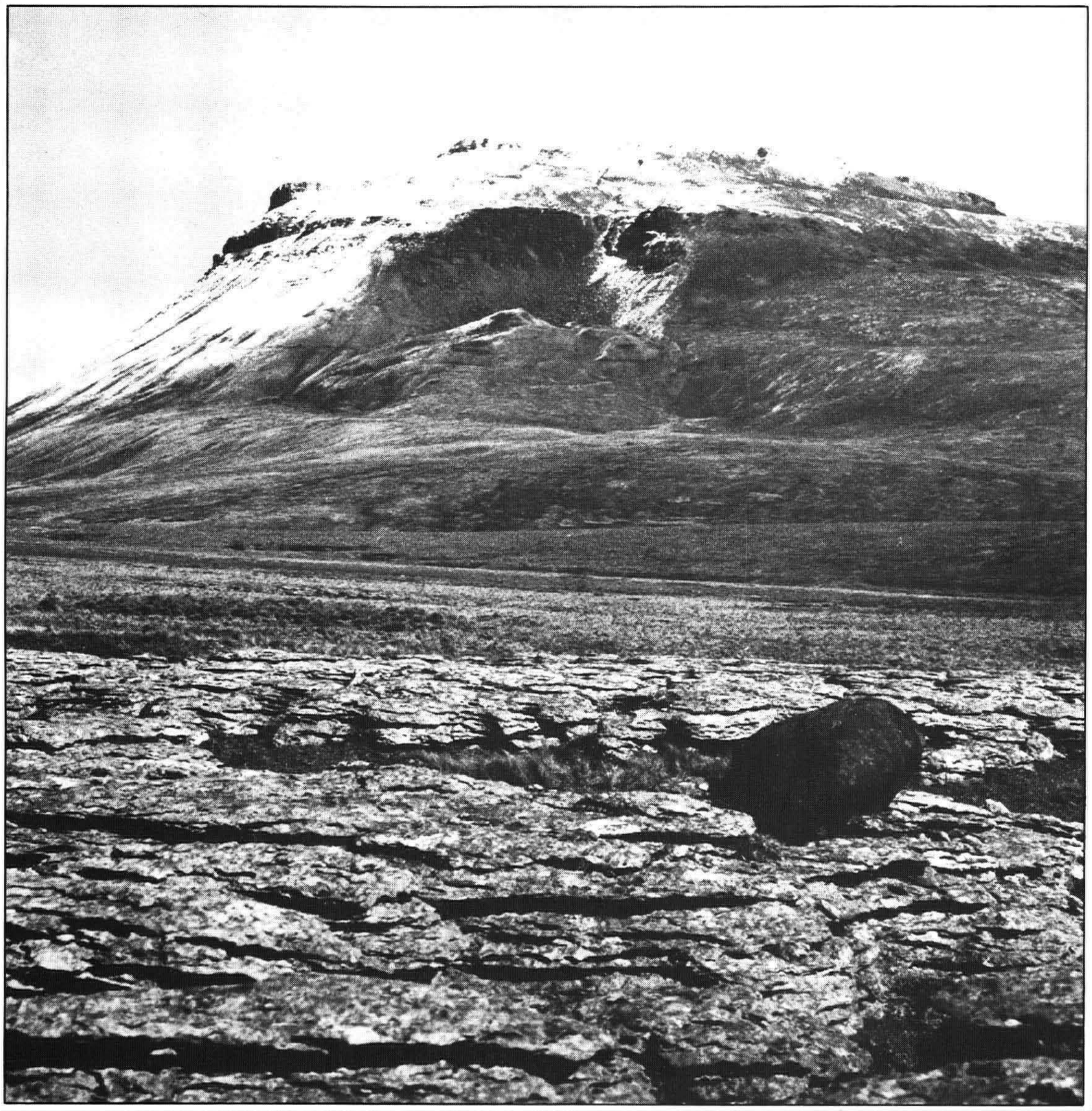
Cave Science

The Transactions of the British Cave Research Association

BCRA

Volume 16 Number 1 April 1989



Cave Science

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

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

Cave Science

TRANSACTION OF THE BRITISH CAVE RESEARCH ASSOCIATION

Volume 16 Number 1 April 1989

Contents

Cover: Ingleborough, from White Scars, with its Yoredale terraces, landslip, drumlined boulder clay, limestone pavement and glacial erratic. The geomorphology of the Ingleborough Site of Special Scientific Interest is currently being mapped and assessed for the Nature Conservancy. By Angus Tillotson.

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BCRA CAVE SCIENCE SYMPOSIUM

at Leeds

Saturday 28th October, 1989

First Circular and Registration Form

After a years absence the 1989 BCRA Cave Science Symposium is to be held at the University of Leeds on Saturday 28th October. Papers are invited on all aspects of cave science and may be presented either orally or as poster displays.

Please return to:

Simon Bottrell, Dept. of Earth Sciences, University of Leeds, LEEDS LS2 9JT.

Name:

Address:

Telephone:

I plan to attend the BCRA Cave Science Symposium at Leeds and enclose a cheque (payable to the "University of Leeds") for:

Symposium registration (4-00) ....

Buffet lunch (7-00) ....

Field Excursion deposit (10-00) ....

Cheque for total ....

My participation in the field excursion is unlikely ___, likely___, definite (deposit enclosed)___.

I wish to present a paper ___/ poster___

entitled:

The symposium is to be held in the Department of Earth Sciences at Leeds University on 28th of October 1989, commencing at 9-30 am. If sufficient people are interested a buffet lunch will be provided. Similarly, if there is sufficient interest a field excursion will be run on Sunday 29th.

TALKS AND POSTER PRESENTATIONS are invited on all aspects of cave science. It is hoped to provide a program spanning as diverse a range of cave topics as possible, with talks lasting approximately 20 minutes.

A BUFFET LUNCH (costing £7-00) will be provided if there are sufficient people interested.

A FIELD EXCURSION, visiting sites in the Yorkshire Dales where cave research is currently taking place, will be organised for Sunday 29th of October, if there is sufficient interest. In order to assist with arrangements for accommodation, transport, etc., it would be useful if anyone hoping to participate could register as soon as possible.

Any payment/deposit for the lunch or excursion will obviously be refunded if these are not arranged.

CAVE SCIENCE Vol. 16, No. 1, April 1989
Transactions of the British Cave Research Association

Uranium-Series Dating of Cave Deposits at Creswell Crags Gorge, England.

P.J. Rowe, T.C. Atkinson and R.D.S. Jenkinson.

Abstract: Creswell Crags Gorge, S.S.S.I, contains several archaeologically important caves that were excavated mainly in the late Nineteenth Century. A programme of speleothem dating by the uranium - series method has indicated that some archaeological deposits in Robin Hood's Cave may be older than generally assumed and that cycles of sediment deposition, erosion and reworking are common phenomena in several of the caves. The results also suggest that the gorge itself is a mid - late Pleistocene feature.

The caves in the Creswell Crags Gorge on the Derbyshire-Nottinghamshire border have been well known to archaeologists and palaeontologists for over a century, the most important sites being Mother Grundy's Parlour, Robin Hood's Cave, Church Hole Cave and Pin Hole Cave (see Fig. 1). The profusion of mammal bones that were constantly eroding out of the cave mouths prompted the Reverend Magens Mello and William Boyd Dawkins to excavate several of the caves in the 1870's (Mello 1875, 1876,1877). Unfortunately the excavation and recording were very poor by modern standards and there can be no doubt that several extremely important palaeolithic sites have been lost forever as a result. Further excavations by Laing (1889) destroyed remaining sedimentary sequences in Robin Hood's Cave. Excavations by A.L. Armstrong in Pin Hole Cave between 1925 and 1932 were of a much higher standard and his published reports are of considerable value (e.g. Armstrong 1928,1929). Since then, small scale excavations have been undertaken in several of the caves by McBurney in 1959-60, Campbell in 1969 and Collcutt in 1974 (McBurney 1959, Campbell 1977, Collcutt 1975). Jenkinson (1984) has reassessed the palaeontological and archaeological work that has been carried out to date and has provided an exhaustive account of all previous excavations and comprehensive references.

In 1981 further, very limited, excavations were carried out in Robin Hood's Cave. At the same time a uranium-series dating programme was begun to establish the age of the numerous calcite deposits (speleothems) that are present in most of the caves in the gorge. It was hoped that this would (a) provide a chronology within which the archaeological finds from the major cave sites could be placed and (b) shed light on the likely age and evolution of the Creswell Crags Gorge and its attendant caves. A full account of the dating work is given by Rowe (1986). The purposes of this paper are to summarise the analytical data and the dates obtained and to discuss the stratigraphy of the caves in the light of the U-series results.

Uranium-Series Dating: Principles and Analytical Results

The principles and methods of uranium-series disequilibrium dating have been fully discussed in the literature (e.g. Schwarcz 1980, Gascoyne et al 1978, Ivanovich and Harmon 1982), and only a brief outline will be given here.

U-series dating has made many valuable contributions to archaeology over the past twenty years (see Cook et al 1982, and Schwarcz 1982 for review). It is used principally for dating carbonate materials of which speleothems are a particularly suitable example, being hard, crystalline and generally free from weathering and leaching. The calcite from which speleothems are formed is precipitated from waters seeping into a cave through the overlying rock and soil. These waters often contain trace amounts of uranium (238-U and 234-U) which is soluble under the aerated chemically oxidising conditions normally found in limestones above a cave roof, but contain no thorium which is very insoluble. When calcite is precipitated from the water to form a speleothem, uranium is incorporated as an impurity with concentrations which may range from near zero to several parts per million. Pure calcite, therefore, initially contains uranium but no thorium. It is this imbalance, or disequilibrium, which provides a means of determining a speleothem's age. With the passage of time, the minor isotope of uranium, 234-U, decays to an isotope of thorium, 230-Th. This isotope is also radioactive, so the activity ratio of 230-Th to 234-U in pure calcite is initially zero but increases, with the ingrowth of 230-Th, and reaches a value of unity after about 350 ka, after which the ratio remains constant. By measuring the 230-Th/234-U activity ratio, (and also making an allowance for the fact that 234-U is produced in the speleothem by radioactive decay of the major isotope 238-U), we can calculate the age of a sample, up to 350 Ka.

The presence of sand, silt or clay that may have become trapped within speleothems during their formation presents problems because such sediments contain thorium isotopes

Figure 1. The locations of the main caves at Creswell Crags Gorge.

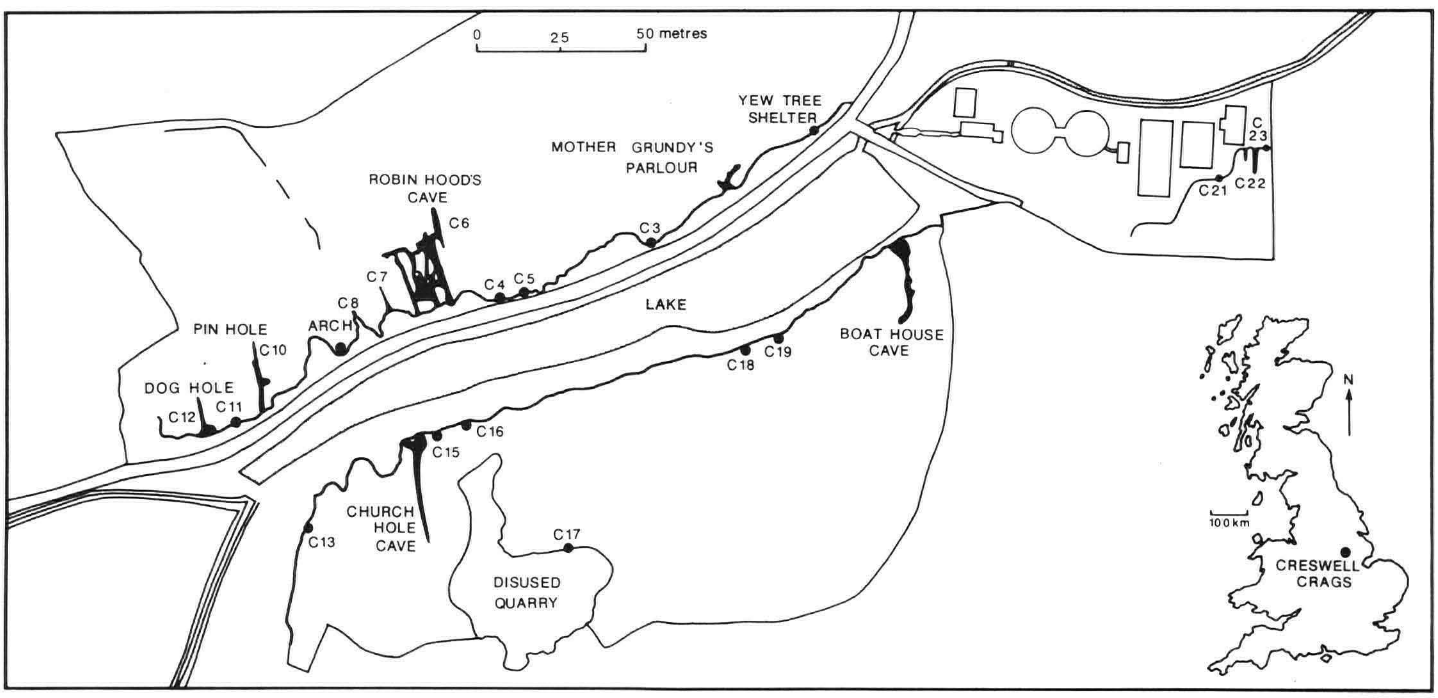


TABLE 1. Uranium series analytical data for speleothems from caves at Creswell Crags.

Site	Sample No.	Lab. No.	U (ppm)	Chemical Yield(%)		234-U / 238-U	230-Th / 232-Th	230-Th / 234-U	Age (Ka)
CAVE C7									
1	830809-1	UEA70	0.10	21	12	1.147±0.042	>1000	0.072±0.014	8.1±1.6
1	830809-3	UEA73	0.58	51	61	1.072±0.013	298.6±56.7	0.871±0.020	211.3+15.4/-13.5
3	830809-9	UEA74	0.16	39	24	1.103±0.022	3.7±0.5	0.077±0.5	8.7±0.6
2	830809-6	UEA78	0.14	32	15	1.197±0.035	31.6±91.8	0.067±0.009	7.6±1.1
2	830809-4	UEA82	0.14	38	70	1.149±0.030	61.7±11.2	0.620±0.019	101.9+5.2/-5.0
1	830809-2	UEA83	0.20	55	65	1.160±0.023	182.4±58.7	0.845±0.023	186.3+13.7/-12.2
4	840228-3	UEA96	0.75	41	53	1.073±0.013	147.2±13.2	0.949±0.028	288.6+49.5/-34.3
4A	840228-4	UEA97	0.11	48	37	1.150±0.026	11.8±3.0	0.118±0.008	13.6±1.0
2	830809-10	UEA98	0.40	74	77	1.215±0.020	76.6±7.7	0.890±0.023	208.1+16.1/-14.2
2A	840228-1	UEA102	0.34	81	85	1.094±0.018	31.0±1.7	0.910±0.027	238.9+27.8/-22.4
4	840228-2	UEA104	0.48	50	67	1.104±0.020	69.5±6.8	0.943±0.029	270.8+40.7/-30.0
2A	830809-5	UEA105	0.29	49	84	1.182±0.023	13.7±0.6	0.901±0.027	219.0+21.0/-17.8
1A	840605-4	UEA111	0.62	59	62	1.095±0.022	112.6±14.5	0.961±0.032	298.0+61.7/-40.6
1A	840605-5	UEA113	0.26	58	60	1.196±0.024	124.3±23.4	0.765±0.023	147.3+9.3/-8.6
4	840606-4	UEA114	0.12	58	74	1.103±0.029	20.8±2.8	0.656±0.024	113.1+7.3/-6.8
3A	840525-1	UEA116	0.90	66	78	1.074±0.021	66.1±5.5	0.936±0.032	270.7+47.6/-33.4
2	840606-1	UEA118	0.19	61	70	1.140±0.019	12.2±0.7	0.699±0.020	125.5+6.7/-6.3
1A	840605-3	UEA138	0.29	66	88	1.119±0.019	8.3±0.4	0.854±0.021	194.9+13.8/-12.3
1A	840605-1	UEA122	0.27	82	80	1.089±0.021	11.7±0.6	0.944±0.028	(276.4+42.1/-30.7)
1A	840605-2	UEA140	0.30	78	79	1.098±0.023	13.7±0.6	0.899±0.023	(228.8+21.2/-17.8)
1A	840605-3	UEA120	0.31	75	90	1.059±0.025	10.1±0.4	0.875±0.029	(215.8+24.4/-20.1)
1A	850222-3	UEA154	0.31	79	70	1.128±0.016	169.4±31.7	0.786±0.018	159.0+8.3/-7.8
1A	850222-2	UEA157	0.28	85	54	1.099±0.019	6.8±0.3	0.839±0.022	187.8+13.5/-12.0
1B	850220-1	UEA155	0.13	78	35	1.238±0.026	6.0±0.8	0.091±0.005	10.4±0.6
ROBIN HOOD'S CAVE									
RH-2	820324-6	UEA34	0.35	51	74	1.106±0.018	131±22	0.797±0.018	165.1+8.7/-8.1
RH-2	820324-6	UEA36	0.35	55	81	1.134±0.018	156±27	0.802±0.018	165.7+8.5/-7.9
RH-3	820324-8	UEA29	0.05	71	41	1.233±0.024	2.1±0.1	0.233±0.009	27.2±1.2 *
RH-3	820324-8	UEA31	0.05	55	27	1.125±0.032	1.2±0.1	0.401±0.019	55.1±3.5 *
RH-3	820324-8	UEA32	0.05	50	20	1.102±0.034	1.4±0.2	0.463±0.040	66.7±0.8 *
RH-3	820324-8	UEA53	0.06	29	44	1.268±0.053	1.6±0.2	0.112±0.009	12.9±1.1 *
RH-3	820324-8	UEA54	0.06	42	28	1.116±0.031	1.3±0.1	0.346±0.020	45.6±3.2 *
RH-3	820324-8	UEA55	0.07	37	36	1.077±0.028	1.3±0.1	0.313±0.015	40.5±2.3 *
RH-3	820324-8	UEA56	0.06	34	19	1.161±0.039	1.3±0.1	0.275±0.018	34.6±2.6 *
RH-3	820324-8	UEA131	0.06	77	80	1.177±0.023	1.9±0.1	0.124±0.006	14.4±8.0 *
RH-3	820324-8	UEA132	0.06	85	43	1.172±0.023	2.0±0.2	0.139±0.008	16.1±1.0 *
RH-3	820324-8	UEA133	0.07	61	19	1.098±0.028	1.2±0.1	0.256±0.018	32.0±2.5 *
RH-3A	811205-1	UEA67	0.24	65	71	1.165±0.022	49.4±4.1	0.835±0.023	180.5+13.0/-11.7
RH-4	820324-9	UEA37	0.13	35	73	1.022±0.032	20.2±1.8	0.715±0.023	135.2+8.9/-8.2
RH-4	820324-9	UEA39	0.12	59	77	1.104±0.036	20.1±3.1	0.645±0.025	109.9+7.4/-7.0
RH-4	820324-12	UEA35	0.14	66	72	1.136±0.025	16.8±1.5	0.636±0.018	106.5+5.1/-4.8
RH-4	820324-11	UEA41	0.12	48	62	1.271±0.038	8.3±0.6	0.602±0.019	95.7±4.8
RH-4	820324-10	UEA40	0.25	64	50	1.280±0.027	7.4±0.8	0.114±0.005	13.1±0.6
RH-5	820324-14	UEA27	0.32	54	56	1.415±0.018	26.9±5.1	0.091±0.003	10.3±0.3
RH-5	820324-14	UEA28	0.35	46	67	1.255±0.022	24.8±5.2	0.110±0.004	12.6±0.5
RH-5	821210-1	UEA51	0.27	58	70	1.134	-	-	Still Active
RH-7A	820324-17	UEA45	0.27	33	68	1.612±0.038	20.9±4.8	0.128±0.005	14.8±0.6 (L)
RH-7A	830810-1	UEA71	0.29	33	78	1.721±0.035	>400	0.109±0.004	12.5±0.5 (L)
RH-7A	820324-16	UEA68	0.17	52	73	1.712±0.042	14.0±3.1	0.079±0.004	8.9±0.4 (U)
RH-7B	831024-1	UEA88	0.34	49	68	1.077±0.019	146±34	0.736±0.020	140.6+8.0/-7.4
RH-7B	840227-4	UEA95	0.36	46	69	1.132±0.017	151±19	0.700±0.022	126.0+7.3/-6.9
RH-7C	831024-2	UEA77	0.10	73	61	1.152±0.029	2.0±0.2	0.115±0.008	13.3±1.0
RH-9	821211-1	UEA46	0.19	59	63	1.184±0.020	11.4±2.9	0.066±0.004	7.4±0.4
RH-1	820324-2	UEA33	0.31	79	45	1.237±0.025	1.7±0.1	0.191±0.008	22.8±1.1
RH-1	820324-3	UEA38	0.35	34	57	1.179±0.022	4.1±0.3	0.149±0.005	17.5±0.7
RH-1A	821209-5-1	UEA62	0.25	60	48	1.218±0.026	3.7±0.3	0.125±0.006	14.5±0.8
RH-1A	821209-5-2	UEA63	0.25	66	57	1.162±0.023	4.0±0.4	0.123±0.006	14.2±0.7
PIN HOLE CAVE									
	850222-4	UEA156	0.09	55	50	1.116±0.032	19.3±3.6	0.648±0.026	110.4+7.6/-7.1
	840227-1	UEA100	0.14	66	52	1.114±0.022	2.5±0.2	0.158±0.007	18.6±0.9
	840322-1	UEA101	0.15	35	52	1.327±0.028	29.5±5.2	0.128±0.005	14.7±0.6
	-	UEA298	0.19	39	54	1.314±0.031	6.8±1.3	0.115±0.006	13.2±0.8
CAVE C8									
	830810-2	UEA72	0.11	47	52	1.209±0.029	164±82	0.630±0.018	103.7+4.9/-4.7

* = Probable age 7.2 Ka from isochron plot (see Fig. A1)
L = Lower calcite layer at this site; U = Upper calcite layer at this site
( ) = Dates in parenthesis indicate probable contamination by older calcite.
Errors quoted are one standard deviation based on counting statistics only.

Table 1. Uranium series analytical data for speleothems from Creswell Crags caves.

whose presence invalidates the basic assumption that no 230-Th was initially present. The existence of such detrital contamination can be recognised by the presence of the isotope 232-Thorium, but correction for its effects is difficult. Generally a speleothem is regarded as uncontaminated if its measured 230-Th/232-Th activity ratio is >20. Many of the calcite deposits at Creswell Crags are flowstones and these are particularly susceptible to detrital contamination because their sub-horizontal morphology encourages the retention of sediment particles on calcite surfaces. Because of this, a large proportion of the samples analysed were detritally contaminated.

In the following discussions, where "corrected" ages are quoted for thorium contaminated samples, corrections have been applied to the data assuming that the 230-Th/232-Th ratio in the sample initially (i.e. the contamination ratio at the time of formation), lay between 0.5 and 2.0 and that this excess (unsupported) 230-Th has been decaying since its incorporation into the calcite (see Schwarcz 1980, and Rowe 1986 for full discussion). This type of correction, which can be applied to single samples, is somewhat arbitrary and also makes no allowance for possible uranium contamination from isotopes carried on the detritus. In the discussion which follows, the reader should bear in mind that "contaminated" dates, even if "corrected", still provide only an approximate indication of the true age. In one case , multiple analyses of a speleothem from Robin Hood's Cave allowed Schwarcz's isochron method of correction to be applied (Schwarcz 1980). Whilst less arbitrary than the single sample method, still no allowance is made for possible uranium contamination. As a result, the corrected date may be somewhat younger than the true age of the sample.

The U-series analytical data are given in Table 1. Standard procedures were followed in the chemical separation of uranium and thorium (Lally 1982) and activity determination was by alpha spectrometry. All errors quoted are ± 1 s.d. based on counting statistics only.

Dates Related to the Stratigraphy of the Cave Deposits

The stratigraphies of the deposits within the Creswell Crags caves are extremely complex and incompletely understood. It is unlikely that the sedimentary sequences that existed in the caves prior to their excavation in the nineteenth century will ever be properly comprehended, as the caves were so completely emptied of their deposits, and reporting and recording were so sketchy. In this section we describe the provenance of the dated speleothem samples in relation to the known stratigraphy of each cave, and then discuss the light which the dates throw upon the stratigraphic succession, the chronology of events by which the succession was formed, and the archaeological and palaeontological record of the sediments.

Geological Background

The Creswell Crags gorge is cut almost directly east-west through a low but prominent fault- bounded ridge of Permian Lower Magnesian Limestone about 10 km west of Worksop (Fig.1). The limestone outcrops in a band several kilometres wide from near Mansfield in the south to the coast of County Durham in the north. Many gorges dissect the limestone surface, of which the most spectacular is that of the River Don at Conisborough, although many smaller gorges exist around Creswell Crags (e.g. Markland and Hollinhill Grips, the Meden Valley at Pleasley Vale). The Creswell Crags ridge has been created by downfaulting along its western edge. The faulting has brought down Middle Permian Marl and erosion of this softer material has created a small vale west of the fault line leaving the more resistant limestone immediately to the east as a higher block of land. Generally the limestone in the gorge is rather massive although thinly bedded towards the top and at the eastern end, where minor downfaulting has occurred.

THE CAVES

Remnants of several fossil phreatic caves are present in the sides of the gorge (Fig. 1), especially in the northern side, and are listed by Jenkinson (1978). The phreatic origin of all these caves is evident from the frequent examples of tubular morphology in chambers, passages and small side tubes (Bretz 1942).

Most of the caves in the gorge contain calcite deposits, usually flowstones although some stalagmites are known. Many of the deposits are thin, detritally contaminated and unsuitable for dating, and where these occur in excavated caves for which there is no excavation record (e.g. Boat House Cave, Dog Hole Cave), no sampling or dating work has been carried out. Dating has therefore concentrated on deposits from those caves for which there are extensive stratigraphic records (albeit of variable quality), or which have an abundance of good quality dateable speleothems. This has meant that archaeologically important caves such as Mother Grundy's Parlour and Church Hole Cave have contributed no data since their calcite deposits are limited and unsuitable. Robin Hood's Cave and Cave C7 on the other hand have been intensively studied. The caves investigated will be considered in turn.

Robin Hood's Cave

This is the largest known cave at Creswell Crags and indeed in the Lower Magnesian Limestone, and its network pattern (Fig.2) leaves little doubt that its development has been strongly joint controlled. It is potentially the most important site at Creswell in terms of the length of statigraphic record that may still be present. Most of the deposits have unfortunately been excavated although some sediments remain in places on the cave walls and on the floors of the Eastern and Central Chambers where *in situ* deposits are over a metre in thickness.

Understanding of the cave stratigraphy is based upon excavation reports, many of which are over a century old. For clarity it is appropriate to delineate the cave into four areas and discuss each separately. These areas are (1) the Western Chamber, (2) the Northwest Chambers, (3) the Central Chamber and associated fissure chamber and connecting passage, (4) the Eastern Chamber. Figure 2 illustrates this subdivision.

The Western Chamber

Today, the chamber has a thin covering of spoil over the bedrock floor, a thin veneer of *in situ* sediment and breccia on the southern wall, and larger *in situ* deposits of sediment and breccia over a fissure in the southwest corner. Remnants of breccia can also be traced widely around the chamber. The breccia is commonly cemented and coated with flowstone, although only in the southwest corner (Site RH-3,Fig.2) is it suitable for dating. Remnants of other flowstones have been found low on the south wall and in a small tube in the northwest wall (Sites RH-2 and RH-4 respectively, Fig.2). Neither of these are mentioned in previous reports.

The first account of the Western Chamber excavations was provided by Mello (1876,1877) and his sections are reproduced in Figures 3a, 3b and 3c. Subsequently controversy arose over the accuracy of these sections and an "alternative" report was issued by Heath (1879) who had supervised most of the excavation and had been present in the cave much more regularly than Mello or Boyd Dawkins. Heath's section is reproduced in Figure 4 and approximately corresponds to Mello's Section 1 (Fig. 3a). The disagreements are mainly concerned with the dimensions of the sections. No fundamental differences exist between the two accounts as to the broad sequence of deposits, although fine detail is totally lacking and the exact provenance of many of the faunal and artefactual finds is uncertain. Where it can be checked, Heath's reporting seems the more reliable.

In summary, both authors agree that the chamber contained deposits which, beneath a thin "surface soil", were capped by *stalagmite and breccia*, with a combined thickness from one to three feet, and present over most of the chamber except for the areas around MD, ME, and MF in Figure 2 (these correspond to areas D, E, and F in Mello's 1877 report and in Heath (1879)). Remnants of stalagmite - cemented breccia can still be seen on the cave walls. Beneath the breccia was a *"cave - earth"* containing bones and implements, of variable thickness up to several feet, and present throughout the chamber. Remnants of this deposit also can be recognised on the south cave wall today. Beneath the "cave - earth" was a layer of *"red sand"* or *"red clayey sand"* in which bones and Mousterian stone tools were found.This was present throughout most of the chamber, although Mello's and Heath's sections and nomenclature conflict in areas MD and ME (Fig. 2). In the interior of the chamber, the "red sand" rested on the bedrock floor but towards the entrance, in the line labelled "1" on Figure 2, Mello (1876) illustrates it resting on a "lighter coloured sand with limestone fragments" (Fig. 3a). Mello (1877) also describes a "white calcareous sand with limestone blocks" as the lowest deposit in the talus outside the cave mouth (Fig. 3c). This latter deposit is

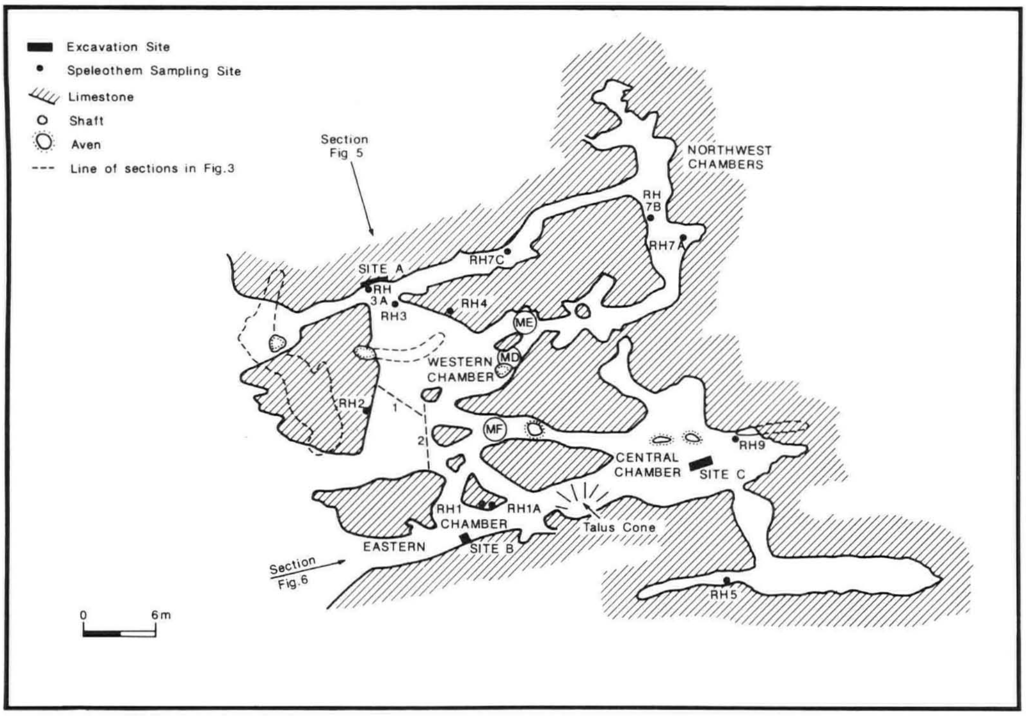


Figure 2. Plan of Robin Hood's Cave showing excavation sites and speleothem sampling sites.

older than the "cave - earth" which lies above it, but the "red sand" was not present.

In 1981 a small excavation was mounted in the extreme southwestern corner of the chamber (Site A, Figs. 2 and 5) where a 1.9 metre section of sediment survives beneath a roof collapse. Preliminary results of this work have been reported in Jenkinson et al 1986.

The section is capped by the stalagmitic breccia of Mello and Heath, but the deposits beneath are stony sands which appear to have been introduced from a collapsed former entrance to the west. Today, these deposits are separated from the rest of the Western Chamber by a fissure which was emptied of deposits by Laing (1889) without proper reportage. Consequently, it is impossible to relate them to the rather generalised stratigraphy described by Mello and Heath.

Speleothem samples were taken from four sites in the Western Chamber, labelled RH-2, 3, 3A and 4 on Figure 2. Sample sites RH-3 and RH-3A are both directly relevant to the excavation at Site A, while RH-3 also dates the "stalagmite and breccia" of Mello and Heath.

Site RH-3: Capping and cementing the roof collapse and breccia, *in situ*, and therefore clearly overlying and post-dating the excavated sediments, is the rather poor quality flowstone referred to above (Fig. 5). Three metres northeast of Excavation Site A, the calcite is locally of dateable quality, although often rather porous at its base. Since many flint implements were recovered from the breccia during the nineteenth century excavations, it is important to obtain as accurate an estimate as possible of the age of this speleothem since it provides a post quem date on the underlying stone tool industry.

A sample weighing c. 2 kg was taken for dating (Sample No. UEA820324-8). Unfortunately, it proved to be heavily contaminated with both detrital thorium and organic matter as well as having a very low uranium content (0.06 ppm). Eleven sub-samples from this material were analysed but two of these were eliminated from further consideration (see Table 1). UEA30 had a thorium yield of only 7% and UEA133 was used for experimental purposes during sample preparation and gave isotopic values that were quite different from the other sub-samples. Because of the heavy organic contamination, thorium yields of the remaining nine sub-samples are lower than normally expected, although still acceptable. Since the analyses are detritally contaminated (230-Th/232-Th = 1.2 - 2.1), the calculated ages will be higher than the true sample ages because of the excess detrital thorium. This is a particular problem for young samples, as these are thought to be, because the amount of authigenic thorium is low and any thorium contamination makes a substantial difference to the age calculation.

To correct for the effects of thorium contamination in this case, the data were used to construct an isochron plot by the method of Shewarcz (1980). The details are discussed in Appendix 1. The "corrected" date for the sample is estimated to be about 7200 years, which should be regarded as an approximate indication of the true age

The stalagmite at RH-3 clearly post - dates the deposition of the breccia. Implements belonging to the Creswellian Culture of the Upper Palaeolithic occurred in the breccia (see Jenkinson 1984 for full discussion). The date of 7200 years thus provides a *post - quem* date for the Creswellian Culture, which is in general agreement with radio-carbon ages of 9,300 years obtained on *Bos* sp. bone fragments from a hearth deposit in Mother Grundy's Parlour (Jacobi 1980, Jenkinson 1984).

Site RH-3a: About 50 cms below the top of the excavated Section A, were found four flowstone fragments, one quite large (10 cms across x 4 cms thick) which from their condition do not appear to be far travelled. Although vuggy in places, there was ample good quality calcite for dating purposes. Part of the larger fragment (UEA811205-1) was analysed and gave an uncontaminated age of 180 +13/-11.7 Ka (UEA67, Table 1). Since all the fragments were close to each other, they may have a similar origin and be of the same age, although this need not be so. The dated derived flowstone provides an *ante quem* date for the deposition of the sediments in which it is incorporated. Thus the upper part of the stony sands at Site A were laid down at some time after 180 ka but before about 7 Ka.

Site RH-4: Seven metres north-east of Site A is a small phreatic tube in the north wall of the chamber across which have been deposited four flowstone layers,each about 2 cms thick,separated by hiatuses. The upper layer is too vuggy for dating purposes. All of these layers have been broken and across the top and down the broken faces of these formations has grown yet another flowstone drape.

Two age determinations on the basal flowstone layer (Sample UEA820324-9, analyses UEA37 and 39) gave uncontaminated ages of 135 +9/-8 Ka and 110 +7/-7 Ka. The second layer (UEA-820324-12, UEA35),gave a slightly contaminated age of 106.5 +5/ -5 Ka (230-Th/232-Th =16.8, probable true age 98 -103 Ka), whilst the third layer (UEA820324-11, UEA41) produced a rather more highly contaminated age of 95.7 +5 /-4.7 Ka (230-Th/232Th = 8.3, probable true age 80 - 88 Ka).

The capping flowstone layer that drapes over the underlying layers (UEA 820324-10, UEA40) dates to 13.1+-0.6 Ka, but has a 230-Th/232-Th ratio of 7.4. Approximate correction suggests an age of 9.7 to 11.5 Ka.

How far these flowstones extended and what their relationship was to the stratigraphy in the rest of the Western Chamber it is impossible to say. They appear,however,to be above the level of the cave sediments that existed in that corner of the cave prior to the nineteenth century excavations, and may therefore have been a very local feature.

Site RH-2: In an alcove in the south wall some eight metres east of Site A are preserved *in situ* sediments that have survived the early excavations. The sediment column is 1.2 metres in height and is capped by the stalagmitic cemented breccia. The

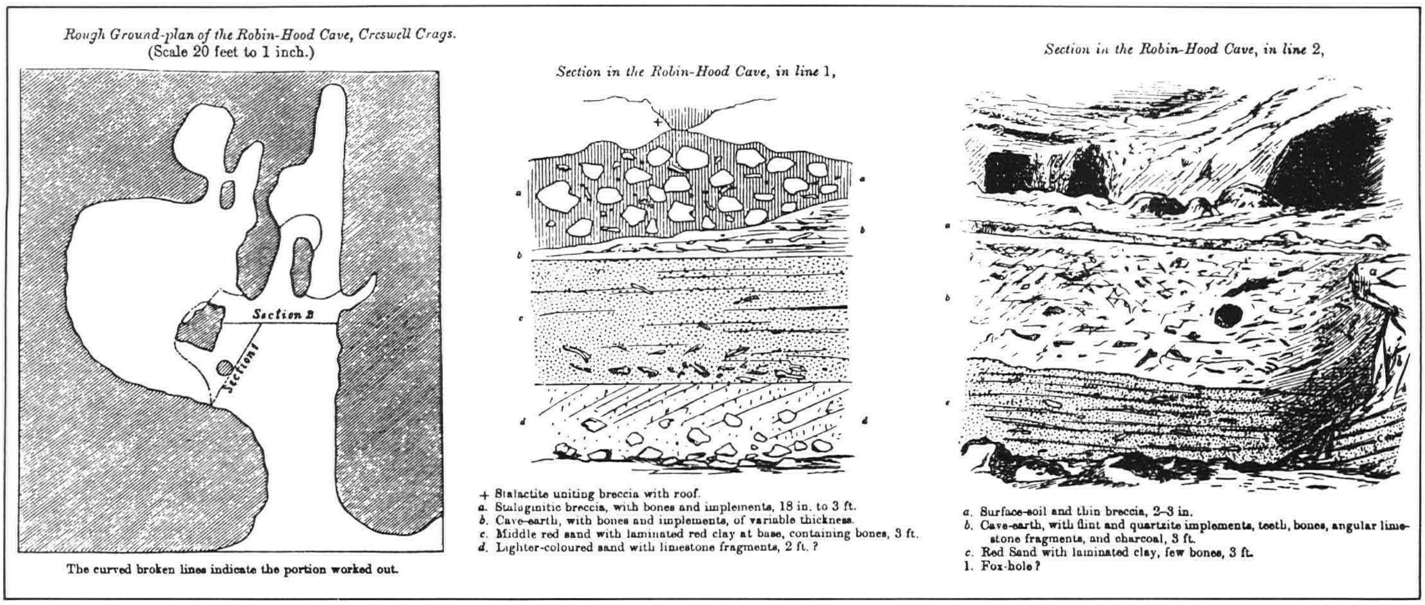


Figure 3a. Robin Hood's Cave. Plan and sections (from Mello 1876).

base of the sequence, which is not seen, occupies a shallow,sediment-filled depression in the cave floor. Interstratified in the sediments, 95 cms below the breccia and 20 cms above the lowest exposed level, is a small reddish laminated flowstone, 3 cms thick, *in situ*, and still attached to the cave wall. Laterally it passes into a layer of heavily indurated sand. Two samples gave uncontaminated ages of 165.1 +8.7/-8.1 and 165.7 +8.5/-7.9 Ka (UEA34 and 36,Table 1). The close agreement strongly suggests that this calcite layer formed at or very near 165 Ka. This was rather an unexpected result since the finds reported from the Western Chamber had previously been interpreted as being of Devensian age (e.g. Stuart 1982). Since Heath (1879) reported patches of stalagmite separating the basal red sand from the overlying cave earth (see Fig. 4), the surviving sediment was examined to establish whether these patches were likely to have corresponded with the dated horizon reported here. If they did it would be important because it would effectively impose constraints on the possible ages of the two main sediment units in the chamber, the "red sand" and the overlying cave earth described by Mello (see Figs. 3 and 4). Each of these contained faunal assemblages of rather similar character although that from the cave earth showed extensive signs of hyaena gnawing (Jenkinson 1984). Middle Palaeolithic stone tools, mainly of quartzite, were also recovered from both sedimentary units and even an approximate age estimate for these would be of considerable value. However, inspection of the *in situ* sediment at RH-2 indicates that the boundary between the two units occurs only some 20 cms below the base of the breccia (75 cms above the flowstone). At this point the breccia is about one metre thick and the excavation reports record that when the breccia was thick, the cave earth was invariably relatively thin (Mello 1876,p.241). The dated flowstone, then, occurs well within the red sand unit and therefore cannot be used to chronologically separate the finds from this unit and those from the overlying cave earth, although it suggests that the faunal remains from the red sand may well be around 165 ka in age since they were apparently recovered from the base of that unit (Mello 1876,1877).

Pollen analyses from samples of stratified sands, silts and clays above and below the flowstone have been reported by Coles et al (1985). They indicate that an open,steppe vegetation was replaced at around the time of flowstone formation by a vegetation much more thermophilous in aspect with *Pinus*, *Quercus*, *Ulmus*, *Tilia*, *Picea*, *Betula* and *Corylus* being represented.An apparently rapid return to steppe conditions is then suggested followed by a further climatic deterioration to a tundra environment. The record of these latter cooling phases also contains,besides Quaternary pollen,exotic Lower Cretaceous palynomorphs,probably derived from the Spilsby Sandstone or Speeton Clay of Lincolnshire and South Yorkshire 80 kms to the northeast.

The Northwest Chambers

Access to these is possible from the northwest corner of the Western Chamber and, via a squeeze, from the bottom of the fissure at Site A. Excavation was by Laing in the 1880's and his report (Laing 1889) is brief. A human radius and humerus were found in red sand in the fissure, and a Holocene fauna was recorded from the passages, although exactly where is not clear. Today, that part of the passage around Site RH-7C is practically devoid of sediment, although some stalagmite bosses are preserved on ledges. Extensive dating work has not been carried out on these bosses, although one date,(Site RH-7C,UEA831024-2, UEA77) indicates a maximum age of 13,300 years B.P. (230-Th/232-Th=2.0). Near sites RH-7A and RH-7B the passages still contain a great deal of sand on their floors and walls and it is evident that this section of cave was at one time filled to the roof with sediment. The sands silts and clays preserved on the walls here are thinly bedded and evidently

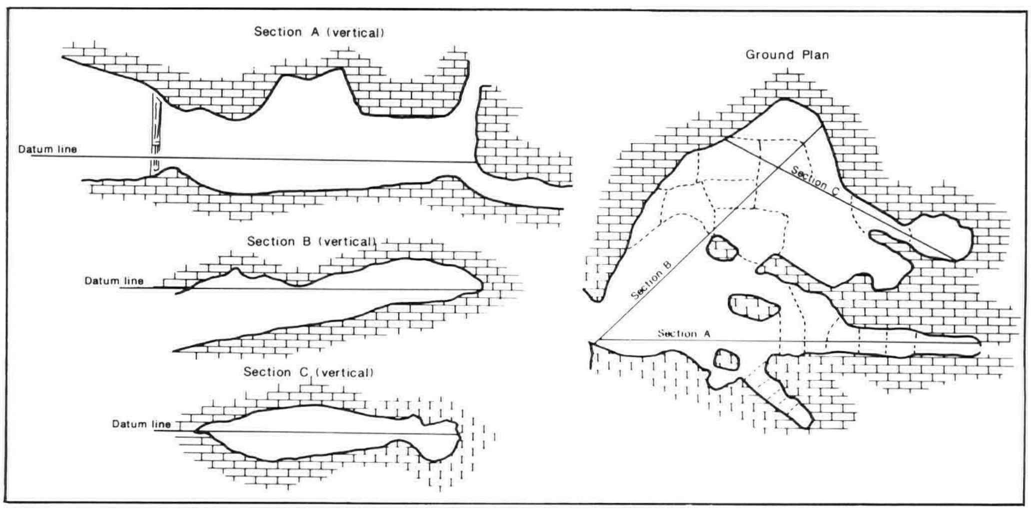


Figure 3b. Robin Hood's Cave. Plan and cross sections (after Mello 1877). Dotted lines on plan represent limits of daily excavations.

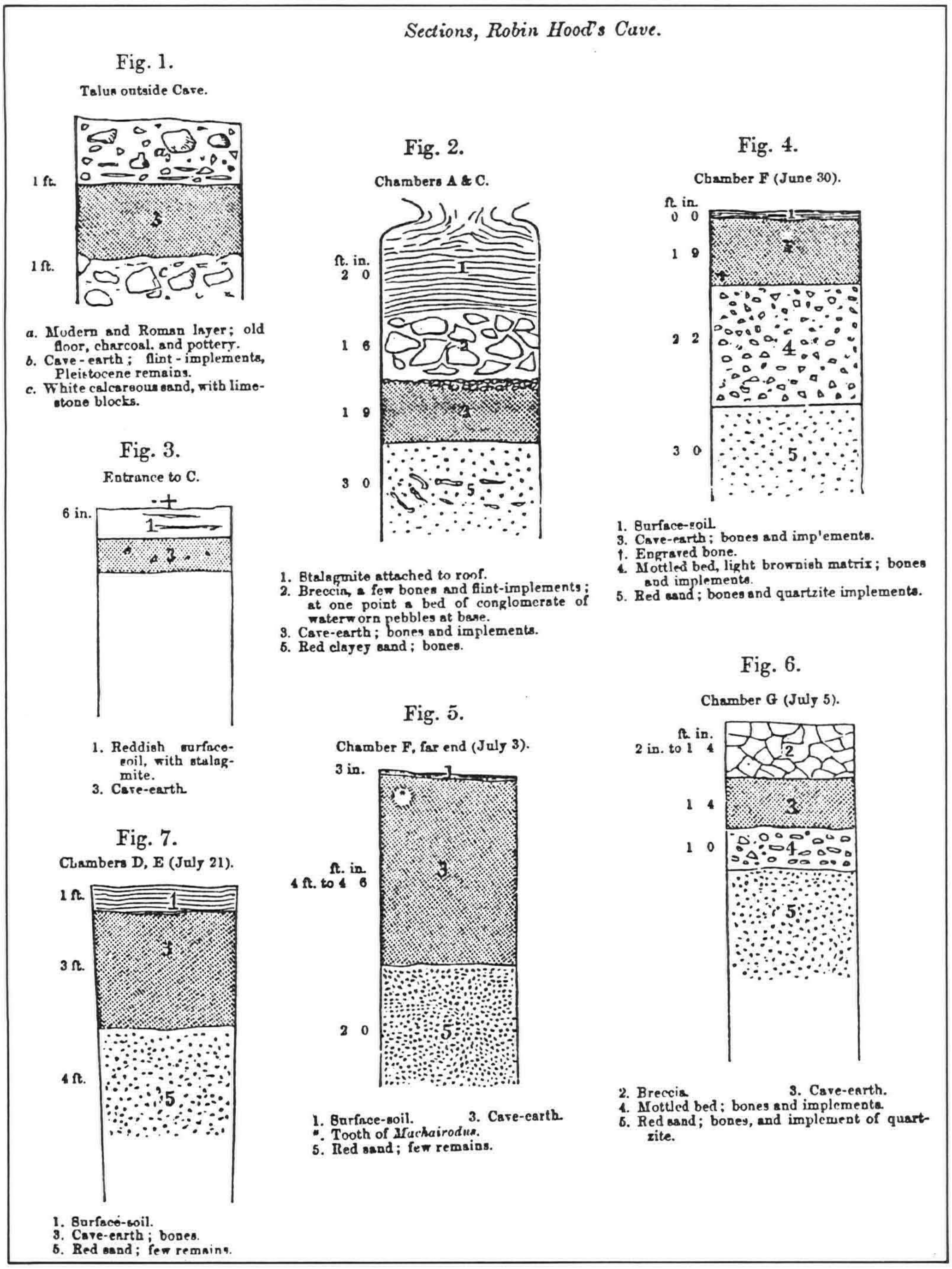


Figure 3c. Robin Hood's Cave. Stratigraphic sections (from Mello 1877).

waterlain. This may have occurred at a time when the cave was flooded, as some blind avens have stratified sediment in them. Site RH-7A (Fig.2) is at the base of a roof fissure and comprises two flowstone layers, each about 3 centimetres thick,underlain by indurated reddish sand and separated by a hiatus and overlain by a few centimetres of indurated brown sediment.The lower of these layers has been dated to 14,800±600 years B.P. (UEA45, 230-Th/232-Th=20.6; probable true age = 13.5 - 14.0 ka) and 12,500±500 years (uncontaminated), and the upper to 8,900±400 years B.P.(UEA68, a maximum age, since 230-Th/232-Th=14.0).

Site RH-7B (Fig.2) is a flowstone, up to 10 cm thick, interstratified in indurated sand,that has survived excavation and remains *in situ* attached to the roof. Casual inspection would suggest that the site probably represents a lateral equivalent of Site RH-7A, but two age determinations on fragments from the flowstone produced ages of 140 +8/-7 Ka and 126 +7/-7 Ka (UEA88 and 95).

Interpretation of the stratigraphy of this chamber has been complicated by excavation. All that can be said at present is that two phases of flowstone formation are represented,the earlier phase occurring at or just before the beginning of the last (Ipswichian) interglacial,and the later phase occuring just prior to and during the present (Holocene)interglacial. More stratigraphic work is required to clarify the detailed sequence of events in this area of the cave.

The Central Chamber

This too was excavated by Laing (1889) and his brief report records the following stratigraphy (from the base upwards):

(1) "stiff red clay and yellow ferruginous sand containing bones and teeth of *Hippopotamus major*, *Rhinoceros leptorhinus*, *Bison priscus*, *Cervus alces*, *Sus scrofa*, *Canis lupus*, *Ursus*, *Hyaena crocuta*, *Arvicola amphibia*".

(11) "sandy clay containing rolled pebbles".

(111) "unfossiliferous red sand continuous with that in the front cave".

Also noted is the presence of human remains, a hearth, and an Acheulian stone tool industry, although it is not stated in which layer these were found. All his finds are now lost. It is not clear whether "front cave" refers to the Eastern or Western Chambers.

Today, thinly bedded veneers of sand cling to the walls in many places, especially in joints and bedding planes, and a fragment of flowstone at the base of an aven, three metres above present floor level, has red sand adhering to its underside, indicating the upper level of cave infill. This flowstone has been dated to 7,400±400 years B.P. (UEA46), a maximum possible age since the 230-Th/232-Th ratio = 11.4 (RH-9,Figs.2 and 6). However, Laing did not reach bedrock in his excavation and as part of the 1981 investigations, a small trench of unknown origin was cleaned up and deepened to about 50 cms (Site C, Figs.2 and 6). This limited excavation showed that beneath a thin layer

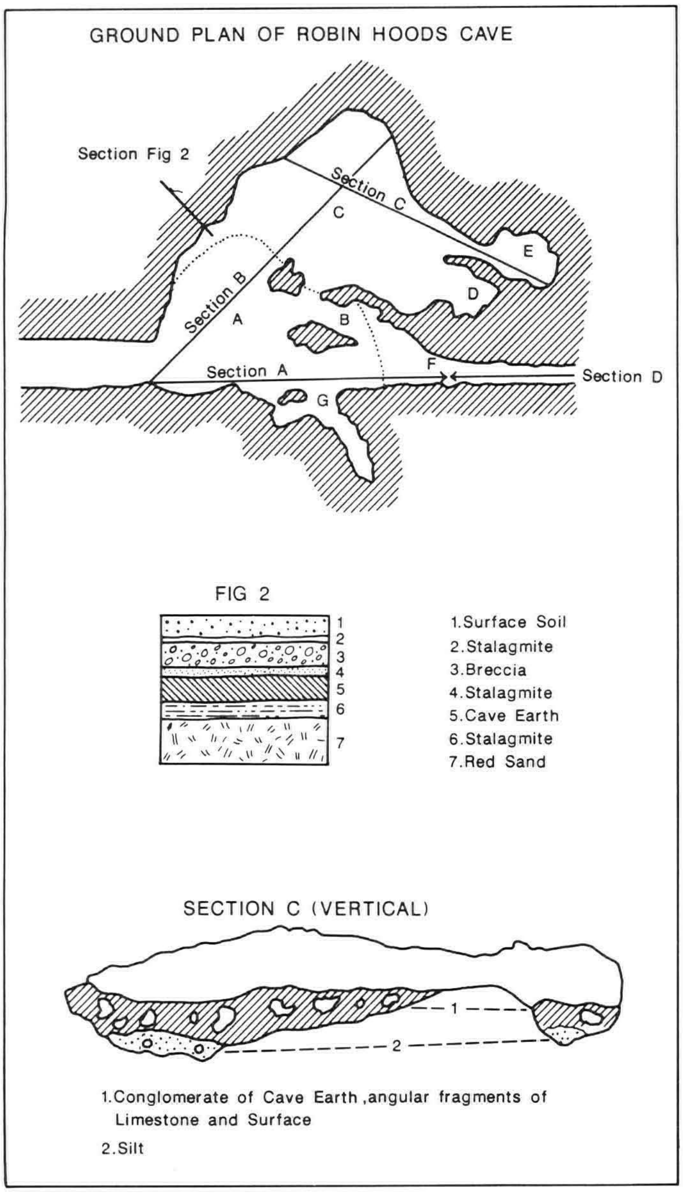


Figure 4. Robin Hood's Cave. Plan and section (after Heath 1879).

of spoil lay undisturbed sediments comprising thinly bedded sands, silts and clays amongst rotted limestone boulders. An undisturbed core 168 cms in length was also recovered.

The flowstone at RH-9 dated to 7400±400 years B.P. lies almost directly above the core site, and although it does provide a *post quem* date for the core sediments, in practical terms this is of very limited value given the 3m thickness of sediment that is missing between the flowstone and the 1981 excavation and core.

It appears that Laing excavated a chamber of enormous stratigraphic and archaeological importance. The find of *Hippopotamus* strongly suggests an Ipswichian Interglacial age for the red clay and yellow sand layer and this presumably lay above the present floor level, so that the underlying sediments in the present floor may be much older than this. Since the top of the sequence terminates in the Mid-Holocene, this chamber may have contained a stratigraphic record from pre-Ipswichian to Holocene times.

A north-south fissure passage to the east of the Central Chamber was also excavated by Laing, although no details are reported. Virtually nothing remains today except a layer of red sand that rests on a bridge of fallen limestone blocks and sediment at the entrance to the southern fissure. This sand is capped by a flowstone and the remains of stalagmite bosses, the former still being actively deposited by dripwater in places. Fragments from the boss have been dated to 10300±300 and 12600±500 years B.P. (RH-5, UEA820324-14, UEA27 and 28,Fig. 2).

The Eastern Chamber

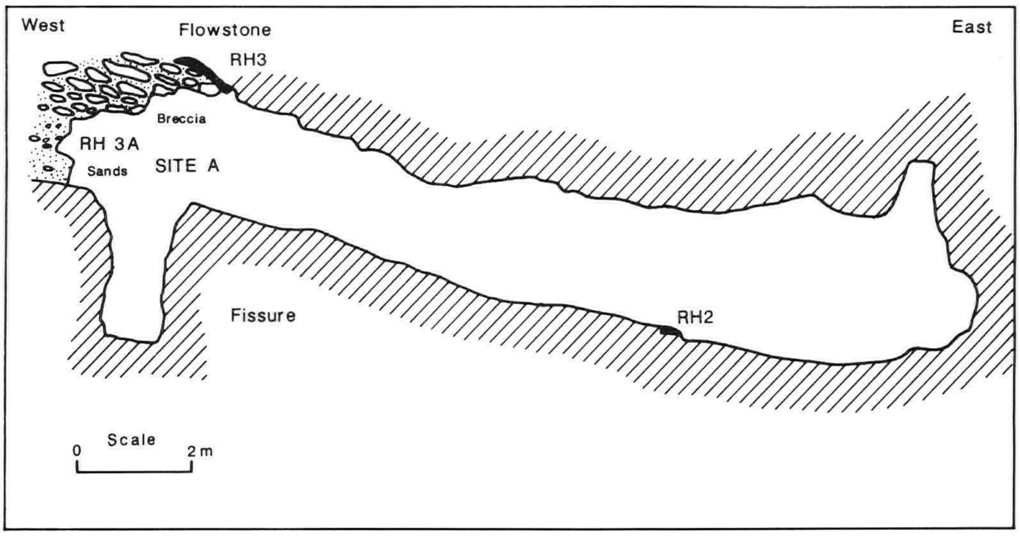
This is presumed to have been excavated by Laing (1889), although his report does not explicitly say so and nothing of the stratigraphy or faunal content is recorded. At present, a breccia of small limestone fragments cemented by flowstone forms a narrow ledge around most of the chamber (Fig. 6), and coalesces with the Western Chamber breccia in the connecting passages. It is generally less than 0.3 metres thick and is underlain by thinly bedded sands that are still widely present on the wall. The floor has several large limestone blocks resting on a layer of spoil covering what are probably *in situ* sediments. These blocks must have recently fallen from the roof. The limited excavation programme in 1981 (Site B, Figs. 2 and 6) revealed laminated water lain silts and sands on the east wall beneath the breccia.

The stalagmite cementing and coating the breccia is typically quite thin (< 2cm),very porous and "vuggy",and in the main quite unsuitable for dating purposes.It has been possible,however,to obtain sufficient reasonable quality flowstone from one locality on the west wall (Site RH-1),to enable two age determinations to be made.Here a thin stalagmitic rind coats the cave wall and the breccia and this material has been sampled,care being taken to avoid contamination by the limestone bedrock which is effectively of infinite age. Sample UEA 820324-3 is from the inner part of this rind and UEA 820324-2 from the outer part. Two metres north of RH-1 is a stalagmite boss that perches on a large limestone block forming part of the breccia (Site RH-1A). Two age determinations have been performed on samples from this boss (UEA 821209-5),UEA-63 from the base and UEA-62 from 3 cm above the base.

All the samples are contaminated with detrital thorium (230-Th/232-Th< 5) producing calculated ages that are in all cases too great. However, approximate corrections suggest that (1) the inner part of the calcite coating on the wall (RH-1,UEA 820324-3, UEA38) probably dates to between 9.5 and 13.5 Ka whilst the outer coating (RH-1, UEA 820324-2, UEA33) dates from around 10 Ka; (2) the base of the stalagmite boss (RH-1A, UEA 821209-5-2,UEA63) is between 7.5 and 10.8 Ka,and the sample just above it,(RH-1A, UEA 821209-5-1, UEA62) from 7 to 10 Ka.

From these data it is evident that latest Devensian and/or early Holocene stalagmite,coats and cements and therefore post-dates

Figure 5. Section across the Western Chamber of Robin Hood's Cave (see also Fig. 2).



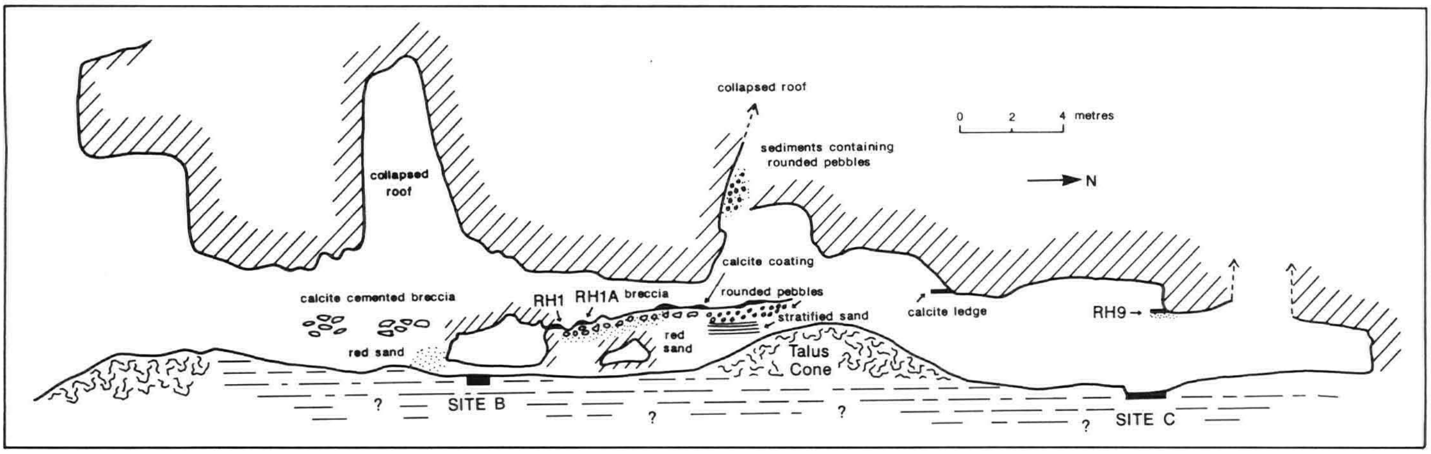


Figure 6. Longitudinal section through the Eastern and Central Chambers of Robin Hood's Cave (see also Fig. 2).

a breccia that overlies the sediments on the wall and in the floor. However,it is probable, that a very considerable time span separates the deposition of the sediments from the influx of the breccia and the formation of the stalagmite.

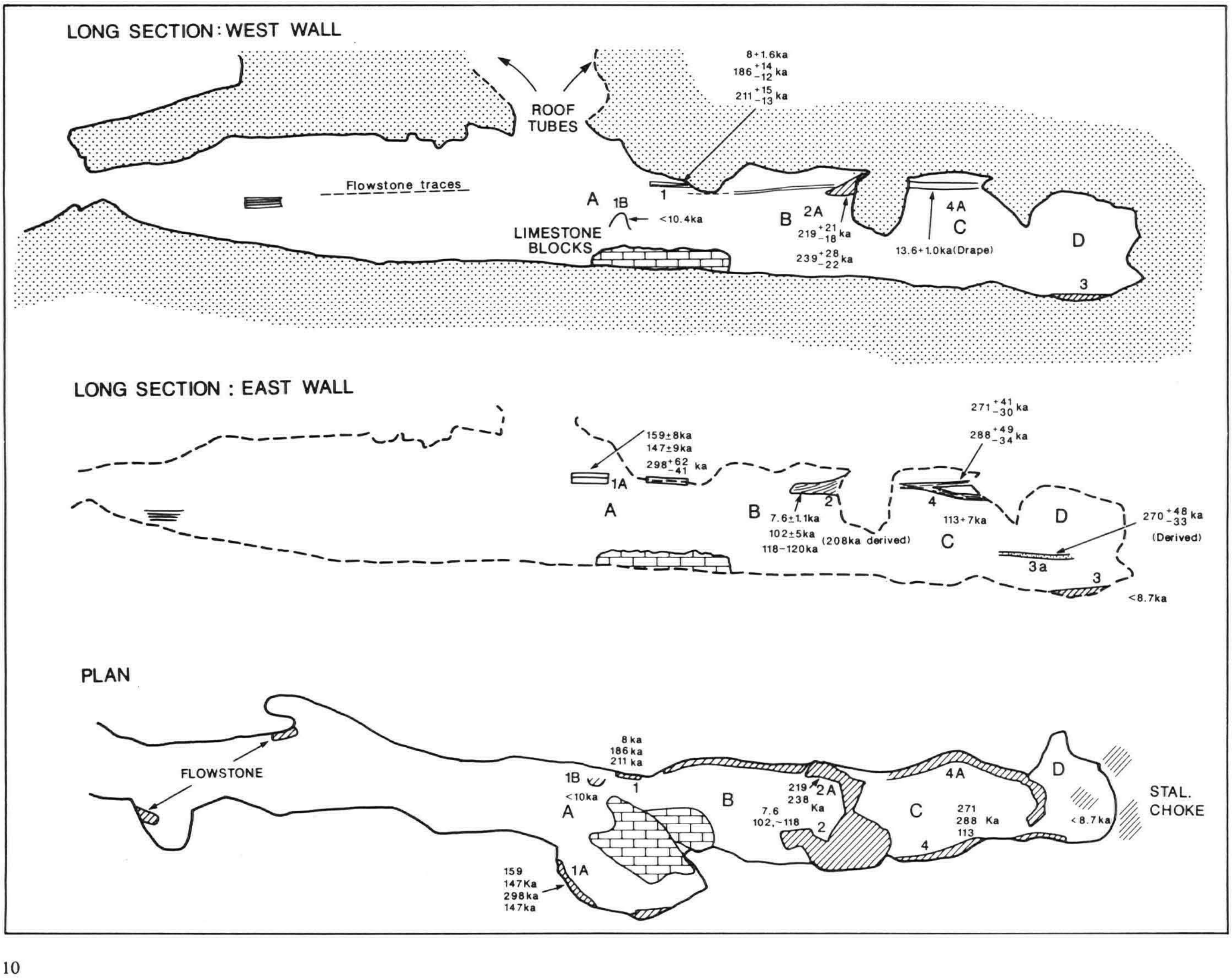
Robin Hood's Cave: Summary

It is evident from examination of the remaining sediments that the complexity of the sedimentation and infilling sequences in Robin Hood's Cave was considerable both in space and time. The earlier excavators unfortunately failed entirely to appreciate this and have left neither adequate records nor adequate remains for any attempt to confidently reconstruct the original stratigraphy. Although some evidence is emerging for the provenance of some of the remaining sediments (Briggs and Griffin 1985), it is very unlikely that detailed correlations between the sedimentary fragments that have survived excavation will ever be possible. The dating programme has established that the youngest sediments in the cave cannot be more recent than early Holocene in age. The evidence from the Western Chamber strongly suggests that the basal red sand unit there was deposited at around 165 Ka. The fossiliferous cave earth must therefore be of intermediate age. Although Laing's report (Laing 1889) of the Central Chamber deposits states that the red sand *overlay* an horizon bearing a hippopotamus fauna (and therefore of presumed Ipswichian age), red sand also underlies flowstone dated to between 126 - 140 Ka in the Northwestern Chambers. The presumption must therefore be that deposition of such sand units was not a unique occurrence.

Cave C7

C7 has developed in the northern face of the gorge. It is the highest of the Creswell Crags caves and also one of the smallest. It is essentially a single relict phreatic tube 20 metres long and

Figure 7. Plan and long sections of Cave C7 showing speleothem sampling sites and uranium-series ages of dated flowstones.



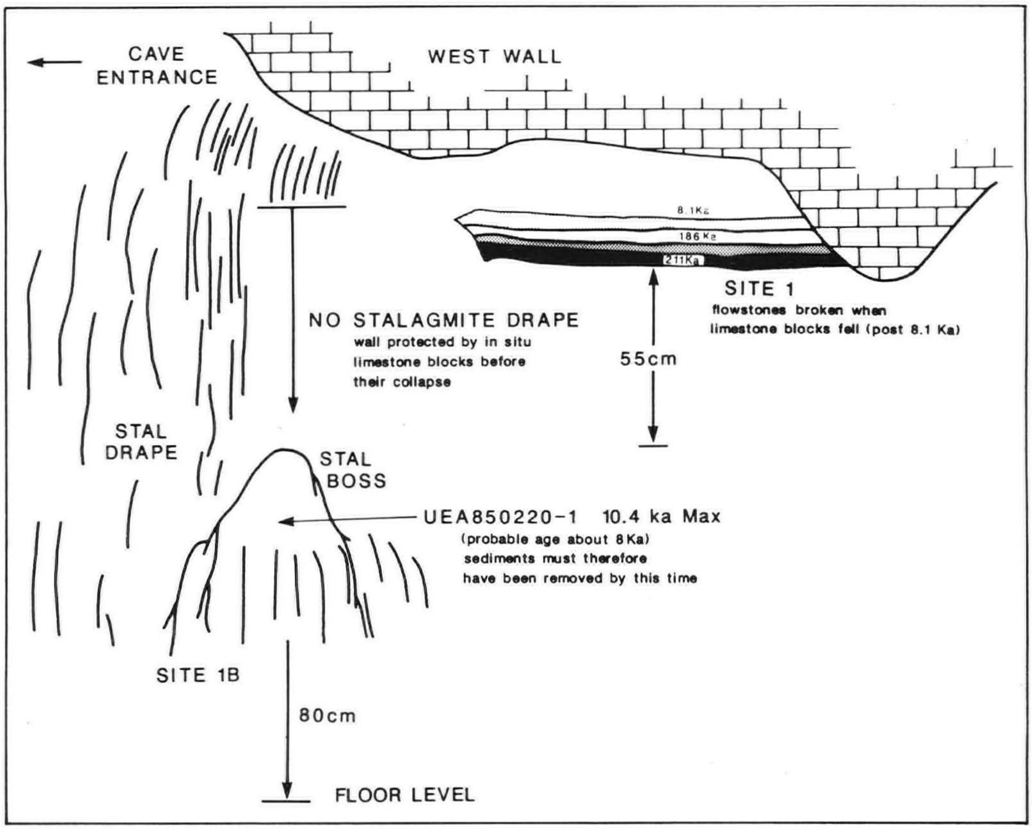


Figure 8. Sites 1 and 1B, Cave C7.

for the most part about 1 - 2 metres in diameter. Eight metres from the entrance the cave widens slightly and here solutional activity has created a roof cavity that bifurcates into two perfect roof tubes that follow the axis of the cave, one towards the front and one towards the rear (Fig. 7). Beyond this area alternate pendant roof blocks and solutional roof domes demarcate the passage into a further three "compartments" (B,C,D,Fig. 7), the final one ending in narrow, tubes and slots choked with flowstone.

Cave formation was originally joint controlled. Much of the front part has now been completely destroyed by erosion, leaving, outside the present entrance, a scree slope between two vertical limestone faces. The relatively high degree of destruction that the cave has suffered is probably related to the thinly bedded nature of the limestone immediately above the roof of the cave.

The stratigraphy of C7 consists almost entirely of ledges of sediment and flowstone representing a series of floors that were formed and destroyed at various stages of the cave's history. As far as is known, the cave has never been excavated by man and unlike the other caves in the gorge, the fragmentary nature of the stratigraphic record here is attributable to natural processes.

The present cave floor slopes very gently downwards away from the entrance and the stratigraphic remnants are near floor level at the entrance but approach roof level further into the cave. The present floor is covered to an unknown depth in limestone slabs, generally about 10 - 30 cms in long axis. Towards the front of the cave it is possible to see where spalling has occurred from the roof and walls, but further back this is not so and the roof, especially, has a largely unaltered phreatic form. Presumably many of the blocks have been carried in via the cave entrance, possibly associated with the destruction of the front part of the cave. They may represent a lag deposit, left after the washing out of finer sediment. Also on the floor are a few slabs of flowstone and indurated sediment that are obviously derived from the hanging floors. In the wider part of the passage, 8 - 10 metres from the entrance, are two very large limestone blocks 1.0 - 1.5 metres in length that have fallen from the roof. These are shown on Figure 7.

Figure 7 summarises the visible deposits. Just inside the entrance, broken flowstone forms false floors across two small side tubes, one in each wall. That across the western tube is the more substantial and consists of three layers, separated by hiatuses, with a total thickness of about 30 cms. It appears, from the evidence of occasional tiny flowstone remnants and lineations on the west wall, to be part of the same floor represented by five thin (1 - 2 cms) flowstone layers on the west wall of the small chamber, 8.5 metres from the entrance and 1.4 metres above the cave floor (Site 1). The upper, middle and lower of these were suitable for dating, producing uncontaminated ages of 211 +15/-13 Ka, 186 +14/-12 Ka and 8±1.6 Ka in correct stratigraphic order (UEA73, 83, and 70, see Table 1 and Fig. 7). Near this point, 55 cms below Site 1 and 80

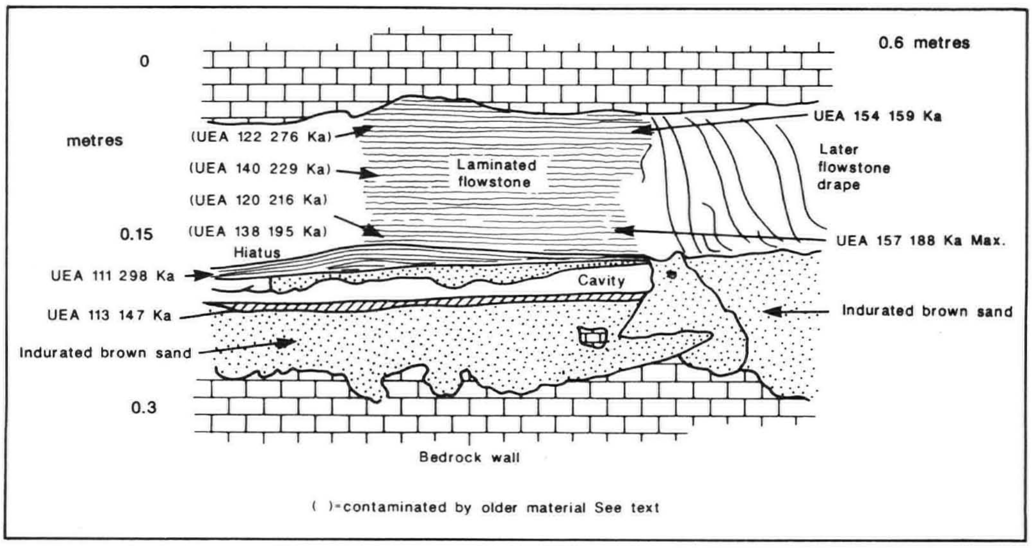


Figure 9. Site 1A, Cave C7.

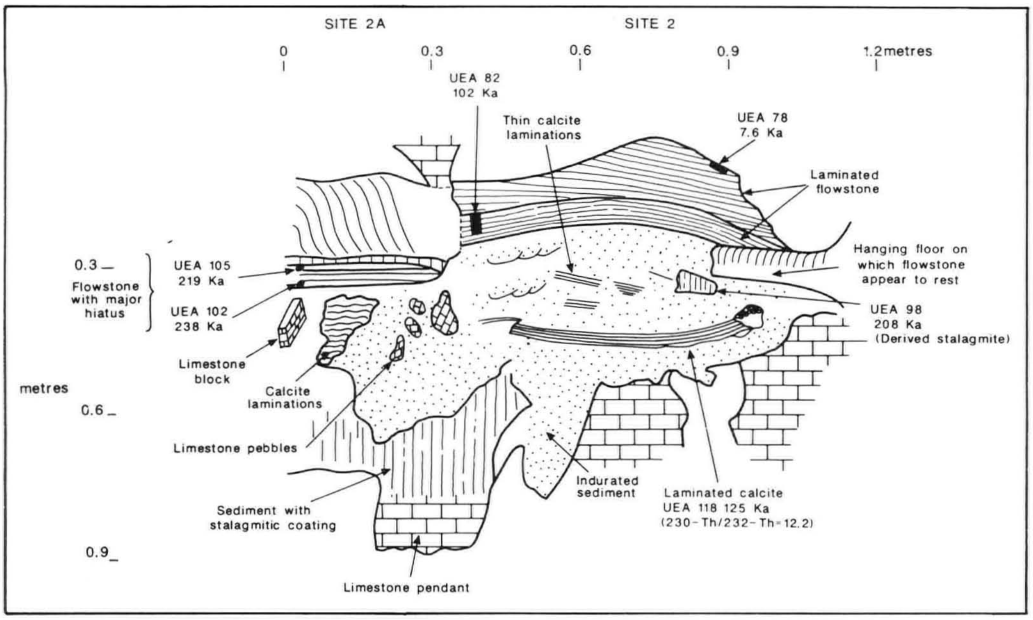


Figure 10. Sites 2 and 2A, Cave C7.

cms above the floor is a small stalagmite boss perched on a limestone ledge on the wall (Site 1B). This is associated with nearby stalagmite drapes on the wall which cut across the level of the Site 1 hanging flowstone floor (Fig. 8) and clearly post-date the removal of the cave sediments at this spot. The stalagmite boss is dated to 10.4±0.6 Ka (230-Th/232-Th = 6.0, UEA155) but the true age is probably about 8 Ka.

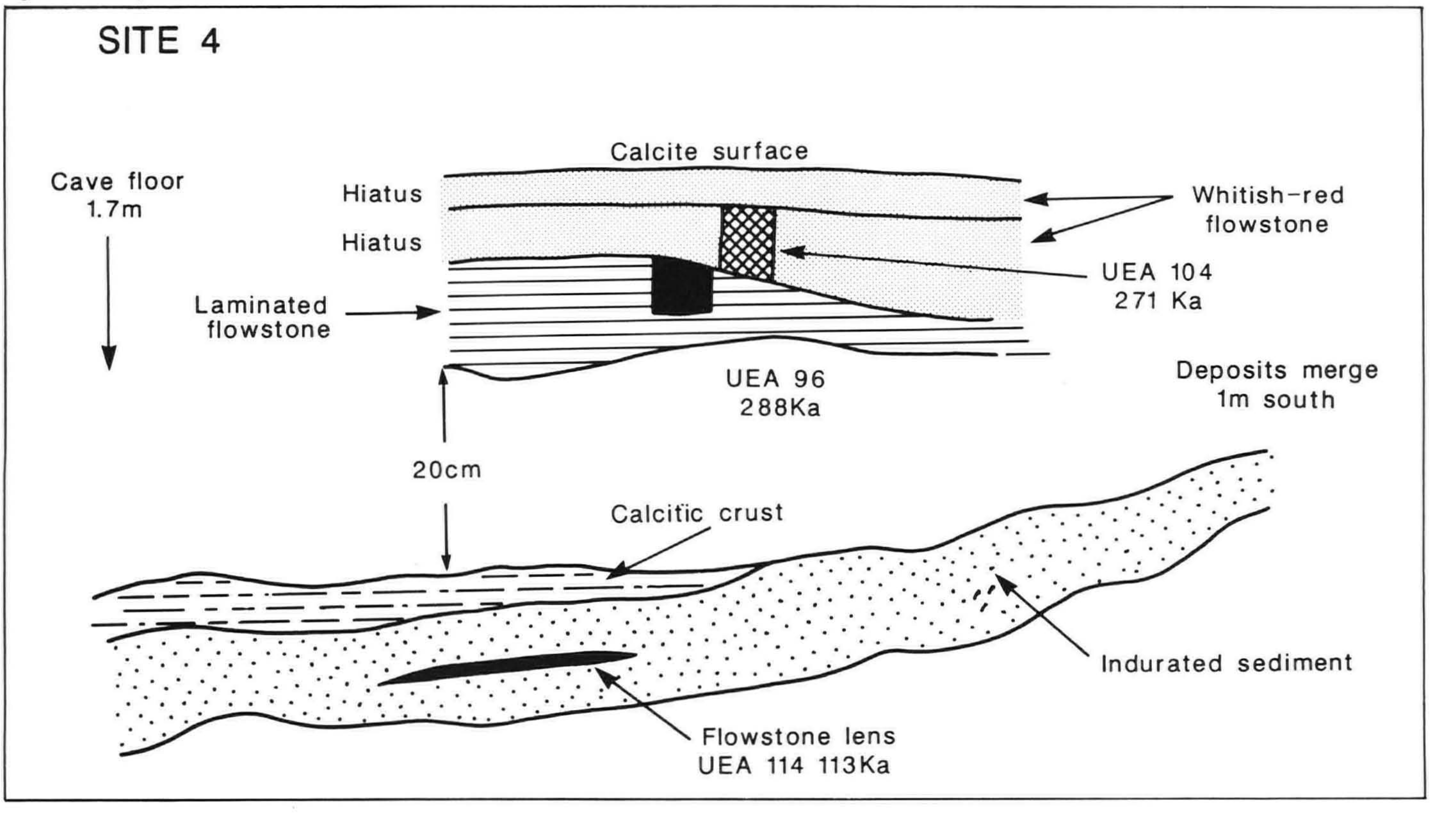
Opposite, on the eastern wall of the cave just below roof level, is a rather more substantial sequence of flowstone (Site 1A, Fig. 9). Part of this has been removed and sampled. A few centimetres of hard indurated sediment at the base is coated with a thin (<1cm) flowstone dated to 147±9 Ka. Above this is a cavity and then another layer of indurated sediment capped by a rather thicker flowstone dated to 298 +62/-41 Ka. A clear unconformity separates this layer from a much thicker (15 cms) capping white laminated flowstone which in turn has a thin overgrowth on its upper surface. Two dates, UEA154 and UEA157 (Fig. 9 and Table 1) show that the white laminated flowstone was formed between about 170 Ka and 160 Ka. (Previous dating of this flowstone had given inconsistent results which were due to the incorporation of an older stalagmite, which was part of the 298 Ka layer below, into the samples. The affected determinations were UEA120, 122, 138 and 140).

The large fallen blocks in this part of the cave, previously referred to, also have on them remnants of indurated sediment and flowstone which are certainly part of the sequences described above from Sites 1 and 1A. Some time after the sediment underlying them had been washed out of the cave, these blocks fell from the roof, bringing down much of the remaining speleothem hanging floors.

Beyond these blocks the cave roof lowers abruptly to form a wall of rock from which two small calcite - choked tubes enter the cave. Across these tubes and on the rock face are preserved the remains of rather a complex stratigraphy of sediment and flowstone (Sites 2 and 2A, Fig. 10). At least two distinct stratigraphic sequences seem to be represented here but their precise lateral relationship is not clear.

In the western half of the section (Site 2A) red - brown sediment containing limestone pebbles and thin laminated calcite which has formed in cavities in the sediment, is overlain by a reddish flowstone 6-8 cms in thickness containg a hiatus about 5 cms above its base. This flowstone has been dated to 239 +28/-22 Ka (lower, UEA102) and 219 +21/-18 Ka (upper, UEA105) with 230-Th/232-Th ratios of 31.0 and 13.7 respectively. The eastern half of the section (Site 2) has indurated red-brown sediment overlain by a 2 cms thick reddish laminated flowstone. The uncorrected age is 125±6.5 Ka (230-Th/232-Th = 12.2, UEA118) but the true age is probably about 118 - 120 Ka. Above

Figure 11. Site 4, Cave C7.



this flowstone is an indurated brown sediment containing cavities and thin flowstone laminations that have evidently formed *in situ*. It also contains a fragment of derived stalagmite, dated to 208 +16/-14 Ka (UEA98). This brown sediment therefore probably represents reworked material, a conclusion supported by the mixed nature of the pollen recovered from this section (Coles pers. comm.). This sediment is overlain by two flowstones separated by a hiatus. The lower is a reddish -white laminated flowstone about 10 cms thick, dated to 102±5 Ka (UEA82), and the upper consists of white laminated calcite varying from 10 -20 cms in thickness, the top of which has been dated to 7.6±1.1 Ka (UEA78).

Beyond Site 2 the next "compartment" (C) contains more remnants of previous cave fills (Sites 4 and 4A, Fig. 7). On the eastern wall, 170 cms above the floor is a ledge (floor 1) consisting of small quantities of indurated sediment overlain by two flowstones each 1 - 3 cms thick separated by a hiatus (Fig.11). Both consist of reddish - white calcite and the lower has been dated to 288.6 +49/-34 Ka (UEA96) and the upper to 271 +41/-30 Ka (UEA102). At the inner (northern) end of the chamber this hanging floor remnant crosses the cave near roof level and part of it can be seen to have collapsed and come to rest on another ledge of sediment (floor 2) just below it. On the eastern wall floor 2 is 20 cms below floor 1 at the point where the dated samples were taken, but the two floors merge together a metre or so southwards along the wall towards the front of the cave (Fig. 7). Floor 2 is composed of sandy sediment heavily indurated with calcite and at one point it was possible to to find sufficient pure calcite for an age determination. This gave 113±7 Ka (UEA114). Floor 1 continues as a ledge along the western wall where it is totally obscured by a later thick stalagmite coating dated to 13.6±1.0 Ka (230-Th/232-Th = 11.8, UEA97).

On the eastern wall, one metre below floor 1 and 0.75 metres above the present rubble covered cave floor are faint traces of yet another previous floor level (Fig. 7). It continues into and is better defined in, the very small rear chamber (D). It comprises a ledge of heavily indurated fine sand, mostly covered by later thin undateable stalagmite coatings. Embedded in the sediment was a small piece of derived laminated flowstone which has been dated to 270 +48/-33 Ka (UEA116).

Beneath the rubble on the floor of the rear chamber is a stalagmite floor some 6 - 10 cms thick (Site 3). It frequently has a rather sugary texture, particularly near the top, but an age determination was made on a sample from the middle of the floor and this gave an age of 8.7±0.6 Ka (UEA74). However, the 230-Th/232-Th ratio was 3.7 and therefore the true age must be considerably less than this. What lies beneath this floor is not known.

C7 is important because it contains the oldest sequences of dateable deposits so far discovered at Creswell Crags. The fragmentary nature of their preservation makes interpretation difficult, but Table 2 attempts to summarise the likely sequence of events. The most notable feature of this long and complex history is that the cave was filled with sediment almost to roof level at Sites 1A and 4 (see Fig. 7) at a very early stage, by about 290 - 300 ka. During the next 150,000 years, the only events within the cave appear to have been the intermittent deposition of flowstones between about 240 ka and 160 ka. In the interval between c.160 Ka (UEA154) and the deposition of UEA113 at 147±9 Ka, the sediments at Site 1A were wholly or partially removed from the cave. The mechanism of removal is not known, but may have involved the sludging of wet sediment from the cave entrance. The 147 Ka flowstone (UEA113, Fig. 9) was deposited on top of surviving or newly deposited sediment. After an interval, further flowstone deposition followed at c. 120 Ka at Site 2, while from c. 120 Ka to c. 100 Ka flowstone deposition at Site 2 appears to have been contemporaneous with the local accumulation of reworked sediment, still at a level which is close to the roof of the cave. By this time (113 Ka) also, the original 288,000 year old floor at Site 4 has been broken, and new flowstone was deposited on the surface of eroded or freshly deposited sediment (UEA114, Fig. 11), again at a level which

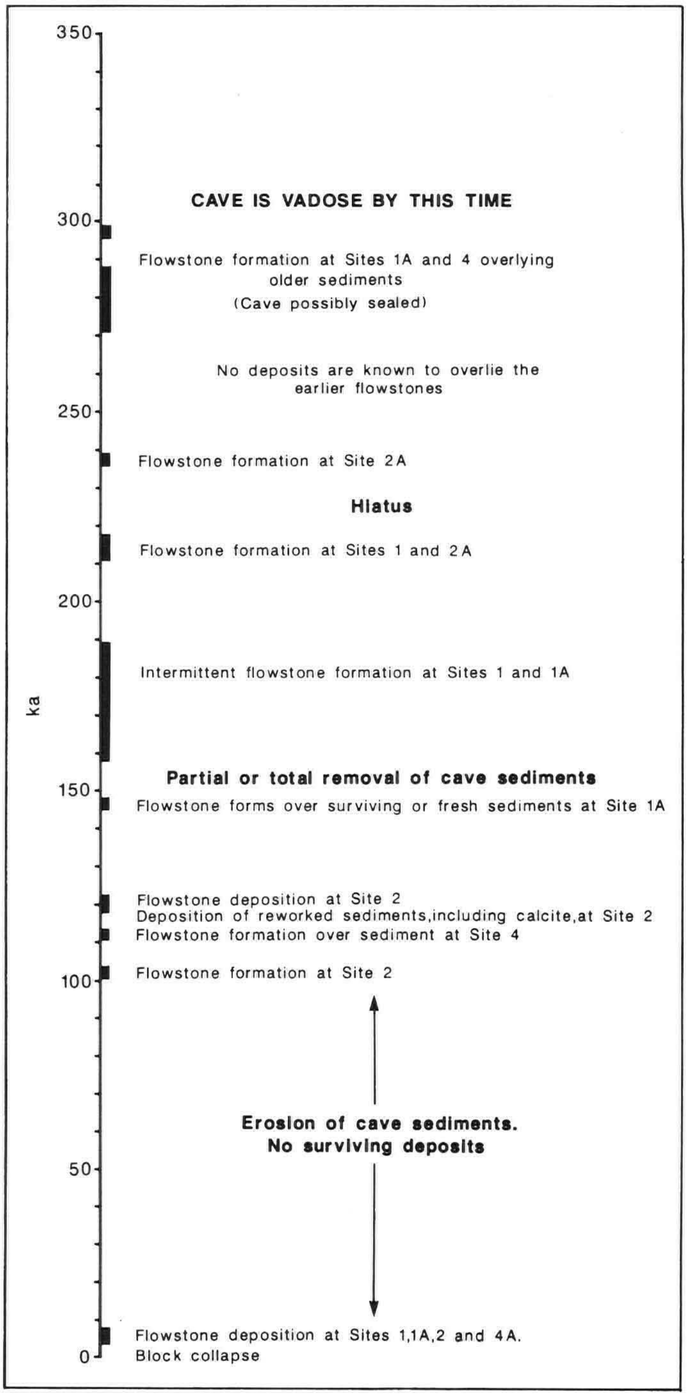
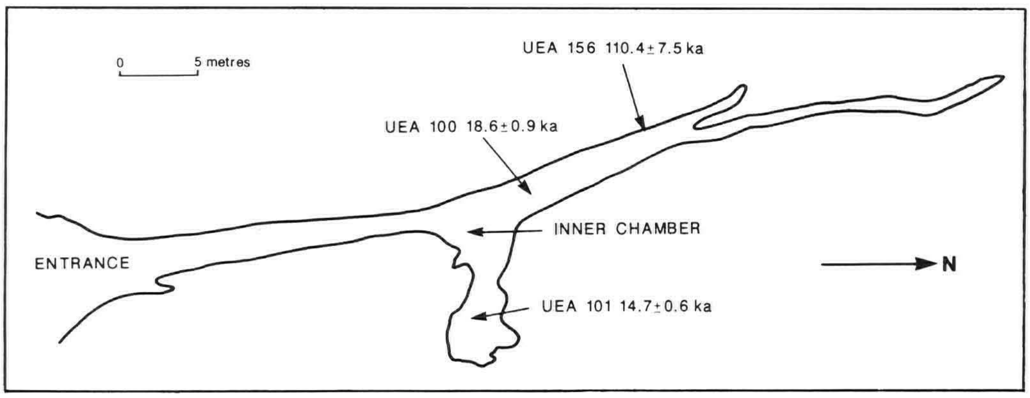


Table 2. Post-phreatic geomorphic sequence of events in Cave C7 as indicated by the speleothem dating evidence.

Figure 12. Plan of Pin Hole Cave showing speleothem sampling locations and uranium-series ages of dated flowstones.



was still close to the cave roof. The bulk of the remaining sediment in the cave appears to have been removed since 100 Ka, probably during the Devensian cold stage. The early Holocene date for the stalagmite boss at Site 1B (Fig. 7), indicates that removal was virtually complete by that time. The slope of the present floor is into the cave, suggesting that the limestone blocks which form it were transported in from the entrance, perhaps as a wet debris flow fed by material falling into the entrance from the short slope of the gorge wall above. The pre - Devensian sediments may also have been removed in an inwards direction, in which case there must exist further passages beyond the known cave, containing these sediments in reworked form. It is more likely that the older sediments were removed by wet sludging out of the cave entrance, but before accumulation of the material forming the present floor.

Cave C8

This cave was partially excavated in 1894 by Duckworth and Swainson (1895). Their report was brief and recorded a white earth passing down into a red sand, with roe deer, fox and badger remains. The red sand was underlain at a sharp boundary by a cave earth containing reindeer, wolf and hyaena. They stopped their excavation on encountering a mass of travertine. Today, deposits remain at the back of the cave, sealed by a thin travertine. Local superficial inspection of the sediment immediately under this layer reveals limestone blocks up to about 50cms across, with yellowish fine sand and small, friable limestone pebbles 2 -10 cms in size.

At the front of the cave on the west wall, a thin flowstone underlain by red sediment forms a narrow ledge of a hanging floor which has been broken and covered with a later flowstone drape. The flowstone in the hanging floor dates to 103.7±4.8 Ka (UEA72). The drape has not been dated. Evidently the original floor was broken and much of the deposits washed out before Duckworth's and Swainson's excavation took place, for even at the back of the cave, which is unexcavated, the flowstone ledge is 1.5 metres above the *in situ* deposits.

Pin Hole Cave

Pin Hole Cave is a fissure 31 metres in length and generally very narrow, typically 1 - 2 metres wide (Figs. 12 and 13). About 17 metres from the entrance, however, it widens sufficiently to form a small chamber, known as the Inner Chamber, which has a small low extension leading off to the east associated with several minor phreatic tubes and solution hollows. Beyond this, the cave narrows again and eventually ends in an impenetrable slot. The main fissure in which the cave is formed extends to the crest of the gorge and in places is sufficiently wide to allow small quantities of water and sediment to wash down into the cave, a process that has probably operated throughout most of the cave's vadose history.

The excavations in this cave are the best executed and recorded of any of the Creswell caves. The sequence remaining is also the most complete of any excavated cave in the gorge and is in the process of being intensively re-examined and sampled.

Only a brief outline of the stratigraphy will be given here. Detailed treatment is provided by Collcutt (1975) and more recently by Jenkinson (1984).

The excavation history began with Mello (1875,1876) who dug out the sediment to about 25 feet from the cave entrance. His recorded stratigraphy was:

"1. Surface soil containing pottery, bones,etc 1-6 ins
2. Damp red sand with rough blocks of Magnesian Lst, quartz quartzite and other pebbles, and numerous bones 3 ft
3. Lighter coloured sand, consolidated by infiltration of lime. No bones found yet. (?) "

The red sand unit was observed to have no regular bedding features in it and the bones recovered included those of wolf, hyaena, bison, horse, and mammoth amongst others. The basal sand was dug to a depth of one foot and found to be unfossiliferous. Mello, joined by Thomas Heath, then "worked out" the red sand in Pin Hole and turned their attentions to Robin Hood's Cave (Mello 1876).

A.L.Armstrong then took up the excavation of the cave from 1925-32. He excavated the remainder of the narrow passage up to and including the Inner Chamber. He records (1) Surface soil (0.15m) above (2) a Limestone Breccia cemented by flowstone (0.15-0.30m) overlying (3) a Red Cave Earth (1.85-0.77m), separated by a limestone "slab layer" from (4) a Yellow Cave Earth (1.85-3.10m thick) in which occurs a second "slab layer". The sequences were thickest in the Inner Chamber and thinned and sloped down towards the entrance. The faunal remains and artifacts recovered by Armstrong from this cave make it one of the most important Palaeolithic cave sites in Britain.

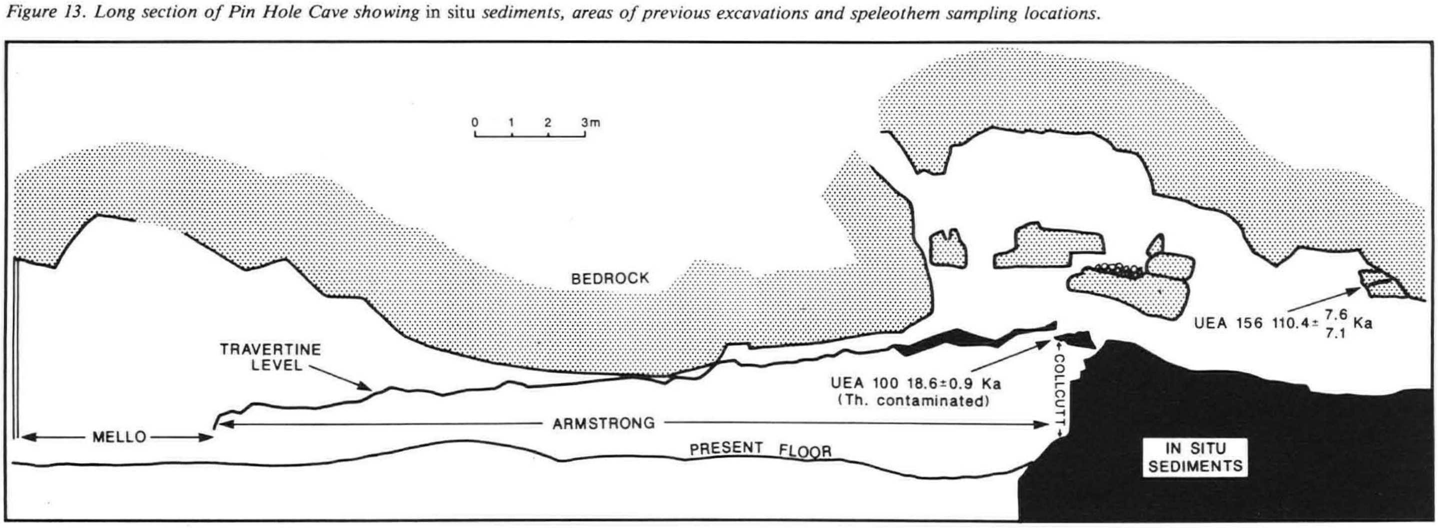
Later, Collcutt (1975), in a very limited excavation, examined and sampled the sediment section left by Armstrong *in situ* just beyond the Inner Chamber.

Armstrong divided his deposits into those of glacial and those of interglacial character based on the presence of stalagmite and "slab layers" (assumed to indicate glacial conditions) and on vertical variations in fauna. Armstrong's sections and interpretations have since passed into the literature and are sometimes quoted as if they were definitive for this part of Britain. In fact the correlation of stalagmite with glacial conditions is erroneous, while correlating the "slab layers" with glacial conditions is at the very least uncertain, and Collcutt (1975) notes that there is no evidence for a "moderately warm" or "temperate" fauna in these sediments.

Jenkinson (1984), in an exhaustive study of the Pin Hole fauna and artefacts, has re-examined over 22,000 vertebrate fragments recovered by Armstrong and, dividing the recorded stratigraphy into 20 one foot levels, has been able to locate the original precise position of over 15,000 of these. Of particular interest is the identification of many bird species, many of which are valuable as palaeoenvironmental indicators.

Figure 13 shows the position of the flowstone floor that cemented and capped the breccia recorded by Armstrong. It can be traced along the wall today and just beyond the Inner Chamber it remains intact, coating limestone blocks that form the upper unit of the sediment column presently being excavated. This column is essentially the section left by Colcutt. A thin flowstone layer also exists in the small eastern extension of the Inner Chamber and here it is interbedded near the top of a block of sediment and limestone slabs that survived excavation and cling to the roof around a limestone pendant. Evidently this small chamber was filled to the roof with deposits. The sediment block has been removed and the flowstone layer dated to

Figure 13. Long section of Pin Hole Cave showing in situ *sediments, areas of previous excavations and speleothem sampling locations.*



14,700±600 years B.P. (UEA840322-1, UEA101, Fig.12). A flowstone sample from the coating over the limestone blocks immediately above the present excavation has also been analysed. This gave an age of 18600±900 years B.P.(UEA840227-1, UEA100, Fig. 12), but is heavily thorium contaminated (230-Th/232-Th=2.5) so that this age is a maximum and all that can be said is that the sample is of Late Devensian - Holocene age. Insufficient deposits remain in the Inner Chamber to determine whether these two flowstones are stratigraphically equivalent. A mammoth bone recovered from the cave by Armstrong in association with a Mousterian stone tool industry shows clear evidence on its surface of tool cut marks and also has a calcite encrustation on one end. An analysis of the calcite gave an age of 13200±800 years BP (230-Th/232-Th = 6.8, UEA298). The true age of the calcite is probably between 10 and 12 ka. It must post date the bone but the length of the time gap between the abandonment of the bone and calcite formation is not known.

Of great significance is the presence, several metres beyond the limit of Armstrong's excavations and about 3 metres above the level of the top of the surviving section, of a small block of sediment adhering to the cave wall (Figs. 12 and 13). Interbedded in this sediment is a thin flowstone that has been dated to 110.4±7.5 Ka (UEA110). The interpretation placed upon this deposit is that it represents all that remains, at that level, of a cave fill sequence that has either been totally or partially removed since the last (Ipswichian) interglacial and has been replaced by the deposits investigated by Armstrong and which are seen today. If the original sediments were totally removed, the present deposits may represent a continuous record of a later depositional sequence, but if only partial removal occurred, then what is seen today may represent two or more sequences, separated by hiatuses of unknown duration. Careful excavation may reveal which alternative is correct. Such evidence emphasises the need for exercising extreme caution when interpreting data from excavations carried out without the benefit of dating techniques or a modern understanding of cave geomorphological processes.

THE CHRONOLOGY OF THE CRESWELL CRAGS CAVES AND THEIR DEPOSITS

The speleothem evidence allows certain conclusions to be drawn as to the geomorphic sequence of events at Creswell Crags. These are summarised in Figure 14.

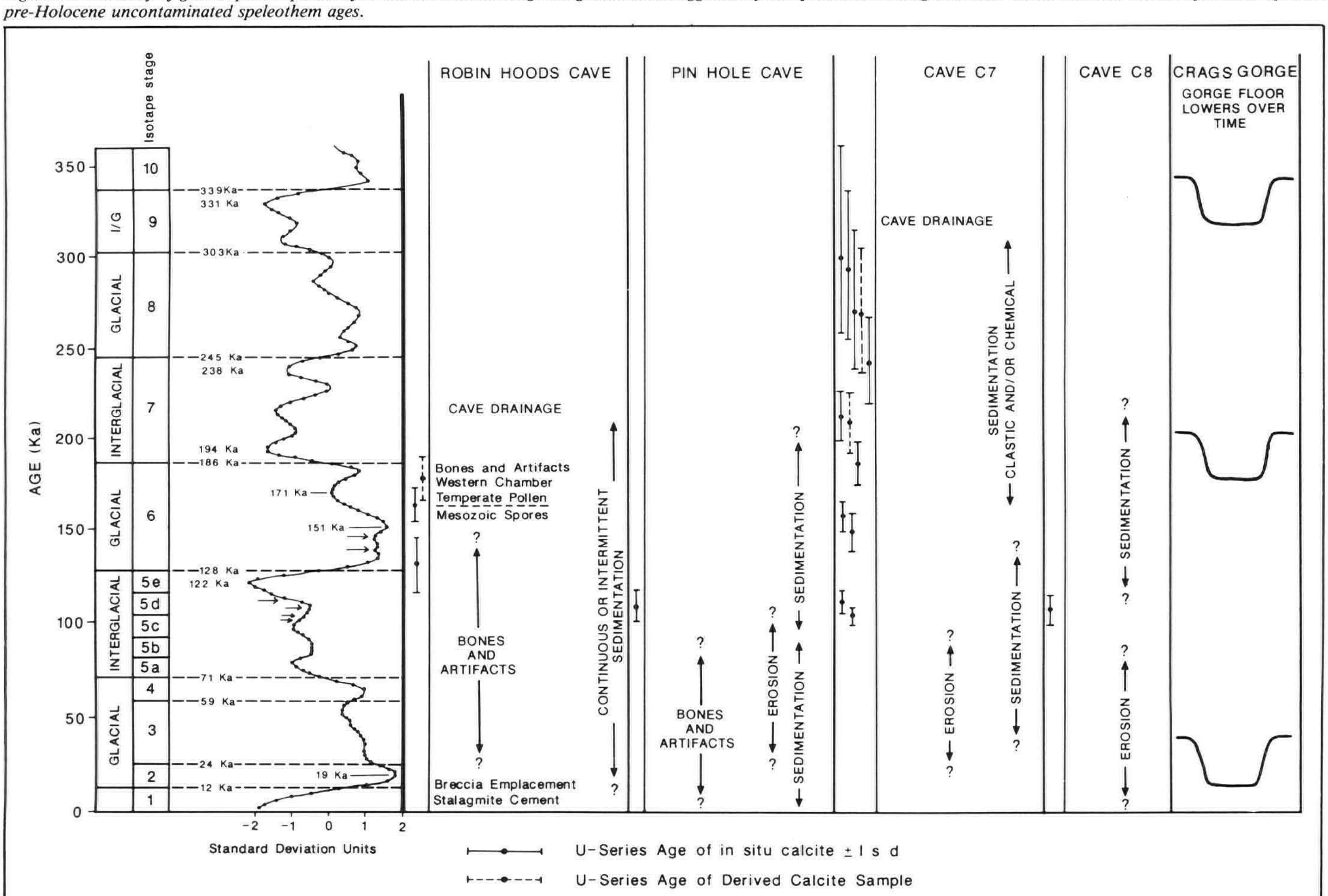
It is evident that Cave C7 had ceased to be phreatic by or soon after 300 Ka since a flowstone of this age (298 Ka) is found at Site 1A and another (288 Ka) is present at Site 4 farther back in the cave . After a hiatus, further flowstone was deposited at around 271 Ka. Since no sediments overlie these flowstones, the cave may have become sealed at this time.

The 239 Ka and 219 Ka flowstones from Site 2A in C7 probably represent a later period of speleothem formation following a 30 Ka hiatus. The apparent lack of speleothem growth between 270 -239 Ka may reflect very cold conditions that prevailed during isotope stage 8. After a further hiatus, intermittent calcite formation then occurred between about 215 Ka and 186 Ka (i.e. during isotope stage 7 and the early part of stage 6).

By 165 Ka the gorge had cut down to at least as far as Robin Hood's Cave where flowstone of this age is recorded. Its association with a thermophilous pollen assemblage suggests there may be a significant temperate episode within isotope stage 6. Although the interpretation of the pollen spectra is a little difficult in view of its as yet poorly understood taphonomy, the rather precisely dated warm episode inferred here may be tentatively correlated with a similar episode at Marsworth (Green et al 1984). This was less precisely dated to between 149 Ka and 171 Ka by uranium series dating of tufa. The source of the Mesozoic spores noted by Coles et al (1985) above the flowstone must lie over 60 km to the east or northeast in Lincolnshire and South Yorkshire. Wind is the most likely transport mechanism and if this were responsible then Eastern England must have been rather devoid of vegetation at that time and a very cold climatic regime can be inferred, corresponding to the later part of isotope stage 6.

Other lines of evidence lend some support to the concept of

Figure 14. Summary of geomorphic sequence of events in Creswell Crags Gorge and caves suggested by the speleothem dating evidence. The arrows near the isotope curve represent pre-Holocene uncontaminated speleothem ages.



a climatic deterioration at this time. Firstly, in the north - west chambers of Robin Hood's Cave are water lain sands near the top of which is an interbedded flowstone between 126 Ka and 140 Ka in age (UEA95 and 88). Flooding of these passages prior to about 140 Ka is inferred. Secondly, at Site 1A in Cave C7, interpretation of a very limited stratigraphy strongly suggests that after about 160 Ka the cave fill capped by the 298 Ka and 159 - 170 Ka flowstones was either partially or totally washed out and a further flowstone deposited at 147±9 Ka. Both of these events require much wetter local conditions than obtain today.

The flowstone at Site 2 in C7, dated to 125±6 Ka (probable true age 118 - 120 Ka), and Site 4 dated to 113±7 Ka may represent later speleothem deposition in different parts of the cave overlying broadly the same sediment body as the 147±9 Ka calcite, although there may have been further erosion and deposition before they were deposited. Between 118 - 120 Ka and 102±5 Ka there was further clastic deposition at Site 2.

Rather surprisingly in view of the pattern of the British speleothem record (Atkinson et al 1978, Gascoyne et al 1983, Gordon et al 1989), only limited flowstone deposition appears to have occurred at Creswell Crags during Isotope Stage 5e, although it is possible that some has been destroyed by excavation. However, calcite formation did occur later in isotope stage 5, as evidenced by the flowstones in Pin Hole Cave (110.4±7.5 Ka), C7 (102±5 Ka), C8 (104±5 Ka), and Robin Hood's Cave (Site RH-4, 80-103 Ka).

No further speleothem deposition appears to have occurred in the Creswell caves until after about 15 Ka.

The remains of the hanging floors in Pin Hole Cave (110 Ka), in C8 (104±5 Ka), and in C7 (113±7 Ka and 102±5 Ka) indicate that these caves suffered considerable erosion of their sediment contents, presumably at approximately the same time but in any case after c. 100 Ka. The most likely means of erosion was by wet sediment flowing or slumping downwards and outwards from the caves' entrances. Jacobi (pers. comm. 1988) has begun a radiocarbon dating programme using bone material excavated by Armstrong from Pin Hole Cave. Results so far indicate that late Devensian and early Holocene faunal and artifact assemblages exist in the upper 0.75 or so metres of the sedimentary succession and these overlie a rather older fauna dated to between 26 - 36 Ka at a depth of up to 1.75 metres. Rae (pers. comm. 1987) attempted to date some of the bones recovered by Armstrong using the uranium series technique. Most of the results showed strong evidence of isotopic migration and were therefore regarded as unreliable, but one determination did appear to give valid results and indicated an age of between 31 and 40 Ka. There is strong reason to believe, therefore, that a mid - Devensian sequence of sediments exists in Pin Hole Cave and the implication must therefore be that the earlier sedimentary succession was removed prior to this time and not, for example, during the last glacial maximum. The precise timing of the destruction of the cave sediments is therefore unresolved.

Speleothem deposition recommenced at 14.7±0.6 Ka in the side chamber of Pin Hole Cave where a thin flowstone is interbedded in sediment, and flowstones of 12 - 13 Ka are known from Robin Hood's Cave (RH-5,RH-7a) and C7 (Site 4A). The capping flowstone over the main deposits in Pin Hole Cave may also date from this time.

A period of abundant speleothem deposition occurred at about 7 - 8 Ka. This is the probable age of the thick flowstone cementing and overlying the breccia in the Western Chamber of Robin Hood's Cave, and smaller flowstones of similar age are found in the Central Chamber (RH-9) and in the North West Chambers (RH-7A). The presence of breccias at the top of the sedimentary sequences in Robin Hood's Cave, Pin Hole Cave and also Church Hole Cave is almost certainly indicative of a period of very cold climate that has frost shattered the limestone. This probably relates to the last full glacial event.

Mid - Holocene speleothem is also common in cave C7 and here the data are interesting in that they allow some conclusions to be drawn regarding a recent sequence of events in the cave that would otherwise be speculative. At Site 2, the top of the upper flowstone is dated to 7.6±1.1 Ka and therefore both this and the underlying flowstone (102±5 Ka) must have been broken after that time since the fracture has created a single face across both layers. Probably the underlying sediment was removed leaving the 102 Ka flowstone in place as a hanging floor, the 7.6 Ka flowstone was deposited on top of it and then subsequently both floors were broken, probably as a result of the collapse of the two large limestone blocks in the adjacent chamber. Further evidence for the recent collapse of these blocks is seen on the west wall of the cave. At Site 1, the upper flowstone is dated to 8.1±1.6 Ka and has been broken at the same time as the underlying flowstones (211 Ka and 186 Ka). It is evident that before the blocks collapsed from the roof, these flowstones formed a short "bridge" between the nearer block and the cave wall, a bridge that was broken after 8.1 Ka. Also, as shown in Fig. 8, adjacent to Site 1 is a quantity of stalagmite drape on the wall that extends down to floor level. A stalagmite, obviously contemporaneous with the drape, has formed on a ledge 80 cms above the floor and 55 cms below the level of Site 1. The stalagmite outer surface is dated to 10.4±0.6 Ka (230-Th/232-Th = 6.0, probable true age about 7 - 8 Ka) and between it and Site 1, no speleothem drape is present on the wall. Two implications follow from this. Firstly that any sediment present must have been removed from the cave by 7 - 8 Ka in order to allow the stalagmite to grow in its present position, and secondly the area immediately next to Site 1 was protected from percolating water at that time and the protective agency was probably the *in situ* roof block and associated stalagmite. The blocks may have fallen very recently, either as a result of direct human interference, or of vibrations from blasting activities in nearby Whitwell Quarry.

CONCLUSIONS

The studies of the cave deposits have served to clarify several aspects relating to both the archaeology and geomorphology of the cave deposits at Creswell Crags, principally by indicating the extent to which previous excavations have destroyed the deposits and the extent to which it might have been possible to reconstruct the stratigraphic jigsaw from the evidence available today.

Unfortunately the indications are that so little of the original deposits survive in the major archaeological caves, and the stratigraphy of what is left has been observed to be so complex, that there is little chance of any substantial reconstruction. Although U-series dating has served to provide a broad chronological framework where none would otherwise exist, not enough calcite deposits have yet been found in positions of sufficient stratigraphic importance to either provide constraining ages for most of the sedimentary units or to substantially aid correlation between such units.

However, in three important respects the dating programme has provided valuable information. Firstly it has become apparent that in at least two caves, C7 and Pin Hole Cave, and probably also in C8, the cave sediments have suffered one or more episodes of substantial erosion followed by further sedimentation of reworked or partially reworked material. It is therefore evident that major hiatuses can occur between and within sedimentary units and it is probable that all the caves have been subjected to this process at some time in their history. The dating evidence suggests that these hiatuses may span very long periods of time and reworking of deposits is also to be expected in such circumstances. The sedimentary sequences may therefore not be as simple as appears from excavation reports, or indeed as appears on even quite close inspection in the field.

Secondly, the antiquity of Mello's red sand deposits and associated Mousterian artifacts in Robin Hood's Cave have been established as being much greater than previously thought, the red sand having been deposited, in part, around 165 ka.

Thirdly, the ages obtained for the speleothems, and particularly the absence of any samples that are beyond the range of the U-series dating techniqe (350 Ka), strongly suggest that the Creswell Crags Gorge itself is a mid - late Pleistocene feature and not some relict feature from, say, the Tertiary, or even an exhumed product of the Permian. The question of the age of the Gorge, and the rate of evolution of the landscape around it, will be fully discussed elsewhere (Rowe and Atkinson in prep.).

ACKNOWLEDGEMENTS

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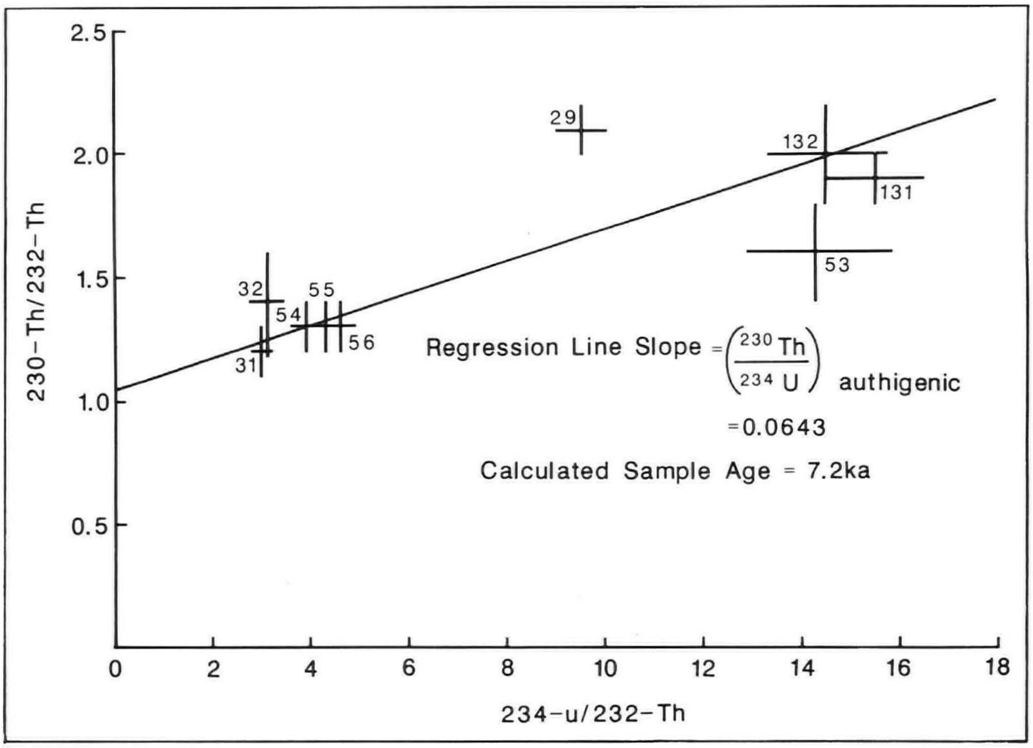

Figure A1. 230Th/232Th vs. 234/232/Th isochron plot for coeval samples from Site RH-3, Robin Hood's Cave.

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APPENDIX 1

Isochron Correction of Detrital Contaminated Dates on Material from Site RH-3.

If it is assumed that (i) all samples of a cogenetic deposit contain identical 230-Th/232-Th ratios in the leachable detrital component but are contaminated to different degrees, and that (ii) no thorium isotope fractionation occurs during sample leaching, then various co-ordinate systems can be constructed to allow linear plots of the data which can be interpreted in terms of the relevant authigenic isotope ratios (Kaufman 1971, Schwarcz 1980).

In the expression

(230-Th/232-Th) total = (230-Th/234-U) auth.(234-U/232-Th) + (230-Th/232-Th)

the slope of a regression line through a number of data points represents the authigenic 230-Th/234-U ratio and the last term is the leachable detrital thorium ratio today. An advantage of this type of approach to contaminant correction is that if a number of data points can be generated, and they are sufficiently widely separated (i.e. reflecting varying degrees of contamination), then the extent to which these data approximate a straight line can be seen and mathematically assessed, thus allowing an estimate of likely precision to be made. The assumption that a "common" 230-Th/232-Th ratio is present over a localised area in the leachable fraction of the detrius appears a reasonable one but it has not been quantitatively investigated.

Figure A1 shows nine samples plotted in co-ordinates of 230-Th/232-Th vs. 234-U/232-Th. The method of calculation of the regression line is of some importance here. Since neither of the variables plotted are dependent on the other, methods of minimising the y-axis residuals by least squares (the normal regression technique) are inappropriate. Instead the reduced major axis line technique is used (Till 1974) in which the areas of right angled triangles joining the plotted points to the best fit regression line are minimised. Unfortunately the samples have suffered similar degrees of contamination and the data points are rather more clustered than is desirable, although this effect has been reduced by leaching with different acid strengths during sample dissolution.

The slope of the regression line is 0.0643 (r = 0.714) which translates into a calculated age of about 7200 years.

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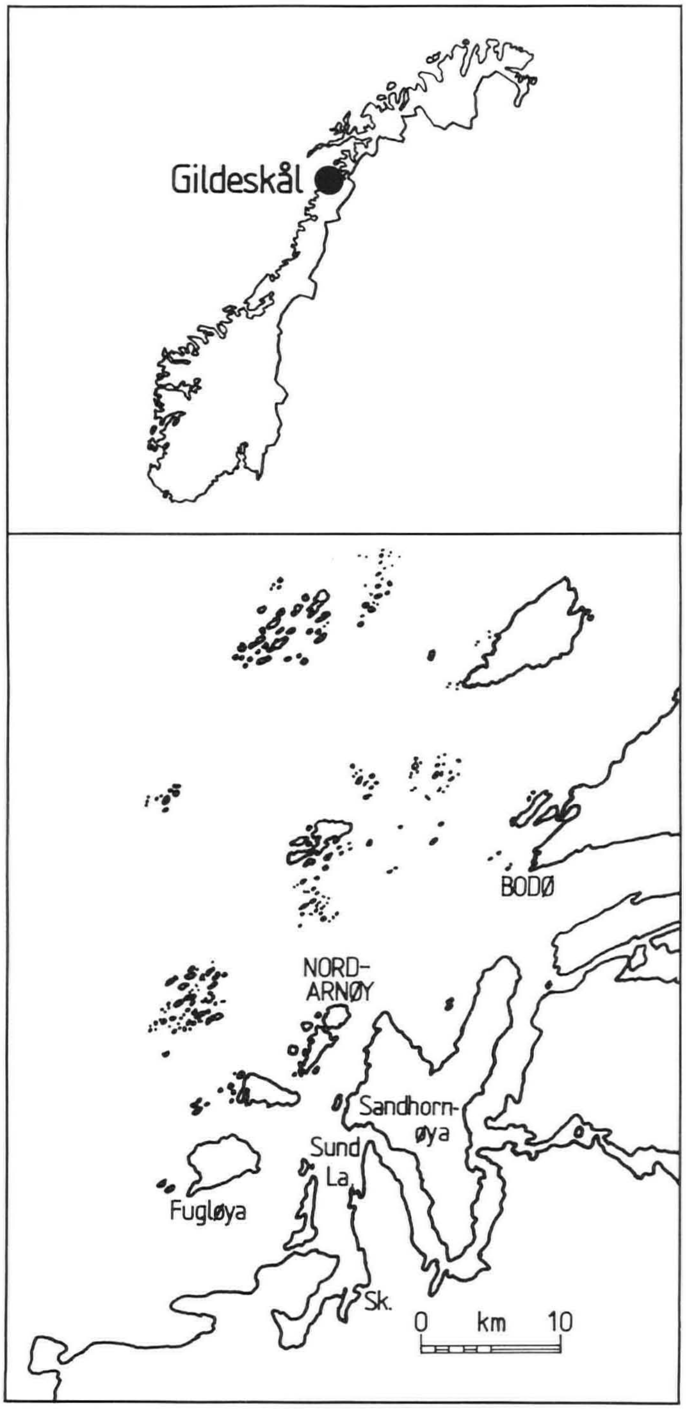
Bowl-karren in the Littoral Karst of Nord-Arnöy, Norway

Ulv HOLBYE

Abstract: Bowl-karren is a characteristic karst form on marble coasts of Northern Norway. The basic form found is a bowl-shaped cup or basin. On Nord-Arnöy, Gildeskaal district, bowls from a few centimetres to 3-4 metres in diameter can be classified in Size Groups, where equal-sized bowls develop on the inner surface of a superior-sized bowl in a strictly hierarchal order. Isostatic uplift gives a zonation where bowl-karren are initiated in the upper littoral zone, then optimally developed in the lower supra-littoral zone. Higher up, the bowl-karren assembly is subject to modification, and then to denudation or transformation into contrasting karren forms. It is suggested that the morphology is generated solutionally by the turbulence of aggressive sea-water, as waves crash against pure, strong marble. The largest Size Group present is a function of the local wave energy level.

Erosional features created by the action of seawater on limestones have received relatively little attention on a world scale. A complicated set of physio-chemical and biological factors may influence their morphology. Both the processes and the resulting forms may vary greatly according to latitude, climate, energy environment and other parameters. Some of the characteristic morphologies have probably not been described yet.

Figure 1. Location of Nord-Arnöy and other bowl-karren localities in the Gildeskaal district. La. = Langholmen, Sk. = Skavollknubben.



This article presents some observations and ideas on what may well be a key locality for coastal karst in a low-temperature and high-energy environment where pure crystalline marbles are uplifted through the littoral zone by isostasy. Although a detailed study has yet to be undertaken, it is clear that there is a unique and striking association of karren forms.

The karst of NW Nord-Arnöy was discovered in spring 1986, and visited together with David and Shirley St. Pierre that summer. Plans were made for the late Shirley St. Pierre and myself to carry out a study of the area. Many of her ideas are included in this paper.

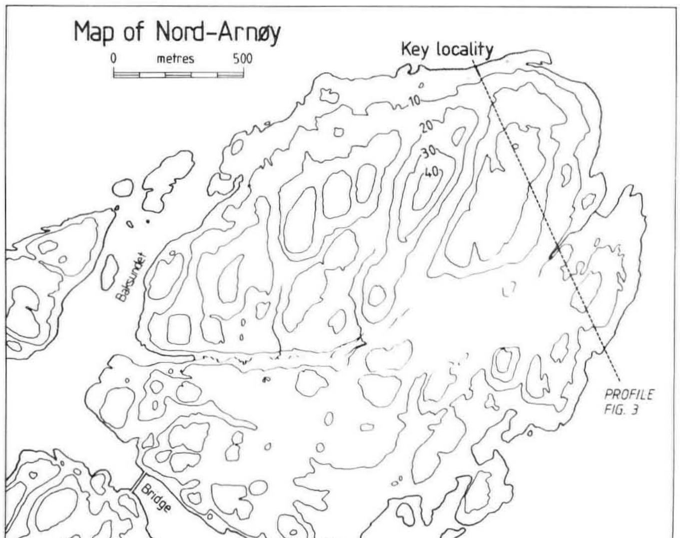
Nord-Arnöy

The island Nord-Arnöy is situated in the district of Gildeskaal, Nordland, on the coast SW of Bodö (figs. 1 & 2). It is composed of marble and mica schist (Rekstad 1929) and has a low relief, the highest point being only 44.8m asl. A profile is shown in fig. 3.

The island displays a well-worked strandflat topography, typical for soft rocks that have been subject to marine abrasion. This is in contrast to the nearby, mountainous islands of Fuglöya and Sandhornöya, composed of granite and quartzite/mica shist respectively.

The Gildeskaal marbles, known from many parts of the district, have been described by Wells and Bradshaw (1970). They are also known to contain some of the most important caves in Norway (Holbye, 1983). They are highly metamorphosed, crystallised as large interlocking grains. With local exceptions they are physically strong, and they contain impurities in the form of schist bands and quartz fragments. As a rule they have a grey, weathered surface lacking in karren sculpture. It appears that freeze-thaw processes discourage the development of solution features at the surface.

Figure 2. Map of Nord-Arnöy, showing the key locality and the trend of the profile in fig. 3. Contour interval 10m. Based on 1:5000 Economical Map sheet DT 213-5-1.



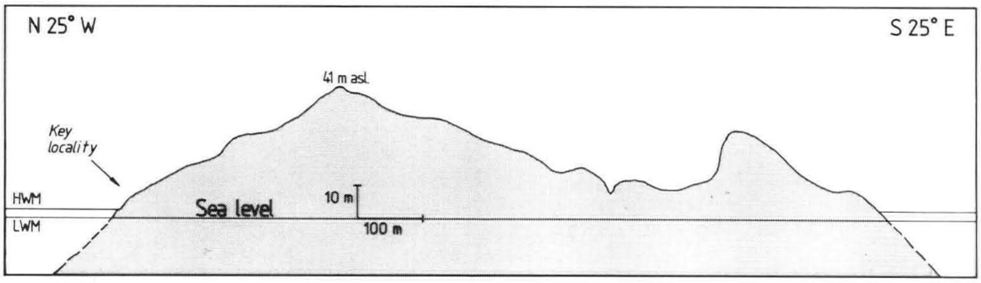


Figure 3. Profile across the northern part of Nord-Arnöy. Vertical exaggeration 5:1.

The island was glaciated up to the Younger Dryas period, c.10,000 years ago (Andersen, 1975). Uplift in postglacial times equals 100m, and Nord-Arnöy started emerging from the sea c.4500 years b.p. Glacial forms dominate the topography.

The tidal range is little different from that of Bodö, shown in fig. 4. Difference between astronomical LWM and HWM is 2.3m with additional effects of atmospheric pressure and winds.

In the littoral zone, most of the surface is bare rock. It is too exposed to be host to an abundance of life forms, but smaller species of sea-weed (e.g. *Fucus spiralis* and *Pelvetia canaliculata)* as well as gastropoda (e.g. *Patella vulgata)* are common. Life is concentrated in the sub-littoral zone, where the rock may be covered with *Mytilus edulis*. At the key locality of north Nord-Arnöy, the sub-littoral zone is also "forested" with a belt of *Laminaria (sp.)* many tens of metres wide.

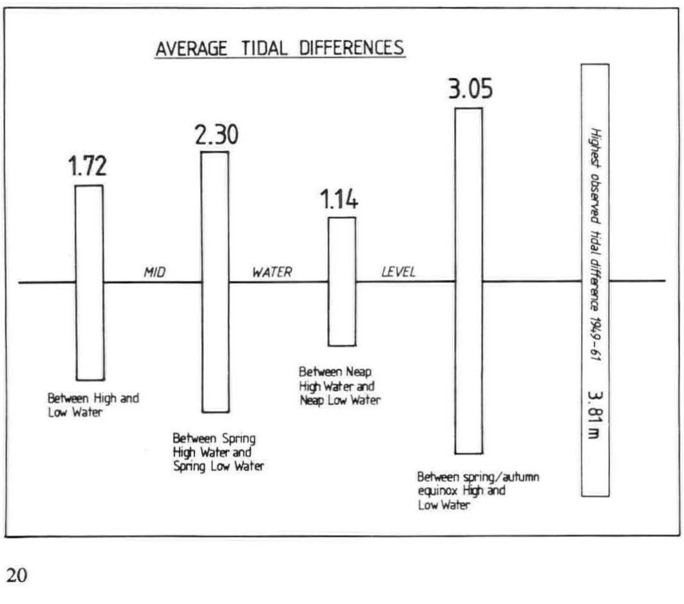
Underground drainage is very immature, and all run-off appears to stay on the surface, or occasionally, at the bottom of shallow grike-like trenches. Apart from the latter, which may be a result of marine erosion mainly, there is modest solution along joints.

MORPHOLOGY OF THE NORD-ARNÖY BOWL-KARREN

A map of north Nord-Arnöy is shown in fig. 2. It is chosen for morphological description of supra-littoral karst, because it displays the optimal development seen so far with regard to size, relief, density and organisation. The main form, and possibly the only true littoral karren form in Gildeskaal, is a circular to oval bowl (cup, basin) eroded into marble surfaces on different slopes. The bowls have some features in common with solutional scallops as seen in phreatic cave passages etc. But there are important differences, and a wide variety of Size Groups is evident, to be described below.

The term *bowl-karren* is proposed for this type of karstic surface, and the mechanism behind its development is not well understood at present. Bowl-karren are common throughout northern Norway; also, workers like Trudgill (1985) and Lundberg (1977) include photos and figures of forms that are apparently related from Co. Clare, Ireland. Comparable features have been observed by the author and described by Haugane (1983) on lake shores in southern Gildeskaal. Cylindrical cups (jettekopper) with vertical axes 2-20cm in diameter and 2-15 cm deep grow on slopes up to 40°. One or two small cups may grow inside a big one. They occur in places exposed to waves, or from 0.5m below to 1m above lake level.

Figure 4. Tidal differences at Bodö harbour. The average figures (four left columns) refer to astronomical tides. Source: Norges Sjökartverk, 1962.



Description of bowls

The karren bowls range in size from a few millimetres to 3-4 metres in diameter. The rim is circular to oval in shape, elongation occurring along the foliation of the marble. Bowls from 2cm in diameter and upwards have been studied. The smaller sizes have a circular profile; occasional bowls are even cylindrically deepened into the rock. The larger bowls are shallower troughs up to 25-30cm deep.

Thus there is a range of forms from the small hemispherical hole (Size Group Four, see below) to the large, gently curved basins (Size Group One). Bowls of comparable size cluster tightly together, but very rarely do they converge into a polygonal pattern. Well-defined rims or ridges remain between the bowls instead.

The larger fraction of bowl-karren surfaces are drained, but rainwater and spray ponds up in bowls on near-horizontal surfaces.

Size Group Organisation

On exposed seaward faces, the karren bowls are arranged in groups of equal-sized members. Bowls of a smaller group are developed on the surface of a next-order bowl in a strict hierarchal fashion. On Nord-Arnöy, four such groups of superimposed karren bowls are common, giving an extremely pitted and irregular surface.

TABLE I. Some characteristics of bowl-karren Size Groups at Nord-Arnøy.

SIZE GROUP	TYPICAL DIAMETER	FORM	DENSITY ON SUPERIOR BOWL SURFACE
One	1-3 m	Shallow trough	——
Two	25-40 cm	Steep-sided trough	12-15 per square meter
Three	10-15 cm	± Hemispherical	2-6 per bowl
Four	2-6 cm	Hemispherical	10-15 per bowl

Table 1 gives some parameters for the Size Groups. The largest bowls are referred to as Size Group One, and so on in descending order. It should be kept in mind that each group has its own characteristics; there are other differences besides that of scale.

Size Group One are shallow troughs or pans 1 to 3-4m across with a gently curving concave shape, and less regular ridges between the bowls. Their depth (excluding that of smaller-group bowls developed on their surface) is in the excess of 25cm.

Size Group Two bowls are often eroded to a similar depth. Having a diameter of 25-40cm typically, and 60-70cm in a few cases, they are steep-walled but still not close to being hemispherical. They are concave to within a few cm from the rim crest. The profile of the rim itself is sharply rounded, but sometimes two bowls touch each other in a point where the rim becomes lower and the two concave surfaces meet in a sharp edge. Visually, the Size Group Two bowls break up the rock surface into a crater-like appearance.

Size Group Three is the least well-defined group. On intensely karstified surfaces they are irregular, but easily recognisable partitions within a Size Group Two surface. In its turn they are densely populated with Size Group Four bowls. In suboptimal localities, where the two larger groups are lacking, they become very characteristic; a near hemispherical bowl 10-15cm in diameter with a rim that meets the surrounding surface in a more or less abrupt fashion.

Size Group Four are almost perfect hemispheres from 2-3 to 6-7cm in diameter. A cylindrically deepened variant of this group occurs, but is not very common.

Variations in the size of a host bowl do not appear to influence the dimensions of the sub-ordinate bowls on its surface. A large

A representative four-group bowl-karren assembly. One good example of a Size Group One bowl is seen on the right, in shadow. Key locality, Nord-Arnöy.

Group Two bowl may well occur inside a small Group One. Each group seem to have some individuality; they maintain their characteristics even if all the other groups are lacking at the spot.

Strangely, bowl-karren maintain their morphology below water level in stagnant pools. Terms as "vadose" and "phreatic" may seem irrelevant to their genesis.

The rim zones of Size Group One and Two bowls are mostly avoided by the smaller groups. This helps maintaining a regular pattern of steeply curved, convex surfaces between bowls. The high relief of rim zones is a prominent feature of the optimal bowl-karren, though not as regular as the bowl forms themselves.

For comparison, the optimal bowl-karren will be referred to as a "4-group assembly". A profile of a 4-group assembly is shown in fig. 5. In Northern Norway, more than 2-group assemblies seem rare. Bowls of Size Groups 3 and 4 are common.

"Micro-bowls", or bowls smaller than Size Group Four, have not been studied and will not be discussed below. It should be noted that they are extremely common, and at a glance they seem to fit in as a Size Group Five, breaking up the inner surface of Size Group Four bowls. In the supra-littoral zone, they may prove too short-lived and fragile to be fitted into a model.

Exposure and slope

Bowl-karren are best developed in exposed places facing the open sea. The 4-group assembly at Nord-Arnöy occurs on surfaces facing the NW, where there is little protection against waves from the Norwegian Sea (fig. 1). Moving to sheltered places, Size Group One and then Size Group Two disappear.

4-group assemblies can be found on any slope except overhangs. However, there is some variation in the intensity of karstification that can be related to slope.

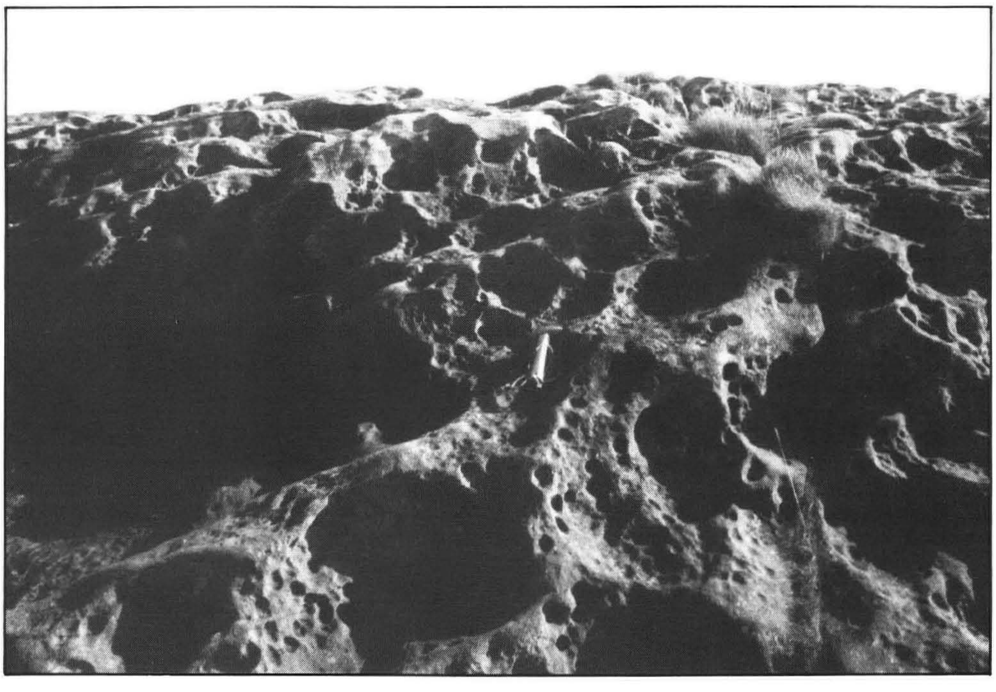
Size Group One bowls seem largely independent of slope. But especially Size Group Two bowls are much better developed on slopes greater than 25° that are facing the open sea. The same often applies to the smaller groups, which are the only ones to be developed on overhangs. But exceeding the vertical they become more scattered and less organised.

On level surfaces, water ponds up inside the bowls. Organic residues collect in the water and influence the water chemistry.

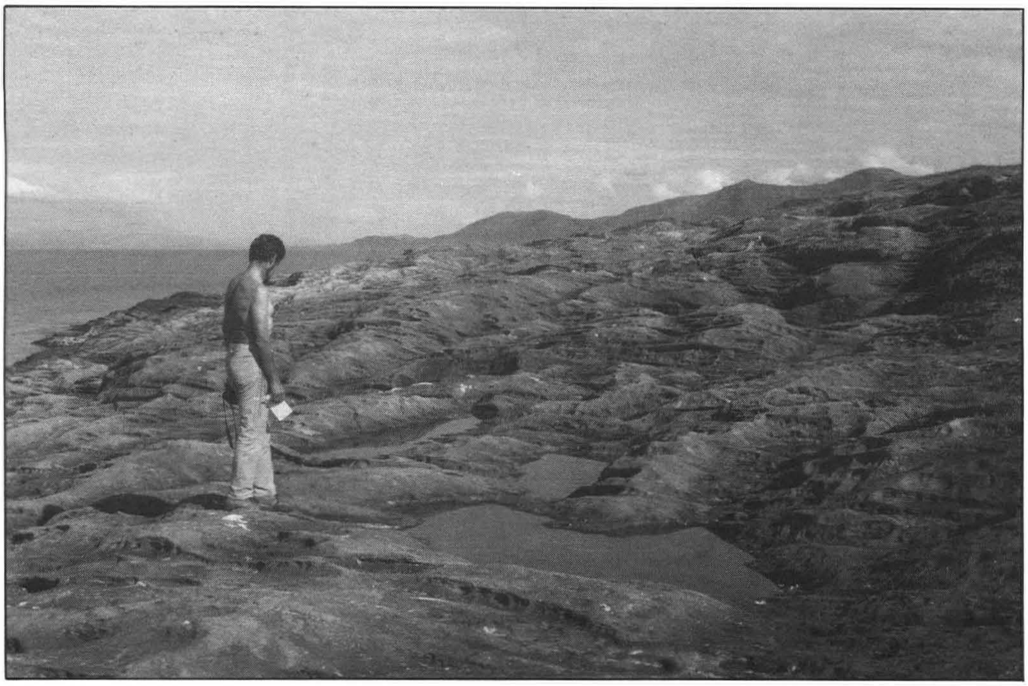
Zonation

The bowl-karren occur in distinct morphological levels which can be related to the tidal system. An attempt to identify these zones is shown in table II and fig. 6. Although preliminary, it establishes the fact that optimal development and organisation of the Size Group hierarchy starts in the lower supra-littoral zone, and is not seen below the High Tide Mark.

Starting from the bottom; bowls are not seen to develop in the sub-littoral zone. Small bowls of Size Group Three and Four gradually show up in the tidal reach, but then as scattered, single features. Passing the Neap Tide Level, the first signs of Size Group Two bowls are seen. These are less accentuated in depth and density, but there is some organisation of Size Groups. The largest Group is absent below the HTM, and the characteristic



Four-group bowl-karren assembly. Ridge between Size Group One bowls in the centre. Key locality, Nord-Arnöy (photo by David St. Pierre).



Flat surface in the supra-littoral zone where water ponds up in Size Group One bowls. At low slopes the other Size Groups may almost be lacking. Key locality, Nord-Arnöy.

rim portion of the morphology is consequently lacking.

The lower limit for optimal bowl-karren is at the level of extreme high tides. Apart from differences caused by slope and locally retarding factors, the morphology maintains the same style up to approx. 9m above the LTM. This is defined as the upper limit of the supra-littoral zone for bowl-karren. The forms are then quickly destroyed or masked by denudation, vegetation or transformation into contrasting karren forms.

The supra-littoral zone can be further divided into an upper and a lower part with a floating transition around 4-5m above the LTM. Above, the bowl-karren has been subject to a characteristic modification by meteoric waters, to be described below. This probably means they are uplifted from the zone of active bowl-karren genesis.

Thus, the zone of active development is narrowed down to the lower supra-littoral zone, c. 2.8 to 4-5 metres above the LTM, the first one or two metres above the reach of the extreme high tides.

Lithology

Optimal bowl-karren are restricted to the occurrence of pure, strong, homogenous marbles. Impurities are however common in the Gildeskaal marbles, primarily in the form of tightly-spaced micaceous bands. Typically, bands may be spaced from 1-2 to 10-20cm apart, and they project from the purer zones as a result of selective erosion.

In impure marble, Size Group One and Two disappear, while the smaller bowls become elongated, arranged along the soluble zones in a linear fashion. The long-axis of these bowls may occasionally approach Group Two sizes, while the width is controlled by the spacing between the resistant bands. It could be said that foliation becomes more important in organising the bowls than the Size Group system. However, bowl-karren develop in marble far too impure for other karren forms to exist.

Even in calcareous schists karren bowls are seen. Near Baksundet at western Nord-Arnöy (fig. 2) a homogenous calc-schist wall displays very characteristic Size Group Three bowls, although they are spaced tens of centimetres apart. Bowls of the smallest Size Group are perhaps too delicate to organise themselves on bowl surfaces in this type of rock.

Other negative factors

The presence of sands in bays and on the floor of clefts etc. effectively inhibits all bowl-karren development, leaving smooth, polished marble surfaces in the tidal and lower supra-tidal zones.

TABLE II. ZONATION OF BOWL-KARREN AT KEY LOCALITY, NORD-ARNØY.

ZONE NO.	APPROXIMATE LEVEL	NAME OF ZONE	MAIN PROCESSES	REMARKS
4 (Highest)		RAISED ZONE	Uplifted bowl-karren either (a) weathering away, (b) transforming to normal karren, (c) preserved by sheltering, or (d) covered by vegetation.	Relation to raised beaches not known.
	9 m			
3 B		HIGHER SUPRA-LITTORAL ZONE	Modification of bowl-karren by meteoric waters. Possibly some final bowl-karren development in lower part of zone.	Bowls with ponds modifying into kamenitzas. Trittkarren/rinnen-karren modification of drained bowls.
	Gradual transition 4-5 m			
3 A		LOWER SUPRA-LITTORAL ZONE	Main development of highly organised bowls of Size Group One to Four.	Neglectable biological activity.
	2.8 m (Extreme HW)			
2 B		UPPER LITTORAL ZONE	Shallow Size Group Two bowls start to appear. Some organisation of bowls.	
	1.7 m (Neap HW)			
2 A		LOWER LITTORAL ZONE	Occasional development of unorganised Size Group Three and Four bowls.	Low density of possible boring and grazing organisms. - Little coincidence between these and individual bowls.
	0.0 m (LWM)			
1 (Lowest)		SUB-LITTORAL ZONE	Non-morphogenic bio-erosion? No bowl-karren development.	High biological activity. Extensive *Laminaria* belt along northern Nord-Arnøy coastline.

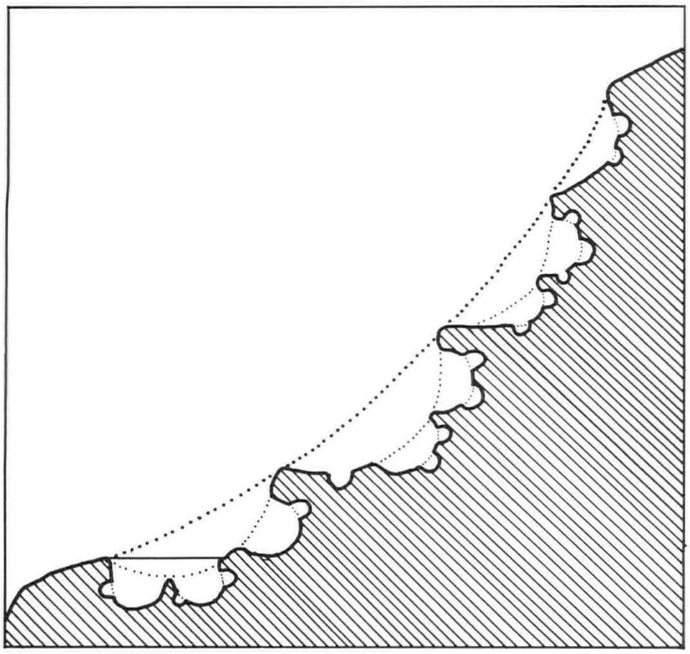


Figure 5. Schematic cross-section of Size Group One bowl with superimposed assembly of bowls of Size Groups Two to Four. Stagnant pool shown in lower part of section. The number of bowls of each Size Group is not representative.

This should exclude abrasion as the mechanism behind bowl-karren formation.

The same applies to sites where marble is in contact with fresh, running waters. Channels of trickles and streams are not present in karren bowls, and pools along these are also void of bowl-karren while neighbouring, stagnant pools may host optimal assemblies.

Modification of bowl-karren

In the upper part of the supra-littoral zone, the bowl-karren assembly is markedly re-worked by the solution of meteoric waters. Two types of modification are prominent.

Kamenitzas are typical on undrained surfaces. Bowls of Size Group Two and Three containing pools are adopting the characteristics of kamenitzas or solution pans (Jennings, 1971). Bottoms are flattened and walls are steepened, apparently encouraged by the presence of organic residue providing a source of aggressivity. Sometimes the process is "doubled" where a Group Three bowl occurs in the bottom of a Group Two bowl; both undergo the same process, and the edge between them is kept sharp. In some cases, the bowls seem to be cylindrically deepened by this process. Their floors may be lowered in addition to being flattened.

At the pool water line, a minor solution groove is common. Above, a radial pattern of microrillenkarren is mostly present. Microrillenkarren can be formed by the direct solutional attack of droplets hitting the rock (Ford 1980), and in the case of kamenitzas return splashes from the pool must play an important role. The microrillenkarren found here are more irregular and less accentuated than those known from mountain karsts of Norway.

To the author's knowledge, kamenitzas have not been described from the high-latitude karsts of Scandinavia. Quite possibly, they may prove restricted to bowl-karren morphology in this climate. They freeze up in winter, unless exposed to spray during lengthy storm periods.

Planation and dissection is the prominent mode of modification of drained bowl-karren surfaces. The bowl bottoms become flattened by wall retreat, and rims between bowls are breached. This process has not gone very far at Nord-Arnöy, but it is apparently taking the form of trittkarren development. At the same time, bowls are linked up along drainage paths in a rinnenkarren (meanderkarren) fashion.

OTHER LOCALITIES

Sub-optimal bowl-karren are a common feature of soluble marbles in Northern Norway. A few sites of special interest in the Gildeskaal marbles are included here. They lie south of Nord-Arnöy (fig. 1), and the chief contrast is that the Size Group One bowls are missing.

Langholmen

The western side of the headland Langholmen displays concentrated and well organised bowl-karren; with a zonation comparable to Nord-Arnöy. Facing Sörfjorden, this shore is sheltered against direct Norwegian Sea waves.

In the upper supra-tidal zone, where modification is active, some areas are altered into pinnacle relief. Planation has gone so far as to join bowl bottoms together into a continuous floor.

Several explanations to this can be offered. Either the bowls have undergone unidirectional expansion after the Size Groups were organised, or trittkarren wall retreat has gone further than at Nord-Arnöy. A combination of the two is possible, but it is also just coneivable that the pinnacles represent an offset case of littoral karren with only a small degree of modification.

At Langholmen, the variant of Size Group Four bowls that are cylindrically deepened into the rock, is far more common than at the key locality. They appear to concentrate in the more sheltered micro-environments along the beach.

Sund

This locality exhibits uplifted and partly transformed bowl-karren, c. 20 to 35m asl. In some NW-facing vertical cliffs, very characteristic Size Group Two bowls up to 35cm across are well protected from attack by meteoric waters. They contain the usual assembly of well-organised bowls of smaller sizes. The cliffs must have been exposed to high-energy waves before being uplifted.

As slope decreases, a gradual change into normal karren is seen. The typical trittkarren-rinnenkarren pattern, known from many mountain karsts of northern Norway, is taking over. But in this case there is evidence that ridges were penetrated and bowls linked up to form straight or meandering rinnenkarren grooves draining trittkarren steps. The preserved localities of intact bowl-karren have a karstic relief of 12-15cm, while the transformed karren have a slightly smaller relief of 8-12cm. This may be a step towards degeneration into the rough, weathered, unsculptured surface of most Gildeskaal marble. Alternatively the transformed karren may have become morphologically stable.

Skavollknubben

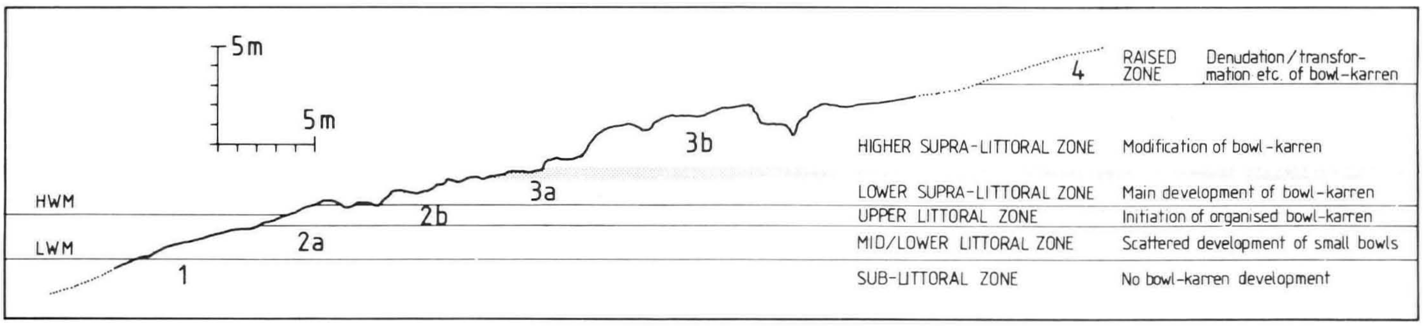
On a steep cliff wall c. 200m asl. and well above the marine limit, some single, scattered bowls of characteristic form are comparable to small Size Group Two members. They had no internal organisation of bowls. No explanation can be offered for these "occasional" or "erratic" features.

DISCUSSION

Active or relict?

The present rate of uplift can be calculated from Haugane (1984). In Bodö it is 0.22cm per year + or − 10%. Change of isostatic gradient is c. 0.016 cm/km at right angles to the isobases.

Figure 6. Morphological zonation of bowl-karren at key locality, Nord-Arnöy. The zones are further explained in Table II. Vertical profile measured by D. & T. St. Pierre, August 1986. Correlated to LTM according to Norges Sjökarverk (1986).



The rate for Nord Arnöy should then equal approx. 0.17cm per year. It has decreased exponentially since the last deglaciation, but there is no difficulty in using this value within the Nord-Arnöy lower supra-littoral zone.

Today's lower limit for optimal bowl-karren is emergence from the sub-littoral zone roughly 1650 years BP. No environmental or climatic change affecting solution by sea-waters is known in this period. There is little likelihood that the development of four Size Groups of karren bowls was a response to conditions of the past only. Bowl-karren must be actively forming today in the lower supra-littoral zone, and the explanation of its presence at Nord-Arnöy should be sought in the local conditions for the active processes.

Rate of erosion

The lower supra-littoral zone constitutes a belt of 1-2m vertical extent. It can be calculated that one bowl must have been in this zone for something like 600-1100 years. A karstic relief in excess of 30cm was created, giving a rate of differential erosion of roughly 0.4mm per year. This value may not reflect the *total* rate of erosion which must be larger, but it seems to be comparable with exposed limestone coasts in other parts of the world (e.g. Trudgill, 1985).

Bowl-karren genesis

The Nord-Arnöy morphology can only be formed by turbulent, aggressive sea water moving against soluble rock. No other agent could create forms of this scale in the short time available. In addition to similarities with cave scallops, the bowl-karren case suggests the circular orbit of individual water molecules in wave movement, and their morphology is linked to the zone where waves break against the rock, with less turbulence.

Bowl-karren are then of true karstic origin. Bowls occur in impure marbles and even in calcareous schists. One is tempted to think in terms of a "violent solutional attack" within a short time span. Wave energy is not a chaotic force. On the contrary, with the aid of solution, it creates forms of impressive regularity.

A possible parallel to bowl-karren has been observed in granite on the island of Corsica, in a semi-arid climate. Cups or bowls arranged in a small-inside-the-big fashion are developed on the rock surface, probably by air turbulence during sand storms (Frederic Murray, 1988, p.c.) It is worth noting that bowl-karren, unlike these forms, are precluded by the immediate presence of sand.

Individual bowls seem not to disturb the development of their close neighbours. That would result in masked, coalesced or partly destroyed forms. This indicates that there is little expansion of the rim circumference as they develop. They seem to belong to one Size Group from their initiation, and, with time, become accentuated in depth until they reach the ideal hemispherical cavity, with a centre that aligns with the surface of the next-order bowl or with the terrain. If this is right, bowls of lesser order should migrate into the rock as their host bowl becomes deeper. Bowls are not over-deepened except by modification, but larger bowls increase their relief until uplifted from the lower supra-tidal zone.

According to this model, the shallower profiles of Size Group One and Two bowls would become semi-circular if exposed to the waves for a long enough time. Today both these groups, although different in diameter, have depths of the same magnitude.

The Size Groups

The breaking of very large waves against pre-existing irregularities produces the turbulence that is necessary for the initiation of Size Group One bowls. The same process is started for the next-order bowls and so on, as the wave energy is broken up into smaller turbulences. This is shown in fig. 7. The

TABLE III. THE NUMBER OF BOWL SIZE GROUPS DEVELOPING IN DIFFERENT ENERGY AND ROCK ENVIRONMENTS.

WAVE ENERGY LEVEL	Calc-schist	Impure marble	Pure, strong marble
High exposure	1	2	4
Medium exposure	0	2	3
Sheltered	0	1	2

PURITY →

turbulence is so violent that the marble surface in pools may be affected to the same degree as drained areas.

The ridge portion of the bowl-karren relief appear to be important in directing and dissecting the turbulence, and thus in organising the Size Group hierarchy.

On near-horizontal surfaces, bowls of the smaller Size Groups occur in much lower density. It may be that waves breaking onto these flats are not broken the same way as when thrown against steeper slopes.

The number of Size Groups present in one locality is mainly a function of exposure on one hand, and rock purity and strength on the other. Evidence from Gildeskaal is presented in table III.

Visual comparison of different bowl-karren localities in Gildeskaal, it appears that each Size Group is recognisable by shape and size, regardless of exposure. But by decreasing exposure, the largest Size Groups disappear one by one, rather than being gradually reduced in average diameter. There seem to be energy thresholds separating the Size Groups, but this needs to be statistically tested.

Zonation

The supra-littoral zone is characterised by spray and storm wave attack, and there is virtually no biological activity. One of the most intriguing aspects of bowl-karren is why it develops in this zone only. Two possibilities arise at first. Either development is favoured at intervals when the sea is close to high tide. Or there are counter-effects subduing the morphogenesis at lower levels.

It is not hard to imagine conditions when waves will break against rock in the lower supra-littoral zone. And during storms and gales from the west, the combination of wind and low atmospheric pressure would produce a higher actual tide than the astronomicial tide levels used as a basis for the zonation of bowl-karren. The far right column in fig. 4 indicates this.

However, waves also break at lower levels without creating the same morphology. Below the HWM, the wave impact shifts within much larger margins according to the weather. The effects on morphology may here be contradictive, so that long periods of low-energy waves counteract the stormy events. The presence of sea-weed and other organisms may also disturb the effect of turbulence.

Above the HWM, the evolving morphology is out of reach by all but the strongest wave attacks. Once initiated, it is conceivable that the bowls organise the turbulence as much as the turbulence organises the bowls. This mutual effect results in rapid accentuation of the karstic relief, caused by higher erosional rates inside bowl surfaces than at the ridges.

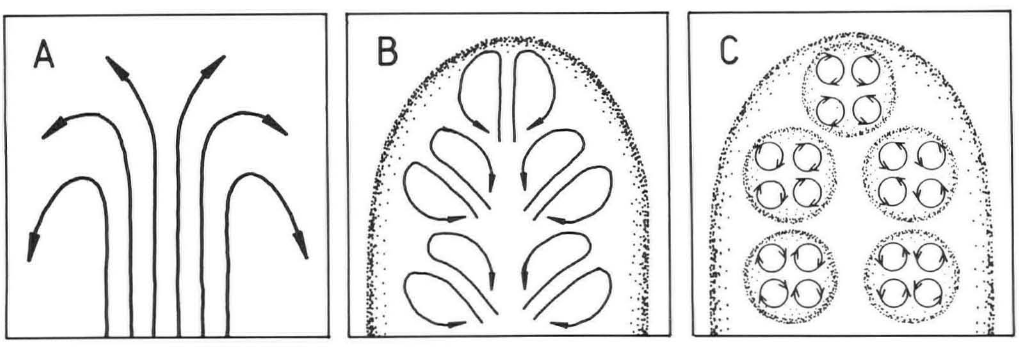


Figure 7. A schematic presentation of the generations of bowl-karren Size Groups. (A) A large wave (arrows) crushes against the marble, initiating a Size Group One bowl form. (B) The wave movement is broken into a number of smaller turbulences, generating Size Group Two bowls inside the large form. (C) The turbulence is further sub-divided, and the process is repeated on smaller scales creating Size Group Three and Four bowls. The whole assembly then develops by accentuation of relief, with little expansion of the rim of each bowl. (Distribution of bowls is not as regular as shown, and large waves come from a variety of directions).

In the littoral zone, the lack of good bowl-karren does not necessarily mean that the total rate of erosion is smaller. But there is little differential erosion, and thus low karstic relief.

In terms of uplift, the largest waves have a prolonged effect on morphology, and the culminating bowl-karren can be expected to be in concordance with the maximal energy environment. Apart from modification, there is no apparent difference in size or shape or bowls in the lower and upper supra-littoral zone. It seems to indicate that storm waves play the dominant role from initiation to culmination of bowl-karren genesis.

Modification

After development, bowl-karren become unstable and will only survive when sheltered from weathering. The two directions of modification — towards kamenitzas where bowls were waterfilled, and a trittkarren/rinnenkarren array where drained — lead in "opposite" directions: kamenitzas are erased by denudation on entering the raised zone, while some of the completely transformed trittkarren/rinnenkarren (Sund, raised locality) have survived a large portion of the post-glacial period. The latter have a relief comparable to that of high altitude karren in Norway, although they had just one third of the time for their development.

One interesting detail is the cylindrically deepened bowls below the water surface of kamenitzas. Organic residue seems responsible for downwards solution along a vertical axis, and they resemble the cups (jettekopper) of lake shores. Lake cups may be formed by the combined effect of water turbulence in windy periods, and downwards solution by residue in calm periods. The latter process would determine their vertical orientation.

Bio-eroders

Organisms able to erode the surface of carbonate rocks are common in northern Norway. Their main effect appears to be tied to the cylindrical deepened variant of Size Group Four bowls. These occur in sheltered spots of sub-optimal localities, and commonly where larger bowls are absent.

The small, hemispherical karren bowls have provided the original shelter for the organisms. The excess depth may be accounted for by bio-erosion. As bio-eroders do not occur above the littoral zone, there are indications that sub-optimal bowl-karren may have attained their final shape before being uplifted into the supra-littoral zone. It is doubtful whether bowls initiated by boring and grazing organisms exist at all in Gildeskaal.

Comparison with other climates

Most earlier workers have concentrated on biological processes and zonation of littoral karst. Few detailed descriptions and classifications of the forms created have been published. Hence it is difficult to draw parallels with work from other climates.

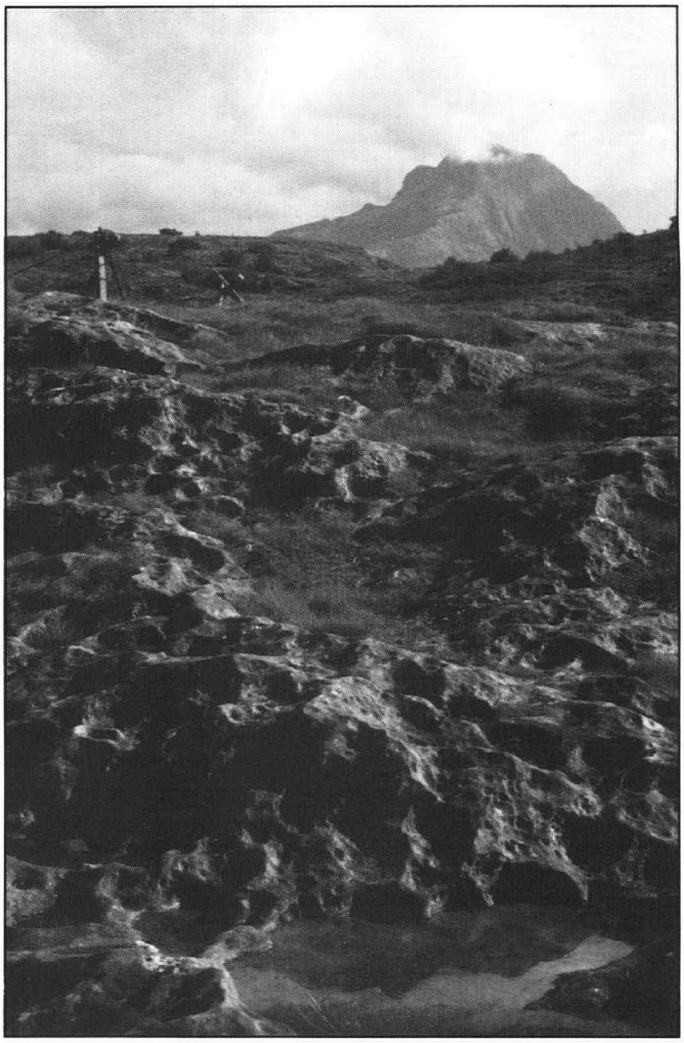
The limestone coasts of Co. Clare, Ireland (Lundberg, 1977; Trudgill, 1985) have some morphological similarities with Gildeskaal. This poses the question whether many of the forms may not in fact be non-biogenic, and that the creation of bowl-like hollows gave invading bio-eroders their original shelter. Lundberg presented a profile showing bowl-shaped pools above the HWM. Due to rising sea level, a situation contrary to isostatic uplift, these pools have never been within the tidal range. The possibility that they are formed by wave turbulence in the supra-littoral zone, and then have suffered some kind of modification prior to being introduced into the littoral zone, may be worth noting.

Solution of the marble

Attempts to identify sources of sea-water aggressivity are beyond the scope of this article. One very important question is therefore left open: — Is the Nord-Arnöy 4-group assembly of bowl-karren a response to locally increased aggressivity of the coastal waters?

Finds of partially corroded mussels in recent sediments (Bromley and Hanken, 1981) indicate that the sea is generally aggressive in the north Norwegian environment, at least intermittently. Of the special features at Nord-Arnöy, it is worth pointing out the extensive sub-littoral belt of *Laminaria* at the key locality. CO_2 release from the algae during respiration phases may add to the local solution rate. The extra acidity will quickly be dispersed and transported away by the coastal current, but an instantaneous effect may be of morphogenic importance.

A higher rate of erosion at Nord-Arnöy than elsewhere could be suggested, but it is hard to see how water chemistry could be linked to the occurrence of a superior Size Group of karren bowls up to 3-4m in diameter. Pure, strong marble and high energy conditions appear to be the key factors to optimal bowl-karren.



Partly vegetated bowl-karren in the upper supra-littoral zone. Pool and kamenitzas with organic residue in the foreground. Size Group Two bowl forms are seen to continue below pool level. The uppermost bare marble is approaching the raised zone, where the morphology is destroyed by denudation. Sandhornet in the background. Key locality, Nord-Arnöy.

CONCLUSION

Bowl-karren are genuine karst forms generated by turbulence in the lower supra-littoral zone exclusively, as high-energy wave tongues impact on pure and strong marble. The massive movement is broken up into smaller and smaller turbulences, and this is reflected morphologically by bowls of different Size Groups becoming superimposed on each other's surfaces. The 4-group assembly of Nord-Arnöy is the optimal development seen so far. Controlled by iso-static uplift, six different morphological zones can be identified. Biological zonation is irrelevant in explaining this tidal karst.

More research is needed to identify the factors controlling bowl-karren development. But its existence rises new perspectives on the non-biological aspects associated with the littoral karsts of the world.

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I wish to thank Shirley and David St. Pierre for taking part in the field work, and Carl A. Boe for help with locating information on tides and meteorology. The above have also provided valuable criticism, together with Erik Haugane and Lloyd Mills. Tanya St. Pierre has assisted in the field, and Gildeskaal commune has supplied the maps.

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Some Caves in Siliceous Rocks in Norway

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Abstract: Around 200 caves in non-limestone rocks are known in Norway particularly in the counties Al, Bjugn, Afjord and the Hardangerfjord area. The caves are mainly developed along tectonic structures, primarily prominent fissure zones and thrust planes. Modes of origin include: (a) tectonic movement and gravity sliding producing fissures, with preferential weathering of breccia zones; (b) dissolution of small limestone lenses within the gneisses; (c) wave erosion of pre-existing cavities and fissures; (d) gas pockets in crystalline rocks. In many cases two or more of the processes appear to have worked together. Abundant speleothem growth suggests that calcareous zones exist in the enclosing rocks.

In addition to numerous limestone caves, Norway has many caves in crystalline rocks. They fall into the following categories: (a) tectonic caves; (b) limestone lens caves; (c) sea caves; (d) gas-pocket caves. Some are of considerable length (Table 1).

Table 1

Norway's Longest and Deepest Non-Limestone Caves
Tectonic cave: Revane > 500m long, 60m deep.
Limestone lens cave: Duehellarhola 100m long, 3m deep.
Sea cave: Halvikhulen 340m long.
Sea cave: Litjbindalskjerka 300m long, 25m deep.
Gas pocket cave: Dvergesteinholene 20m long, 4m deep.

TECTONIC CAVES

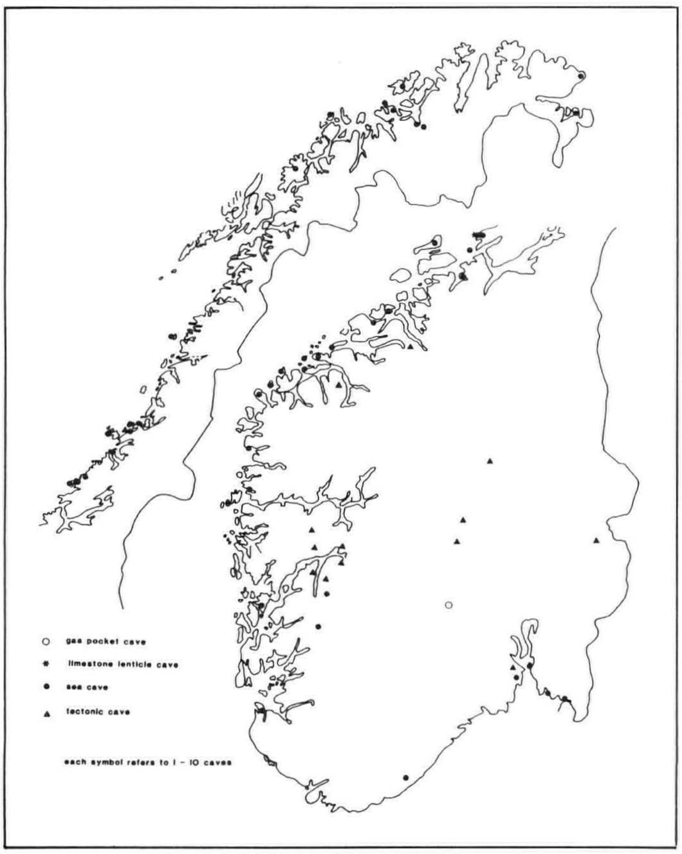
Tectonic caves are cavities resulting from movements and dislocations in the earth's crust. They can be divided into two main groups; fissure caves and thrust plane caves.

Fissure Caves

Large, open, generally vertical, fissures are usually found in steep hillsides and are thought to be the result of gravity sliding or tilting and warping of sections of hills or mountains. Very large fissures are found in areas with gneisses located on layers of phyllites.

In many cases pre-existing fissures may have been enlarged by the expansion and movement of ice during the Pleistocene. Deposits from ice and/or water are often found in fissure caves.

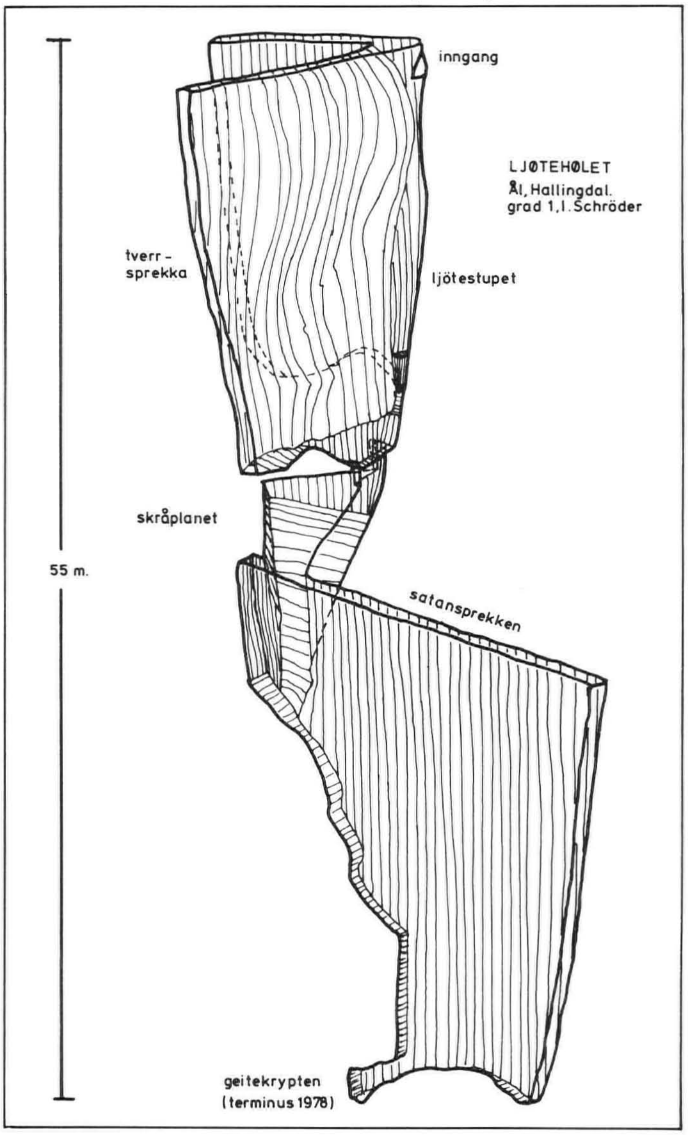
Figure 1. Location map of caves not in limestone in Norway.



The large amounts of water present during the end of the ice-ages must obviously have had a great influence on the modification of these caves, and weathering has often picked out breccia zones as lines of weakness. Caves are formed by flooring and roofing of the fissure at different levels by means of blocks and slabs becoming wedged, often in combination with irregularities such as horizontal ridges along the fissures.

Probably the best example of a tectonic cave in Norway is Ljötehölet, Al, Hallingdal, south-eastern Norway. Ljötehölet (fig. 2) is 55m deep and has a horizontal extent of about 70m. The fissure is about 2m wide at the top and 0.5m at the bottom. Vertical rope techniques are necessary to explore Ljöthölet. It is located in a steep hillside with frequent minor landslides, indicating some ground instability. The fissure is probably the result of gravitational forces acting on an unstable part of the hillside. The walls of the lower part of the fissure are very smooth and slickensided suggesting that the fracture was initiated by shear forces.

Figure 2. Ljötenhölet tectonic cave.



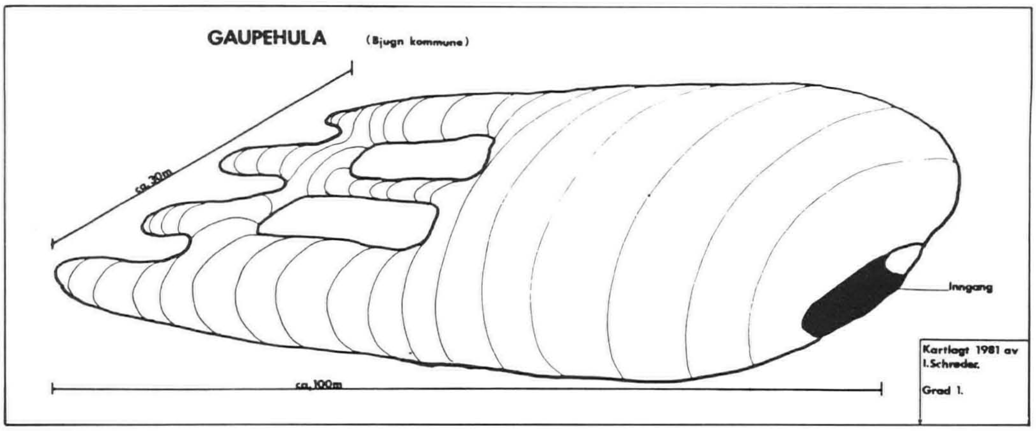


Figure 3. Gaupehola thrust plane cave.

In the Hardangerfjord area a great number of very large and deep fissures are known. One of them is about 500m long and up to 60m deep. This contains caves at 3 levels. During the snow-melt in spring and during heavy rainfall, a large stream runs into the fissure, forming a 25m waterfall. So far no passage that might convey the water away has been found. Most likely it just drains away between the rocks on the floor.

So far about 90 fissure caves are known from a number of sites mainly in southern Norway. Less than half of them are fully explored. The number of fissure caves is probably much higher than reported so far.

Thrust Plane Caves

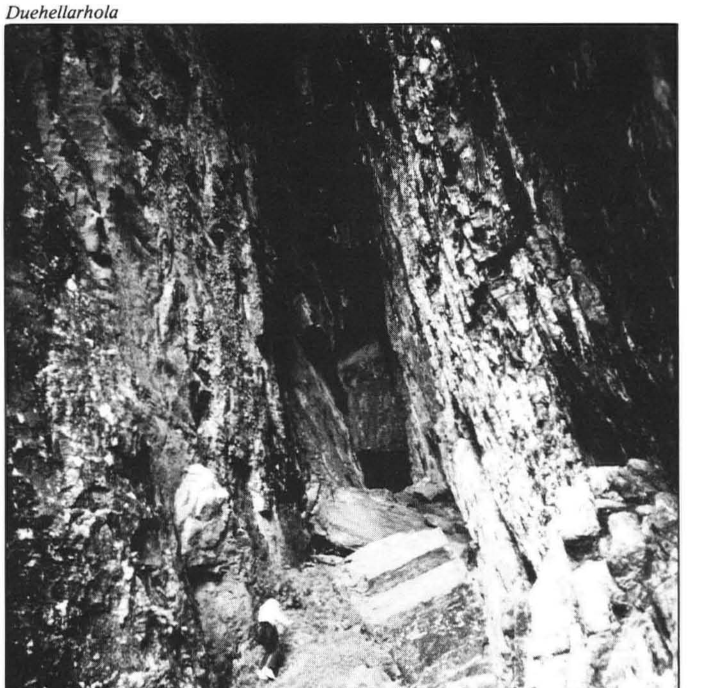
Thrust plane caves are hollows between two rock masses which have had a relative movement on a thrust fault. The movement is thought to have caused grinding and disintegration in the shear zone, leaving a zone of brecciated rocks very vulnerable to flowing water, frost wedging, sea breakers and other weathering effects.

The best known example of a thrust plane cave in Norway is the Gaupehola in Bjugn, Sör — Trönderlag, (Schröder 1982; Sjöberg 1983). From a distance, what is thought to be the remains of a thrust having a 30° inclination forming almost half of the Römmesfjell is clearly seen. The entrance to Gaupehola is situated at the bottom of the overhanging cliff at an altitude of about 170m. The passages of Gaupehola are shown in outline in fig. 3. The walls and ceiling of the cave are to a great extent lined with a crust of gypsum formations. The gypsum has been dated (using the Uranium method, by S. E. Lauritzen), to an age of about 10,000 years, i.e. the end of the last ice age. This may indicate that the cave lay on the coast at the end of the ice age and was formed by breakers washing out brecciated rock. The development of the gypsum crust started after uplift had raised the cave above sea level. Another example of what is thought to be a thrust plane cave is Pyntehula situated just a few km from Gaupehola. Pyntehula lies at about 160m asl. and is probably formed in the same manner as Gaupehula. The innermost part of the cave is decorated by flowstone, stalactites and stalagmites, indicating that the rock contains calcareous lenses or layers.

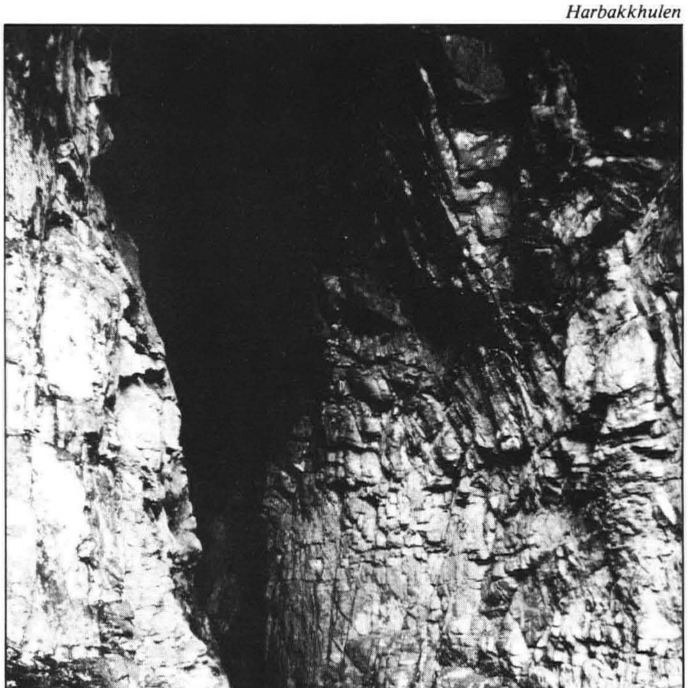
LIMESTONE LENS CAVES

Some caves found in Bjugn, Sör — Trönderlag seem to have been formed neither by tectonic nor marine processes. An

Duehellarhola



Harbakkhulen



Nedre Flatheiahula

example of this is Duehellarhola (Helland 1889; Schröder 1982). This cave contains none of the typical rounded forms created by breakers; the cave seemingly has a solid rock roof unlike fissures created by faulting. It is therefore proposed that the cave is the result of solution of one or more large limestone lenses. Duehellarhola lies about 130m asl. where both sea and meltwater might have acted on the soluble rocks. The discovery of a partially dissolved limestone lens about 2km east of Duehellarhola supports the limestone lens cave hypothesis (Schröder 1984).

SEA CAVES

Along the entire coast of Norway, and especially the west coast, there are a great number of caves formed mainly by wave action. They are situated at distances of up to 5km from today's coast and lie from up to 170m asl. These caves have initially been fissures created by tectonic or solutional processes. A sea cave usually is a combination of both a fissure and a tunnel-like cave formed by breaker abrasion (Sjöberg, 1986).

One of the largest and most beautiful sea caves in Norway is the well known Harbakkhulen in Afjord, Sör — Trönderlag (Helland 1889; Sjöberg, 1983; Schröder, 1986). Harbakkhulen lies about 1km from the coast at about 130m asl. It consists of an entrance chamber 100m long, 30m high, 12m wide. At the end of the entrance chamber, a steep hill leads up to 10m below the ceiling. From here the cave branches into two fissure-shaped passages 30 and 40m long respectively. A close inspection of the roof and walls of Harbakkhulen shows that they are smooth and unbroken with no sign of any significant crack or fissure. This indicates that the speleogenesis of this cave started by dissolution of a limestone lens.

Another small, but beautiful sea cave is Nedre Flatheiahula in Bjugn (Schröder 1984). This lies in the midst of the forest about 4km from the coast. It lies about 120m asl. and is 45m long. The walls are beautifully smoothed and rounded and the cave has the typical sea cave profile with tunnel shape in the lower part and fissure above. The floor of the first 20m consists of sharp cut rocks and mud, not, as expected, rounded rocks and pebbles. The rocks probably have been introduced by a passing glacier.

About 5km west of Nedre Flatheiahula lies Styggholet (Schröder 1982, 1984). From a distance this cave seems to be a pure fissure cave, but a closer look reveals a fairly large wave-eroded hall about 25m below the entrance. From the innermost end of the hall a narrow fissure leads inwards and upwards another 40m. The waves forming this part of the cave must have been active during one or more intermediate ice age periods, whilst the closure of the entrance has been caused by rockfall or by glacially transported rocks since the end of the latest ice phase.

GAS POCKET CAVES

Small pockets in crystalline rocks are present, if rare, in Norway. These pockets are thought to be the result of the expansion of steam or other gases while the rock was in a magmatic state. Very few of these pockets have the size of a cave, and less than 10 enterable gas-pocket caves have been reported.

Probably the best known example of such caves are the Dvergesteinholene (Drammen og omland Turistforenings arbok 1971; Schröder 1983) in Numedal, south-eastern Norway, lying about 1100m asl. The Dvergesteinholene consist of four separate cavities within a distance of not more than a 100m. The longest one is about 15m long with a diameter of about 1m. Old legends say that there was an abundance of beautiful quartz crystals in these caves 100 years ago. They have all been removed since them. One might, of course, speculate upon whether the Dvergesteinholene, all lying in a steep mountain side, once were parts of a much larger cave that has been dismembered during the ice age.

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Amblyrhiza and the Quaternary Bone Caves of Anguilla, British West Indies

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Abstract: The island of Anguilla, British West Indies, is the type locality for a giant extinct rodent described in the late 19th Century. Few additional specimens have come to light in this century, and the original localities are very imperfectly known. This paper summarises knowledge of the Quaternary bone caves of the island in the light of fieldwork conducted in 1988.

The islands of the West Indian archipelago are known to have lost almost 90% of their non-flying land mammals (Morgan and Woods, 1986) since the late Pleistocene, an extraordinary catastrophe whose record has survived solely in the natural bone reliquaries provided by the caves of the islands. Neither the proximate nor the distal causes of these extinctions are known with any certainty, although most workers infer that man's activities were largely responsible, in some combination of direct hunting, the destruction of habitat, and the introduction of exotics (particularly *Rattus* and *Herpestes*). Recently, the West Indies have emerged as a potential key to the debate concerning late Quaternary extinctions in general (MacPhee et al., 1989), because, whereas in North American terminal Pleistocene climate changes were nearly synchronous with human colonisation, humans did not reach the Antilles until the mid-Holocene (Rouse and Allaire, 1978). Accurate dating of the West Indian extinction chronology therefore provides an opportunity to distinguish between climatically- and anthropogenically-mediated processes.

Among the more unusual members of the ill-fated West Indian fauna were a diverse assemblage of heptaxodontid rodents. These are defined here as a family endemic to the West Indies, with no living representatives, and of uncertain relationships to the other caviomorph rodents of South America and the Antilles. Insular rodent faunas commonly evolve large body sizes, but the heptaxodontids took this trend to an extreme. The largest known member of the family, *Amblyrhiza,* has been variously estimated to have weighed as much as a Virginia deer or a small American Black Bear. Remarkably, this giant beast is known only from the tiny islands of Anguilla (78km^2) and St. Martin (93km^2), the most northerly members of the Lesser Antillean chain.

The original discovery of *Amblyrhiza* was made in 1868 during phosphate mining operations, but unfortunately field notes have not survived and there is no contemporary account describing the excavations from which the fossils were recovered. In June of 1988 the present authors visited Anguilla with the intent of tracing the original localities and finding additional sites from which datable remains might be collected.

The caves of Anguilla have been very poorly documented in the speleological literature (cf. Murray, 1972). Except for a basement of igneous rocks exposed at two coastal localities, Anguilla consists of a single limestone formation of early Miocene age (Christman, 1953). Karst features on the island include a number of springs which feed the few permanent bodies of water on Anguilla (e.g. Caul's Pond), and extensive exposures of limestone pavement. Significant caves are few, and no active systems are known.

The finds of 1868 were made in a shipment of phosphatic cave earth sent to Philadelphia to determine its value as a fertiliser. The large bones in the material were brought to the attention of the famous palaeontologist Edward Drinker Cope (1869a, 1883), who recognised their importance and requested that H. E. van Rijgersma, colonial physician of neighbouring Sint Maarten (= St. Martin), make a visit to Anguilla with a view to securing additional specimens. Rijgersma made at least three such visits and was successful in collecting numerous remains from a cave or caves whose identity is not known with any certainty (but see description of Cavannagh Cave). However, in the Cope's Anguilla collection (now at the American Museum of Natural History), a handwritten note was found which appears to pertain to the first set of specimens sent by van Rijgersma. The note reads: "1868. From out the Bat Cave. H. E. van Rijgersma". Unfortunately 'Bat Cave' is not a present-day named feature and could apply to any of several caves where bats are normally resident.

Cope first described the giant rodent at a meeting of the Philadelphia Academy of Natural Sciences on December 1st 1868, the report of the meeting appearing in February of the following year (Cope, 1869a). Cope named the animal *Amblyrhiza inundata,* and brought attention to its exceptional size and its phylogenetic relationship to caviomorph rodent stock. In subsequent months, Cope went on to describe three 'closely related' animals, *Loxomylus longidens, L. latidens,* and *L. quadradens* (Cope, 1869b, 1871a, 1871b). Finally, in his summary of 1883 (Cope, 1883), *Loxomylus* was combined with the earlier

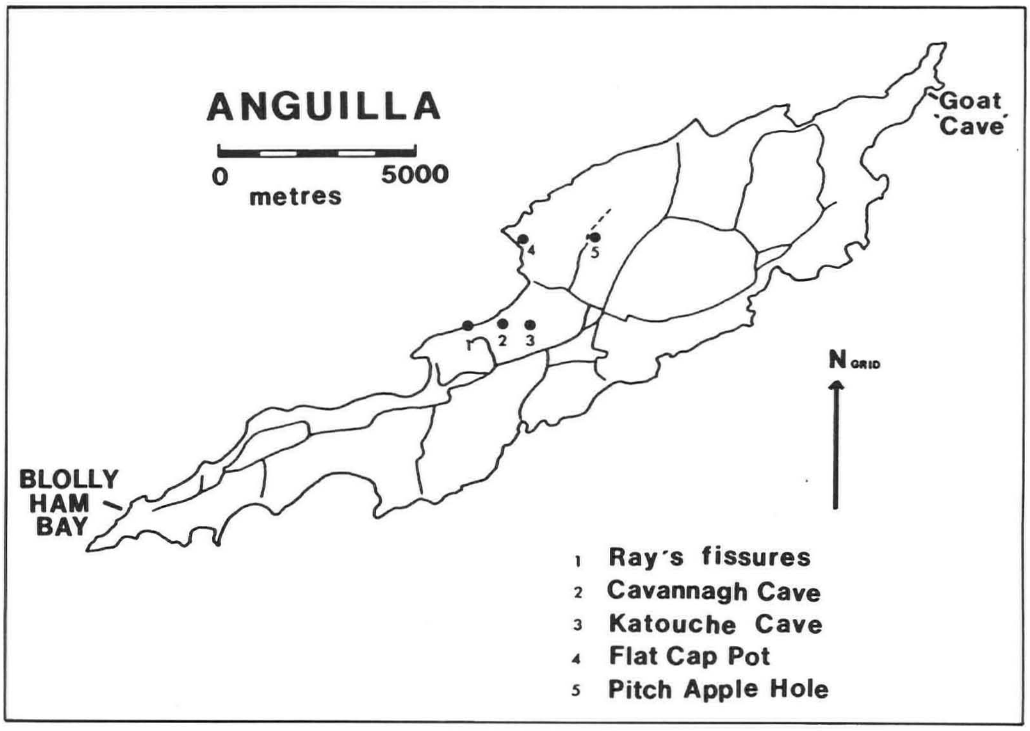

Figure 1. Principal Caves and Amblyrhiza *localities on Anguilla.*

genus *Amblyrhiza,* although the three original species were retained *(A. inundata, A. latidens* and *A. quadridens).* These nominal species differ principally in size and several later workers have inferred that only a single species, *A. inundata,* may be valid (e.g. Schreuder, 1933).

The geologist J. W. Spencer visited Anguilla around the turn of the century, and he recorded the first mention of new *Amblyrhiza* finds since the Rijgersma expeditions (Spencer, 1901). He described a visit to a number of eroded sea caves and fissures located in the cliffs between what is now Benzies Bay and Katouche Bay. However, Spencer's wording is enigmatic on the question of whether these fissures were the ones from which Cope's (Rijgersma's) material was obtained, or whether they were merely of a similar nature:

"In Anguilla, Mr. Wager Ray found a number of mammalian remains when digging for phosphate. I was fortunate in finding him on the island, and he kindly took me to the locality where he had obtained them — perhaps a mile northeast of the present landing, east of Road Bay . . . In such a fissure the bones were obtained, among which Cope discovered remains of three species of *Amblyrhiza* — a rodent as large as a Virginia Deer" (Spencer, 1901).

Spencer noted the presence of a mammalian radius in one of these fissures, but he evidently did not collect it and recorded no further details of the locality. We did not have the opportunity to examine this area in 1988 and no further insight can be provided.

The next expedition to Anguilla and Sint Maartin was organised by H. E. Anthony of the American Museum. In April of 1926, after concluding field operations in Sint Maartin where a few *Amblyrhiza* remains were collected, he dispatched his assistant, George Goodwin, on a short visit to Anguilla to search for additional specimens. Goodwin's field notes, which have been preserved in the archives of the Department of Mammalogy, American Museum of Natural History, were examined prior to our 1988 fieldwork. According to these notes, Goodwin collected *Amblyrhiza* bone fragments from a lateritic matrix exposed in shallow fissures in the limestone pavement along the north coast. These fissure fills consist of a distinctive, hard red matrix filling enlarged subaerial joints. Goodwin believed them to be remnant fills of collapsed caves, but they more closely resemble the ironstone fills of the Portland Ridge of southern Jamaica (Wadge *et al,* 1979). None of Goodwin's localities is well described. He mentioned finding fossiliferous fissures near "Briningham? Hollow about 5 miles west of Flat Cap". This is not an existing place name, although there is a "Blolly Ham Bay" some 8 miles WSW of Flat Cap Point. Elsewhere, Goodwin referred to the locality as being closest to the general area known as 'Goat Cave' on the northern tip of the island. Goat 'Cave' is apparently not a subterranean feature, the limestone surface being only a few meters above sea level in this area. In addition, Goodwin collected material from a cave in the ridge of Flat Cap Point, and from a cave on the North Side Estate. The cave in Flat Cap Point, which he described as a "deep cavern going through to the face of the cliff" could not be located in 1988. A shaft mined for phosphate in this immediate locality is described elsewhere in this paper. The description of the North Side Estate cave is so vague as to be useless in relocating this site.

With the exception of a few isolated and unpublished finds, there appear to have been no significant recoveries of *Amblyrhiza* on Anguilla between Goodwin's 1926 visit and our fieldwork in 1988. The 1988 field season yielded a large quantity of *Amblyrhiza* material representing at least four individuals, from a new locality called Pitch Apple Hole. This site is described here for the first time, together with two other historically important localities. A summary of Anguilla's known *Amblyrhiza* sites appears in Table 1 and Figure 1.

The demise of *Amblyrhiza* has given rise to considerable speculation as to the cause and timing of its extinction. In the same blocks of matrix that yielded bones of the giant rodent, Cope (1883) recovered shells of the mollusc *Turbo picta.* He used this as evidence for applying a post-Pliocene date to *Amblyrhiza.* However, he also noted that *Amblyrhiza* may have survived until comparatively recent times, because in one of the shipments received from van Rijgersma there was a shell of the bivalve *Strombus* modified into a scraper. Although Cope pointed out that there was no sure association between the scraper and the rodent bones, some later authors have made this assumption and postulated that humans were responsible for the extinction of the beast (Anderson (1984) takes the extreme view that *Amblyrhiza* may not have been exterminated until the 16th century.) If the extinction of *Amblyrhiza* was indeed caused by human agency, we would have yet another instance of the rapid, anthropogenic extinction of a native island land mammal (Martin, 1984). However, at the present time such an interpretation is unsupported by any direct evidence, and other viable explanations exist. *Clidomys,* a somewhat smaller relative of *Amblyrhiza* that lived on Jamaica, may have disappeared as early as 120,000 years ago (MacPhee *et. al,* 1989). If *Amblyrhiza* died out around the same time, we would have evidence of a truly Pleistocene wave of extinction that took place long before the arrival of human colonists on the islands.

In order to test these alternatives, it was originally proposed to utilise two radiometric dating methods — radiocarbon and uranium (U) series — to fix the date of the disappearance of *Amblyrhiza.* A 500g sample of bone fragments submitted for radiocarbon dating proved to have too little organic material for analysis, although it is not clear whether this is the result of great age or rapid diagenesis in a moist environment. Earlier attempts to use uranium-series methods to date bone samples from Caribbean cave sites have proven unsatisfactory (MacPhee *et al.,* 1989), but experience has shown that more reliable results can often be obtained by dating associated flowstone. None of the 1988 specimens were recovered in association with speleothems, although some of the material in the AMNH collections has

Table 1

Summary of Known *Amblyrhiza* sites in Anguilla

Locality	Date	Collector	Comments
Unnamed	1868	—	Block of guano and cave-earth sent to E. D. Cope by a phosphate mining company; *Amblyrhiza inundata* described
Bat Cave	1868	H. E. van Rijgersma	One of the caves visited by van Rijgersma and the source of the first shipment to Cope. *Loxomylus longidens* described from this material
Unnamed	1869?	H. E. van Rijgersma	Van Rijgersma made two more visits to Anguilla, probably in 1869. *Loxomylus latidens* and *Loxomylus quadridens* were described from this material. (The genus *Loxomylus* was sunk into *Amblyrhiza* in 1883.)
Caves at Flat Cap Point, North Side, and fissures at "Brinington Hollow"	1926	G. G. Goodwin	Numerous caves visited, but success only at the listed sites
Pitch Apple Hole	1988	R. MacPhee D. McFarlane	Remains of at least 4 *Amblyrhiza*

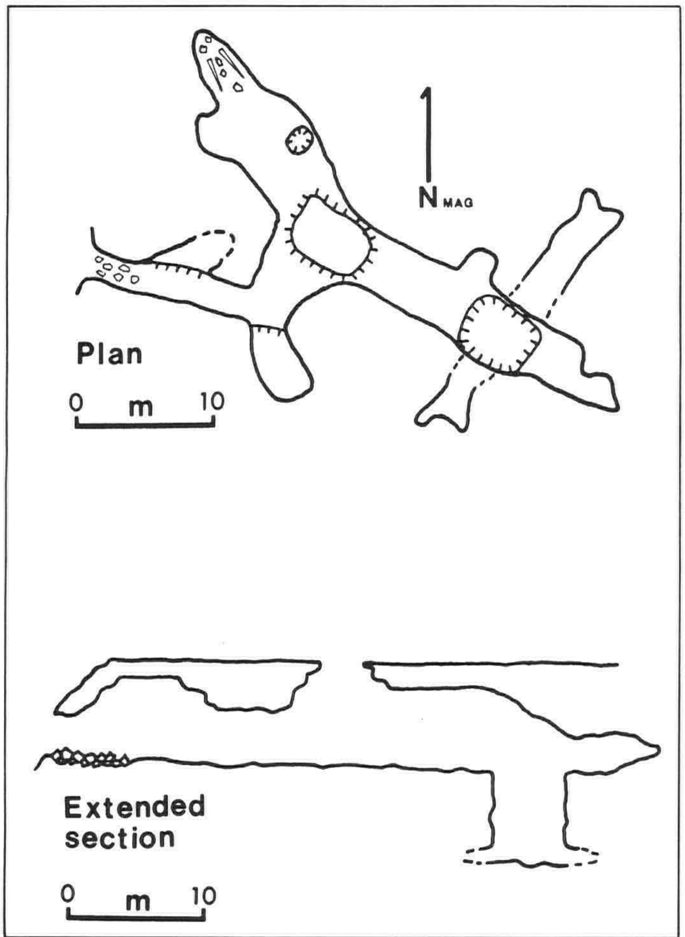

Figure 2. Cavannagh Cave, Anguilla.

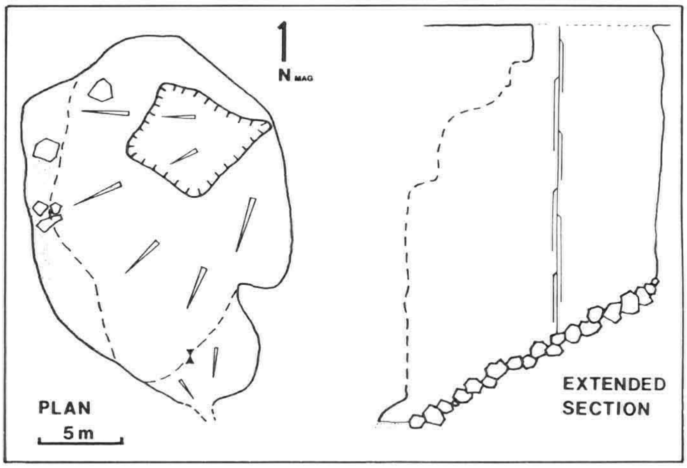

Figure 3. Pitch Apple Hole, Anguilla.

preserved remnants of a calcite matrix. Unfortunately, a test of one calcite-matrix sample failed to yield any thorium, indicating that this material at least may not be usable for uranium-series dating (Derek Ford, pers. comm.)

CAVE DESCRIPTIONS

Cavannagh Cave

Grid Reference: 866/140. Altitude: 38 metres. Length 87m.

Located some 350m north-northwest of the Governor's Residence, in the south wall of Katouche Valley. Cavannagh Cave is frequently confused with Katouche Cave, a significant abandoned stream cave located up-valley at grid reference 871/140.

The Anguilla Archaeological and Historical Society believes Cavannagh Cave to be the original locality from which *Amblyrhiza* was recovered, based on the evidence of extensive phosphate mining in the cave. If this is correct, then Cavannagh Cave is Rijgersma's 'Bat Cave'. Antillean Fruit Bats *(Brachyphylla cavernarum)* roosted in the cave in 1988. Shot-holes in the walls indicate that phosphatic earth or sediment originally filled the cave to a depth of at least 2.5 metres in the main passage and presumably much deeper in the excavated pit. Unfortunately the thoroughness of the mining operation precludes any possibility of recovering additional *Amblyrhiza* from this site.

Flat Cap Pot

Grid Reference: 8690/1607. Altitude: 25m. Depth: 10m.

Located on the west side of the road to Limestone Bay from Crocus Bay.

Flat Cap Pot is a simple shaft choked with rubble. Significant quantities or red earth have been eroding into the cave from fissures in the fractured limestone. The shaft has been extensively modified by phosphate mining operations, and shot-holes are obvious on all the walls. No fossils were recovered from here in 1988. However Rijgersma referred to the source of his *Amblyrhiza* finds as follows:

"Perhaps it will please you to learn that I have found some fossils in the phosphate of lime pit on Anguilla, and also some in a cave there . . ." (Private correspondence of H. E. van Rijgersma to Snellen van Vollenhoven, March 26th 1869, quoted in translation in Holthuis (1959)).

Clearly, two different sites were involved and Rijgersma makes the distinction between a 'pit' and a cave. The only two phosphate mining sites we were able to locate in 1988 were Cavannagh Cave and the site we have called Flat Cap Pot. Although we have not examined Wager Ray's fissures, Cavannagh Cave and Flat Cap Pot are currently the best candidates for Rijgersma's cave and pit respectively.

Pitch Apple Hole

Grid Reference: 8870/1633. Altitude: 53m. Depth: 23m.

Located on the east side of the North Side road, beneath a large pitch-apple tree.

Pitch Apple Hole is a collapse feature with overhanging walls. The large talus cone blocks any horizontal passage that might be present, with the exception of a short, constricted bedding plane passage beneath the southwest wall.

The west wall of the pit is undercut into a protected alcove, free of talus debris. The floor here consists of a narrow strip of deep red, lateritic cave earth of undetermined depth. *Amblyrhiza* bones were widely distributed in the earth, from a depth of some two centimetres to approximately 40cms. The specimens are now the property of the Anguillan Government, in the care of the Anguillan Archaeological and Historical Society.

In addition, the site yielded bones of the bats *Brachyphylla cavernarum* and *Artibeus jamaicensis,* and a number of birds and reptiles currently under study.

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