± 85 RCYBP
GX-23893	Composite organic matter, Quadrat _/6, Stratum 1, -12 to -21cm	6,870 ± 105 RCYBP
GX-23894	Composite organic matter, Quadrat _/6, Stratum 3, -27 to -34cm	8,770 ± 140 RCYBP
SOAN-3569	Wood charcoal, Quadrat _/6, Horizon 2, Hearth 6, -36cm	8,940 ± 100 RCYBP
SOAN-3570	Wood charcoal, Quadrat _/6, Horizon 3, Hearth 10, -43cm	11,110 ± 60 RCYBP
SOAN-3571	Wood charcoal, Quadrat _/6, Horizon 3, Hearth 10, -54cm	11,160 ± 160 RCYBP
SOAN- 3572	Wood charcoal, Quadrat _/5, Horizon 1, Hearth 4	8,055 ± 155 RCYBP
SOAN-3573	Wood charcoal, Quadrat _/8, Horizon 2, Hearth 5	8,600 ± 135 RCYBP

Table 4. Radiocarbon ages of samples from Chikhen Agui Cave, Bayankhongor aimag.

old as Proterozoic. Among them, expedition members studied two caves of archaeological importance in Bayan Khongor aimag (Table 2), Tsagaan Agui (Plate 13) and Chikhen Agui (Plate 14).

Tsagaan Agui lies some 40km northeast of the centre of Bayan Lig suum [*suum* is an administrative unit equivalent to a district or county]. This cave occurs in a block of carbonate rocks bisected by a valley trending north–south (Plate 1). A dissolution cavity called Tsagaan Agui (White Cave) formed in dolomitic limestone consists of a narrow, inclined entryway, a lower grotto, a rotunda-like main chamber and at least two smaller chambers beyond the main rotunda.

Tsagaan Agui was discovered by a joint Soviet-Mongolian expedition in 1987. In 1988 and 1989, joint Soviet-Mongolian expeditions excavated a 16m x 2 to 6m trench spanning the drip line along the southern margin of the cave's inclined entryway. In 1995 the north profile of that trench was cut back an additional 50cm and was extended two metres east into the cave's main chamber. In 1996, the excavation in the main rotunda was extended to the east and west to determine the maximum depth of the culture-bearing deposits and resolve the degree to which post-occupational roof-fall has affected the underlying sediments. In 1997 and 1998 JMRAAE's focus of activity in Tsagaan Agui was to link the original Soviet-Mongolian sinkings of 1988–1989

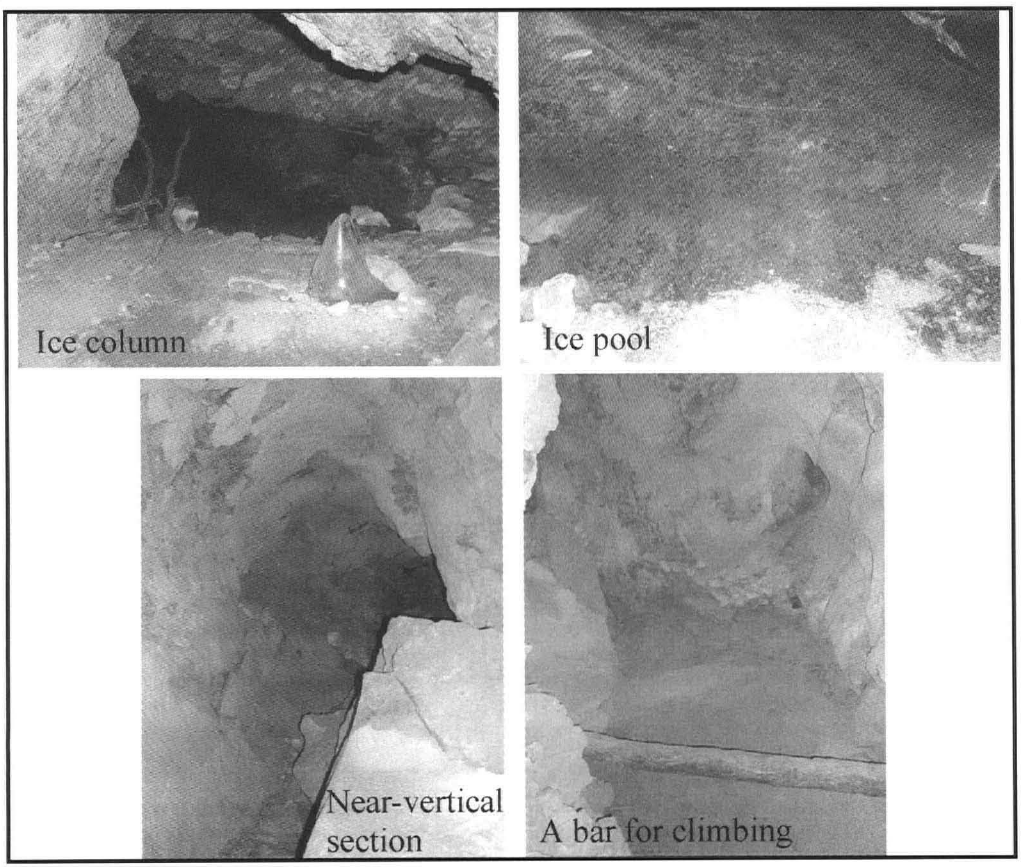


Plate 6. Inside the upper cave. Ice pool, ice column, near-vertical section, and a log for climbing in the steep section. Alag Erdene 5, Khovsgol aimag.

with the excavations of 1995–1996 to yield a continuous longitudinal profile of the cave's main chamber down to the bedrock floor of the dissolution cavity. In 1996 and 1997 Tsagaan Agui's innermost chambers were also tested. Bedrock and large blocks of dolomite debris occur at depths of up to four metres below the present surface of the cave interior. Erosional episodes related to an open chimney in the roof of the main rotunda and to sporadically active streams within the cave complex itself have had a profound influence upon the composition and distribution of the cave's sediments.

The cave's lower grotto was examined in 1995, yielding a small collection of stone tools, more simple typologically than those recovered from strata within the cave's main chamber. Based on this suggestive evidence, more extensive excavations were conducted in the lower grotto in 1997, 1998 and 2000, yielding many hundreds of artifacts. Sediment analyses conducted in conjunction with the 1995-1998 excavations suggest that the lower grotto principally contains redeposited materials from elsewhere in the Tsagaan Agui complex. Expanded excavations within the lower grotto confirm this hypothesis. The lower grotto appears to be a complex network of fissures and channels, some of which may well connect directly with the cave's main rotunda.

More than 3,400 stone artifacts were recovered in the Tsagaan Agui excavations in 1995–1998, in addition to perhaps twice that many pieces of debris and unused flakes. In 2000, almost 6,500 lithic artifacts were recovered from approximately 18m^3 of sediment removed from the lower grotto alone, suggesting that the lower grotto deposits probably represent concentrated redeposited material rather than a primary context assemblage.

Preliminary data from the year 2000 excavations at Tsagaan Agui reinforce several general conclusions drawn from analyses of archaeological materials from the four previous field seasons:

1. Raw material appears to be exclusively local (obtained from within just a few hundred metres of the cave entrance), consisting mostly of jasper and other cryptocrystalline quartz.
2. A stratified cultural sequence representing the late Stone Age/early Bronze down to the Middle Palaeolithic has been identified.
3. Tools recovered from the deepest strata consist mostly of flake scrapers, and comprise only a small portion (approximately 4%) of the lithic collection from these horizons.
4. Flakes were derived both from prepared platform "*Levallois*" and from polyhedral cores (Plate 15), with primary reduction having taken place outside the cave, principally at the source of the raw material.

The limestone massif containing Tsagaan Agui is littered with the waste products of lithic reduction. Jasper cobbles and boulders crop out above the cave entrance and many are surrounded by large primary flakes and smaller debris indicating in *situ* reduction. Detailed contour and scatter density mapping of this workshop was completed in 1996 and ongoing analysis of these data is proving instructive as regards the origins of raw materials encountered in the Tsagaan Agui stone industry.

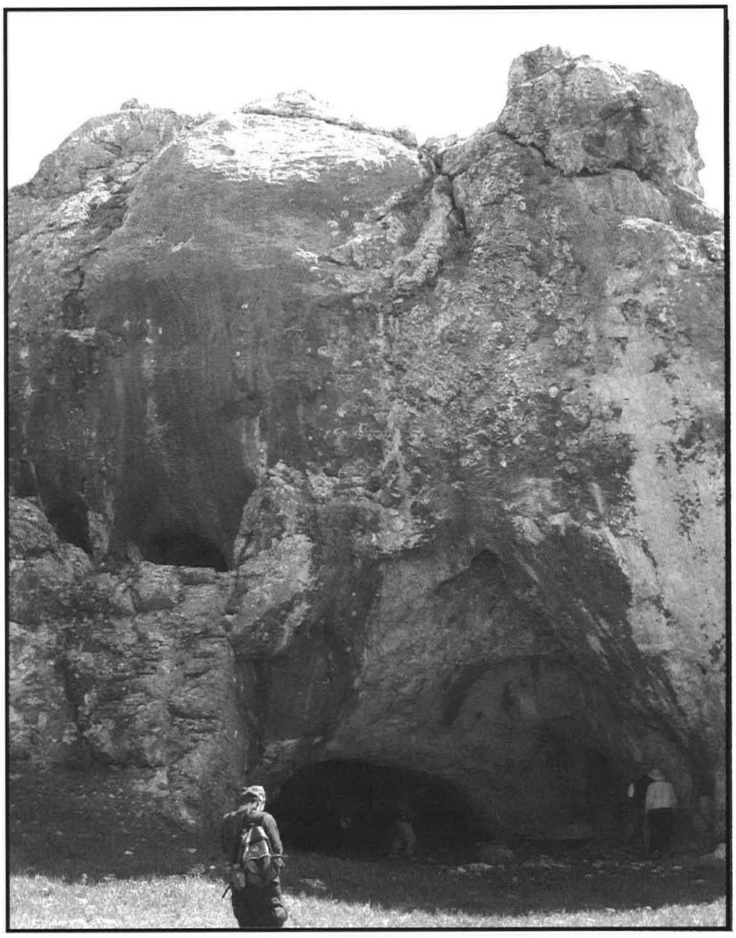


Plate 7. Carbonate outcrop hosting a complex cave called Hurtsyin Agui. Alag Erdene 7, Khovsgol aimag.

A large and diverse faunal collection recovered in the Tsagaan Agui excavations is currently undergoing analysis at the Zoological Institute of the Russian Academy of Sciences in St Petersburg, by professors G F Baryshnikov (large vertebrates), A K Agadjanian (microfauna) and A Pantelyev (avifauna). Thus far a wide range of mammalian and avian

Plate 8. Cave interior. Animal faeces, mostly sheep and goat, litter the floor. Egiin Gol 1, Khovsgol aimag.

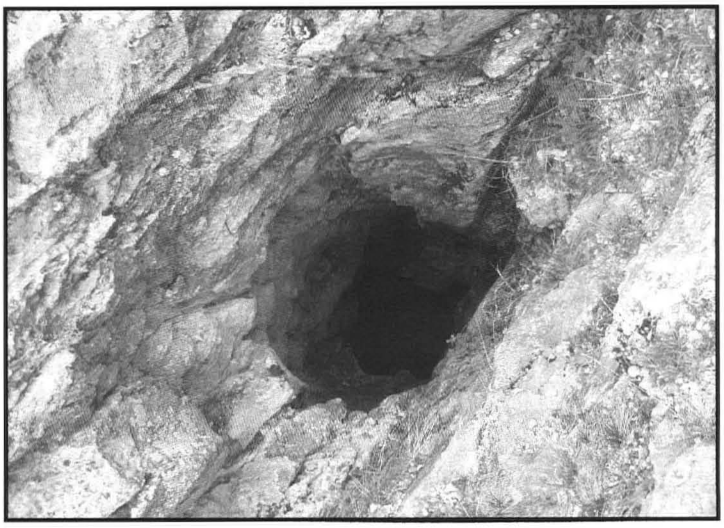


Plate 9. Entrance of the deepest known cave in Mongolia (Khavtsgait Agui). Alag Erdene 5v, Khovsgol aimag.

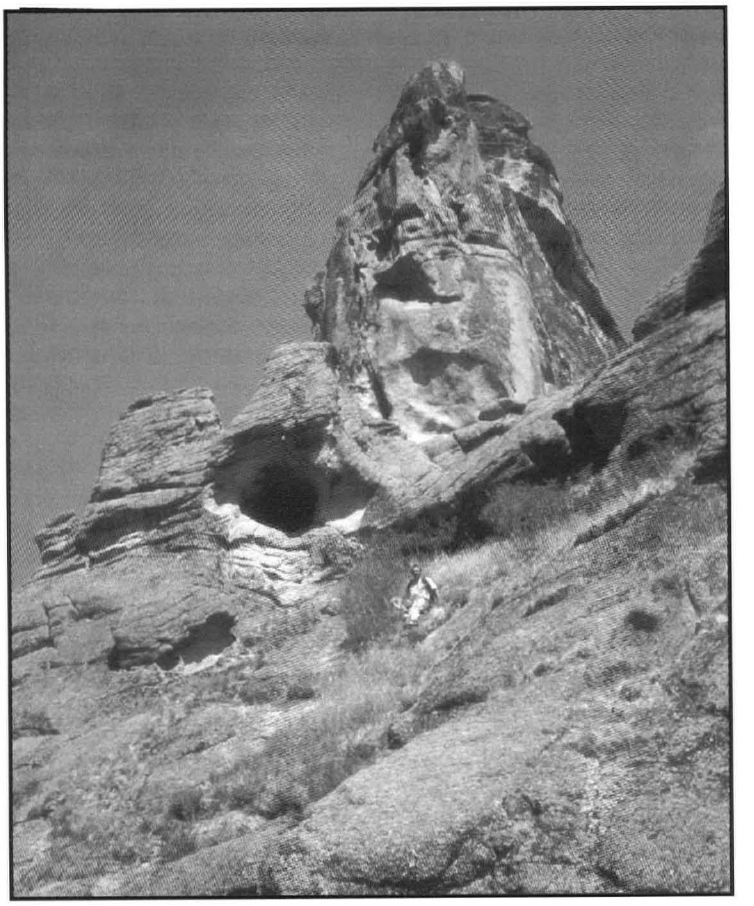


Plate 10. Entrance of a cave formed in granitic rock (smaller of two caves identified in this area). Note the rock surface with holes and a rough texture, which is interpreted as formed by weathering. Caves in this area appear to have formed at least in part by weathering of the rock surface. Alag Erdene 2, Khovsgol aimag.

species has been identified, many with important palaeoecological implications. These include the chiru or Tibetan antelope (*Pantholops hodgsonii*), which is currently restricted in its distribution to the Qinghai–Tibet Plateau, numerous rodents and 17 species of birds including the Saker Falcon (*Falco cherrug*), Blue Hill Pigeon (*Columba rupestris*), Pallas's Sandgrouse (*Syrrhaptes paradoxus*), Horned Lark (*Eremophilia alpestris*) and Rock Sparrow (*Petronia petronia*).

Six accelerator mass spectrometer (AMS) radiocarbon determinations are currently available for the main chamber in Tsagaan Agui (Table 3) and their ages suggest late Pleistocene affinity. One additional infinite radiocarbon date (>42,000 RCYBP, MGU-1449) was obtained using conventional methods on a wood charcoal sample from Stratum 5, about midway down the stratigraphic section within the cave's ramp-like entryway. Palaeomagnetic samples collected from the lower grotto are undergoing analysis in an attempt further to resolve the depositional history of that accumulation. Wood charcoal collected beneath and in contact with a stone slab feature of indeterminate function (altar?) yielded an AMS ^{14}C date of 3,820 ± 55 RCYBP (calibrated to 2460–2049 BC; AA-23160), suggesting late Neolithic or early Bronze Age use of the cave's deep interior, and perhaps use as a regular pilgrimage spot during the Buddhist period. The evidence for historic occupation includes clay votive tablets (*Tibetan tsa tsa*), scraps of birch bark texts, and inscribed sheep scapulae.

Chikhen Agui rock shelter is located in Bayan Öndör suum, approximately 30km north of the settlement of Shine Jinst. The rock shelter was discovered in 1995, by the JMRAAE, and tested in 1996 with full excavations conducted in 1997, 1998 and 2000. The rock shelter's longitudinal axis (WNW) is almost parallel to the axis of the ridge in which it is situated, but its entrance is south facing. Excavations produced a thin but clearly stratified sequence of cultural materials in the rock shelter itself and on the adjacent talus slope. Ranging from aceramic microlithic materials at the top of the sequence to Levallois-like prepared core flake-based assemblages (resembling early Upper Pleistocene sites in Siberia such as Denisova Cave, Kokorevo, and Kara Bom), the Chikhen Agui collections may contain technological evidence of the Middle-Upper Palaeolithic transition.

Seven conventional ^{14}C dates generated by the Russian Academy of Sciences and three AMS determinations performed at Arizona on samples from the upper culture-bearing stratum suggest a range of c.8,000 to 11,000 RCYBP for the microlithic component of the assemblage (Table 4). At present, only one AMS date for the lower culture-bearing stratum is available (AA-26580). This date suggests a much greater antiquity for the lower horizons. These dates provide a basis for preliminary interpretation of the prehistoric materials excavated in Chikhen Agui, and two interim conclusions can be reached:

1. The microlithic industry recovered in the three upper horizons may be broadly defined as Epipalaeolithic (i.e., terminal Pleistocene/early Holocene aceramic microlithic).
2. The large blade complex with Mousterian-like points recovered from Cultural Horizon 4 in Stratum 3 is best considered transitional — perhaps Middle to Upper Palaeolithic.

In 2000, JMRAAE team members excavated a buried open-air concentration of artifacts south-east of Chikhen Agui, above a narrow canyon leading to an active spring. The areal excavation encompassing more than 20m² yielded stratified stone tools similar to those recovered from Stratum 4 in the rock shelter and artiodactyl (*Gazella?*) bones to a depth of at least 30cm. This locality holds great potential for future excavation.

DISCUSSION

Cave formation and prehistoric archaeology in Khovsgol aimag
Considering that there are areas with large caves, including the more than 45km-long speleosystem Bolshaya Oreshnaya, the largest in Russia (Tzykin and Tzykina, 2001), in neighboring southern Russia, Khovsgol aimag, where bedrock geology has many similarities, could also host caves of great dimensions. However, despite the fact that there are extensive old carbonate rock units, wide (>10m) and long (>100m) caves are rare in Khovsgol aimag. It is possible that there are many unknown large caves, or simply that they are extremely rare. Cave formation is strongly influenced by local structural, stratigraphical, topographical and hydrological regimes (Gillieson, 1996). In the Russian Altai-Sayan Mountains, an irregularity of cave distribution in carbonate areas has been noted (Tzykin and Tzykina, 2001). Therefore, this may indicate that the factors contributing to cave formation in the vast carbonate outcrops in northern Mongolia and the Russian Altai-Sayan Mountains vary widely. The morphology of many caves studied in 2002 is clearly guided by the bedding planes of the parent carbonate rocks. Therefore, one potential problem is that the original strata are extensively deformed due to accretional processes and later mountain building. As a result, the bedding planes available for water transport are discontinuous. In addition, such circumstances also frequently lead to the destruction of previously formed caves. Water is another factor. Khovsgol aimag is an essentially periglacial environment; the extensive presence of permafrost is documented (Sharkhuu, 1998). Cryogenic processes such as frost heaves, cracks, icing, thermokarst, solifluction and stone polygons are also common in the permafrost zone of Mongolia (Sharkhuu, 2002). Water is commonly found in a frozen state, frequently at levels higher than the local water table. In this way, many passages to deeper cave levels are blocked. Interestingly, permafrost in the Selenge River basin, including the Khovsgol Nuur area, has experienced degradation in recent years (Irkutsk State University *et al.*, 1989). If this trend continues, permafrost with current thicknesses of 15 to 20m will disappear by the middle of the 21st century (Sharkhuu, 1998). Of course, potentially, this circumstance could also lead to the opening of passages in some caves. The local nomads' metaphysical

Plate 11. A carbonate massif with many holes in its rocky surface. Southern Darkhadyn Khotgor Basin, western Khovsgol aimag.

and practical perceptions of caves may also contribute to the difficulty in identifying large caverns. For example, pastoralists often intentionally fill in vertical shafts, since they pose significant dangers for the domestic animals that nomads rely upon for their livelihood. Some Mongols also prefer that foreign explorers do not enter caves if they are considered sacred. Caves used by Buddhist lamas as sanctuaries and retreats exist in many parts of Mongolia. These factors may lead to the deliberate hiding of caves in many regions.

Although cave formation can occur above, at, or below the water table (Palmer, 1984), this horizon is still very important for the development of caverns. The palaeohydrology of northern Mongolia during the Quaternary epoch is complex, to say the least (Grosswald, 1999; Komatsu *et al.*, submitted). For example, the water table of the region fluctuated throughout the Quaternary, notably due to extensive glaciation. The most significant apparent fluctuations in this region are the formation of glacier-, landslide- and even possibly lava-dammed lakes in the Darkhadyn Khotgor Basin (Plate 12). These lakes formed as a result of the damming of the headwaters of the upper Little Yenisei River (the Shishigt Gol). Lake surfaces seem to have reached 1720m a.s.l., or 150 to 200m above current lake levels (Grosswald, 1999). Even higher palaeo-lake levels may have existed. A new field study has found that recent dammed-lakes may have formed at 9200 to 9500 RCYBP and 32,000 to 40,000 RCYBP (A R Gillespie, personal communication), and older dammed-lakes are likely to have existed. These palaeolakes appear to have experienced catastrophic drainage down the Yenisei River, similar to events that occurred in the Altai (Baker *et al.*, 1993; Rudy, 2002). Fluctuation of regional water tables as a result of climatic changes and permafrost formation and melting can make understanding cave formation processes very difficult. Clearly, this is a research topic that warrants further investigation.

The presence of granitic caves in north central Mongolia is also interesting. In the area of granitic outcrops studied in 2002, a rock surface pattern similar to tafoni is common. Tafoni is a weathering pattern and this weathering occurs as both physical and chemical processes. The physical process includes frost shattering and expansion of minerals comprising granites through temperature fluctuations and hydration, and the growth of halite from the accumulation of soluble NaCl. Halite, in particular, has a very large thermal expansion coefficient. Salts may have been supplied from the nearby saline Lake Erhel Nuur area (Plate 2). The crystal growth leads to the loosening of

Plate 12. Lacustrine strandlines formed in a carbonate massif. Note person for scale (arrow). Darkhadyn Khotgor Basin, western Khovsgol aimag.

rocks. If the supply of moisture is abundant, chemical weathering becomes more significant, and granitic rocks saturated with moisture lead to the chemical weathering of minerals. As a result of suction from evaporation during dry periods, the solutions that have reached the surface cause a hardening of the intergranulars, on and near the surface, by iron hydroxide and silica. The chemically weathered and now softened rock material breaks down behind the hard weathering crust and leaves tafoni hollows. Two caves and smaller cavities identified in the granites appear to be at least partially linked to this weathering process. Caves in granites are rare in Khovsgol aimag, but since granites are distributed widely in this region, additional reconnaissance is recommended.

Another important aspect of caves in Khovsgol aimag is that evidence of human occupation is rare, even in the historic period. This is unusual, since evidence of ancient human activity is common in the region. For example, in 2002 the expedition located a large number of late Palaeolithic and Neolithic sites all over Khovsgol aimag (unpublished). However, the majority of the caves in this aimag appear to have been unused by prehistoric humans. Even occupation during the historical period may have been uncommon, except for occasional use by Buddhist clergy during meditational retreats. This situation is in stark contrast to caves in the Gobi-Altai (Derevianko *et al.*, 1996, 1998, 2000) and the high Altai (Chlachula, 2001), where evidence of human occupation extending well back into the Pleistocene is widely documented. The known caves in Khovsgol aimag are not large, but certainly large enough for human occupation, based on evidence from caves excavated elsewhere in Central Asia. Explanations for the lack of archaeological materials in these caves may include:

1. caves in Khovsgol aimag do not usually occur near the sources of high quality raw materials (such as quartzite, chert, obsidian, etc.) for the production of stone tools;
2. cave entrances are located too far from local water sources, and
3. periodic inundation of caves by water or ice during various palaeo-climatic intervals.

The third point has important implications for future archaeological work in the region. In some areas, the local water table is known to have fluctuated tremendously, as discussed above. Therefore, in the search for additional archaeological sites, past water tables must not be assumed to have mimicked present-day circumstances. Presence of ice deposits in caves may block access to deeper sections on the one hand, but they could also preserve archaeological materials in excellent conditions. From this point of view, the future search for archaeological sites in ice-filled caves should not be excluded.

Use of caves by humans in Mongolia

The presence of rich Palaeolithic and Neolithic archaeological assemblages in the Gobi-Altai region of Mongolia implies favourable palaeoenvironmental circumstances, access to high-quality stone raw materials, and the presence of sufficient surface water to support low-density human populations. One significant parameter, the presence of surface water is attested to by the presence of extensive palaeo-lakes in currently arid environmental niches (e.g., Komatsu *et al.*, 2001). Whether or not ancient humans really used caves in Khovsgol aimag is not fully determined and this point requires further more detailed investigations. But the Quaternary palaeohydrological history of northern Mongolia is very complex and water must have been the essential factor affecting the human occupation in this region as well.

It is clear from the extant archaeological record that humans have utilized and occasionally inhabited caves in Mongolia from the Middle Palaeolithic down to the historic period. A spectrum of archaeological materials in interpretable geological contexts suggests that in palaeo-ecological settings ranging from the Gobi Desert to the mixed steppe-taiga zone of northern and far western Mongolia, early human populations focused subsistence, foraging, resource collection and, from time to time, residential activity on cave complexes. Ancillary evidence, such as associated pictographs and petroglyphs (Jacobson *et al.*, 2001) corroborate a reconstruction of prehistoric human lifeways in many areas of Mongolia that circulated around cave complexes to varying degrees.

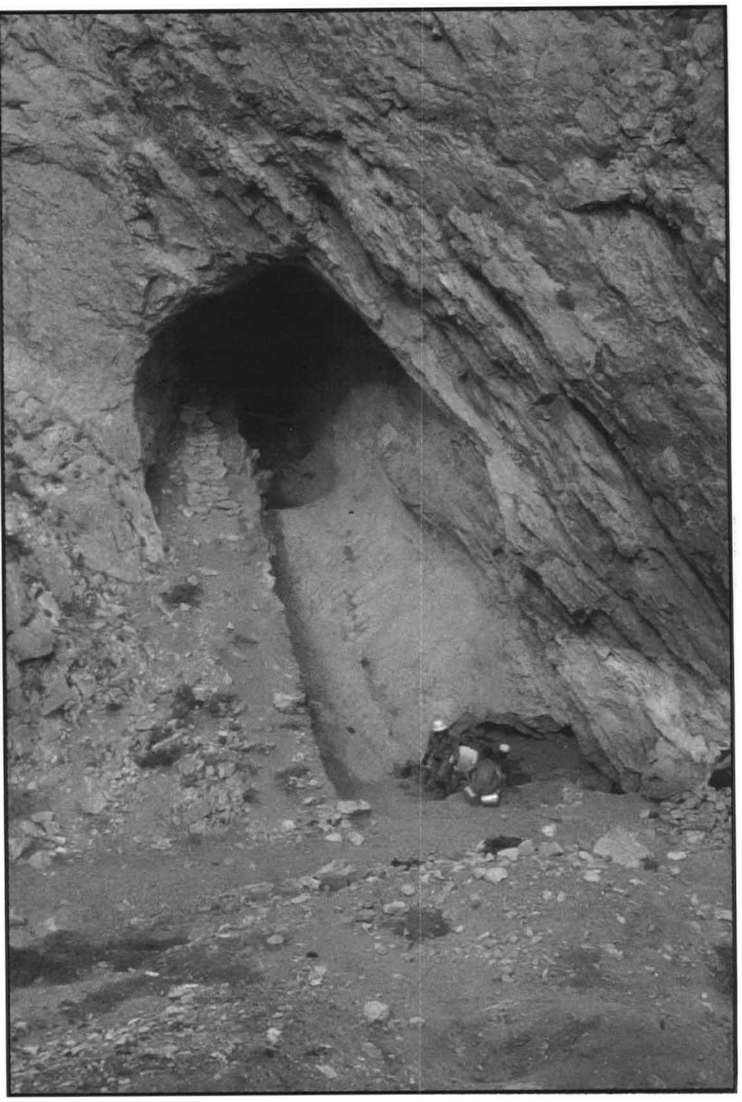
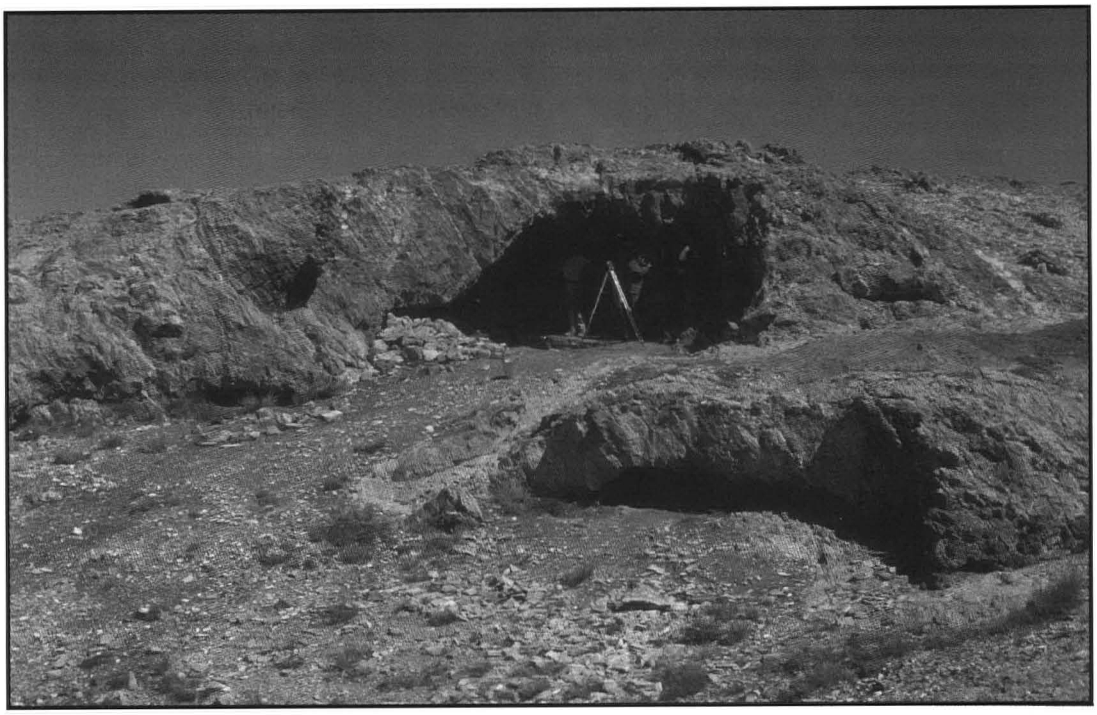


Plate 13. Tsagaan Agui Cave exterior as seen from the northeast, Bayan Khongor aimag.

CONCLUSIONS

Carbonate rocks are widespread in Mongolia, particularly in Khovsgol aimag where such rock types are especially common. Due to its cave potential, Khovsgol aimag has been visited by a limited number of cave explorers in the past. However, scientifically-based speleological investigation of the region is still in its infancy. The 2002 Expedition members conducted preliminary surveys of caves in several areas of the aimag, documenting their dimensions and geological contexts. Caves in this region are relatively small (<100m long) and their physical layouts are principally determined by the stratigraphical structures of the host rocks. Archaeological materials appear to be rare, at least within the caves investigated in 2002. The area covered by the survey is relatively small, leaving great potential for future discovery of large cavern complexes. Scientific opportunities for speleologists are also abundant in Khovsgol aimag, particularly from the point of view of caves in periglacial environments with great fluctuations of palaeohydrological conditions. Caves in the Gobi-Altai have been more extensively studied in the past. Two caves in particular, Tsagaan Agui and Chikhen Agui have yielded abundant archaeological evidence of human occupation from the Middle Palaeolithic to the historic period. This implies environmental conditions more favourable for human occupation in the past; conditions presumably better than those that characterize the Gobi-Altai today.

Plate 14. Chikhen Agui rockshelter exterior, Bayan Khongor aimag.



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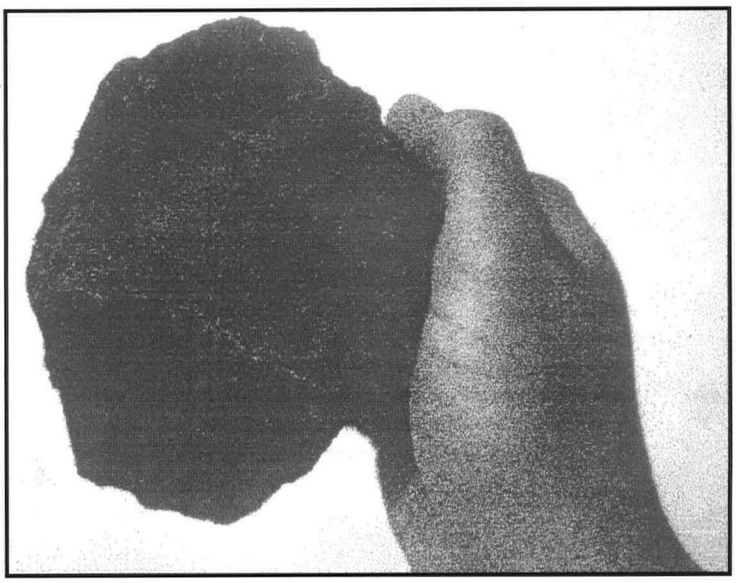

Plate 15. Palaeolithic polyhedral flake core from lower deposits at Tsagaan Agui Cave, Bayan Khongor aimag.

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The Kingsdale reindeer revisited.

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Abstract: Limited surviving evidence for the occurrence in the West Kingsdale Master Cave of reindeer bones, deriving from a species supposedly extinct for 8000 years, is re-examined and described. Indisputable examples of reindeer remains recovered from other caves in northwest Yorkshire are discussed. The nature and ages of these specimens, when compared to recently collected bone samples from the West Kingsdale System and a photograph of some of the original Master Cave finds, cast doubt upon the reliability of the West Kingsdale reindeer identification.

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INTRODUCTION

Arguably the West Kingsdale Cave System is the finest example of integrated underground drainage so far explored in the north of England (Fig.1). Influent streams from at least five caves combine at River Junction and flow through the Master Cave before entering the active phreas behind Keld Head. The section of the West Kingsdale Cave System between Swinsto Hole and Keld Head has been proposed as the type example of cave development in the Yorkshire Dales (Waltham *et al.*, 1981). At River Junction streams from the individual feeders of Simpsons Pot and Swinsto Hole meet with the combined inputs of Rowten Pot, Jingling Hole and Yordas Cave. A detailed account of the morphology and development of the system is given in Waltham *et al.* (1997) and Brook (1974).

During the initial exploration of the West Kingsdale Master Cave in 1967 (a detailed account is given in Brook and Crabtree, 1969) bones were retrieved from banks of sediment (described as "shingle") in the region of the Master Junction (Fig.2). The bones were identified as reindeer and assigned an age of at least 8000 years (Brook and Crabtree, 1969; Brook, 1974). The identification of the bones took place in Bristol and the bones were not returned to Leeds. Recent enquiries have failed to locate the bones or establish who made the identification, but have confirmed that they are not in the University of Bristol Spelaeological Society collection.

DISCUSSION

Reindeer remains are actually quite rare finds in caves in northwest Yorkshire. Re-examination of the bone collections recovered from nearly thirty caves in the area has identified reindeer specimens from only four caves. Early archaeological excavations in caves near Settle produced reindeer remains from three sites. During the large-scale excavations at Victoria Cave in the 1870s reindeer bones and antlers were reported from inside the cave on the surfaces of laminated clays believed to be of glacial origin (Tiddeman, 1875, 1876). Re-examination of the finds from the 1870s excavations at Victoria Cave has established that reindeer remains were also found in the breccia at the cave entrance. Two specimens from the entrance breccia have been dated directly by the AMS radiocarbon technique. The results indicate the presence of reindeer in the vicinity of the cave during the declining phase of the Late Glacial Interstadial, about 13,000 years ago (Hedges *et al.*, 1992).

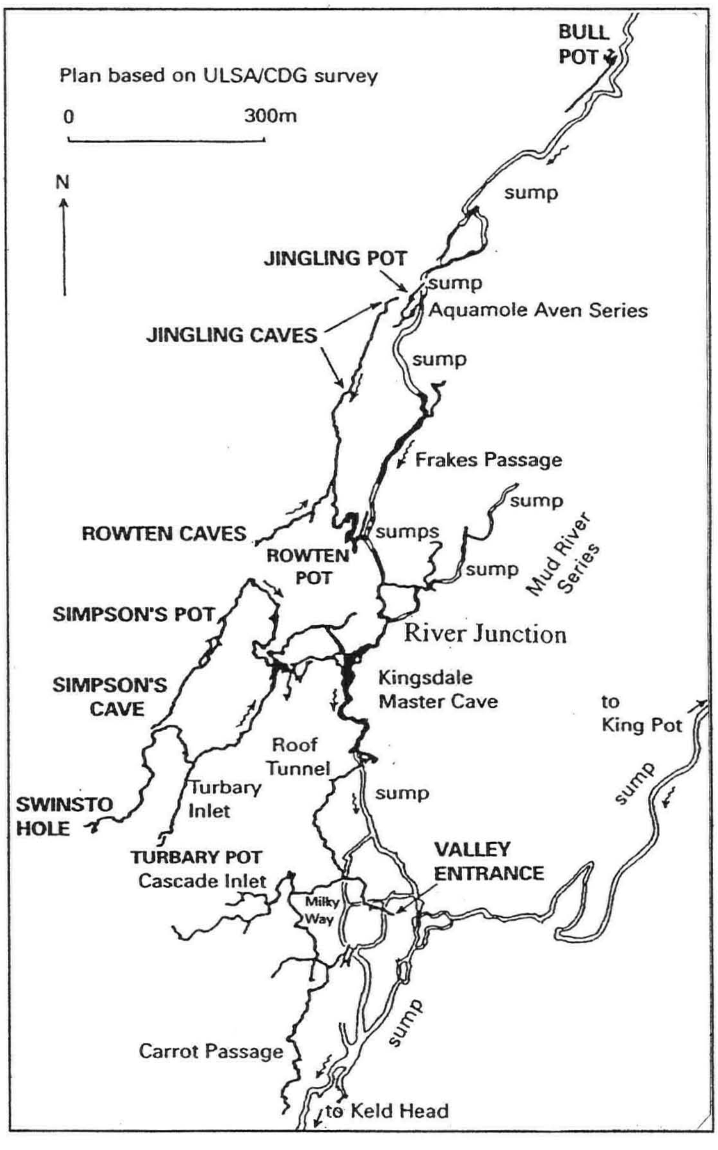

Figure 1. Plan of the West Kingsdale Cave System. Reproduced from Brook et al., 1994, with permission.

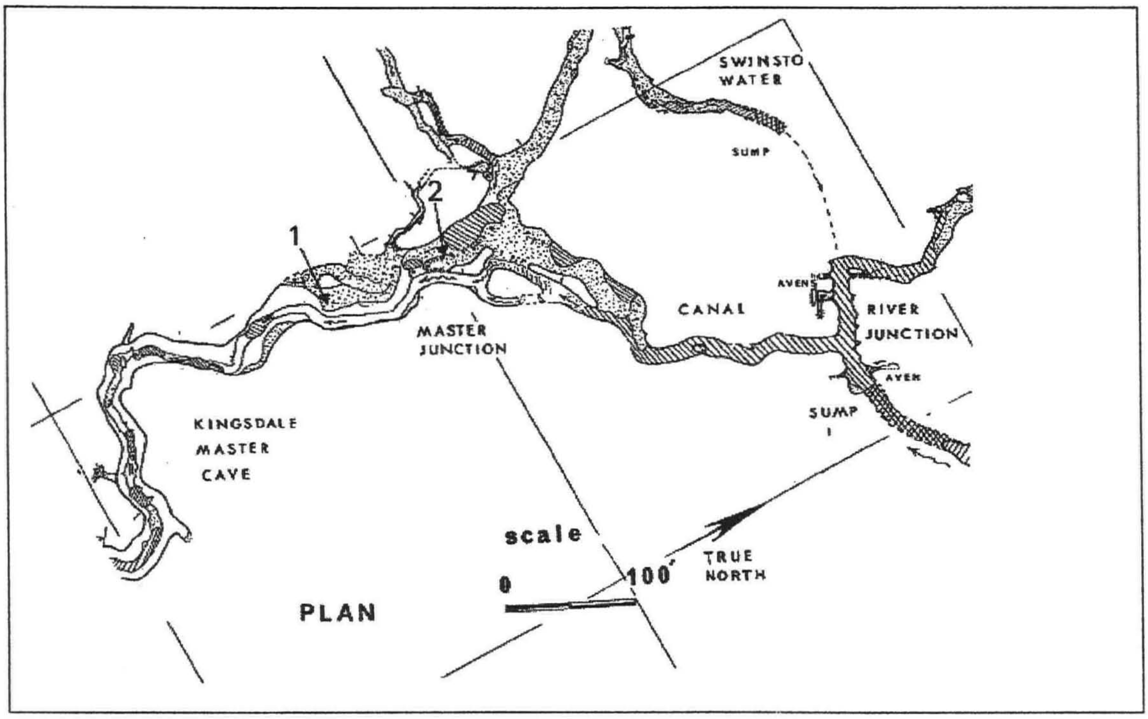

Figure 2. Plan of the upstream part of the West Kingsdale Master cave. Reproduced from the University of Leeds Speleological Association survey.
1. Location of the bones recovered in 1967
2. Location of the bone recovered by P. Murphy and J. Nasse 17/12/2001.

Similar unpublished AMS radiocarbon dates have been obtained on reindeer specimens excavated in the 1920s and 1930s in two caves on Giggleswick Scar. Here the reindeer remains were clearly sparse. The dated specimens consist of a reindeer antler fragment from Kinsey Cave (Jackson and Mattison, 1932) and a previously unidentified reindeer pelvis fragment from Sewells Cave (Raistrick, 1936). The excavators record finding reindeer remains above glacial clays at both caves.

The largest collection of reindeer specimens from the area consists of the material found during extensions to the show cave at Stump Cross Caverns. In the 1950s the remains of a number of reindeer that must have fallen from the surface were found in sediments partly filling a narrow rift. At the time the remains were considered to be Late Glacial in age (Collins, 1959). However, an unpublished ASU date of about 30,000 years on a cap flowstone formed above the bones suggests they are considerably older (Angela Rae, Pers. Com.). Elsewhere in the show cave, ASU dates on associated stalagmites indicate an age of about 80,000 years for a reindeer bone and remains of bison, wolverine and wolf excavated in the Bowling Alley Passage in the 1980s (Sutcliffe *et al.*, 1985).

Given the relative rarity of reindeer remains in caves in the area, and the dating evidence supporting the presence of reindeer at different times in the Late Pleistocene, the claim that reindeer remains were found in the West Kingsdale Master Cave is of considerable interest.

A 35mm slide of the Kingsdale bones, taken shortly after they were recovered and before being sent to Bristol, shows several bones and a possible tooth (Fig.3). The largest bone is a complete metatarsal of a large form of wild or domestic cattle or, just possibly, a bison. Behind this bone is a shaft of a large limb bone with the articulations missing. It is possibly a metacarpal of the same species as the metatarsal. There is also a large limb bone fragment. All three bones are clearly not reindeer. There are also two or more smaller pieces of bone that are difficult to make out, and also a tooth. The tooth, which is possibly a lower third molar, is much too large to be reindeer. Whereas the species

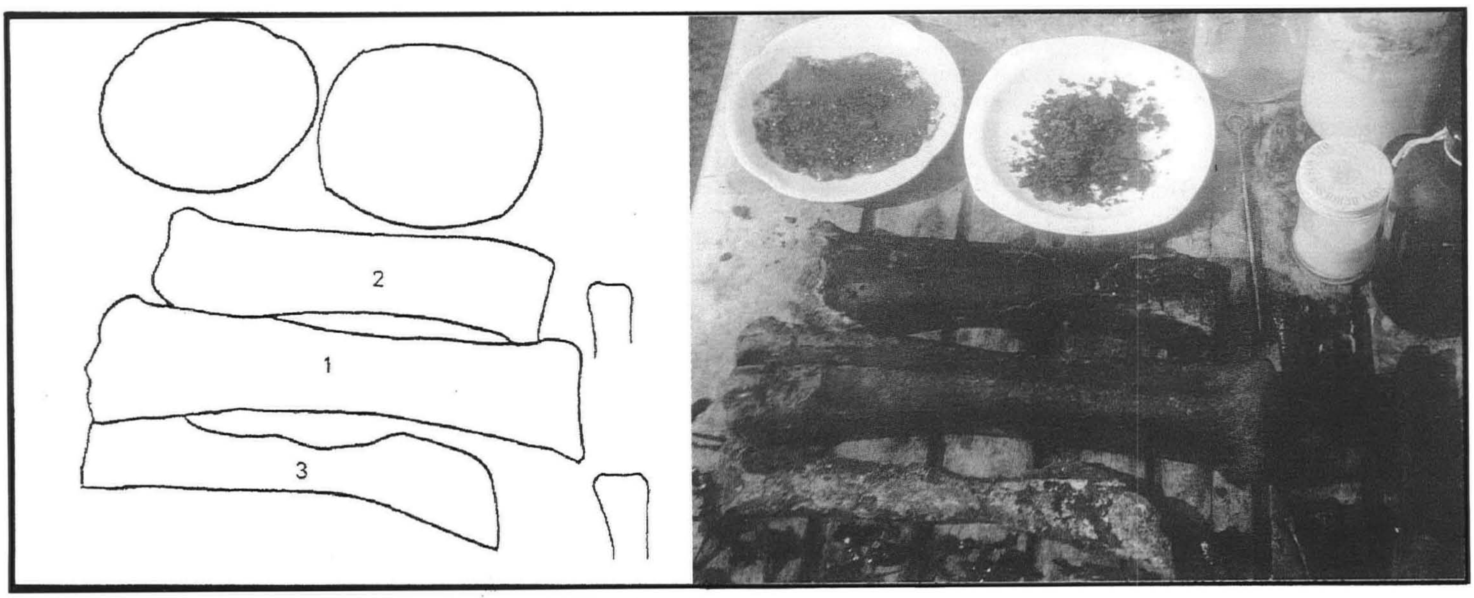

Figure 3. The 35mm slide image showing some of the bones recovered in 1967.
1. metatarsal. Cattle or possibly bison
2. damaged metacarpal (? same as No. 1)
3. ?tibia of unknown affinity

of the bones in the photograph cannot be determined precisely, the larger bones and the tooth are clearly not reindeer. This must cast considerable doubt on the original claim that reindeer bones were found in the West Kingsdale Master Cave. The most likely explanations are that the bones were never properly identified, or that the identifications were subsequently misreported. Had a competent bone specialist seen the material, then the presence of large cattle bones would certainly have been noted.

A visit to the site of the original discovery resulted in the recovery of a distal fragment of a left scapula identified as *Equus* sp. 10m upstream of the previous finds (Fig.2). A horse tooth found outside Keld Head (the resurgence for the West Kingsdale System), believed to have been recovered from within the phreas by an unknown diver (Cordingley, 1999), is a permanent upper second premolar, left side. The colour of the horse bone resembles that of the bones recovered in 1967. Carbon dating of the scapula fragment has shown it to be less than 200 years old (University of Waikito No. WK-10730).

Skeletal material could enter the cave system via any one of several pothole entrances upstream of the River Junction and then be transported downstream. In the River Junction area the sediments consist of pebble- and cobble-grade material in a sandy matrix. The bone fragment recovered in 2001 was from the upper part of a sediment bank, and several pebbles had to be moved in order to retrieve the bone. It was not incorporated into the sandy matrix. Recent material can become incorporated into older unconsolidated sediment (e.g. Pirrie *et al.*, 2001). No signs of excavation can be seen at the site of the original discovery, suggesting that the bones were on top of the sediments, but flooding of the area may have obliterated any evidence.

CONCLUSIONS

No evidence of reindeer is shown on the 35mm slide or was found on revisiting the site of the 1967 discovery. Because the photograph does not include all the bones found in 1967, the occurrence of reindeer bones cannot be ruled out, but the available evidence points to a much younger age for the bones than the 8000 years quoted by Brook and Crabtree (1969) and by Brook (1974). The recent date for the scapula fragment shows that skeletal material has entered the cave system much more recently, and shows that appearance is no guide to the age of bones recovered from cave environments.

The loss of the original material emphasizes the importance of proper recording and conservation of skeletal material recovered by cavers, to allow future scientific study of any such deposit.

ACKNOWLEDGEMENTS

This research was supported by a grant from the British Cave Research Association Research Fund. Mr J Nasse provided invaluable help with fieldwork and G J Mullan provided information on the University of Bristol Spelaeological Society museum collection. Andrew Chamberlain, of the University of Sheffield, undertook the identification of the tooth from Keld Head.

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Decoupled density stratified groundwater circulation on the Caribbean coast of the Yucatán Peninsula, Mexico

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Coastal carbonate aquifers are density stratified with a thin fresh water lens that floats on top of higher density saline water. The conventional Dupuit-Ghyben-Herzberg (DGH) model indicates that coastward discharge of fresh water entrains the underlying saline water, thus inducing a deep saline return flow from the ocean into the aquifer. Regional observations of saline groundwater temperature on the Caribbean coast of the Yucatán Peninsula, suggest that warm ocean water derived from the Caribbean Sea circulates to >9km inland prior to thermal equilibration. Incorporation of saline groundwater in the overlying fresh water occurs progressively seawards at a relatively slow rate, but within 1km of the coast there is a much more rapid incorporation within the discharging fresh waters. These observations may be interpreted to accord well with the conventional DGH circulation model for density stratified coastal aquifers. However, detailed in situ monitoring of groundwater velocities and dye tracing strongly suggest an alternative model, in which at least some of the saline groundwater is recharging via inland flow immediately beneath the saline-fresh water interface in the caves. This occurs during periods of rising net ocean-level, with saline discharge occurring when ocean levels fall. Fresh groundwater discharges at all times, the fresh and saline flows being decoupled, rather than the fresh water simply entraining saline groundwater flow. Sustained inland flow of saline water can occur, with subsequent mixing leading to potential contamination of the freshwater lens, coastal outlets, and the barrier reef systems, all of which are essential resources for the rapidly expanding local population and tourism industry on the Caribbean Yucatán coast.

Predictive modelling of archaeological caves

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In recent decades predictive modelling has been developed and deployed as a powerful tool for landscape archaeology and cultural resource management. The essence of predictive modelling in landscape archaeology is to identify combinations of topographic and environmental variables that together are correlated with – and hence predictive of – the occurrence of archaeological sites. Most case studies in archaeological predictive modelling have used logistic regression to estimate the probability of archaeology being present, as this regression method yields estimates that range in value between zero (maximum likelihood of site absence) and one (likelihood of site presence). The regression coefficients for the individual variables can be interpreted as weights or scaling factors, which encapsulate the contribution that each environmental variable makes to the overall probability of archaeology being preserved at a particular location. A preliminary test of archaeological predictive modelling has been carried out on a set of caves located within a short (4km) section of the Manifold Valley in Staffordshire. The area was surveyed intensively on behalf of the National Trust by professional archaeologists in 1989–92 with a view to identifying the archaeological potential of all of the cave sites in the survey area. The dataset includes 84 field-visited caves, of which 17 are classified as archaeological and 67 as non-archaeological. Statistically significant associations with environmental variables include the concentration of archaeological caves at higher altitude locations and with cave entrances positioned on less steep slopes and with aspects facing towards the northern quadrants. Possible explanations for these associations are proposed.

Constructing a karst drainage system: Agen Allwedd

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Water characteristics can be used to assess the source and type of water inputs in a karstic aquifer. This study investigated the waters of the Agen Allwedd streamway, to infer the physical structure of the aquifer. Thirty-seven sampling sites were selected. Of these twenty-five were in Agen Allwedd, eight on the peat moorland above and four at the resurgence. Samples were collected four times between July 2002 to October 2002. Conductivity, temperature, pH, alkalinity, calcium, magnesium, manganese and iron content were measured, with calcium to magnesium ratios and colour being used to differentiate between diffuse, fissure or conduit flowpaths. These water characteristics from Agen Allwedd were distinctive, relative to similar studies, for a considerable distance into the cave. The water characteristics do suggest particular inlets have rapid response times, which may have important implications for flooding and pollution events in the cave.

In addition flow-depths up and downstream of the major Cascade Passage inlet were recorded hourly over an eleven-week period until mid-November 2002. The lag time between rainfall events on the Llangattwg escarpment and rising pool depth was assessed. Response to rainfall was substantially more complex than suggested by the water characteristics. For example at Cascade Passage Pool there appear to be at least two distinct responses to rainfall events. At various points during the study period, water depths within the cave actually rise before the rainfall event starts.

"The ins and outs of Ogof Draenen": a study of cave speleogenesis

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Discovered in 1994, Ogof Draenen is now one of the longest caves in Britain, with a length in excess of 70km. At the time of writing it is among the twenty longest caves in the world. Like other great caves, Ogof Draenen has had a complex multi-phase history. The proposed genetic history described here is based on speleo-morphological observations throughout the system. Evidence of at least four phases of cave development, associated with major 180° changes in flow direction and resurgence location can be identified. Joint control has had a dominant influence on passage genesis. In particular it has facilitated the development of maze networks and remarkably shallow, horizontal phreatic conduits. The amplitude of these conduits is much shallower than predicted by models based on flow path length and stratal dip. Here, we suggest that presence of laterally extensive open joints, orientated perpendicular to the regional neotectonic principal stress field, determines the depth of flow in the aquifer. Geomorphic observations of former water-table levels in the cave can be related to surface changes in the landscape. This offers a far more detailed landscape evolution chronology than previously available, and suggests that the highest parts of Ogof Draenen are of the order of 1 - 1.5 million years old.

How common is diverging flow in karst aquifers?

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Most models of permeability development in karstic carbonate aquifers are based on an assumption that groundwater flows through a dendritic network of conduits and targets a single, integrative, outlet spring. Whereas it is recognized that a single conduit may discharge through a number of distributary springs and these may exhibit underflow and overflow characteristics, it is rare to find acknowledgement or discussion of karst aquifers in which water sinking at one point flows in two or more completely divergent directions. It is possible that this lack of consideration is a consequence of a failure to recognize and monitor all possible outlet points when designing water tracing experiments. In addition, most workers aim to use the minimum possible amount of tracer to avoid visual coloration at the spring. This can result in a failure to detect divergent flow. For example, if 90% of water entering sink 'X' flows to spring 'A' and the remainder to springs 'B' and 'C' then, if the amount of tracer injected at 'A' is just sufficient for detection at 'A' it is likely to be below the limit of detection at 'B' and 'C'. The situation is made worse if the discharge from springs 'B' or 'C' is larger than that from spring 'A'. Repeated tracing experiments in the Cuilcagh Karst (County Fermanagh, Ireland) and in the Peak District (England) have shown that both allogenic and autogenic recharge may target multiple springs several kilometres apart and in completely different drainage basins. This has implications both for models of speleogenesis and karst aquifer evolution and for pollutant dispersal modelling and source area protection.

Coupled ESR- and U-series-Dating of equid teeth from archaeological sites

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Many caves are known as important archaeological sites where remains of early human settling are found. Beyond the limitations of radiocarbon dating of about 40ka there are few dating methods that can be applied to fossil materials. In archaeology, ESR-dating of tooth enamel and carbonates is of particular interest.

The ESR-dating method is based on the accumulation of radiation-induced storage of unpaired electrons in the crystal lattice. Teeth in sediments are naturally irradiated, resulting in an absorbed dose DE (equivalent dose). The dose rate D is determined by means of the concentration of radioactive nuclides in the teeth and surrounding sediment as well as by cosmic rays.

The basics of the ESR-dating method and applications to samples from cave deposits (e.g. Vogelherd (Germany), Bockstein (Germany), Cueva de la Cariguela (Spain)) as well as other archaeological sites (Achenheim, Gramat, Bramefond (France)) will be presented. The potential of the dating method is discussed, with a particular focus on problems associated with the open system behaviour of teeth.

Palaeohydrology in the Eastern Mediterranean from speleothem fluid inclusion D/H analyses

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The Eastern Mediterranean region, being located in a climate transition zone, was very sensitive in the past to environmental changes such as temperature, amount of rainfall, pattern and origin of storm tracks and changes in the desert boundary, and thus Israel is an ideal location for the study of palaeoclimate change. In order to predict future climate change in an area where human societies and their activities are profoundly influenced by the migration of the desert boundary and the availability of water, it is necessary to reconstruct and understand the continental climate of the past, based on a variety of proxy data.

Speleothems are climate-sensitive cave carbonate deposits that record the average surface temperature. The stable isotope composition of speleothems are influenced by temperature, as well as the isotopic composition of the rainfall (D/H and $^{18}O/^{16}O$), soil-water interaction and isotopic fractionation in the upper vadose zone. The aim of this study is to gain an understanding of the palaeohydrological conditions in different climatic zones in the Eastern Mediterranean region at various times in the past. This has been achieved by the analysis of the isotopic composition ($\delta^{18}O$) of the speleothem calcite and of the coeval speleothem fluid inclusions, (D/H ratios) which act as a proxy for the isotopic composition of the palaeo-rainwater from which the inclusion originated.

The speleothems chosen for this study are from a variety of climatic regimes in Israel and formed during distinct time periods during the past 130 ka, covering 3 glacial and 2 interglacial periods. The fluid inclusions were extracted and analysed by thermal decrepitation (heating calcite under vacuum) (Matthews *et al.*, 2000) and a technique of vacuum crushing was also applied and further developed (Dennis *et al.*, 2001).

The results (δD vs. $\delta^{18}O$ variations) show a significant range in their isotopic composition but these changes broadly parallel variations observed in present-day rain and cave waters in Israel and suggest the rainwater had its source in the Eastern Mediterranean. In addition the samples show climatic zoning. The isotopic composition of the samples taken from northern Israel reflect the high elevation and rainfall at this site while those of samples taken at the desert boundary clearly indicate the high evaporation and low precipitation in this climate. A temporal trend is also seen in which speleothems formed during interglacial sapropel (wet) periods have isotopic compositions reflecting the markedly higher rainfall during these periods, which is in contrast to those speleothems that formed during glacial conditions.

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Speleothem geochemistry and morphology as indicators of variations in rainfall during the Holocene in semi-arid regions

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There is currently a need for more information regarding climate change during the Holocene. Changes in rainfall regime are particularly important in semiarid regions such as southeast Spain. Speleothems provide useful tools for studying variations in precipitation as they can be dated accurately and allow several parameters to be exploited.

Geochemical and morphological characteristics of selected speleothems will be examined from selected active sites, together with theoretical aspects of speleothem growth published in general literature. These will be compiled to formulate criteria that will be applied to selected speleothems in order to attempt qualitative analysis of rainfall variation during the Holocene in southeast Spain. The criteria developed will be based around overall speleothem morphology, specific trace element concentrations e.g. magnesium/calcium ratios, isotopic signatures e.g. $\delta^{18}O$ and the relative chemistry and structure of individual laminae within speleothems.

The overall output of this research should be a set of improved criteria for application in semiarid regions, which allows analysis of changes in past rainfall regimes. Wider applications of this study will include the prediction of the possible effects of climate change on such climatically sensitive semiarid regions. The results of this study will be of particular interest when considering the effect of regional-scale climate variations caused by changes in North Atlantic atmospheric circulation.

Amino acids in stalagmites: what do they mean?

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Proteins in living organisms are composed exclusively of L-amino acids. After death, the amino acids interconvert to the optical D-isomer, a process known as amino acid racemization (AAR); the process continues until equilibrium is reached. In the past, AAR has been used as a geochronometer and geothermometer in shells, teeth and bones; the technique has even been applied to ancient carpets.

The amino acid present in soil as a result of decaying organisms is transported with dripwater, and incorporated in very small concentrations (< 3 $pmol.g^{-1}$ calcite) onto the growing speleothems. Fortunately, using high performance liquid chromatography (HPLC) available in the AAR laboratory at Newcastle University, these concentrations are measurable. Six amino acids and their optical isomers were consistently resolved by HPLC from a 147cm-long speleothem from the Dordogne, France, with ages ranging from 82ka to 33ka before Present. The concentrations of individual isomers and the extent of racemization were determined with age.

The D/L ratios were highly variable down core. Using principal component analysis, it was determined that there were three groups of amino acids within which racemization co-varies. One group, consisting of aspartic acid, glutamic acid and serine, was found to have D/L values that were inversely proportional to $\delta^{18}O$ and $\delta^{13}C$. These amino acids are known to be prominent in bacterial cell walls, and reflect a bacterial input of amino acids, providing another paleoenvironmental proxy.

Sediment dynamics in Ogof Draenen – an assessment into past flow regime

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Geomorphological analysis in Ogof Draenen (Farrant et al., in press) has revealed a complex series of underground flow switching. Initial cave development was towards southern resurgences, then following valley incision, the general drainage direction reversed to the north. Modern drainage is currently again to the south, towards Pontypool. The results of comprehensive sediment analysis are presented in order to assess the validity of the complex drainage pattern revealed by the geomorphological analysis.

Thirty two sediment samples were collected along parallel and presumed sequentially aged pathways. These include: Relict Megadrive, Gilwern Passage and Beyond a Choke Streamway. Four surface samples were also collected from the surrounding area in order to characterize the source rock mineralogy from which the in-cave sediment may be derived. The results of clast size analysis, lithological analysis, and loss-on-ignition techniques (to determine organic carbon content), were used to characterize the cave sediments as well as to compare them with surface samples.

The results indicate that at least four 'facies' or types of genetically related sediment fills are distributed in the Draenen cave system. The first facies is related to the Present day southerly flow regime and is characterised by an abundance of Coal Measures and Millstone Grit, suggesting a source location draining directly from the Coal Measures that overly much of the cave. The second facies is a coarse sandstone fill located at higher elevations in the Present day streamway, which is linked to a previous development of the cave. Gilwern Passage has the third facies, with a dominance of contrasting coal-rich sands, with a northerly flow direction. The Megadrive suite of sediments contrasts to the three other facies, with a dramatic increase in the <63mm size class downstream to the south.

This work has provided a comprehensive initial insight into the palaeohydrology of the system and demonstrates evidence to back up geomorphological work. Future research involving scanning electron microscopy of quartz grains of the sediments, scallop analysis, dating techniques, and sediment comparisons from other caves in the area, would help in the reconstruction of the areas palaeo-landscape.

Hazelton - A digital database of the Biological Records: a demonstration and preliminary analysis.

Graham PROUDLOVE
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Almost the total knowledge of the British subterranean fauna is printed in 16 volumes called the "Biological Records". They were compiled and published by the Biological Recorder of the Cave Research Group, Mary Hazelton, between 1955 and 1978 with data from 1938 to 1976. A computer-readable version is now being created so that meaningful interrogation of this valuable dataset can be carried out. There are approximately 5000 records from subterranean sites country wide, including caves and other sites. The presentation will show how the database is created and what it can do.

The ontogeny of speleothems

Charles SELF
Chairman of Genetic Mineralogy Working Group, Mineralogy Commission, UIS.

Speleothems are secondary mineral deposits whose growth in caves can be studied by mineralogical techniques. One of these techniques is the ontogeny of minerals, which is the study of individual crystals and their aggregates as physical bodies rather than as mineral species. Ontogeny of minerals as a scientific subject has been developed in Russia but is poorly understood in the West. In this lecture, I will introduce the basic principles of this subject and explain a hierarchy scheme whereby mineral bodies can be studied as crystal individuals, aggregates of individuals, associations of aggregates (termed koras), and as sequences of koras (ensembles). Selenite needles are crystal individuals, most other speleothems are aggregates, while the association (kora) of calcite stalactites and stalagmites is known even to members of the public. Most cavers understand that crystallization in caves is a cyclic process, the product of any one cycle being termed (in ontogeny) an ensemble. Individuals, aggregates, koras and ensembles are classed as "minor mineral bodies" because they can be studied by mineralogical rather than by petrographic techniques.

Ontogeny of minerals is not simply a new classification system for mineral bodies, it is a method by which past crystallization environments can be interpreted. The structure and texture of minor mineral bodies can be directly related to environmental factors at the time of their development. Speleothems are ideal subjects for this type of study, since there are few common mineral species in caves, yet there is a great variety in the forms that these minerals can take.

Does quarrying affect water availability in the adjacent unsaturated zone?

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The aim of this study was to examine the possible effect of quarrying on unsaturated moisture availability as indicated by tree growth. Rates of growth were determined by standard ring measurement techniques on duplicate cores from 10 oak trees sampled from a site adjacent to the face of an inactive limestone quarry, and from a more distant matched control site. For each core, the ring width for each year was divided by the mean width for that core over the period 1925 – 2000 to produce a relative ring width index. Data from individual cores were averaged, and then combined to produce an average growth index for each site.

There is clear evidence of covariation in the growth rates at the experimental and control sites that is indicative of external inter-annual differences in regional climate. Regression analysis indicates that there is an inverse relationship between tree growth and average summer potential evapotranspiration, the MORECS soil moisture deficit, the number of sunshine hours in the summer and autumn and the maximum annual temperature recorded in the years during and prior to that of the ring. Spring and summer rainfall (April /May – August) was found to be directly related to tree ring growth. The nature of these relationships suggests moisture availability is a major limiting factor for tree growth, with hot dry sunny summers giving significantly less growth than in cool wet years.

In the early years (1925–1956) there is a general decline in tree growth at both sites, but trees in the experimental site grew at a significantly greater rate than those in the control site (paired t test, 95% confidence interval). From 1956 (when quarrying activities began) to 1978 (some years after quarrying stopped), there is no overall change in growth rates with time, nor a significant difference in growth rates at the 2 sites. After 1978, both sites show a significant decline in growth rates with time, but rates in the experimental plot are significantly less than those in the control plot. The high face of the quarry (2 benches) first approached the experimental site in 1971. There thus appears to have been a significant impact on growth rates at the experimental site, although this has not been sufficiently great as to adversely affect the viability of the trees at the site.

Active dolomitisation by saline groundwaters in the Yucatán Peninsula, Mexico

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The Yucatán Peninsula is a 300km-wide carbonate platform that hosts a salinity-stratified aquifer where a thin meteoric lens is separated from the underlying saline water by a well-defined mixing zone. An extensive network of flooded caves along the eastern coast permits direct access to the saline groundwaters. Water and wall-rock samples were collected from sites up to 40km inland and 105m depth below the water table. Saline groundwaters are depleted of magnesium (-7.7 to -0.1 mM, mean = -3.6 mM) and enriched in calcium (-0.1 to +10.4 mM, mean = +2.3 mM) relative to local seawater, suggesting that these waters have formed replacement dolomites. The pCO_2 of saline groundwaters is ~11.5 times greater than that of local Caribbean seawater, and they are undersaturated with respect to aragonite (SI_A = -0.47 ± 0.12) and calcite (SI_C = -0.34 ± 0.08). However, the waters are marginally supersaturated with respect to ordered dolomite (SI_D = +0.18 ± 0.22), providing the potential for dolomitisation.

Some caves host a marked H2S layer. Bacterial sulphate reduction is evidenced by an increase in $\delta^{34}S\text{-}SO_4$, relative to the surrounding saline groundwater, and is supported by the successful enrichment of viable sulphate-reducing bacteria (SRB). Also, compared with surrounding saline groundwaters, the water within the H_2S layer is depleted of Ca^{2+} (by -3.2 mM) as well as Mg^{2+} (by -4.5 mM), suggesting that sulphate reduction may stimulate primary dolomite precipitation. These findings support previous laboratory simulations that suggest SRB decrease the kinetic barriers to dolomite nucleation. In addition, viable thiosulphate-oxidizing bacteria (SOX), enriched from the waters, actively re-oxidize the reduced sulphur species produced by SRB, generating acidity and consequently enhancing the dissolution of carbonate rock. Thus, both SRB and SOX play a role in dolomitization and carbonate dissolution.

Wall-rock samples from the zone of saline groundwater are partially dolomitized (up to 80%) with both fabric-preserving dolomitization of grains and dolomite cements lining inter- and intra-granular pores. Preliminary analysis indicates these dolomites are characteristically non-stoichiometric (~41 mol% Mg) and Sr/Ca ratios indicate a seawater origin. No dolomites were found outside the saline zone and dolomite content increases with depth, due to slow incremental dolomitization over time or dissolution at shallow depths. Dolomitization is more prevalent within a centimetre of the sediment-water interface and also where there is interconnected porosity. This confirms the importance of the active circulation of Mg^{2+}-rich fluids and/or the significant mediation of diagenesis by bacteria, which are 1 to 2 orders of magnitude more abundant at sediment-water interfaces, compared with the numbers found in the surrounding groundwater.

The life history of the cave spider Meta menardi

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Spiders are well-known members of the cave fauna, being principally associated with the entrance and twilight zones. This study focused on Meta menardi, the species most frequently encountered in the twilight zone of caves but which is also found in dark and damp situations such as cellars, air raid shelters, culverts, drains and abandoned mine workings. It is common throughout Europe and North America extending into Asia as far as Korea and Japan.

The work described investigated the life cycle of M. menardi with particular reference to its method of dispersal. The spider population in an abandoned mine adit was monitored on a weekly basis over two years, recording the numbers of each developmental stages in various sections of the adit. The results indicate that females produce egg cocoons in early summer and spiderlings emerge from them in the following spring. The number of cocoons containing spiderlings correlates well with day length, suggesting that increasing day length may trigger spiderling emergence. Decreasing day length in the autumn correlates well with the number of new cocoons, suggesting that this may stimulate cocoon production by females.

The fate of freshly emerged (2nd instar) spiderlings was investigated using an artificial cave. Results indicate that spiderlings exhibit a positive phototaxis and move towards the entrance of the cave.

Observations in the field indicated a protracted period (between October and March) over which 2nd instar spiderlings left their cocoons. The numbers of 2nd instars present in the mine correlated with maximum temperature, suggesting that an increase in temperature within the chamber may have triggered an exodus of spiderlings from the mine.

Once outside the chamber the spiderlings disperse by ballooning. They then construct small orb webs in the low vegetation and feed on small flying insects. In the late summer they begin to seek out dark damp situations and thus find there way back into caves.

Auditing the cave archaeology resource

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The importance of caves as locations where archaeological and palaeontological material is preserved has been recognized for more than two centuries. In England, the archaeological evidence ranges from the Middle Pleistocene almost to the present day, although cave research has historically concentrated on the Palaeolithic. This chronological bias has an impact on how cave dwelling is perceived by the public; popular images often show grunting, Neanderthal-like cavemen, dragging large cuts of meat into caves with fires, to the visible delight of other, hairy, grunting family members.

One problem affecting the recognition of other periods of cave usage since the Palaeolithic is the lack of synthesis of excavated sites. Understanding the wealth of archaeological material in caves is essential for the development of both future research, and future conservation management strategies. English Heritage has recently reviewed its strategy for caves and rock-shelters. This has identified the need to produce an audit of all the known archaeology of England's caves and rock-shelters from published and unpublished sources, and to assess this against the current deposits within the caves. This presentation will review the elements of this new strategy, and also consider how the protection and management of cave archaeology can be integrated with the work of other conservation agencies, as well as recreational users of caves.

The feeding relationships of invertebrate fauna within the Peak–Speedwell cave system

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Caves are typically food-limited when compared to photosynthetically-based epigean systems. A four-year study of the invertebrate community of the Peak-Speedwell Cave system (Castleton, Derbyshire, UK) has allowed the identification of aquatic food chains / webs for several subterranean sites, the Peak Cavern Rising (mainly autogenic fed spring) and Russet Well/Slop Moll, the two main allogenic-fed springs. Energy transfer within Speedwell Cavern and Peak Cavern is dominated by allochthonous organic material transported underground by sinking streams and by percolation water respectively. The spring communities contain elements of the cave fauna, but have been colonized by a wide range of taxa exploiting primary production in the epigean environment. The influence of illumination and lampenflora development and the impact of pollution on the trophic structure of subterranean communities will be discussed.

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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*.

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

CORRESPONDENCE

The following communication was "held over" pending expected receipt of other contributions on the same seemingly contentious topic, but no further contributions have yet been received...

Dear friends,
After having read your Editorial in issue 28(2) of *Cave and Karst Science* I was eager and curious to read the paper by Cyril Hromnik in the same issue. Well, I think that this paper was one of the most interesting, well-written and best-constructed papers to appear in the journal (which anyway has a very high standard). It would have been very difficult to discuss the question of "kras" in a better way. However, I do understand your hesitation to publish, because you are not experts on languages and were unable to involve such experts. An etymologist would probably have introduced a different viewpoint but, in my opinion, the chance of being right in opposition to Hromnik's views is small or perhaps negligible. Hromnik had the enormous advantage, it appears, of being an expert in both fields, speleology and etymology, and I think he was extremely successful in his work.

Some years ago I examined in detail "*De rerum natura*" by Titus Lucretius Carus, because it is a veritable mine of scientific information. In addition to the original Latin version I had an Italian one (as well as an English one) The translation into Italian was excellent, but its meaning was changed completely by the Italian translator, because he was totally ignorant of the subject matter and produced nonsensical output. My own translation from Latin into Italian was certainly less "elegant", but nevertheless it kept the sense of the original. My conclusion is: don't place too much trust in experts from the literary field!

My best compliments to you and to Dr Hromnik

Arrigo

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Received 05 March 2002.

Comments on the paper "The macroinvertebrate communities of limestone springs in the Wye Valley" by H Smith, P J Wood & J Gunn, (Cave and Karst Science, Vol.28(2), 2001).

This paper is a very useful contribution to our knowledge of limestone springs in the White Peak. The information on the specialist fauna characteristic of intermittent flows and the processes of regular recolonisation of such intermittent waters is of particular interest. However, it might be worth pointing out that, contrary to the points made in the second paragraph of the introduction, freshwater springs are recognised and specifically protected biological features of the White Peak. Not only are they mentioned in the criteria for the selection of the Wye Valley and Monk's Dale (the latter is not included in the paper but contains some very good examples of the habitat) Sites of Special Scientific Interest (SSSI), but they are also specific features of the Peak District Dales candidate Special Area of Conservation (cSAC). This is a designation made under the European Habitats Directive, in which they are described as 'basic flushes'. The stated scientific interest is, as is usually the case, based on floristics.

The confusion appears to lie in the fact that although the springs themselves are karstic features, their floristic and faunal communities are, of course, biological. If these communities are interesting enough, as they are at these sites, they can become part of biological SSSIs. Likewise, if the springs are considered to be of sufficient scientific interest in their own right as karstic features, they could be part of an earth science SSSI. In the cases of the Wye Valley and Monk's Dale SSSIs, they are not. Although the Wye Valley site is a 'mixed interest' SSSI, with both biological and geological/geomorphological features, its earth science component does not include the springs. The Monk's Dale SSSI is purely biological.

There is a limited amount of data available regarding the fauna of the Wye Valley springs. We have reports on the molluscan fauna by Peter Tatersfield and some data on Tipulids from Rhodri Thomas. Undoubtedly, however, this report takes us much further forward.

Conservation of springs does present some management dilemmas. The protection of spring sources from cattle poaching, as mentioned on p.76 of the paper, will lead to vegetation succession unless grazing is permitted on a rotational basis or mechanical means are used to remove scrub and trees as they develop. Even if occasional grazing or scrub control is undertaken, there will inevitably be changes to microhabitats, which may have an effect on invertebrates. On balance, bad poaching is probably the worse scenario, but it is worth bearing in mind that springs in grazed pastures are an unstable habitat and whatever form of management is undertaken will be a balancing act.

Ben Le Bas, English Nature, Manor Barn, Over Haddon, Bakewell, Derbyshire, DE45 1JE.

Reply from the authors: H Smith, P J Wood and J Gunn

We thank Ben Le Bas for his positive comments on our paper and for his clarification of the protection afforded to the springs. Ben is correct in that most, but not all, of the springs lie within SSSI and a cSAC. As such they are afforded "indirect protection", as we mentioned in our text. However, as Ben says, the stated scientific interest is based on floristics and aquatic invertebrates are only mentioned specifically in the Lathkill Dale SSSI citation, and there for the river, not springs. They are mentioned indirectly for the Wye Valley SSSI, but not at all in the other 9 dales in the cSAC, though many of these are dry for most or all of the year. As Ben also rightly says, conservation of springs inevitably presents management dilemmas. If, for instance, the aquatic invertebrates are not listed as interest features, then decisions will always favour vegetation, and this may not always be in the best interest of the invertebrates. Similar considerations apply to the ten cave/karst SSSI in the Peak District, none of whose citations include aquatic invertebrates as an interest feature. This means that if a pollution incident occurs, wiping out all aquatic fauna in a cave, as happened recently at Castleton, it cannot be considered to have affected the scientific interest of the site unless features of geological / geomorphological interest mentioned in the citation are also damaged. We know that Ben and his colleagues in English Nature are aware of this problem, and we look forward to working with them to resolve it.

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Dear Editors

I am intrigued by the persistence of the depth of Gaping Gill Main Shaft being quoted as 112m (c.367 feet), as for example on p.23 of *Cave and Karst Science,* 29(1).

Many years ago I naively tied a rope around a big boulder near the edge of the Main Shaft, lowered the end down the hole, and abseiled down ... no re-belays, but possibly a rope protector at the top. I wandered around the Main Chamber for a bit, sat and contemplated the scene, thus allowing the rope to shrink back to its natural length. Then I tied a knot where the rope reached the floor, and I climbed back out, tying another knot where the rope went over the lip of the shaft. After returning home I measured the distance between the knots as 308 feet (c.93.9m).

Shortly after that episode I was talking to some guys who wanted to descend the Main Shaft, and they said, "*So our 100m rope will be long enough?*". I replied that it probably would, but just in case I'd messed up the measurement they should tie another rope on the end, and ensure that every member of their party was adept at passing knots. On their return they said that, sure enough, there had been lots of spare rope on the floor of the Main Chamber.

Subsequently, of course, Dave Elliot and Dick Lawson published their rigging guide, which gives the depth of the Main Shaft as 95m (c.312 feet)... not far from my figure of 94m.
So – why does the depth myth persist?

Yours sincerely,

John Forder

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THESIS ABSTRACT

DEVLIN, R, 2002

The situation and dynamics of the North Yorkshire windypits: A geophysical and geomorphological investigation.

MSc Thesis [Engineering Geology], University of Leeds, UK.

Sub-surface slip-rift fissures and shafts, known locally as 'windypits', are numerous in the Upper Jurassic strata of the Hambleton Hills and Ryedale district of North Yorkshire. Windypits are predominantly open gull-formations, formed as a result of cambering between competent Corallian Group sandstone and limestone beds above weak clay beds of the Oxford Clay Formation. They relate to the natural pattern of steeply-dipping, widened joint-plane discontinuities, with individual blocks of caprock moving relative to one another along these surfaces. The most extensive fissure systems are up to 40m deep and over 300m long, and typically run sub-parallel to slope contours and linear topographic features, rupturing the surface above the line of maximum gradient. More complex and unpredictable structures occur where there is more than one direction of movement, resulting in a radial fissure network. Windypits have been associated with other forms of scarp recession and landslide activity, most notably the formation of unstable block detachments along vertical cliff-exposures. Aerial photographic interpretation and terrain analysis based on field observations and mapping have been used here in a detailed geomorphological investigation of windypit structures and their related landforms. They appear to play a significant role within a far more complex model of superficial slope evolution, with important consequences for rock-slope stability. The potential hazards from landslides and natural cavities are also assessed in the light of engineering geological evaluation. Shallow geophysical surveying techniques have been used to profile the electrical contrasts between void space and host rock, at a number of selected sites. It has been found that non-contacting electromagnetic conductivity methods are unsuitable for producing a discrete windypit anomaly, due to their limited depth of penetration. Tomographic resistivity techniques appear to be the most promising for accurately locating sub-surface fissures, and helping to map their true depth and full extent. Comprehensive ground investigation would allow better interpretation of the geophysical data collected.

Keywords: windypit; slip-rift; fissure; North Yorkshire Moors; Corallian Group; Oxford Clay Formation; cambering; gulls; natural cavities; geomorphology; terrain analysis; aerial photographs; void detection; EM31; conductivity; resistivity; tomography.

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 BCRA Honorary Secretary (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, UK (e-mail: d.judson@bcra.org.uk). Closing dates for applications are: 31 August 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, HDI 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, UK (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.

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 organises field meetings. Occasional publications include a *Bibliography and Guide to Regulations*, etc.

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

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

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

Copies of BCRA Publications are obtainable from: Ernie Shield, Publication Sales, Village Farm, Great Thirkleby, Thirsk, North Yorkshire, 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, ST17 9BT, UK.