Cave Science

The Transactions of the British Cave Research Association

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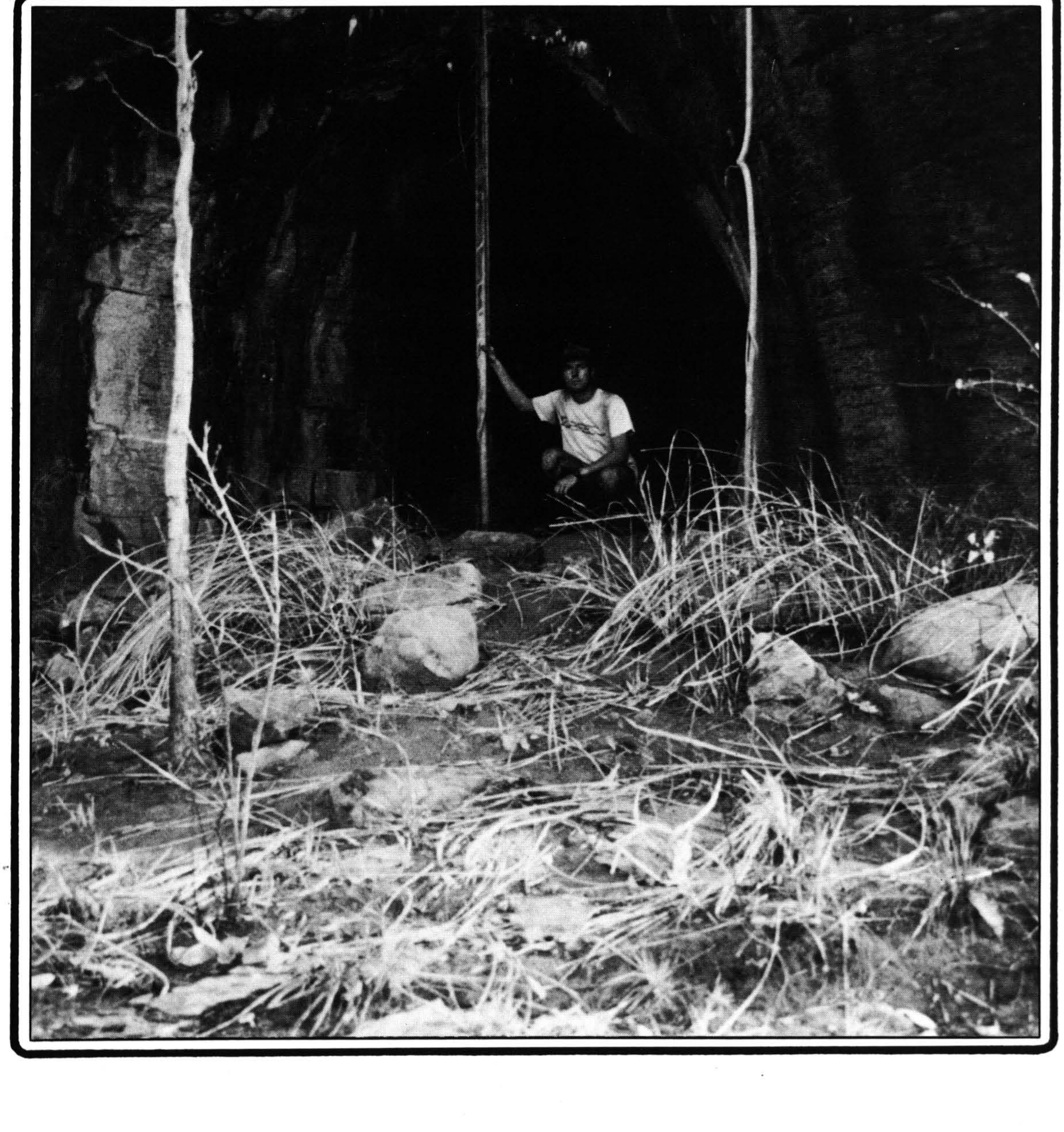

Symposium on radon in caves

Maze caves in Northern Territory, Australia

Karsts of the Nepal Himalayas

Karst of Anamas Daglari, Turkey

Artificial anchors in caves

Cave Science

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Cover: The entrance to Jalaman Wanga Jarin, one of the maze caves in the Gregory National Park in Australia's Northern Territory, recently explored by teams from Operation Raleigh. By David Smith

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Research on Radon in British Limestone Caves and Mines, 1970-1990

John GUNN, Stanley FLETCHER and David PRIME

Abstract: Radon is a naturally occurring radioactive gas which has three isotopes, the most significant being radon-222, a member of the uranium-238 decay series. More significant in terms of human health are the short lived radon daughters which are isotopes of polonium, lead and bismuth. The first measurements of radon gas and radon daughters in British limestone caves/mines were probably those undertaken at several of the Castleton show caves/mines during 1974/75. Although these revealed high concentrations no follow up work appears to have been undertaken until 1987, the driving force being new legislation. Subsequently observations were made by the authors in most tourist caves/mines and in some wild caves and abandoned lead mines. The present paper draws together the available data for the period up to July 1990 when a more detailed survey commenced. The data are spatially and temporally discontinuous but three points do emerge: 1. Radon daughter concentrations are generally lowest in Devonian limestones and highest in the Peak District Carboniferous limestones, where Giant's Hole has what is probably the greatest recorded radon daughter concentration in any natural cave in the world, 42 WL (c. 155,400 Bq m^{-3} equilibrium equivalent radon gas). 2. Radon daughter concentrations are broadly similar in the Carboniferous limestones of South Wales, the Mendip Hills and the Northern Pennines. 3. Radon daughter concentrations are generally higher in the summer and lower in the winter.

Radon is a naturally occurring, colourless and odourless radioactive gas, the most significant isotope of which is radon-222. This is a decay product of natural uranium, an element which is widely distributed in the earth's crust, though generally in low concentrations. When radon in turn decays, it forms very small particles of other radioactive substances, the short lived isotopes of lead, polonium and bismuth which are collectively known as radon daughters. The particles tend to attach themselves to dust or water particles and can thus be inhaled and deposited in the lungs. The alpha-particles from the radon daughters lodge in, and irritate, the lungs. Although exposure to high concentrations of radon daughters has been shown to increase the risk of lung cancer and possibly also other cancers such as acute myeloid leukaemia, the actual health risks which result from exposure to radon daughters are still not clearly defined. This is particularly the case with respect to short-term exposure to relatively high doses as could happen in some caves/mines. However, recent figures (BEIR IV, 1988) suggest that exposure to about 204 WLH per year for life doubles one's risk of dying from lung cancer whereas lifetime smoking increases the risk of dying from lung cancer tenfold. When there is exposure to high concentrations of radon *and* to cigarette smoke the risk is increased in a multiplicative rather than additive manner.

UNITS AND METHODS OF MEASUREMENT

The concentrations of radon gas are most commonly expressed in Bq m^{-3} and concentrations of radon daughters in Working Levels (WL), although there are several other units of measurement. In assessing the risk to health it is necessary to compute dose which is concentration multiplied by exposure-time. Dose is commonly expressed as millisieverts per unit time (e.g. mSv y^{-1}) or as working level hours where 1 WLh equals one hour's exposure to 1 WL which is approximately 0.0735 mSv. Concentrations of radon gas may be measured directly using Lucas Cells or indirectly using film which is sensitive to alpha particles such as TASTRAK or CR-39. The film may be exposed in yogurt cartons or some similar receptacle (e.g. Reaich, 1989) or placed in dosemeters which may be left underground or worn on an individual. In order to convert concentrations of radon gas into concentrations of radon daughters (and hence to estimate dose) it is necessary to know the equilibration factor between parent and daughter which varies from 0.1 to 0.9. Radon daughter concentrations may be determined directly in several ways, the most practical for caves being (1) the "Kusnetz" method which is relatively quick but requires access to a scintillation counter to process the samples within 90 minutes of collection or (2) a battery operated 'Radon Sniffer' which will give an initial estimate in 15-20 minutes but takes 30-60 minutes to produce a reliable reading.

In Britain, the Ionising Radiations Regulations 1985 and the Approved Code of Practice (ACOP) Part 3 "Exposure to Radon", 1988 apply to any place of work where the radon daughter concentrations exceed 0.03 WL. If the concentrations exceed 0.1 WL then a 'Controlled Area' must be designated and this may only be entered by Classified Radiation Workers or others operating under a written System of Work. The act sets an annual dose limit for employees of 15 mSv (about 204 WLh) and although a classified radiation worker may receive up to 50 mSv y^{-1} (about 680 WLh) such a high dose is considered undesirable

Table 1.
Statutory Limits on Radon Daughter Concentrations in the U.K.

0.03 WL = Concentration at which the Ionising Radiations Regulations apply
0.05 WL = Government action level for radon in houses
0.10 WL = Concentration above which a controlled area must be designated
(A controlled area may only be entered by classified radiation workers or by unclassified workers as part of a written scheme of work under the guidance of a radiation protection adviser)

Table 2.
Radon Daughter Concentrations in British Caving Regions (all values in Working Levels)

	n	Range	Mean
Devon	93	0.00–0.49	0.14
Mendip, Winter	83	0.00–0.39	0.09
Mendip, Summer	81	0.00–1.23	0.31
Mendip, (Cuckoo Cleeves)		1.62–2.56	
South Wales, Winter	61	0.00–1.00	0.05
South Wales, Summer	76	0.06–2.85	1.14
North Pennines, Winter	68	0.00–0.38	0.07
North Pennines, Summer	82	0.19–1.56	0.69
Peak District			
1. Spot measurements using working level meter ('radon sniffer')			
Carlswark Cavern (Eyam)	8	0.04–5.02	2.15
Giants (Summer)		2.10–41.97	
(Winter)	34	0.00–1.63	0.28
Hillocks (Summer)	8	0.94–3.52	2.13
Knotlow	7	0.03–1.73	0.93
Oxlow	16	0.18–16.40	3.63
P8 (Summer)	12	1.80–10.36	4.72
Peak Cavern	121	0.00–12.60	2.26
Pooles Cavern	144	0.00–0.98	0.30

2. Radon dose meters exposed for 5 x 28 day periods

Cave	Sampling duration	Range	Mean
Axe Hole (1 site)	11/89–03/90	0.03–0.04	0.03
Carlswark (5 sites)	11/89–03/90	0.01–0.23	0.06
Carlswark (1 site)	11/89–03/90	0.37–1.41	0.83
Devonshire (3 sites)	11/89–03/90	0.00–0.33	0.09
Gautries (2 sites)	11/89–03/90	0.33–0.48	0.40
Giants (6 sites)	11/89–03/90	0.03–1.18	0.28
Hillocks (2 sites)	11/89–03/90	0.23–0.50	0.34
Jug Holes (2 sites)	11/89–03/90	0.01–0.05	0.02
P8 (4 sites)	11/89–03/90	0.03–0.63	0.14

and would warrant an investigation. The dose limit for other persons is set at 5 mSv y^{-1} although the National Radiation Protection Board (NRPB) recommends that a member of the public should not receive more than 0.5 mSv y^{-1} above the average natural background which is around 2.5 mSv. However, at least 20,000 people in Cornwall and Devon receive over 10 times this amount from radon in their homes.

RADON GAS & RADON DAUGHTERS IN CAVE/MINE AIR

Andrews & Wood (1972) examined radon concentrations in rock matrices and in limestone spring water in the Mendip Hills but the first measurements of radon gas and radon daughters in British caves were probably those undertaken by the Manchester University Radiological Protection Service at several of the Castleton show caves during 1974/75. These revealed high concentrations and in one cave a borehole was drilled to improve ventilation. In 1976 measurements were made in Gilfield Mine, Greenhow, which is an abandoned lead mine excavated in Carboniferous Limestone and Millstone Grit which is operated for training and research purposes by the Department of Mining and Mineral Engineering, University of Leeds. The results of these and subsequent measurements were reported by McFarlane (1984). The maximum instantaneous concentration was 1.18 WL but summer means ranged from 0.37–0.56 WL and winter means from 0.01–0.11 WL (McFarlane, 1984).

In 1986, a draft code of practice (DCOP) covering exposure to radon was circulated to all show cave and show mine operators by the Health and Safety Executive (HSE). Following the DCOP, and the later Approved Code of Practice, it became a legal requirement for measurements to be made of radon daughter concentrations in caves/mines open to the public. Most of these measurements were made by the authors although Andrews (1991) undertook measurements in Wookey Hole. The results of these surveys are confidential but have been used to build up a broad picture of variations across the country. In most cases concentrations were found to exceed 0.1 WL for at least part of the year, and as a result appropriate measures have had to be taken either to reduce concentrations (by the installation of ventilation systems) or to control employees' exposure time and hence their annual dose.

The only wild cave for which detailed information is available is Giant's Hole, Derbyshire, where Middleton *et al.* (1991) and Williamson (1990) recorded extremely high concentrations. Kerr and Reaich (1989) have described a radon survey in Cuckoo Cleeves Cave which was undertaken over a six-day period using TASTRAK film. Radon gas concentrations were in the range 12-19,000 Bq m^{-3}, eqivalent to daughter concentrations of *c.*1.62–2.56 WL if an equilibrium factor of 0.5 is assumed. During the period 1987–1990 the authors collected data on radon daughter concentrations somewhat sporadically from a number of wild caves, principally in the Derbyshire Peak District, using a Radon Sniffer and, for shorter systems, the Kusnetz method (Table 2). In addition, Derbyshire County Council commissioned a survey (using passive radon monitors) of winter radon concentrations in the cave/mines most popular with Outdoor Education Centres (Table 2). This was further extended to cover a full year and will be the subject of a subsequent paper. Although there have been insufficient measurements to draw any firm conclusions, the results from both wild and show cave/mines indicate that radon daughter concentrations vary spatially at three scales: within cave, from cave to cave in the same area, and from area to area.

Within cave variation

Most caves exhibit variations from site to site and in some cases these are very large. For example, on 4 November 1987 the lowest reading in Peak Cavern was 0.17 WL and the highest, at a site less than 100m away, was 12.6 WL. Similarly, in Giant's Hole on 2 July 1988 concentrations ranged from 5.5 to 24.3 WL. In Pooles Cavern the absolute values are lower but maximum concentrations on any one day are generally 3–6 times the minimum. For example, on 23 September 1987 the range was 0.18–0.98 WL and on 14 December 1988, 0.05–0.29. Another good example of within cave variation comes from Carlswark Cavern where 5 sites are in the range 0.01–0.23 WL with a mean of 0.06 WL whereas the sixth, located in an area where there is little ventilation, has a range of 0.37–1.41 and a mean of 0.83.

Between cave variation

The only region for which there is sufficient data to permit comparison of individual caves is the Derbyshire Peak District. Concentrations are generally higher in the Castleton area, particularly during the summer months, and lowest in the Buxton and Matlock areas (Table 2). The variations are a result of geology and cave microclimate which is itself in part a function of passage morphology and topology.

Between area variation

The results of our very limited sampling of caves beyond the Peak District indicate that in all areas of the country there are some caves with low concentrations, at least during the winter months. Maximum concentrations were 0.49 WL in Devon, 1.56 WL in the northern Pennines, 2.56 WL in the Mendip Hills and 2.85 WL in the Penwyllt area of South Wales. These are an order of magnitude less than the maximum of almost 42 WL from the Peak District.

Temporal variations

Measurements in both tourist and wild caves have clearly demonstrated a clear seasonal trend in radon daughter concentrations, with higher values in summer than in winter. There may also be marked diurnal variations as observed in Giant's Hole (Middleton *et al.,* 1991).

IMPLICATIONS

On the basis of our limited results we would suggest that active recreational cavers in the Peak District probably receive a greater annual radiation dose than that received at work by the majority of British coal, fluorspar or tin miners or by workers in the nuclear industry. Current legislation does not apply to recreational caving and we would suggest that provided the individuals are aware that they are placing themselves at risk then nothing more can or should be done. Further measurements are underway to establish which caves have the highest concentrations and at which particular time of day or season so that cavers may choose to plan their trips accordingly. No element of compulsion is necessary as the presence of radon would be accepted as one of the risks of caving. However, the risk is long term and not readily observable.

The current legislation does cover cavers who are employed as instructors at Outdoor Pursuits Centres. As a result many Outdoor Centres have temporarily suspended caving activities in the Peak District until further data become available on the magnitude of the problem. Although this is to the detriment of the sport of caving it could have positive impacts in terms of cave conservation. On the other hand, it would seem likely that those caves and caving areas which are identified as having low radon daughter concentrations will receive greater traffic in the future than those with high concentrations and this will consequently lead to increased pressure. The implications of this for cave conservation will need to be considered as more information becomes available.

CONCLUSIONS

An initial survey of radon daughter concentrations in some British caves has shown: (1) that there are wide spatial variations at all scales (within cave; cave to cave; area to area). (2) there are substantial diurnal and seasonal variations. (3) some caves, principally those in the Castleton area of the Derbyshire Peak District, have very high concentrations for at least part of the year. The first two observations are substantially in accord with overseas experience (e.g. Yarborough *et al* 1976, Ahlstrand and Fry 1976, Ahlstrand 1980) and reflect the fact that radon levels vary with proximity to source (uranium), ventilation, atmospheric pressure and, less clearly, water levels. However, our initial literature review suggests that the radon daughter concentrations in some of the Castleton caves are substantially higher than anywhere else in the world although greater concentrations have been recorded in mines and natural cavities intersected by mine workings.

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Radon Daughter Concentrations in Giant's Hole, Derbyshire

Terry MIDDLETON, John GUNN, Stan FLETCHER and David PRIME

Abstract: The purpose of this study is to investigate whether the concentration of radon daughter elements found in Giant's Hole, Derbyshire, varies according to predictable patterns and, subsequently, to assess the potential health risk posed by such radioactivity. A spatial and temporal study was made of radon daughter levels inside the cave from May 1988 to June 1989. The levels observed were found to be very varied with some appearing to be the highest ever recorded in a natural cave. The study found that the airflow direction within the cave was a dominant factor affecting both spatial and temporal patterns and that this was in turn related on a seasonal and diurnal scale to the temperature gradient which exists between the inside and outside air. In addition, some of the temporal variations could be related to changes in atmospheric pressure. The data collected are compared with the maximum dose rates and associated risk estimates of premature death through lung cancer which are permissible for Classified Radiation Workers. The results show that although the concentration of radon daughter elements present in the cave during the winter is not harmful, those that are encountered by cavers making regular visits to the system during the summer do pose a significant health risk.

Radon-222 is a radioactive gas which is produced ultimately from the decay of Uranium-238. Uranium-238 is widely distributed within the earth's crust albeit in fairly low concentrations, typical levels being 5 ppm (by weight) in granite and 1 ppm in basalt (Open University, 1973). The element decays through a series of essentially uranium and thorium isotopes to form Radium-226 which is the parent nuclide of the gas Radon-222. This gas emanates in small quantities from buildings, rocks and the soil. In open situations the gas is rapidly dispersed by atmospheric turbulence. However, in the confines of a house, mine or cave, the gas may begin to accumulate allowing the build up of daughter elements such as Polonium, Lead and Bismuth. These radon daughters may then become attached to minute dust particles or moisture droplets and be inhaled into the lungs where the emission of alpha particles can contribute to the development of lung cancer.

The earliest research on radon daughter levels in caves was undertaken in the United States during the mid-seventies and early eighties and focused on a number of show caves administered by the National Park Service. Ahlstrand and Fry (1976) and Ahlstrand (1980) suggested from work based on Carlsbad Cavern, New Mexico that temporal variations in radon daughter levels existed which could be associated with seasonal, diurnal and pressure related phenomena. Similar mechanisms were noted by Knutson (1977), Wilkening *et al* (1976) and Yarborough *et al* (1976). There was no comparable work in Britain, and research into radon daughter levels in caves is still comparatively in its infancy, the first papers being published in 1989 (Gunn *et al.,* 1989a, b). A detailed study of radon daughter levels in the influent cave of Giant's Hole, Derbyshire (see location map 1) was carried out over the period from May 1988 to June 1989 during which over 130 measurements of radon daughter concentrations were made. The objectives of the study were: 1) to investigate any spatial or temporal patterns in radon daughter concentrations which might exist within the cave with a view to facilitating the prediction of variations; and 2) to assess the potential health risk posed by such radioactivity to visiting cavers.

METHODOLOGY

The entrance to Giant's Hole is situated at grid reference SK119826 on the limestone plateau approximately 3 km west-southwest of the village of Castleton in Derbyshire (Figure 1). The following temporal data were collected at various sites within the cave (Figure 2):

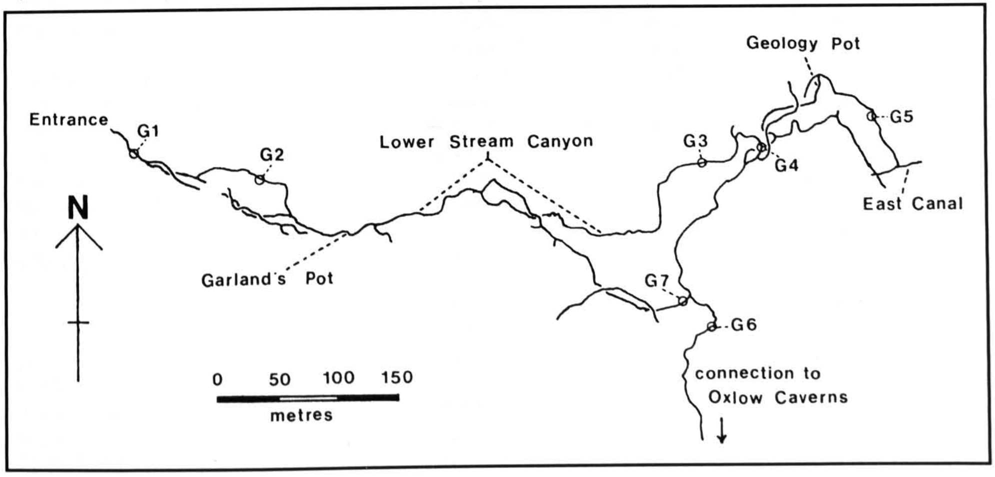
1) radon daughter concentrations (WL).
2) air velocity and direction measurements.
3) internal temperature and pressure readings.

In addition, the external temperature and pressure were noted at the beginning and end of each trip into the system and both a thermograph and barograph were set up in the vicinity of the cave. Measurement of radon daughter concentrations was made using a Thompson and Nielson Instant Working Level Meter ('Radon Sniffer'), a light and reliable instrument which gives comparable results to those obtained using the well established Kusnetz method which is commonly employed in mines. The Sniffer works by allowing radon daughter products from the cave atmosphere to become deposited on a filter within the device where they emit alpha particles. The Sniffer then records the number of alpha counts and these can, at a later stage, be converted into working levels (WL). Unless the concentration of radon daughters was particularly high, the Sniffer was normally set to sample for a 30 minute period.

Air velocity measurements were made by using both a hot-wire anemometer and a rugged purpose-built airflow meter. Unfortunately the airflow velocities encountered within Giant's Hole were all found to be very low and only 20% of the measurements collected were sufficiently high (0.05ms^{-1} or greater) to be recorded by the hot-wire anemometer. The purpose-built airflow meter, which was based on studying the deflection of both a candle flame and joss stick smoke against a scale, was found to be surprisingly sensitive, enabling air velocities to be measured against a 16 point scale. In addition, the joss stick smoke gave clear evidence of the direction of movement of the air mass. Further details of this instrument are given in Middleton (1988).

Figure 1. Location map for Giant's Hole

Figure 2. Location of Sampling Sites, Giant's Hole (adapted from a B.S.A. Survey)



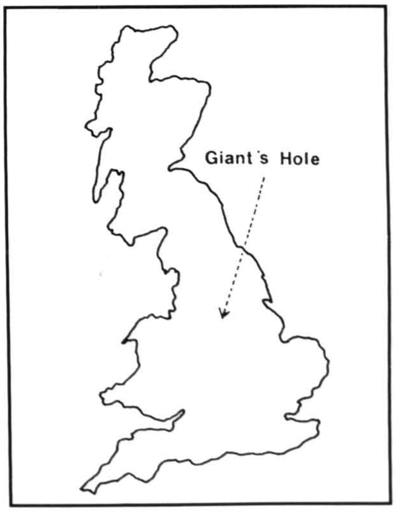


Table 1.
Seasonal Variations in Radon Daughter Concentrations (WL)

Date	Daytime airflow at entrance	Readings	Mean WL	Range WL
May-Oct 1988 (mainly June/July)	Outflow	70	9.70	2.10-24.30
Dec 88-April 1989	Inflow	43	0.32	0.00-1.63
June 1989	Outflow	9	5.85	2.82-9.73

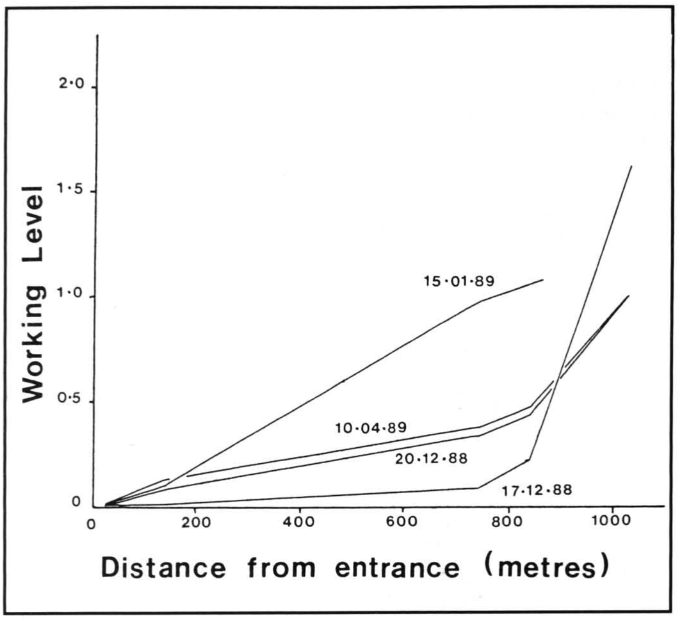


Figure 3. Increasing Radon Daughter Concentrations with distance from the entrance when air is inflowing (winter).

Table 2.
Seasonal Variations for Grouped Sites

Date	Daytime airflow at entrance	Mean WL for G1,G2,G3,G4	Mean WL for G5,G6,G7	Range WL
24/06/88	Outflow	9.20	3.86	3.91-12.54
02/07/88	Outflow	17.46	12.19	5.52-24.26
17/12/88	Inflow	0.06	0.82	0.00-1.63
20/12/88	Inflow	0.18	1.03	0.01-1.22
10/04/89	Inflow	0.18	1.08	0.00-1.19
13/06/89	Outflow	6.28	4.98	2.82-9.73

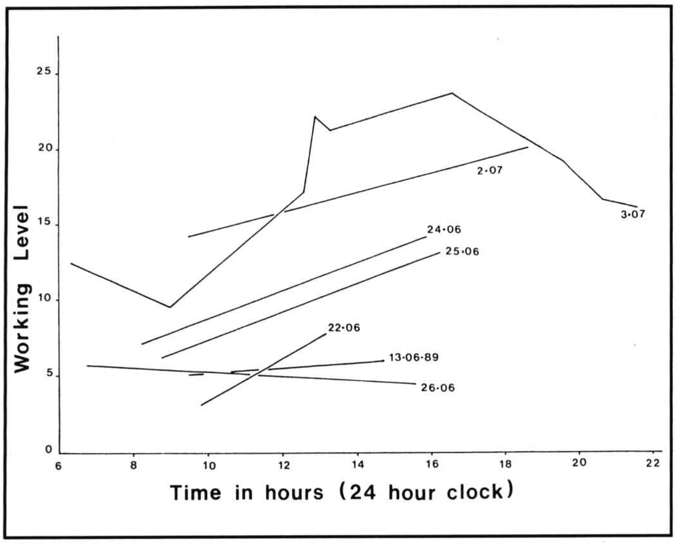


Figure 4. Radon Daughter Concentrations over time at G2 (Values are for 1988 unless otherwise stated).

RESULTS

Both spatial and temporal variations in radon daughter concentrations were identified at Giant's Hole. However, before these are described in detail, it is first necessary to discuss some of the airflow characteristics of the system as these have proved to be a key factor affecting the concentration of radon daughter elements.

Internal Air Circulation:

The general airflow pattern within the cave is directly dependent upon temperature related criteria. In winter, when the mean external air temperature is lower than that found inside the cave, cold dense air from outside flows into the cave entrance and down the streamway to the bottom of the cave. The air then returns towards the surface via the upper series of passages. However, in summer, the cave atmosphere is generally colder and denser than that found outside and, as a result, it is more stable and less mixing occurs. In addition, the circulation is reversed. Whilst the airflow patterns in the streamway and entrance passages appear to be very straightforward and can be easily analysed, those found in the Upper Series are more complex and occasionally appear to pass through sections which are inaccessible to cavers. Airflow readings taken both in the summer and winter at Sardine Chamber (G6, Figure 2)) suggest that although there is an air connection to Oxlow Caverns for most of the year this makes a negligible contribution to the air circulation in Giant's Hole.

In addition to the seasonal variations in airflow, a diurnal temperature pattern can be identified in the entrance series during the summer months. Although air is normally found to be flowing out of the entrance during the summer, as the evening progresses and the external temperatures fall significantly below those found inside the cave, air from outside begins to flow back into the entrance series at a higher level. Thus at Gl (Figure 2), the air in the bottom of the passage will be flowing out whilst that encountered at the top of the passage will be flowing in. This inflowing air continues into Upper East Passage where it disappears into inaccessible fissures. Under such conditions, strong downdrafts of air, sufficient to invert the smoke from a joss stick, fall down the two main avens just before Garland's Pot to join the main body of air flowing out of the system via the Giant's Highway (G2, Figure 2). Although the air which disappears in Upper East Passage has not actually been traced, it does seem likely that it is the same air which contributes to the downdrafts found at the avens. The estimated time for the air to complete this 400m entrance circuit is 2 hours at $0.05ms^{-1}$ and 5 hours at $0.02ms^{-1}$. Evidence collected late at night in the summer indicates that the airflow in the vicinity of G2 may even reverse in the early hours of the morning as the external air temperatures continue to fall. However, during the winter months all of the air sampled in the entrance series was found to be inflowing.

Seasonal variations in radon daughter levels:

The marked seasonal variations in airflow result in distinct patterns in the concentrations of radon daughters within the cave. Whereas the summer conditions encourage air stability in the system and a subsequent build up of concentrations, the strong draft of air flowing into the entrance during the winter has a diluting effect on the concentration of radon daughters (Table 1).

There are also clear spatial patterns and often considerable spatial variations in the radon daughter concentrations which relate to the direction of air movement in the cave. When the air is flowing into the entrance and down the streamway, the concentrations associated with this incoming air are found to increase with distance into the cave (Figure 3), some of the highest concentrations being recorded at Spout Hall (G5) effectively the bottom of the cave. High concentrations would also be expected in the Upper Series (G6 and G7) where the older air is returning towards the surface. When the circulation is reversed, the lowest concentrations are found to be associated with inflowing air at G6 and G7 and, again, the concentrations associated with this air increase with distance into the cave. Under these conditions, the highest concentrations will be found in the outflowing air in the vicinity of the streamway (G3, G4) and by the entrance (Gl, G2; Table 2).

Diurnal Variations:

In discussing the internal air circulation, it was noted that certain diurnal patterns can appear in the entrance series during the summer. These airflow patterns, in turn, affect the radon daughter concentrations in the entrance section. The reversal of

Table 3.
A Comparison of Radon Daughter Concentrations at G2 on 3/9/88 and Outside Air Temperature

Time	Radon daughter concentrations (WL)	External Temperature (°C)
6.16	12.46	7.1
8.57	9.61	9.5
12.03	16.1	15.9
13.11	21.3	16.3
16.31	23.74	14.7
19.25	19.5	12.4
20.34	16.8	12.0
21.10	16.26	11.7

Table 4.
Radon Daughter Concentrations (WL) in Giant's Hole under high (HP) and low (LP) Barometric Pressure

Site	24/6/88 (HP)	2/7/88 (LP)
G1	3.91	14.78
G2	7.26	14.29
G3	8.66	12.10
G4	12.54	24.26
G5	4.79	5.52
G6	4.65	15.24
G7	6.40	15.80
G2	14.27	20.10
G1	8.56	10.21
Mean	7.89	15.70

airflow which develops when the external temperatures fall at night results in a significant dilution of the 'radon' laden air which is emanating from deeper in the system. As the air is moving very slowly (< 0.05ms^{-1}, the minimum recordable with the hot-wire anemometer), it would probably take 2 to 3 hours for the effects to be felt at G2. As a result these lower radon daughter concentrations continue until the mid-morning. However, as the day progresses and the external temperature rises, the dilution effect disappears resulting in higher radon daughter concentrations in the entrance series (Figure 4). The anomalous downward trend in concentrations on 26th June (Figure 4) is due to the comparatively low daytime temperatures (as recorded by the thermograph) which were insufficient to set the diurnal mechanism into operation.

The concentrations at G2 on the 3rd of July were correlated with the external air temperature using the non-parametric Spearman's Rank method. A correlation co-efficient of 1.0 is obtained if the external air temperature data are compared to concentrations some 2½-3 hours later (Table 3). This supports the earlier suggestion that it takes 2 to 3 hours for the effects of a change in outside air temperature to be felt at G2. There is also a significant correlation (rho = 0.857, 97% confidence level) between radon daughter concentrations at G2 on the 3rd of July and the air velocity at the same site.

Certain diurnal fluctuations in radon daughter concentrations were also noted during the winter at G1 and G2. However, there are no clear patterns and the levels are so low that their significance is likely to be negligible. It should be noted, as exemplified by the previous correlation, that the whole issue of diurnal fluctuations is made more complex by the delayed response underground (possibly several hours or even days) to the effects of external changes in temperature or pressure. This is a whole area of study which could be developed further particularly for sites deeper within the system.

Pressure related variations:

Ahlstrand (1980), in his work on Carlsbad Caverns, noted that fluctuations in radon daughter concentrations appeared to occur on a daily basis associated with changes in atmospheric pressure. The basic process, which is well known in mining circles, involves the increased release of gases from permeable rocks during periods of low pressure. On the 23rd and 24th of June 1988 the atmospheric pressure in the Castleton area remained stable and high at 1027mb, whilst on the 1st and 2nd of July 1988 the pressure was stable and low at 991mb. Data collected on the 24th of June and the 2nd of July (Table 4; Figure 5) show that for every site within the cave the concentrations of radon daughters are significantly higher under conditions of low pressure. Similar results were obtained in a study of concentrations in the entrance series over a slightly longer period (Table 5).

Table 5.
Radon Daughter Concentrations (WL) at Sites G1 & G2 in Giant's Hole under High (HP) and Low (LP) Barometric Pressure

Date	Working Level G1	Working Level G2
22/6/88 (HP)	4.84	5.42
24/6/88 (HP)	6.24	10.77
25/6/88 (HP)	9.66	9.67
Mean (HP)	6.91	8.62
2/7/88 (LP)	12.50	17.20
3/7/88 (LP)	16.28	17.48
Mean (LP)	14.39	17.34

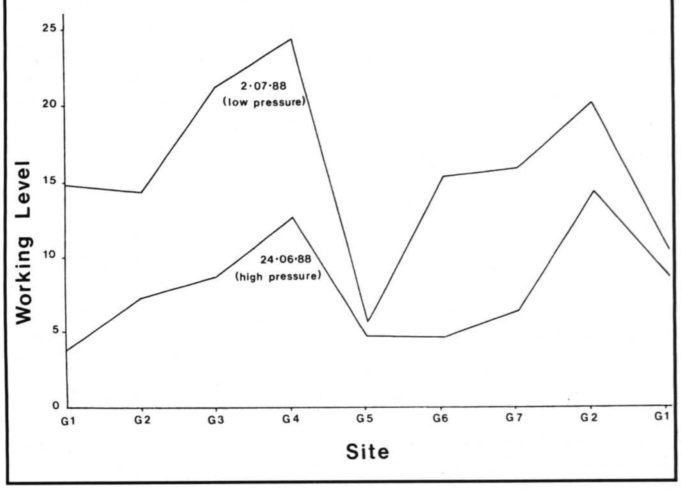


Figure 5. Comparison of Radon Daughter Concentrations at 7 sites under Low and High Barometric Pressure.

IMPLICATIONS

In Britain, Government legislation (The Ionising Radiations Regulations 1985 and the Approved Code of Practice Part 3 "Exposure to Radon", 1988) controls the annual dose which may be received by an employee at a place of work. Normally, a worker should receive no more than 15mSv y^{-1} (about 204 Working Level Hours [WLH]) but a classified radiation worker may receive up to 50mSv y^{-1} (about 680 WLH) although such a high dose is considered undesirable and would be subject to an investigation. The National Radiological Protection Board (NRPB) recommend that a member of the public should not receive more than 0.5 mSv y^{-1} (about 6.8 WLH) above the average natural background radiation. However, at least 20,000 people in Cornwall and Devon receive over 40 times this amount from radon in their homes.

One hour in Giant's Hole in summer would be sufficient to exceed the recommended maximum annual 'additional' dose of radiation for a member of the public and during the ten caving trips made to collect the data for June and July 1988, Middleton received almost 500 WLH (>36 mSv) of exposure. This represents over 70 per cent of the maximum permitted annual dose for a classified radiation worker and is well in excess of the dose received by the vast majority of workers in the nuclear industry. Assessing the health risks associated with exposure to radon daughters is a notoriously difficult task although recent figures suggest that exposure to about 200 WLH per year for life doubles one's risk of dying from lung cancer, whereas lifetime smoking increases the risk of dying from lung cancer tenfold (BEIR, 1988). It is also important to note that exposure to both radon and cigarette smoke has a multiplicative effect which significantly increases the risk to health.

Although the current legislation does not apply to recreational cavers, it does cover cavers who are employed as instructors at outdoor pursuits centres and, as a result, many of these centres have temporarily suspended their caving activities. However, the results of this research have shown that there are clear spatial and temporal patterns in the occurrence of radon daughter elements within the cave and that these could be of use to visitors when planning their trips to Giant's Hole. For instance, the 498 WLH of exposure that was received by the observer from 10 trips in the summer compares with a winter exposure from 5 similar trips of just 14.25 WLH. Two further factors need to be considered when assessing the implications to health of the data collected. Firstly, all of the concentrations were measured 18cm above floor level and as radon is a heavy gas this could, in theory, lead to an overestimate of the concentrations in the air that the caver breathes. However, on 15th July 1988 at sites in the Entrance Serie, Daryl Dixon from the NRPB obtained similar readings at head height to those measured near floor level by the Sniffer. There is also a certain amount of controversy as to whether the risk estimates associated with alpha radiation in mines can be fairly transferred to the conditions found in a cave (Aley, 1980/81). Mine air tends to be contaminated by both smoke and dust and these pollutants are in themselves harmful to lungs. Using an epidemiological approach, the effect of these pollutants on lung tissues cannot be separated from those induced by alpha radiation. However, air in the cave environment tends to be considerably cleaner and risk estimates based on the health of miners may well appear to be overestimates when applied to cavers.

Notwithstanding the above, cavers who visit Giant's Hole regularly, perhaps on digging operations or as a result of work commitments, do have some cause for concern. A survey of over 50 references to radon concentrations in caves throughout the world has failed to locate any in which the radon daughter concentrations approach those measured in Giant's Hole in the summer and it would therefore appear to have some claim to being the world's most radioactive cave. It is also important to remember that the risks associated with exposure to radiation are of a long term nature and are not readily observable.

CONCLUSIONS

Measurements have been made of radon daughter concentrations in Giant's Hole during the winter and during the summer. These show:

1. that this cave has some of the highest radon daughter concentrations ever recorded in a natural cave.
2. that wide spatial variations in concentrations occur within the cave and these can be related to air circulation within the cave system.
3. that there are substantial seasonal variations in concentrations which are associated with changes in the direction of airflow within the cave. This in turn is dependent upon the temperature gradient between the internal and external air.
4. that a diurnal temperature related mechanism can operate in the entrance series during the summer affecting radon daughter concentrations.
5. that changes in barometric pressure can have a substantial effect on radon daughter concentrations within the cave.

It may also be concluded from this study that it is necessary to measure concentrations at different locations within a cave system and at different times.

Although some of the mechanisms which influence radon daughter concentrations at sites in Giant's Hole have been identified, the actual sources of radon gas require further research. Possible sources include:

1. the uranium-rich basal Namurian shales which, in the Castleton district, lie in close proximity to the Carboniferous limestone. Sediments from such deposits could, in the past, have easily been transported into the system.
2. emplaced vein minerals, in particular the lead ores, which have been intruded into the limestones.
3. volcanic horizons present within the limestones.
4. collophane, a uraniferous phosphatic deposit which is occasionally found within limestones in both the Peak District and the Yorkshire Dales.

In addition, as radon is a soluble gas, it could be transported by water into caves.

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Radon Daughter Concentrations in Pooles Cavern, Derbyshire

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Abstract: The radon daughter concentration was sampled at eight sites in Pooles Cavern on 25 occasions during September and October 1989, using the Kusnetz method. The mean concentration was found to be 0.46 WL with a variation between 0.01 and 0.73 WL. Average radon daughter concentration at each site over this period correlated strongly with average air movement at each site ($p < 0.002$). Radon daughter concentration was also influenced strongly by external wind direction and speed. The other external factors of humidity, barometric pressure, rainfall, maximum and minimum temperature had no significant effect on the radon daughter concentration.

The aim of this study was to investigate, within a simple cave system, the variation in radon daughter concentration and how this might be influenced by both internal and external factors. Pooles Cavern was chosen for the study because of its ease of access and for its simple layout (figure 1).

Since Pooles is a show cave a further aim of the study was to obtain an estimation of radiation doses received by guides and visitors.

Radon and its daughter products

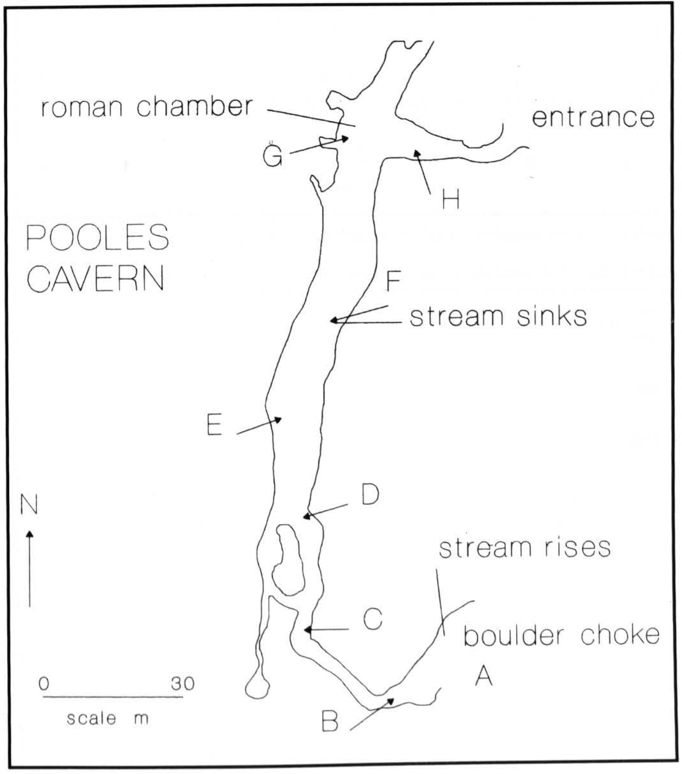
Radon is a naturally occurring, colourless, odourless radioactive noble gas. It originates from the decay of uranium (figure 2), which is itself a natural primordial constituent of all rocks and soils. When radon in turn decays, it forms minute particles of other radioactive substances which are collectively known as radon decay or daughter products. If formed in air, these particles attach themselves to aerosols which may be inhaled and deposited in the lungs. The radiation emitted by the particles as they decay further can then give a dose to sensitive lung tissue and hence increase the risk of developing lung cancer. Recent evidence has indicated that other cancers may be induced by radon and daughters, particularly acute myeloid leukaemia and melanoma (Henshaw *et al,* 1990).

Radon daughter products are for the majority in the UK, the most significant source of radiation exposure (figure 3).

Radon as a problem underground

The first known report of the hazards of radon was made by Agricola in 1556. In his classic text on mining, *De Re Metallica,* he reported the effect of a 'corrosive dust that eats away the lungs'. However, he did mention another hazard namely 'demons of ferocious aspect' which might, although not entirely unknown to cavers, cast some doubt on his total accuracy (Brenner, 1989).

Figure 1. Sampling sites.



That radioactivity causes lung cancer amongst miners was well established by the 1940s (Lorenz, 1944). The interest in radon in caves only started in the 1970s (Aley and Rhodes, 1977). In the UK this interest is of even more recent origin (Gunn *et al,* 1989).

Radon and daughter concentrations in caves

Radon and daughter levels in cave atmospheres are dependent on the radon emanation rate from surfaces and the introduction and removal of radon in air and water. Emanation is controlled by the concentration of radium in the cave structure, the physical structure of the cave which affects diffusion rates and by atmospheric pressure changes (Clements *et al,* 1974). Water has not been shown to be an important source of radon in caves but can be the predominant source of indoor radon if the concentration is high in ground water (Hess *et al,* 1983) and hence might be an important contributing factor to radon concentration in some cave systems.

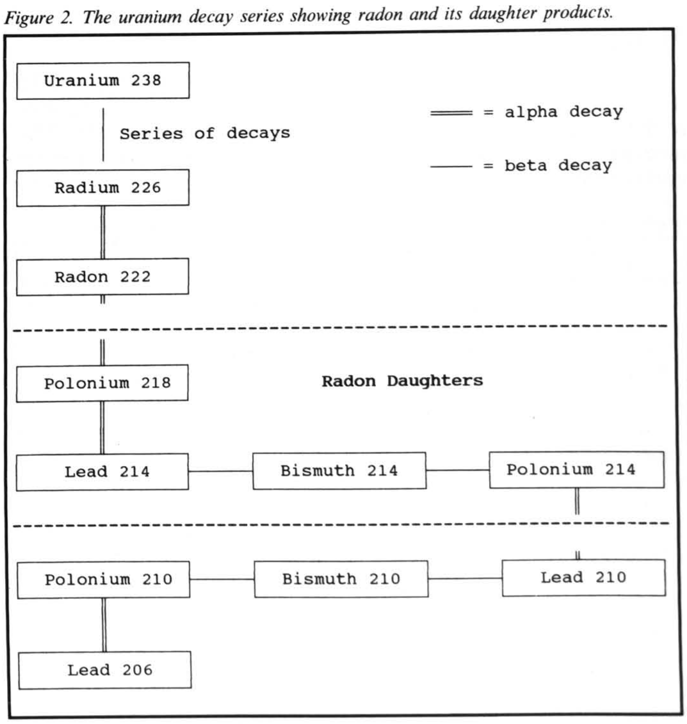
Exchange rates between cave air and outside air are dependent on cave configuration (Yarborough *et al,* 1979) and temperature induced differences between the densities of cave and outside air (Ahlstrand, 1980).

Wind direction can be important in cave airflow as shown in Robin Hood's Cave, Creswell Crags (Coles *et al,* 1989) as can the presence of active streamways. All factors which can alter airflow within a cave are likely to change the radon and radon daughter concentration.

Radiation doses and risks from radon and daughters

If a worker is exposed to the present derived limit of 0.3 WL for a working year of 2000 hours, he would receive the annual dose equivalent limit of 50 mSv or an exposure of 3.6 WLM (working level months). Hence one can say approximately that 1 WLM is equivalent to 14 mSv or 1 WLh (working level hour) is equivalent to 0.08 mSv. The National Radiological Protection Board (NRPB, 1990) estimate the risk to the UK population as 3.5 x 10^{-2} per Sv.

Figure 2. The uranium decay series showing radon and its daughter products.



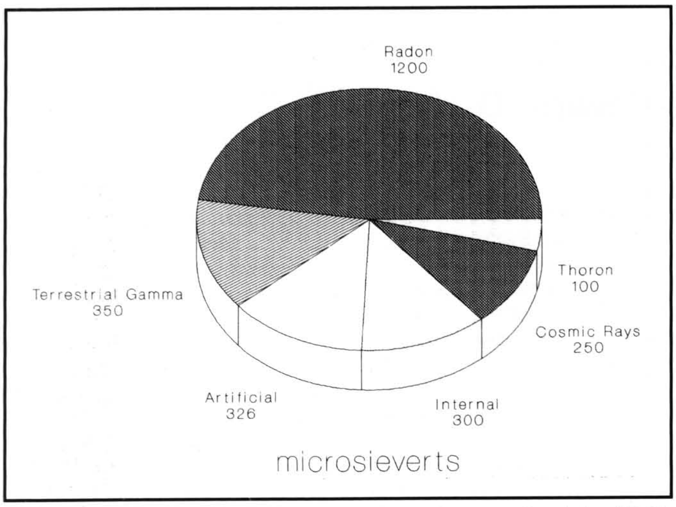


Figure 3. Radiation background UK annual effective dose equivalent (after NRPB, 1989)

This figure can be used in combination with average radon concentration and time spent underground to calculate the risk to members of the Pooles Cavern staff.

METHODS

Sample sites were chosen at approximately equal intervals throughout the cave (figure 1). At each site, measurements were taken at approximately the same time each day (starting at 16.00) of radon daughter concentration and air movement. External meteorological readings were obtained from the Buxton weather station operated by the High Peak Environmental Health Department.

Measurement of radon daughter concentration

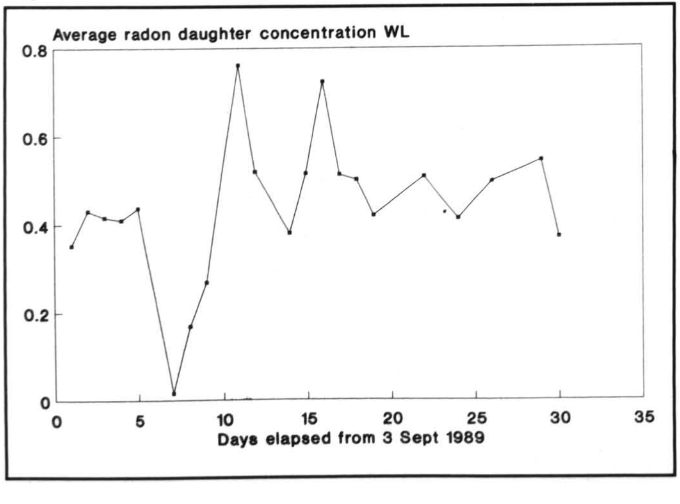
The measurement method used was that of Kusnetz (Kusnetz, 1956). A portable monitor was used to draw 100 litres of air through a 6 cm glass microfibre GFA filter paper. The air sampling rate was fixed at 10 litres per minute. The alpha particles from this sample were then counted on a calibrated zinc sulphide scintillation detector in a time window of between 40 and 90 minutes from the mid point of the sampling period.

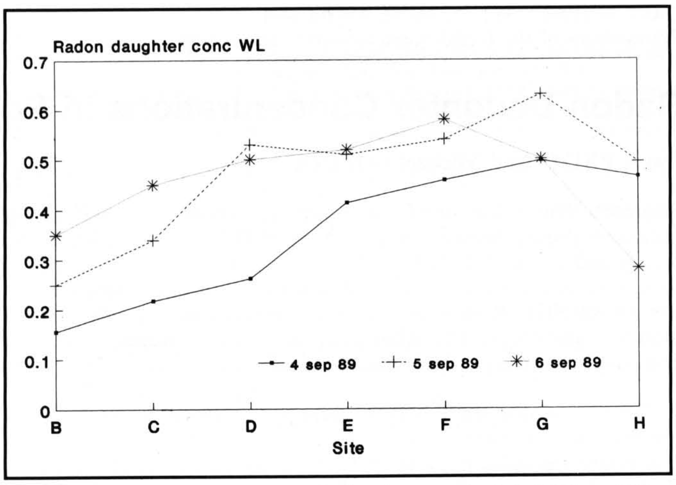
This period is chosen to allow decay of polonium-218 so that only the alphas from polonium-214 are counted (figure 2). This count can then be used in the standard Kusnetz method to estimate the concentration of radon daughters present in working levels (WL). 1 WL is any concentration of short-lived radon decay products in 1 m^3 of air which will result in the emission of 1.3 x 10^8 MeV of alpha energy (equivalent to 3700 Bq.m^{-3} of radon in equilibrium with its daughters).

Measurement of air movement

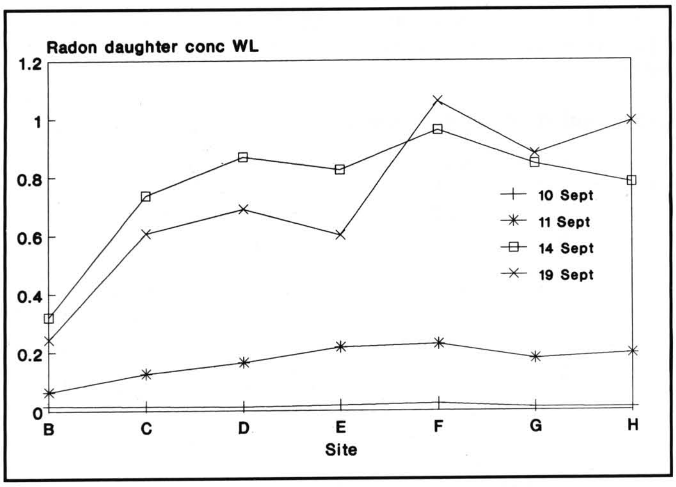
The air movement in this cave was very little and a smoke technique was used to categorize any movement. Categories ranged from -2 (strongly inwards) to $+2$ (strongly outwards). The measurement of the flow was carried out using either Drager air current tubes, lighted joss-sticks or smoke pellets.

Graph 1. Variation in radon daughter concentration over the sampling period

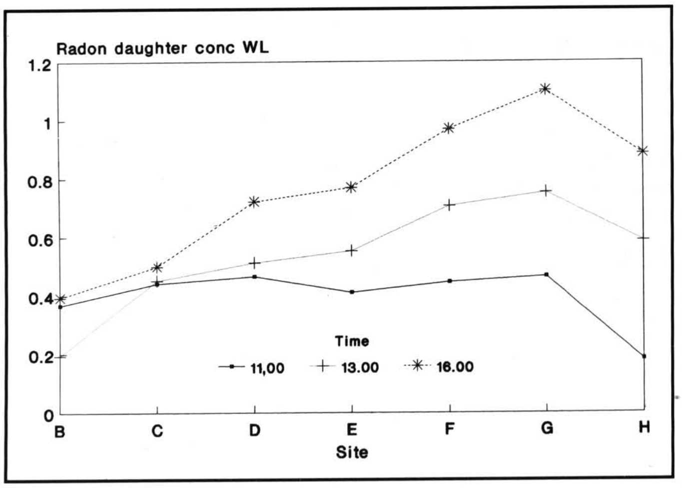




Graph 2. Radon daughter variations in Pooles Cavern on the 4, 5 & 6 Sept. 1989

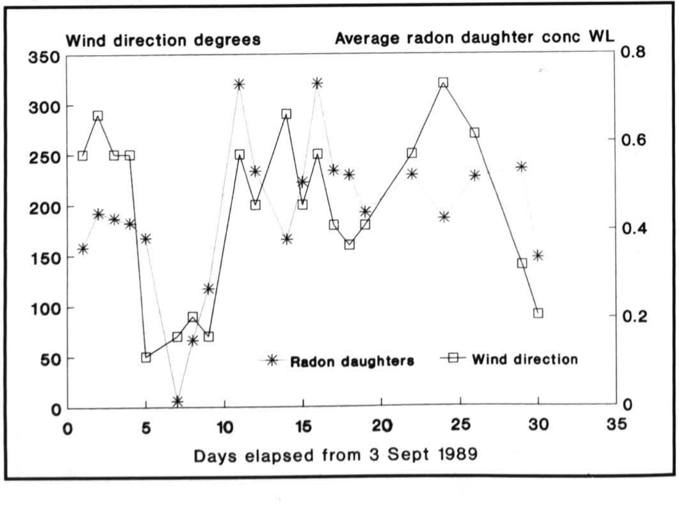


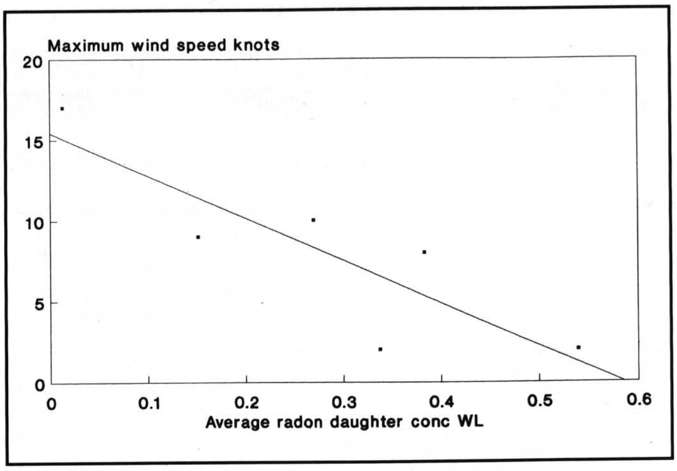
Graph 3. Variation in radon daughter concentration at each sampling site



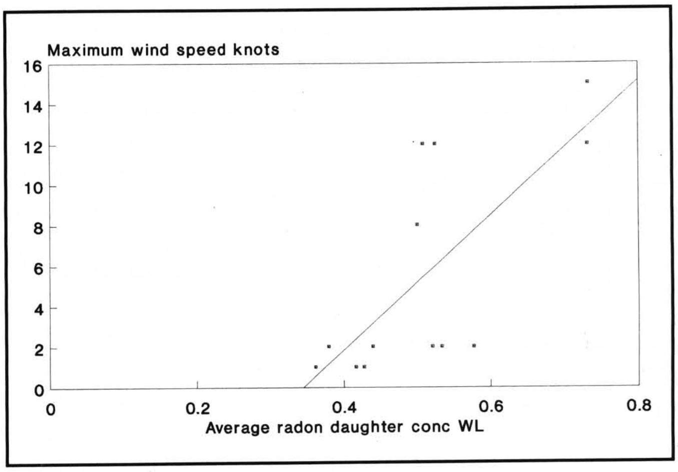
Graph 4. Diurnal variation in radon daughter concentration

Graph 5. Effect of wind direction on radon daughter concentration

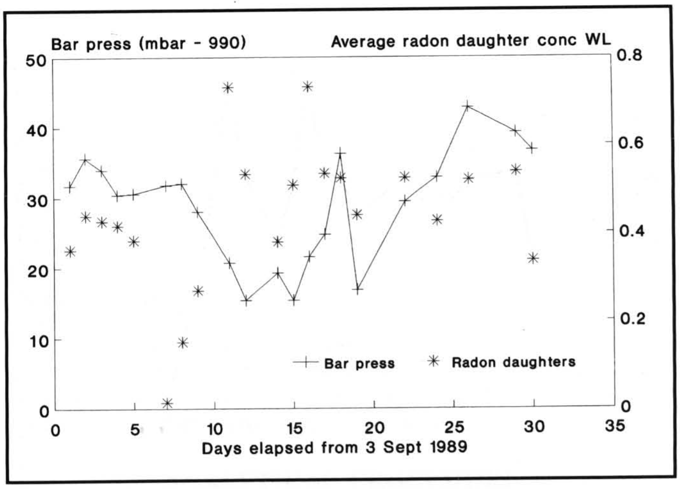




Graph 6. Wind speed vs radon daughter concentration
Wind direction 50-150 degrees

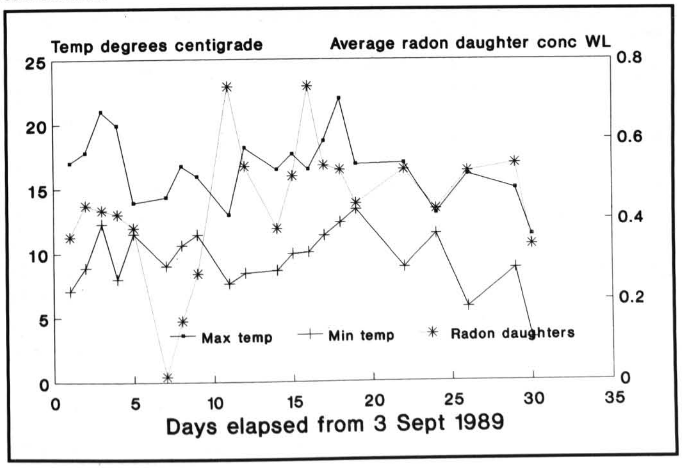


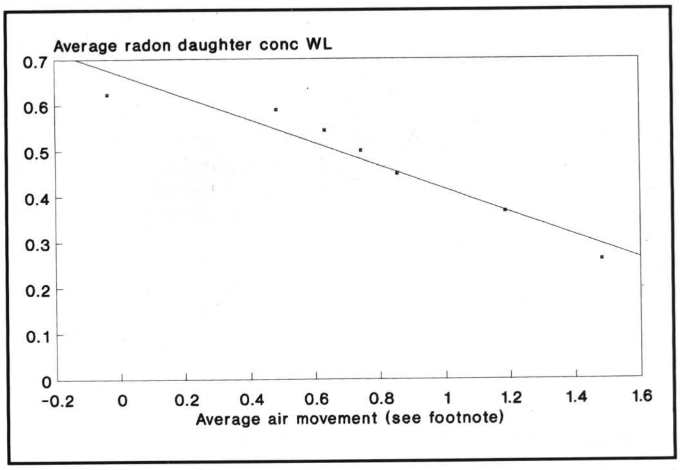
Graph 7. Wind speed vs radon daughter concentration
Wind direction 200-300 degrees



Graph 8. Effect of barometric pressure on radon daughter concentration

Graph 9. Effect of maximum and minimum temperature on radon daugther concentration





Graph 10. Effect of air movement on radon daughter concentration at each internal sampling site (+2 = strongly out; −2 = strongly in).

Results

A plan of the cavern indicating sampling sites is shown in figure 1. Summaries of the results obtained are shown in graphs 1-10. Regression analysis was carried out on the readings obtained in order to locate factors which may have influenced the levels of radon daughters. The only significant external influence detected ($p < 0.02$) on the level of radon daughters within the cavern was wind direction. Further analysis revealed that wind speed also had an effect at certain wind directions (graphs 6 and 7). An analysis of average radon daughter concentration at each site also showed a correlation with air movement at that site (graph 10).

DISCUSSION

Radon daughter behaviour — external factors

The average radon daughter concentration varied from 0.01 WL to 0.73 WL with a mean of 0.46. The results followed a cyclic pattern with a period of approximately 6 days (graph 1).

This variation in radon daughter concentration is likely to be due to a number of factors (see the introduction). The principal factors found to influence radon in previous studies have been atmospheric pressure variations and temperature differences between the cave and the outside. The former factor can influence the emanation rate of radon whilst the latter affects the airflow between the cave and the outside and hence the concentration of radon within the cave.

Graph 8 shows the variation of radon daughter concentration with barometric pressure. The general trend is that low pressure corresponds to high radon concentration and vice versa. A statistical analysis of the results yielded a probability of 0.056 for the hypothesis that atmospheric pressure does not affect radon daughter concentration and hence sufficient evidence to warrant further investigation.

Graph 9 shows the effect of maximum and minimum external temperature on the radon daughter concentration. There is no apparent link between external temperature and radon daughter concentration and this was confirmed by statistical analysis. For most of the study period, the external minimum temperature was close to or above the cave average of 8°C and consequently there would be no reversal of the temperature driven outflow of air from the cave. The effect of temperature would be expected to be more important when the night time temperature was consistently below that of the cave. This would result in a diurnal reversal of airflow into the cave and hence a likely change in the concentration of radon.

Graph 5 indicates the possibility of a correlation between wind direction and radon daughter concentration. For a wind direction of between 50° and 150°, radon daughter concentration was usually low, whilst between 200° and 300° radon daughter concentration was usually high. Statistical analysis of the results confirmed this observation ($p = 0.017$). An examination of the plan of the cave (figure 1) indicates that winds of direction 50° to 100° would blow directly into the entrance. It would seem, therefore, that the wind blowing into the entrance would dilute the air within the cave and hence lower the radon concentration. The maximum radon daughter concentrations found at 200° to 300° wind direction could be explained by the lowering of the pressure caused by the induction of air drawn from the cave by winds blowing at around 180° to the entrance. This lowering of pressure within the cave would cause an increase in the emanation of radon without a corresponding increase in airflow into the cave.

If these explanations are correct, it would be expected that wind speed, at these particular wind directions, would affect radon daughter concentration within the cave. Graphs 6 and 7 show that this is the case. When the wind blows into the entrance radon daughter concentration increases with increasing wind speed ($p = 0.027$) and when the wind blows out of the entrance the reverse is true ($p = 0.005$).

There appeared to be no correlation between radon daughter concentration and rainfall in the previous 24 hours or with relative humidity. However, the study period had very few periods of rain and it would be worthwhile repeating the study during a more typical Buxton wet period.

Radon daughter behaviour — internal factors

Graph 2 shows the variations in radon daughter concentration at seven sites within the cave over a period of three days. The patterns shown are typical, usually there was an initial increase in radon daughter concentration peaking at site F or G, followed by a fall in concentration towards the entrance. Graph 4, illustrates a similar pattern with considerable variation in radon daughter concentration during the course of one day. Graph 3 shows a particularly turbulent time when radon daughter concentrations varied over a wide range in a few days and there was some disturbance in the regular pattern observed at other times.

Graph 10 is a plot of average radon daughter concentration at each site against average air movement at that site. There is a good correlation between these factors ($p = 0.001$), indicating that maximum radon daughter concentration occurs at minimum air movement. This illustrates the great importance of internal airflow patterns on radon daughter concentrations.

Radiation doses and risks

The average radon daughter concentration during the study period was 0.46 WL. The maximum time that anyone spends in the cave during the year is approximately 200 hours. If the 0.46 WL average was maintained for a year the total radiation dose would be 0.46×200 WLh = 92 WLh. This would correspond to a radiation dose equivalent of 92×0.08 mSv = 7.4 mSv. The risk, therefore, of fatal lung cancer = $7.4 \times 3.5 \times 10^{-5}$ or 0.03%. The risk rate used (NRPB, 1990) is an average figure which implies a greater risk for smokers and a much lower risk for non-smokers.

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Radon in Derbyshire Limestone Groundwaters

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Abstract: Measurements of radon concentration were made in North Derbyshire by sampling the rivers Wye, Lathkill and Bradford and associated springs over a number of years. Lead mine drainage levels were also sampled over the North Derbyshire limestones. The radon was measured by using solvent extraction into toluene followed by counting in a liquid scintillation counter. From these measurements sources of radon were identified as mainly springs, river resurgences and lead mine drainage levels. Radon levels varied from <0.03 Bq/l to 90 Bq/l. There was little temporal variation in the radon concentration in the Wye except at one site at which the concentration decreased with increasing rainfall. There was a greater temporal variation in radon concentration in the Lathkill and Bradford and also at one site there was a similar inverse relationship with rainfall over the previous week. Most springs and mine drainage levels showed little variation of radon concentration with time.

Radon-222 is the principal component in the natural radiation background of the United Kingdom. There have been a number of studies of radon in various waters in the UK and of the significance of such levels and considerable interest in this topic in North America (e.g. Hess *et al,* 1985).

The first measurements of radioactivity in water in the UK were made by Thomson in Cambridge water in 1902. Interest in recent years has concentrated on radon-222 and it has been found that the radon content of rivers and other surface waters is usually <10 Bq/l (Hesketh, 1982). Radon is present in substantial amounts only in areas where geology or mineralisation provides significant entry to groundwater. For example, in the granite areas of Devon and Cornwall, the underground waters may contain several hundred bequerels per litre. Fortunately, these high levels do not pose a serious problem in drinking water, for a number of reasons. Firstly, the radon usually is unsupported by the presence of its much more toxic parent, radium; secondly, it can be removed easily by aeration. Radon in water presents a much more important risk to consumers via inhalation rather than ingestion. Inhalation can occur when the gas is released into the atmosphere as a result of the use of water in such operations as washing, bathing and the flushing of toilets.

Turner, Radley and Mayneord (1961) examined various water supplies throughout the UK. The samples were checked for long lived alpha activity as well as radon-222 and its daughters. Water from different sites showed very large variations, the highest figure for total alpha activity from radon and its daughters being 370 Bq/l from two sites in Cornwall. They observed that the highest values of long lived alpha activity were found in spa waters. Lower values were seen in waters derived from boreholes and the lowest values in rivers, lakes and reservoirs.

This region of study was chosen because it was thought that, from the geology of the area, considerable concentrations of radon and its daughters might be present in surface waters, represented by the rivers Wye, Lathkill and Bradford.

After the identification of sources of radon along these rivers a study of the climatic conditions which might influence radon concentration was made. Further analysis was also carried out on a number of other water sources in the area.

ANALYTICAL PROCEDURE

Sampling Method

The sampling method adopted was designed to minimise radon losses between collection and sample analysis. Laboratory trials showed that glass containers fulfilled this criteria better than plastic ones and that air-tight rubber seals were desirable. "Grolsch" type lager bottles proved to meet all these conditions and were of convenient size (500cm^3), widely available and cheap to purchase.

The water sample was collected with minimum agitation and subjected to a visual check that no air remained trapped in the bottle. The sample was then labelled and transported to the laboratory in an ice box where it was stored in a refrigerator until processed. Low temperature storage was adopted because of the decreasing solubility of radon with increasing temperature (Jennings, 1948).

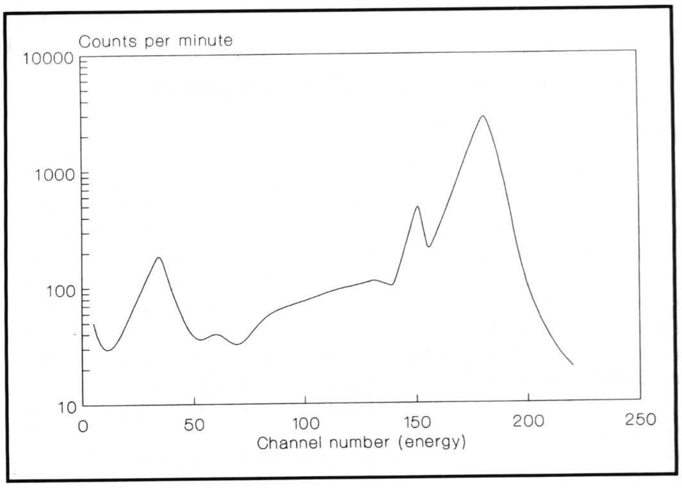


Figure 1. Energy spectrum of radon in toluene.

The whole analytical method was calibrated using a series of radium-226 standards which were allowed to equilibrate with the radon-produced daughters for a minimum time of 40 days. Intrinsic background of the equipment was allowed for by counting a distilled water sample treated to the same analytical procedure.

Solvent Extraction

In order to increase the concentration of radon to be counted, the water sample was mixed with 75cm^3 of toluene since radon is approximately fifty times more soluble in toluene than water at 20°C (Pritchard, 1977). The mixing process was carried out with magnetic stirring for one hour and the mixture was allowed to settle in a separating funnel for a further hour before the aqueous phase was discarded.

Liquid Scintillation Counting

Liquid scintillation counting was carried out in a LKB 256 channel 'Minibeta' machine using National Diagnostics scintillant 'Ecoscint'. The counting region selected on the basis of a scan of channel contents (Figure 1) was from channel 140 to 190 and the counting period chosen was 12000 seconds. A half life check on this region gave a value of 3.844 days which compares

Table 1. Sampling sites on the River Wye

Site	Location
1	Level lane SK 038723
2	Mini roundabout SK 063736
3	Before gasworks SK 065730
4	Below 2nd sewerage works SK 083725
5	Wyedale car park SK 104725
6	Above Wormhill springs SK 123735
7	Below 2nd Wormhill spring SK 128735
8	Water-cum-Jolly SK 171729
9	Below Taddington Dale SK 172706
10	Above Magpie sough SK 179697
11	Below Magpie sough SK 180697
12	Ashford Old Bridge SK 195696
13	Bakewell Bridge SK 220707
14	Rowsley SK 257738

closely to the published value for radon-222 of 3.8235 days (ICRP 1983). An external standard channel ratio method was used to check for quenching and it was found that with this analysis method no quenching of significance occurred.

Table 2. Sampling sites on the Rivers Lathkill and Bradford

Site	Location
1	Lathkill resurgence SK 173657
2	Cales Dale SK 174654
3	100m downstream of Cales Dale SK 176655
4	First waterfall SK 182657
5	Mandale mine sough SK 196661
6	Bubble springs SK 205661
7	Downstream of Bubble springs SK 205661
8	After wall SK 206661
9	Bradford resurgence Sk 199633

RESULTS AND CONCLUSIONS

River Wye

Figure 2 shows the variation of radon concentration in water with time along the river Wye, at 14 sites chosen at approximately equal intervals or adjacent to springs or other water sources. Table 1 describes the location of each site. High concentrations of radon in the river tended to be localised around the point of entry of radon from adjacent springs. At only site 9 was there any significant variation of radon concentration and this site was selected for further study. At this particular site an inverse relationship between radon in water and rainfall over the previous week to sampling was found (Figure 3). The explanation of this particular result lies probably in the dilution effect of run off water in the Taddington Dale spring which is the principal source of radon into the river at this point, but is opposite to the results found by Andrews and Wood in 1972.

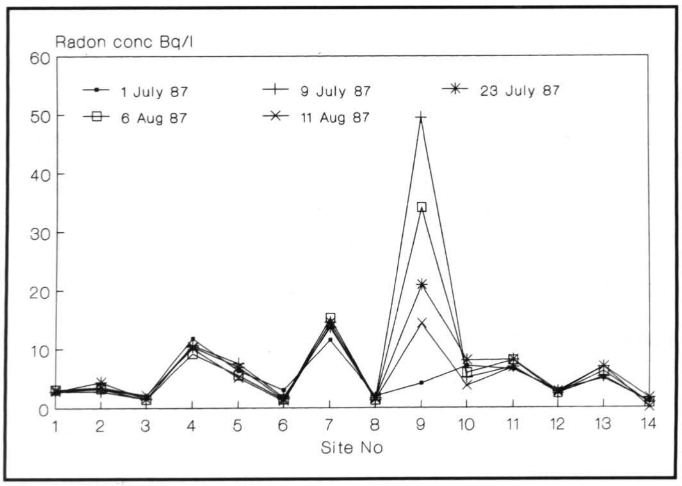
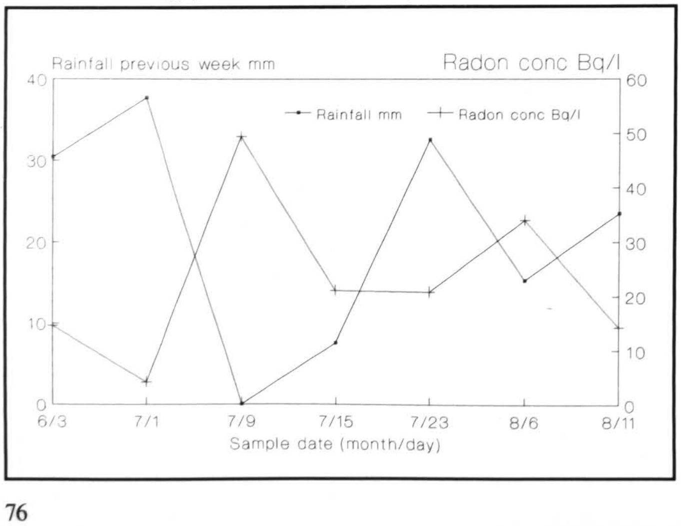


Figure 2. Temporal variation of radon in the river Wye.

Figure 3. Radon levels vs rainfall at site 9 (Taddington Dale). The results show a significant correlation (p <0.05)



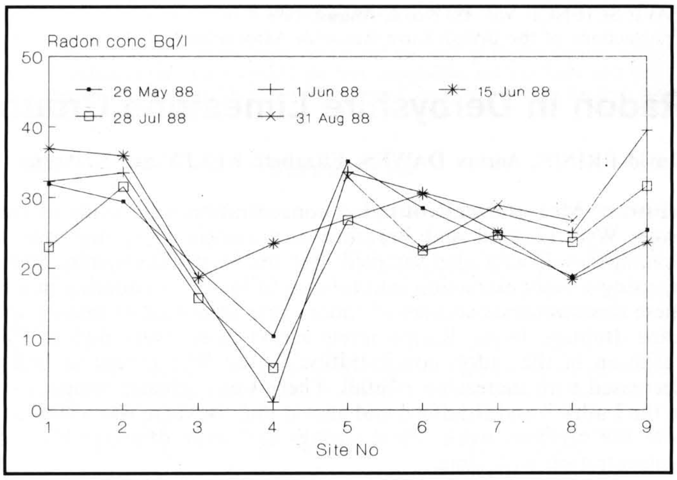


Figure 4. Temporal variation of radon in the rivers Lathkill and Bradford.

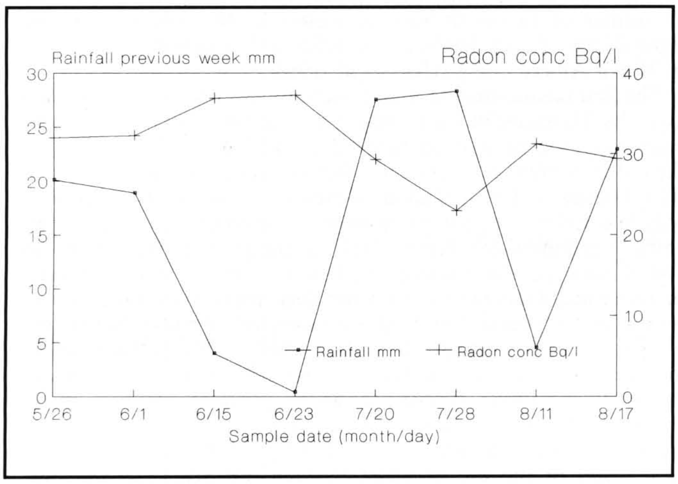


Figure 5. Radon levels vs rainfall at site 1 (Lathkill resurgence). The results show a significant correlation (p <0.05)

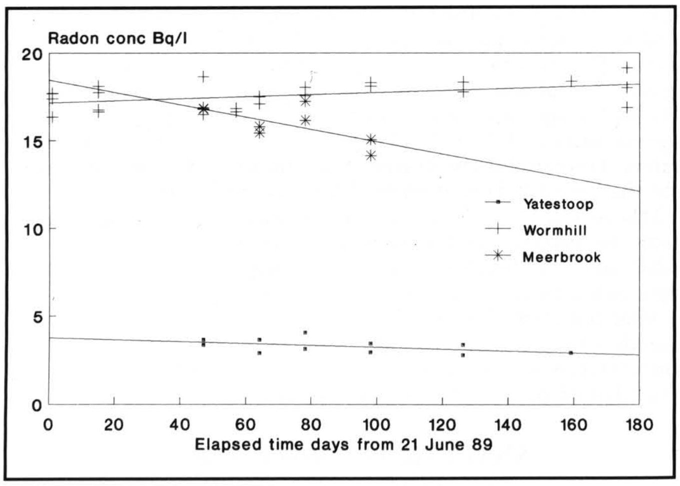


Figure 6. Temporal variation of radon levels at three water sources.

Rivers Lathkill and Bradford

Figure 4 shows the variation of radon concentration in water with time along the rivers Lathkill and Bradford, at 9 sites which proved to be of particular interest. The locations of the sites are described in Table 2. Although there was considerable variation in radon concentration at the sites, only at site 1 was there a significant variation of radon concentration at the sites, only at Site 1 was there a significant variation of radon with rainfall (Figure 5) and this followed the same pattern as that at Taddington Dale as described above. Once again it is assumed that rainwater is diluting the radon.

Miscellaneous springs and resurgencies

Table 3 summarises the results obtained from 50 samples taken between June and December 1989. There was no significant variation in radon concentration at any of the sources. Figure 6 illustrates the variation for Yatestoop and Meerbrook Soughs and Wormhill Springs, the most frequently sampled of the sources.

Water from St Anns Well in Buxton is bottled and sold commercially. However, radon at a concentration of 81 Bq/l poses a negligible ingestion hazard. It is the use of water containing radon for washing, flushing toilets etc. which causes the release of the gas into the atmosphere with attendant inhalation hazards.

Table 3.
Mean radon in water concentrations at five water sources.
Errors quoted are to one standard deviation.

Site name	Mean radon conc Bq/l (No. of samples)	Location
Magpie sough	10.37 ± 0.57 (2)	SK 179697
Meerbrook sough	15.93 ± 1.04 (8)	SK 325553
St Anns well	80.98 ± 2.12 (4)	SK 058734
Wormhill springs	17.56 ± 0.74 (25)	SK 123735
Yatestoop sough	3.29 ± 0.40 (11)	SK 263626

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Radon Production and Release from Cave Sediments

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Abstract: Sediments from Speedwell Cavern, Castleton, Derbyshire, were analysed for uranium content and Pb-214 activity. Whilst U contents of modern sediment range from <2 to 5 ppm and Pb-214 activity suggests little radon loss from mineral grains, U contents of ancient sediments are much higher (15 to 24 ppm) and Pb-214 activity indicates that up to 85% of Rn produced may be lost from the mineral grains. The high U content of ancient sediments means that exhalation of Rn produced within them may contribute significantly to Rn levels in the cave atmosphere.

Despite the recognition of enhanced levels of radon in cave atmospheres (e.g. Gunn, 1988) there has been relatively little work on the sources of radon and radon parents within the cave environment. In Britain the Carboniferous Limestone is overlain by Namurian shales which are generally enriched in uranium above the levels in most sedimentary rocks (Bloxham, 1964; Leeder *et al.*, 1990), in the case of the Edale shales in Derbyshire this uranium enrichment is especially marked (up to 30ppm U, based on field gamma logging, J. Maynard, pers. comm.). Uranium and other radon parents from these shales may enter the underlying limestone and cave systems by two routes, dissolved in groundwaters (e.g. Hand and Banikowski, 1988) or in sediment derived from weathering of the shales and transported into cave systems. It is the extent to which radon parents enter the cave environment by the latter route, and the impact which subsequent radon release has on radon and radon-daughter concentrations in cave atmospheres, which are addressed in this paper.

SAMPLING AND ANALYTICAL DETAILS

Samples 1 to 7 were collected by pressing a 7cm diameter, 15cm long plastic sample tube into the sediment at right angles to the surface. The tube was then withdrawn with the enclosed, relatively undisturbed, sediments and capped for transport. At site 8 a thin veneer of sediment on the boulders was scraped into a plastic film canister. The CC-series samples were collected by pushing smaller plastic tubes into a vertical exposure of a mudbank below Cliff Cavern (Fig. 1). These samples were taken with a spacing of *c.*3cm, the length of section being *c.*30cm. Sample sites are shown in Fig. 1 and described in Table 1.

The larger core samples were split into two for inspection, subdivided into depth intervals as shown in Table 1 and dried at 90°C. In the case of the larger cores, one half of the core was used for gamma counting (see below) whilst the other half was disaggregated, crushed to pass 120 mesh and homogenised. In the case of the smaller CC-series samples the disaggregated sample was homogenised, sufficient material for chemical analysis removed for crushing and gamma counting performed on the remainder. Uranium and other major and trace elements were analysed by X-ray fluorescence (details given by Bottrell, in prep.). Analyses of Pb-214 activity were performed by gamma spectrometry by Dr. D. Prime (University of Manchester, Radiation Protection Service), these analyses were made on unequilibrated samples from which Rn was allowed to escape.

RESULTS

The U contents of the analysed sediments are reported in Table 2. The data clearly fall into two groups, one with U contents from <2 to 5 mg/kg (ppm) and another with higher U concentrations of 15 to 24 ppm. The lower U concentration group corresponds to sediment samples from sites with active water flow (samples 1, 3, 4, 5, 6, 7, 8) whilst the higher U concentrations are found in older sediments from sites where there is no active water flow. The Pb-214 activity of those samples on which measurements were made are also reported in Table 2, and are all around 30 to 40 Bq kg^{-1} irrespective of U content.

Table 1. Sediment sample sites, Speedwell Cavern.

Core No.	Site description (see Fig. 1)	Split No.	Depth range (cm)
1.	Sediment bank in lee of boulders in main stream way, near entrance to Bathing Pool Passage	A B C	0-3 3-6 6-9
2.	Old sediment bank in Bathing Pool Passage	A B C	0-4 4-8 8-12
3.	Sediment bank on west side of Far Canal	A B C	0-4 4-8 8-12
4.	Sediment accumulation behind dexion and boards on east side of Far Canal	A B C	0-4 4-8 8-12
5.	Sediment accumulation on sunken tourist boat in Far Canal. Sediment surface covered in casts from bioturbation.	A B C	0-4 4-8 8-12
6.	Sediment bank on west side of Far Canal. Surface covered in casts from bioturbation.	A B C D	0-1 1-4 4-8 8-12
7.	Sediment bank on north side of entrance to Assault Course. Surface covered in casts from bioturbation.	T A B C	0-1 1-4 4-8 8-12
8.	Sample scraped from recent accumulation of sediment on surface of boulders, upstream of boulder pile.	—	—
CC1 to CC10	Small samples collected in vertical sequence in old sediment bank below Cliff Cavern.	—	—

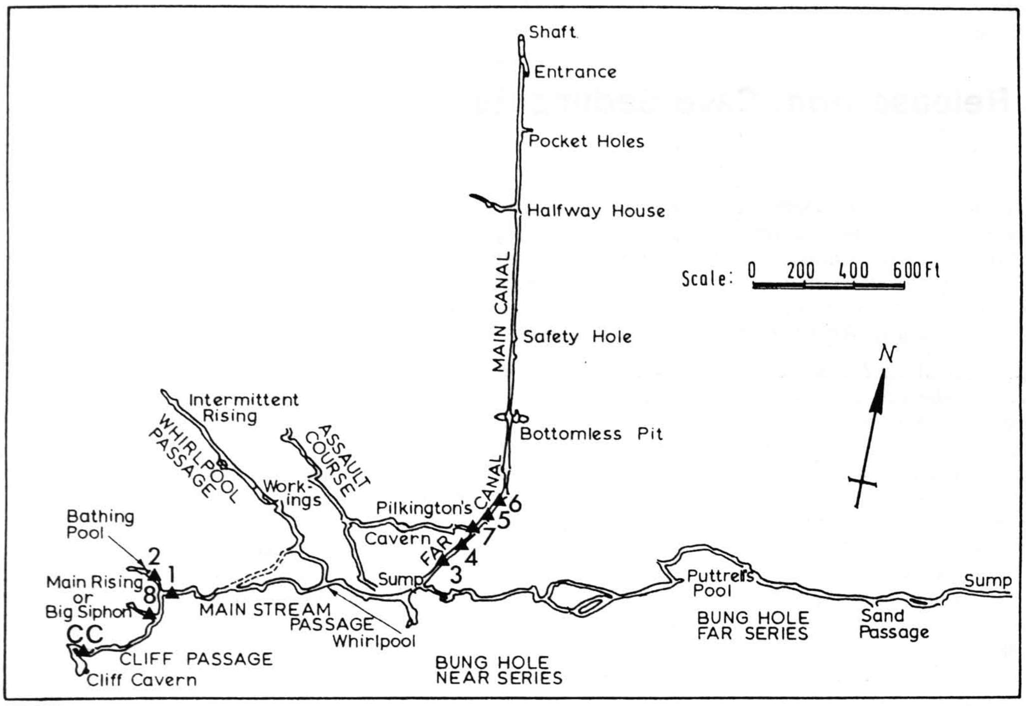

Figure 1.
Location map and sample sites in Speedwell Cavern, Castleton, Derbyshire.

Table 2. Sediment U and Pb-214 contents.

Core No.	Split No.	U(mg/Kg)	Pb-214(Bq/kg)
1.	A	<2	
	B	3	36
	C	2	
2.	A	15	
	B	15	27
	C	16	
3.	A	3	
	B	2	47
	C	2	
4.	A	3	
	B	2	
	C	2	
5.	A	4	
	B	5	39
	C	4	
6.	A	4	
	B	3	
	C	3	
	D	3	
7.	T	2	
	A	3	
	B	2	
	C	<2	
8.	—	2	
CC.	1	24	
	2	19	
	3	17	
	4	18	
	5	22	
	6	24	
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	9	17	
	10	16	

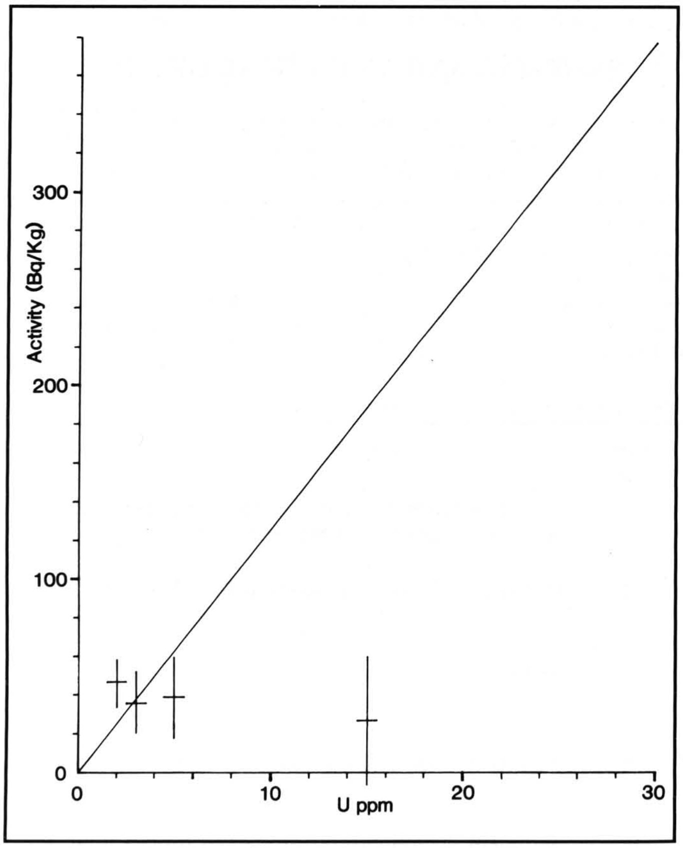

Figure 2. Activity versus Uranium content plot. The diagonal line gives activities of nuclides in secular equilibrium at given U content. U content and Pb-214 activities are plotted for four cores, error bars are two standard deviations.

DISCUSSION

The decay series of U-238, the most abundant naturally occurring isotope of U, includes the radon isotope Rn-222. Radon is a noble gas and therefore can escape from the original mineral hosting the U and intermediate daughters into any surrounding fluid medium. Where Rn escapes into air the build-up of Rn-222 and its radioactive daughters poses a health threat due to accumulation of radon daughters in the lungs.

Systematics of U-series nuclides in cave sediments

The activity of U-238 in sediment is simply a function of the decay constant of U-238 (1.55×10^{-10} yr^{-1}) and the concentration of U in the sediment. Since U-238 comprises 99.3% of natural U, total U concentrations can be used to estimate U-238 activity. The activity of 1 mg U is 12.5 Bq, so the U-238 activity of a sediment is 12.5 Bq Kg^{-1} ppm U^{-1}, this relationship is portrayed as the diagonal line in Fig. 2. Provided that the radioactive decay series has had sufficient time to reach "secular equilibrium" then the activities of all the daughters in the series will be the same as that of U-238. The activity of Pb-214 is plotted against the U content for 4 core samples. Three of these lie close to the line for U-238 activity whilst one has Pb-214 activity lower than U-238 activity.

Before discussing the significance of the data of Fig. 2 some consideration of the systematics of both the U-238 decay series and the geochemistry of the nuclides involved in the cave environment. In the simple model presented here the only

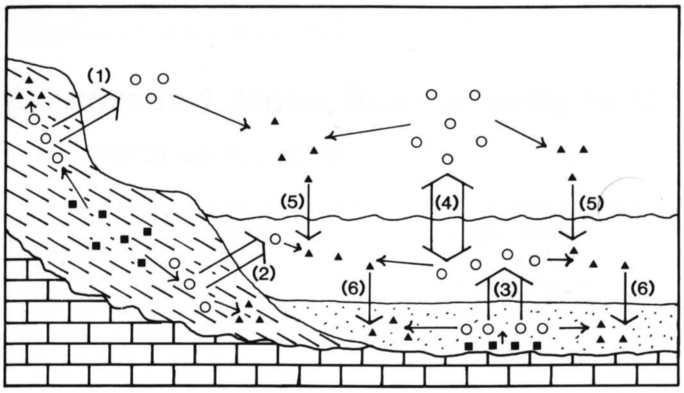

Figure 3. Schematic representation of geochemical processes involving ^{238}U-series nuclides in the cave environment. ^{238}U (filled squares) is present in both ancient (diagonal hatching) and modern (stippled) sediment. This decays via a chain of nuclides which are relatively immobile to ^{222}Rn (open circles) which, as a noble gas, is relatively mobile and may leave the sediment to the air (1) or water (2) and (3). ^{222}Rn not leaving the sediment will decay in situ to produce radon daughters (filled triangles). Radon is relatively soluble and may exchange between air and water (4). Radon daughters formed by decay of airborne ^{222}Rn are likely to "wash-out" into the water (5) and these, together with any daughters produced by decay of water-borne radon, sediment-out into modern sediment (6).

reservoirs of U-238 under consideration are those in sediments (some U-238 will be present in both the bedrock and groundwaters but are not the subject of this paper); two types of sediment are considered here, "modern" sediment is that which is associated with and transported by active stream flow, "ancient" sediment is that deposited under previous flow regimes, but which may be eroded by active stream flow. The reservoirs of U-238 and daughters to Ra-226, Rn-222 and Rn-222 daughters are depicted schematically in Fig. 3. U-238 in mineral grains in sediment decays via Th-234, Pa-234, U-234, Th-230 and Ra-226 to Rn-222. All of the intermediate nuclides are relatively immobile in the mineral lattice, but Rn, a noble gas, can diffuse out of the mineral grain. The extent of Rn loss or emanation from the grain is a function of mineralogy and grain size (since Rn-222 with a half life of 3.825 days may decay before diffusing out of the grain). Furthermore the recoil effect on the Rn-222 nucleus when Ra-226 decays may enhance Rn-222 emanation since the Rn nucleus may be propelled for 0.03-0.04 μm in a mineral grain (Semkow, 1990). The subsequent Rn daughters are isotopes of the heavy metals Pb (including Pb-214), Pa, Bi and Tl (the series ending at stable Pb-206) and can be considered immobile in the mineral lattice. Thus part of the Rn-222 produced in the sediment may escape from mineral grains and then diffuse relatively rapidly through the sediment pore space into either air or water (see Fig. 3). The process of Rn escape from the bulk sediment is termed exhalation and rates of exhalation will be lower than rates of emanation since some Rn-222 will decay between leaving the grains and reaching the sediment surface. Rn gas may exchange between water and air, but the heavy metal Rn daughters are likely to be "washed-out" of cave air into water and may subsequently settle out into modern sediments (Fig. 3).

The data in Fig. 2 show that the activity of Pb-214 (a Rn daughter) in three of the sediment cores is approximately what would be predicted from their U contents. This implies that little Rn is lost from these sediments, since all Rn daughters up to and including Pb-214 have short half-lives and these unequilibrated Pb-214 analyses effectively monitor the amount of Rn which decays before escaping from the mineral grains. These three data points all correspond to modern sediments, thus is seems probable that the nuclides of the U-238 decay series are transported in "conveyor belt" fashion in the active sediments, with no significant net loss or fractionation of any of the nuclides in the chain.

The remaining datum on Fig. 2 is from a core of ancient sediment. In this case the Pb-214 activity is only *c.* 15% of that which would be predicted from its U content. There are two possible explanations for this; firstly, the sediment may have become enriched in U-238 without the associated decay products and not had sufficient time to reach secular equilibrium (approx. 3 million years for Pb-214, using the method of Bateman, 1910). Alternatively the decay series may be in secular equilibrium but significant Rn loss from the sediment causes the activity of Pb-214 to be depressed below that predicted for its U content. Given that the modern sediments appear to transport the U-238-series nuclides without fractionation it would appear reasonable to assume that the nuclides in the series as far as Rn had been similarly transported in the case of the ancient sediments, especially as there may be reasons to believe that net Rn loss might be more efficiently achieved from these (see next section).

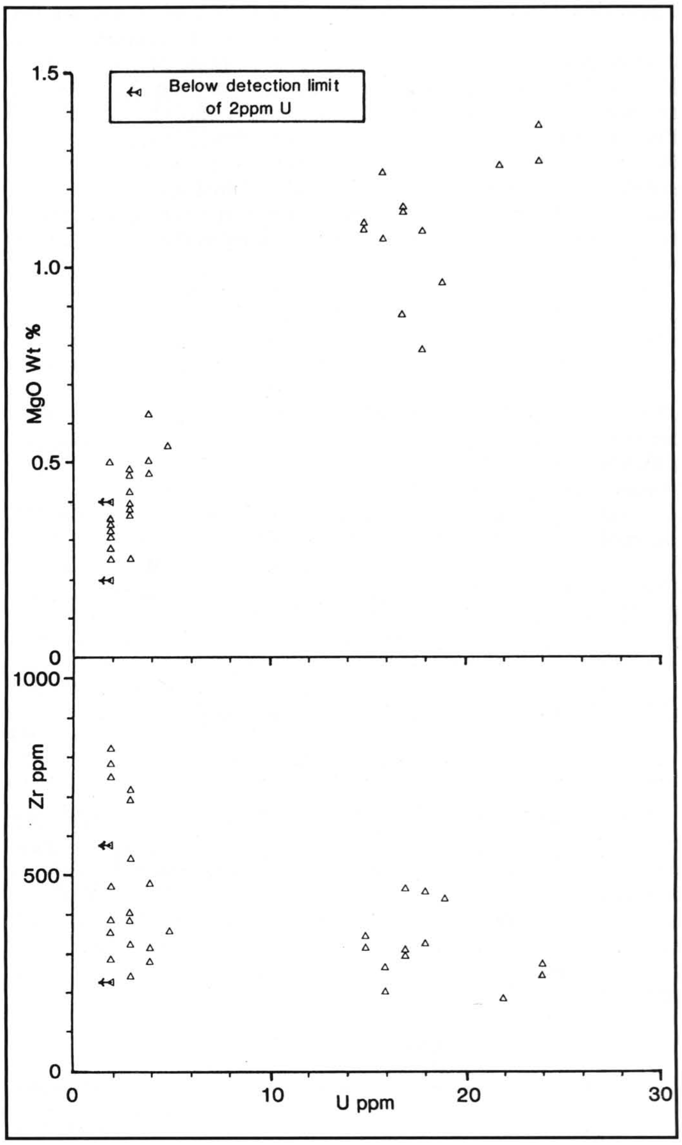

Figure 4. Plots of U content of cores versus MgO and Zr.

Radon loss from ancient sediments

In Speedwell Cavern the ancient sediments investigated here differ sedimentologically and mineralogically from the modern sediments. They are finer grained, mainly clay-sized material as opposed to silt and fine sand in the modern sediment, and they are richer in the clay minerals smectite, illite and kaolinite (details will be given by Bottrell, in prep.). The high clay mineral content is shown by the higher MgO content of the U-rich ancient sediments compared to U-poor modern sediments (Fig. 4). Similar positive correlations exist between U and Al, Fe and K (Bottrell, in prep.) all major elements found in clay minerals. This correlation between U and clay minerals may be a genetic one, since in sedimentary U ores U is known to partition into clay minerals (Doi *et al.*, 1975). Certainly the lack of correlation between U and Zr (Fig. 4) indicates that U is not principally resident in detrital zircons which are relatively resistant to Rn loss (Gascoyne, 1982).

The association of U with fine-grained clays has two important implications for assessment of Rn release from these sediments. Firstly, as the U was fixed in clays during diagenesis in the Namurian (*c.*315 Myr ago), the subsequent chain of immobile daughters to Rn will have grown into secular equilibrium in the mineral lattices (which takes 3 Myr). This further strengthens the assumption that Rn production will be in equilibrium with the U-238 concentration. Secondly, it will promote the emanation of Rn since rate of diffusion-controlled emanation increases with decreasing grain size. The effect of recoil-emanation will also increase in smaller grains, since proportionally more Rn nuclei will be with "escape range" of the mineral surface in small grains.

These two grain-size related effects will thus lead to greater Rn emanation in the finer-grained ancient sediments compared to the coarser-grained modern sediments. The estimate of approx. 85% Rn loss for core 2 from Fig. 2 is effectively an estimate of the Rn emanation from the disaggregated sediment (since the half-lives of Pb-214 and intermediate nuclides from Rn-222 are all short). However most of the ancient sediment beds in Speedwell are exposed to air and relatively dry. Hence diffusion of Rn out into the cave atmosphere, from at least the surface layers, is likely to be relatively rapid and net Rn exhalation from the sediment may be large.

Assuming secular equilibrium for the decay series from U-238 to Rn-222 in the ancient sediments, then production of Rn-222 is simply a function of U concentration as discussed earlier. The activity of Rn-222 released from the sediment (A) is given by:

$$A = 12.5 \times [U] \times M \times \varnothing$$

where [U] is the U concentration of the sediment (in ppm), M is the mass of sediment and ø is the proportion of Rn-222 produced which is lost to the atmosphere (exhalation coefficient). Taking a "round-figure-average" of 20ppm U for the ancient sediments and a maximum estimate of 0.85 for ø (equal to the observed Rn-222 emanation) then the activity of Rn-222 released to the atmosphere is 213 Bq/Kg of sediment. One "Working Level" (WL) for Rn is 3700 Bq m^{-3}, so 17.4 Kg of sediment would release enough Rn-222 to raise $1m^3$ of cave passage to 1 WL; this corresponds to a degree of passage fill with ancient sediment of less than 1%. Actual values of ø may be lower than the 0.85 used here, but clearly Rn exhalation from U rich sediment can have significant impact on Rn-222 activity of cave atmospheres.

CONCLUSIONS

Ancient cave sediments in Speedwell Cavern are substantially enriched in U derived from Namurian shales. Because of their fine-grained nature, radon release from mineral grains is likely to be relatively efficient. Analyses of Pb-214 activity show that whilst in modern sediment net radon loss is small, the finer-grained ancient sediment may lose up to 85% of radon produced to the cave atmosphere, representing a significant input to the atmospheric radon budget.

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Background Alpha Radioactivity in Cuckoo Cleeves Cavern, Mendips

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Abstract: During a June week of hot settled weather in 1989 BCSS members conducted a radon survey of Cuckoo Cleeves under the Mendips. They used an inexpensive detector known as TASTRAK and processed the slides themselves within a school laboratory. The results showed surprisingly high levels of radon, up to 19,000 Bq m^{-3}. The cavers have subsequently used RADOSURE detectors to record their personal exposure to radon in visits to Box Stone Mines and Eastwater Cavern. These detectors were processed professionally and indicate a dosage of approximatelty 0.15 mSv.

Background radiation is one of those things that you can't do much about. In school you are told that Cornwall and Aberdeen are regions with above average background activity and that there are three types, alpha, beta and gamma radiation. Recent articles in the press and New Scientist have indicated that radon gas build up is a major problem in some houses and that in the USA small extractor pumps have been installed in cellars. After reading about the lecture by John Gunn and David Prime at a BCRA conference (Descent 86) it is now plain that when you are caving you can be breathing in a radioactive gas which may be more concentrated than the nuclear industry permits.

There is now much data about Derbyshire caves and other information concerning the caves of Yorkshire, Devon and the Swansea Valley in South Wales. We were interested in our local caves beneath the Mendips. The school we work in has had experience in carrying out alpha radiation surveys and so we saw it as a realistic project to undertake.

The detectors we used were small plastic squares of TASTRAK which have been widely used in schools as organised through the Physics Department at Bristol University. The instructions are straight forward and can be processed with a little care in a school science laboratory.

We chose Cuckoo Cleeves Cavern (NGR ST 559 505) as it is gated and not frequently visited, so minimising the risk of disturbance. On Sunday 18th June we unwrapped the TASTRAK from the protective foil and assembled the detectors by the cave. Using a thick needle we inscribed each square with a number. Each square was then attached to the base of a yoghurt pot using Blu-tac and then the pot was sealed with clingfilm (figure 1).

It took two hours to place the pots in the cave and log the sites on a survey sheet. Our strategy was to spread the detectors at a distance of every 6 metres and also to have clusters of 10 pots at 6 sites. From previous studies we were aware that there would be both large and small scale variations and so the clusters would be used to provide some idea of the errors involved. We placed 88 detectors in the cave and left one outside as a control.

Exactly six days later the pots were collected and dismantled outside the cave. The TASTRAK squares were immediately wrapped in several layers of cooking foil to prevent further alpha particles from reaching the plastic. The plastic squares were then processed in school on the Monday and the horror was revealed. The squares on average had about 16,000 tracks per square centimetre, but the one outside the cave had only 411.

With such a large number of "dots" to count some statistical method was required. The TASTRAK square was placed in a slide and projected onto a board so that one square centimetre was in view. Four identical pieces of card were placed onto the board at random and the total area of the cards was one hundredth that of the board. The four readings were used to give a mean and the standard error in that mean was also calculated. These figures were scaled by 400. The clusters were then processed in a similar way. Counting even a small number of detectors proved tedious and frequent breaks were needed.

Since the experiment took exactly six days the calculations are simplified in that the number of tracks per square centimetre equals the activity in becquerels per cubic metre, Bq m^{-3}.

The results are best shown on the vertical section (figure 2). There is a pronounced increase from 12,000 ± 400 Bq m^{-3} at the bottom of the cave to the main chamber with a value of 19,000 ± 400 Bq m^{-3}. The cave entrance has a metal cover with only a small hole to allow ventilation to occur. The entrance passage showed readings of 15,000 ± Bq m^{-3}. Outside the cave but still in the doline the count was 411 Bq m^{-3}, this being some 40 times lower than that inside.

These values need to be considered in the light of the recommended national limit of 200 Bq m^{-3}. If a household has an activity level greater than this then action is required to reduce it. The normal background radon activity is 20 Bq m^{-3} but some "hot spots" are as high as 10,000 Bq m^{-3}. All these values are in becquerels per cubic metre and this is an activity. It needs to be converted to a dose which is measured in sieverts. This is done so that different types of radiation can be introduced into the equation and yields a better idea of the potential biological damage. For radon a rough conversion is 20 Bq m^{-3} for a year

Figure 1. Construction of a radon dosemeter.

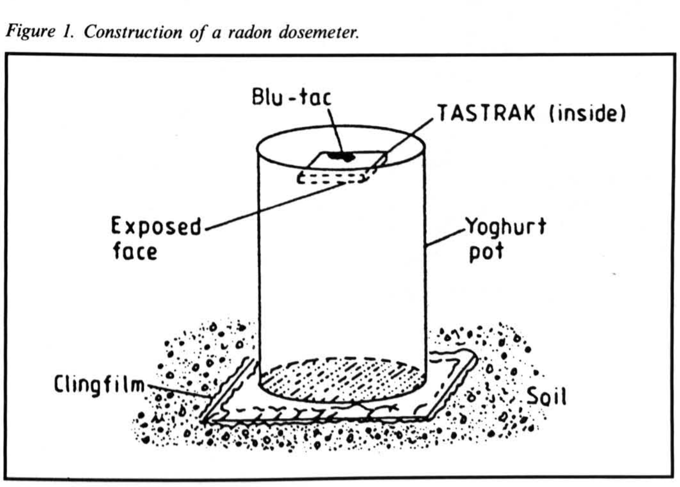
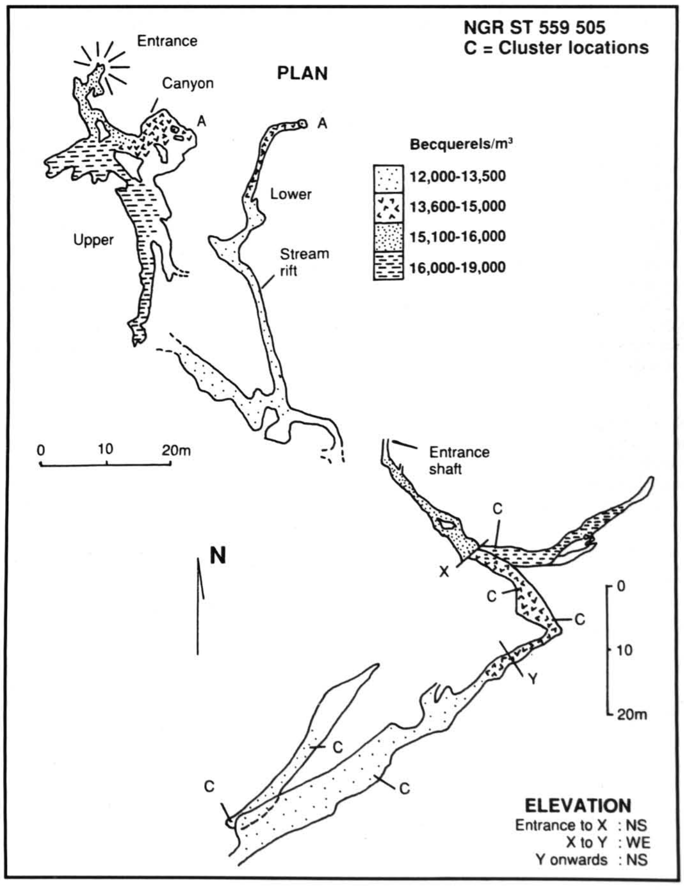


Figure 2. Cuckoo Cleeves radiation survey.



equals 1 mSv (one thousandth of a sievert). The nuclear industry has now set a level of 15 mSv for its workforce. Taking a value for our results of 15,000 Bq m^{-3}, every hour spent in the cave is equivalent to 0.086 mSv.

$$\text{Dosage (mSv)} = \frac{\text{Activity x time (hours)}}{20 \text{ x } (365 \text{ x } 24)}$$

An adult would need to spend 175 hours in this cave to reach the 15 mSv limit assuming these levels were present all year. It is now established that levels in winter can be significantly lower. It should also be noted that this experiment was conducted in a very hot, settled period in anticyclonic conditions. Nonetheless there is now a difficult and sensitive issue to tackle, that of young people under 18 years of age. They are still growing and so are at more risk from radiation damage, consequently their maximum radiation limit should be less than that of adults. They should also avoid receiving large doses over a short period.

The value of this experiment is that for £50 a survey can be executed and a value placed on alpha radiation concentrations in a cave. The value may well change significantly with seasons and may be different in a neighbouring cave; however we know that the summer value is high.

To investigate the exposure an individual receives on a single caving trip a second experiment was conducted using RADOSURE badges. These use a plastic slide held in a waterproof container. We sent these off for processing and they were analysed by computer. Two trips were made using the badges, one in early May to Box Stone Mines and the other also in May to Eastwater Cavern (down the Twin Verts to the bottom of the twelve pots and up via Dolphin). The mines trip lasted 2 hours and 36 minutes and produced a reading of 8,468 Bq m^{-3} and the Eastwater trip lasted 3 hours to produce a reading of 9,251 Bq m^{-3}.

Using the equation quoted above this gives a dose of 0.126 mSv and 0.158 mSv respectively. Being fully aware that radon levels vary from time to time and place to place, if this calculation is taken further then it gives between 5 and 6 hours caving per week to take you up to the maximum level for nuclear workers.

The RADOSURE badge allows cavers to monitor their radiation dose and could contribute to a data bank that may be used in radiation studies. The badge including processing costs about £16.

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Radon Concentrations in three Russian cave areas

John GUNN

Abstract: This paper describes the first measurements of radon gas and radon daughter concentrations in three Russian caving areas visited in 1990 by the Red Rose Caving Group Expedition: the Kirktau Massif, the Arabika Massif and Podolia. In the Kirktau Massif measurements were made in five caves four of which had relatively low concentrations (0.08-0.21 WL) whilst the fifth had the highest concentrations recorded on the expedition (1.52-1.73 WL). In the Arabika Massif measurements in four caves were in the range 0.02-0.41 WL. In neither area was there any correlation between radon daughter concentrations and depth below the entrance although some individual caves showed an increase with depth. In Podolia measurements were made in two gypsum caves, Ozernaja (0.39-0.73 WL) and Optimistichaya (1.16 WL). Although most of the caves have relatively low concentrations it is worth noting that in 42½ hours caving the author received a radiation dose of about 0.75 mSv. This is 30% of the normal annual background radiation dose in Britain and it is 75% of the maximum annual additional dose (i.e. dose above background) recommended by the International Commission on Radiological Protection.

The radioactive gas radon and its daughters (isotopes of polonium, lead and bismuth) are present in all caves at concentrations which vary from little more than those of the outside atmosphere (c. 0.001 WL) to several thousand times higher. For example, Middleton *et al* 1991 have measured radon daughter concentrations in excess of 20 WL in Giant's Hole in the English Peak District and suggested that this may be the most radioactive cave in the world. In a more recent study in the same cave Williamson (pers. comm.) measured concentrations in excess of 40 WL. Prolonged exposure to such high concentrations of radon daughters increases the risk of developing lung cancer and leukaemia and may also have other harmful effects. The risk to cavers will depend on concentrations in the caves visited and the duration of exposure. As yet only a small number of other caves have been tested in Britain but initial measurements (Gunn *et al* 1989; 1991) have shown that radon daughter concentrations vary spatially (from cave to cave and from site to site within a cave) and temporally (seasonally, daily and diurnally). Measurements of cave radon concentrations have been made in several other countries including Hungary, Italy, Japan, the USA, and Yugoslavia but to the author's knowledge there have been no previous measurements in the USSR. This paper describes measurements made on the 1990 Red Rose Expedition which visited three areas, the Kirktau Massif and the Arabika Massif which are areas of alpine limestone karst and the Podolian gypsum karst. (Figure 1).

Methodology

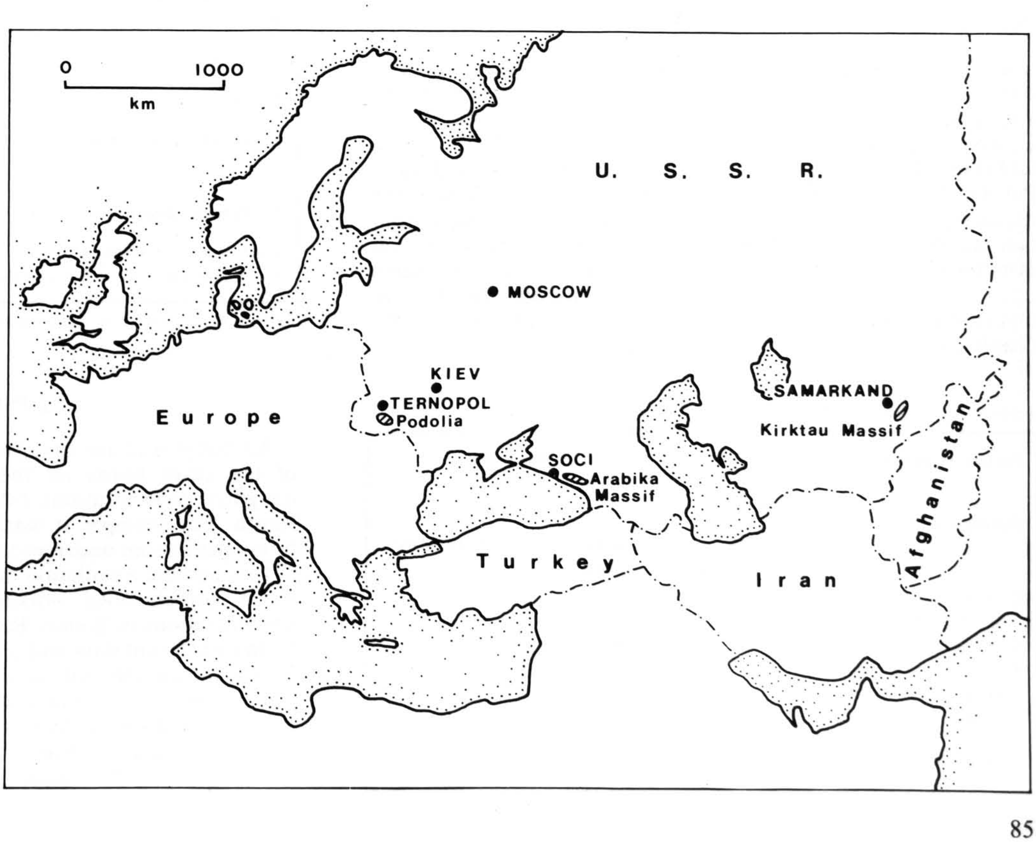
Spot measurements of radon daughter concentrations in Working Levels (WL) were made using a Thompson & Nielson Instant Working Level Meter (IWLM or 'radon sniffer') which was usually run for 15-30 minutes. Ten surface and 26 underground measurements were made. Time integrated measurements of radon gas were obtained by exposing 14 National Radiation Protection Board (NRPB) passive radon monitors for set periods of time. In addition John Gunn wore a NRPB personal dose meter on each underground trip to record his individual radiation dose. The NRPB meters record cumulative radon gas concentration expressed as kBqh m^{-3} and in order to convert these to Working Levels the radon equilibrium factor (F) must be calculated. F ranges from 0.1 in very well ventilated caves to 0.9 in poorly ventilated areas.

RESULTS

Kirktau Massif

One surface and ten spot underground measurements were made (Table 1) and five radon monitors were exposed (Table 4). The atmospheric radon daughter concentration was 0.0012 WL which is typical of concentrations in Britain. With the exception of Bounty Pot, spot concentrations are generally low (mean 0.15, range 0.09-0.21 WL). Concentrations in Bounty Pot were over one

Figure 1. Location of study areas.



DEPTH	TW3	FRIDGE POT	KT58	KIEVESKAYA	BOUNTY POT
− 11 m					1.73
− 25 m	0.19	0.09			
− 32 m					1.52
− 37 m			0.20		
− 50 m		0.17			
− 65 m	0.21				
− 75 m				0.12	
− 92 m	0.08				
− 120 m				0.14	
Mean (excluding Bounty Pot)			0.152 WL		
Surface			0.001 WL		

Table 1. Spot Radon Daughter Concentrations (WL), Kirktau Massif.

hundred times higher than the mean for the other caves. This points to a source of radon (ultimately uranium) in Bounty Pot but it is not possible to suggest what the source may be without further work. On the basis of the spot measurements from Kieveskaya the radon equilibrium factor may be estimated as 0.65, indicative of relatively poor ventilation. With the exception of the −90 m measurement in TW3 the concentrations increase with depth in each individual cave although there is no consistent trend with depth for the massif as a whole (Table 1).

Arabika

One surface and seven underground spot measurements were made (Table 2) and four radon monitors were exposed (Table 4). The atmospheric radon daughter concentration was 0.0003, a little lower than normal. Spot concentrations are similar to Kirktau with a range of 0.06-0.41 WL and a mean of 0.22 WL (Table 2). The radon equilibrium factor was estimated on the basis of measurements in V.V. Iljukhina as 0.50. There are insufficient measurements to establish whether there is any trend with depth.

Cave/site	Depth (m)	WL	
Moscow Cave	−2	0.26	
Watch Cave site 1	−15	0.02	
Watch Cave site 2	−31	0.33	
V.V.Illjukhina	−60	0.20 &	0.16
White Horse Cave	−80	0.41	
V.V.Illjukhina	−95		0.10
Mean		0.217 WL	
Surface		0.0003 WL	

Table 2. Spot Radon Daughter Concentrations (WL), Arabika Massif.

Podolia

Daily measurement of atmospheric radon daughter concentrations over a seven day period gave a mean of 0.0029 with a range of 0.0006-0.0079, higher than in the other two areas (Table 3). Spot concentrations in Ozernaja Cave (mean 0.53 WL; range 0.39-0.73 WL, Table 3)) were higher than anywhere except Bounty Pot. On the basis of observations at two stations in Ozernaja the radon equilibrium factor was estimated as 0.5 and results from two stations further into the cave suggest that there is an even distribution of radon daughters through the sytem. The same equilibrium factor was used for the radon monitor in Optimisticeskaja which yielded a higher concentration of 1.16 WL (Table 3).

Table 3. Radon Daughter Concentrations (WL), Podolia.

Surface measurements	0.0006, 0.0029, 0.0079, 0.0006, 0.0021 0.0021, 0.0041 (mean = 0.0029)		
Ozernaya Cave			
	SPOT MEASUREMENTS		RADON MONITOR
	23/8/90	25/8/90	
1. Sun Chamber	0.43	0.73	0.49
2. Southwest boundary	0.39	0.63	0.63
3. No Waiting Lake	0.45	0.40	
4. Partisan's Chamber	0.53	0.65	
5. Base Camp Chamber			0.55
6. Stone Peak Chamber			0.56
Optimisticeskaja Cave			1.16

CAVE	DATES	HOURS	kBqh m³	F	WL
1. KIRKTAU MASSIF					
KT16 −100 m	29/7-3/8	128.5	48	0.65	0.07
KT16 −215 m	29/7-3/8	128.5	65	0.65	0.09
Kieveskaya	1/8-6/8	111.0	87	0.65	0.14
Kieveskaya	1/8-6/8	111.0	73	0.65	0.11
Kieveskaya	1/8-6/8	111.0	77	0.65	0.12
2. ARABIKA MASSIF					
Gelgelukskaya −20 m	13/8-17/8	100.0	33	0.50	0.04
Gelgelukskaya −30 m	13/8-15/8	49.0	61	0.50	0.17
White Horse −90 m	13/8-16/8	71.5	203	0.50	0.38
V.V.Illjukhina −60 m	14/8-18/8	97.0	99	0.50	0.14
3. PODOLIA					
Ozernaya Site 1	23/8-25/8	45.3	164	0.50	0.49
Ozernaya Site 2	23/8-25/8	45.3	211	0.50	0.63
Ozernaya Site 5	25/8-29/8	106.5	430	0.50	0.55
Ozernaya Site 6	25/8-29/8	106.5	443	0.50	0.56
Optimistichaya	28/8-29/8	20.0	171	0.50	1.16

[1]CONVERSION: WL = kBqh m³ x equilibrium factor / (3.7 * hrs in cave)

Table 4. Radon Monitor Analyses[1]

Individual dose

The radiation dose received by John Gunn has been estimated on the basis of area monitoring (where the mean concentration for a cave is multiplied by the amount of time spent in the cave) as 0.91 mSv (Table 5). This is some 20 per cent higher than the estimate from the personal dose meter (Table 5) which suggests either that the actual mean cave radon concentrations are somewhat less than the estimates based on spot samples or that the equilibrium factor is higher than estimated. Approximately half of the dose resulted from caving in the Kirktau Massif.

1. **Area monitoring**

DATE	CAVE	HOURS IN CAVE	WL	WLH
29.07	TW3	6.5	0.200	1.300
31.07	KT26	1.0	0.001	0.001
01.08	Fridge Pot	1.0	0.090	0.090
02.08	Fridge Pot	2.5	0.130	0.325
03.08	Fridge Pot	2.5	0.130	0.325
05.08	Kieveskaya	5.0	0.130	0.650
06.08	Bounty Pot	2.5	1.400	3.500
13.08	White Horse	3.0	0.410	1.230
14.08	V.V.Illjukhina	1.0	0.130	0.130
16.08	Watch Cave	3.0	0.200	0.600
17.08	Watch Cave	3.5	0.200	0.700
17.08	Moscow Cave	1.0	0.260	0.260
18.08	V.V.Illjukhina	4.0	0.130	0.520
23.08	Ozernaya	6.0	0.450	2.700
TOTAL		42.5		12.331

12.331 WLH = 0.91 mSv

2. **Personal dose meter**

Total dose = 75 kBqh m³
If equilibrium factor = 0.5 then this gives a dose of 0.64mSv

Table 5. Estimation of Personal Dose for John Gunn.

DISCUSSION

All but one of the caves tested on the Kirktau Massif and all of the caves tested on the Arabika Massif have low radon daughter concentrations (<0.2 WL) and present little risk to health. For example, it would be necessary to spend over 1000 hours per annum underground at an average concentration of 0.2 WL to achieve a radiation dose of 15 mSv, the annual dose limit for a non-classified worker in the U.K. However, the high concentrations in Bounty Pot point to the danger of generalising from insufficient data and it should be noted that all of the caves in which measurements were made had at least one value greater than 0.1 WL, the threshold above which a 'Controlled Area' must be designated under the British Ionising Radiations Regulations. The British annual dose limit would be achieved in about 127 hours at the 1.6 WL mean in Bounty Pot. Concentrations in the gypsum caves were somewhat higher than in most of the limestone caves and a dose of 15 mSv would be achieved by spending about 400 hours in Ozernaja. One of the Russian cavers who acted as our guide estimated that he spends about 720 hours per annum in the cave which would result in a radiation dose of about 28 mSv if the measurements are typical. A similar amount of time spent in Optimisticeskaja would result in a very significant radiation dose of 61 mSv.

On the basis of the radiation dose received by John Gunn it is suggested that participants in the first part of the expedition probably received a radiation dose of about 0.5 mSv and those participating in the second half between 0.5 and 0.7 mSv depending on the amount of time spent in the gypsum caves. This may be compared with the 'normal' *annual* radiation dose at the ground surface of about 2.5 mSv.

ACKNOWLEDGEMENTS

The measurements described in this paper formed part of the scientific programme on the 1990 Red Rose Exploration Group Expedition to Russia. Thanks are due to all of those who participated in the expedition and particularly to Allan Richardson and Nigel Ball. The expedition members would like to thank The Manchester Geographical Society, The Royal Geographical Society, The Sports Council and The Mount Everest Foundation for financial support and Vladimir Kisseljov for being 'Mr Fixit'!

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Radon in Limestone Cave Air and Groundwaters

NCA/BCRA Symposium, Manchester, May 1990

SYMPOSIUM INTRODUCTION

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Although the presence of the radioactive gas radon in caves throughout the world has been known since the mid-1960's it was not until 1987 that it became a cause for concern to British cavers. This was largely a result of measurements made by the Limestone Research Group at Manchester Polytechnic which showed that during the summer months radon concentrations in some Derbyshire caves and abandoned lead mines are exceptionally high. As a result many outdoor pursuits centres suspended caving activities indefinitely. Measurements elsewhere in the country revealed summer concentrations significantly less than the Derbyshire maxima but still well above the level at which the Ionising Radiations Regulations apply. Increasing concern over the implications for cavers resulted in the establishment of a Radon Working Party by the National Caving Association (NCA) in March 1989.

In addition to holding meetings with the Health & Safety Executive, the Working Party, in conjunction with BCRA, sponsored a Symposium on radon at Manchester Polytechnic on Saturday 19th May 1990. Twelve papers were presented on various aspects of radon in limestone cave air and in limestone groundwaters. After an initial paper in which Smart expanded on some early work in Castleguard Cave, Canada (Atkinson *et al.*, 1983) the theme returned to Britain and Gunn summarised work to date. Middleton and Prime respectively described more detailed investigations of radon in the air of Giant's Hole and Poole's Cavern in the Peak District whilst Andrews and Reaich both described investigations in the Mendip Hills. Aspects of radon production from cave sediments were examined by Bottrell and health aspects by Dixon. The work of the Radon Working Party was reviewed by Edwards and attention then turned to radon in groundwaters with papers by Andrews (British groundwaters), Prime (Derbyshire limestone groundwaters) and Smart (Mendip limestone groundwaters). All authors were invited to submit articles for publication in Cave Science and this volume includes six of these papers together with abstracts for the other six.

These papers represent the state of knowledge of radon in British caves at at May 1990 but investigations are ongoing and will be the subject of papers at the biennial Cave Science Symposium of the BCRA. This volume also contains a paper describing the first radon measurements in the USSR and it is hoped that it will stimulate contributions from other countries in which research into cave radon is ongoing.

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RADON IN MENDIP CAVE AIR

John N. Andrews, University of Bath.

Radon-222 concentrations in air have been determined for several caves in the Carboniferous Limestone of the Mendip Hills, Somerset. Occasional measurements were made in caves which are accessible only to speleologists and amateur cavers. A series of regular measurements have been carried out during the last 3 years for one of the major tourist caves, Wookey Hole near Wells. The objective of this investigation was to determine the controlling factors on air-radon concentrations and to assess the occupational exposure of cave guides. Radon-daughters were determined in Wookey Hole by aerosol filtration using the Tsivouglou procedure.

The effect of seasonal changes in cave ventilation on radon concentrations and their implications for the mechanism of radon release into cave air are discussed. The influence on radon in air concentrations of a forced ventilation system is described. An estimate is made of cavern volume based on the rate of change of radon concentration during start-up of the forced ventilation.

RADON IN UK GROUNDWATER

John N. Andrews, University of Bath.

The concentrations of Rn-222 in groundwaters from various lithologies are briefly reviewed in relation to U content of the rock and the relative importance of intergranular and fracture flow for the lithology. Radon is not subject to geochemical controls on its solubility because of its noble gas character. Its solution in groundwater occurs by release from mineral surfaces into the surrounding water phase and the diffusion of Rn-222 from within the rock matrix is the most significant process which determines groundwater Rn contents. It is shown that the diffusion coefficients for Rn in rock matrices may be theoretically related to its release from sized samples of crushed rock. The Rn flux from plane rock surfaces may then be estimated and the Rn contents for both intergranular and fracture fluids may then be calculated. These theoretical concepts are then used to explain the observed distributions of Rn-222 contents for groundwaters from different lithologies. Controlling parameters for groundwater Rn content are the aquifer U content, porosity and the relative importance of intergranular and fracture flow.

CONTROLS ON RADON IN THE ATMOSPHERE OF CASTLEGUARD CAVE

P. L. Smart, Dept. of Geography, University of Bristol.
T. C. Atkinson, Environmental Sciences, University of East Anglia.

Measurements of Rn-222 were made using CR39 solid state track detectors over a five day period in spring 1980 in the 9km long main passage of the Castleguard cave. A strong inflow of cold external air occurs through the main entrance and passes through the cave to higher elevation outlets in the Columbia Icefield. Radon concentrations initially increase into the cave, but decrease again at points where shafts penetrating the cave roof bring additional air into the system. Some radon is derived by degassing of percolation water entering into the cave, but the volume of this inflow decreases with distance from the entrance, and dissolved radon concentrations are low. Direct emanation from the cave walls is insufficient to explain the observed rate of change in radon concentrations in the air. Advection of air from small fissures adjacent to the cave, occurring in response to the pressure gradient generated between cold air in the overlying rock and warmer cave air, is probably the main mechanism for radon release to the cave atmosphere.

HYDROLOGICAL IMPLICATIONS OF RADON IN MENDIP LIMESTONE GROUNDWATERS

P. L. Smart, H. Friedrich and F. F. Whitaker, Dept. of Geography, University of Bristol.
A. Zereshi and J. N. Andrews, Dept. of Chemistry, University of Bath.

The equilibrium concentration of radon in a fissured aquifer is dependent upon the uranium concentration and fissure width, with high concentrations in tight fissures and low in conduits. In the unsaturated zone radon concentrations are low as a result of degassing, and concentrations in the saturated zone are therefore decoupled. In the saturated zone recharge to fissures causes reduction of residence time below that required for equilibrium (*c.*26 days), and radon concentrations fall. In springs and in the unsaturated zone, initial reductions are followed by increasing concentrations, as long residence waters with high radon concentrations are expelled from fissure and fracture storage. Radon concentrations vary inversely with spring catchment area (discharge) because of the increased unsupported residence time in conduits. This also explains the low radon concentrations observed at base-flow in the summer, and the effect of catchment shape (low in elongate catchments). Radon concentrations are significantly lower in the western Mendips than in the eastern, which may be explained by the greater width of fissures in the west, where the karst is older and more mature.

HEALTH ASPECTS AND CONTROL OF EXPOSURE TO RADON DAUGHTERS

Daryl Dixon, NRPB, Didcot.

Trace quantities of uranium in terrestrial materials produce elevated concentrations of radon gas underground whether in small interstitial spaces or in large underground cavities such as mines or caves. The type of rock or mineral has some bearing on the radon concentration, but even in the absence of particularly active minerals, the normal levels of uranium are sufficient to cause radon concentrations at which continued exposure could have significant implications for health. The mechanisms by which radon daughters become available for inhalation and the potential detriment to health will be described.

Epidemiological studies of groups of men exposed occupationally for long periods in mines with high radon concentrations have been in progress for many years and allow the risks from radon daughters to be quantified. The characteristics and results of these studies will be described and their impact on the development of regulatory standards for the limitation of radon exposure will be reviewed.

The interpretation of standards in terms of operational control procedures will be examined and the requirements for the protection of workers and the public will be described. Practical objectives of control systems will be described and illustrated with descriptions of methods of measuring radon gas and daughters and of assessing radiation doses. The importance of reliable and accurate methods of evaluating doses and the utility of such data for ensuring that doses are minimised will be discussed. The role and application of administrative controls will be considered including the need to identify areas where action to reduce doses may be required and the need to maintain records.

The influence of meteorological conditions, cave development and ventilation characteristics on radon concentrations will be discussed, and recent progress with reducing radon concentrations in caves and mines will be illustrated. These experiences will be used to emphasise the importance of measurement programmes on quantifying and reducing risk and facilitating compliance with regulations at relatively little cost.

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Transactions of the British Cave Research Association

The Caves of Gregory National Park, Northern Territory, Australia

Richard STORM and David SMITH

Abstract: As part of Operation Raleigh Warrgarr Expedition to the Northern Territory of Australia, a caving expedition was sent to find and explore caves in Gregory National Park being newly opened and having a relatively unexplored area of karst. The expedition mainly concentrated its efforts in the Limestone Gorge and the Bulitta areas of the park. Six caves were found, explored and surveyed, giving a total length surveyed of over 13 kilometres.

Gregory National Park is in the Victoria River basin approximately 300km west of Katherine in the Northern Territory of Australia. Timber Creek, the nearest town with pub, phone and shop is situated on the Victoria highway 45km north of Limestone Gorge, via a track which requires a 4WD vehicle for access. Bulitta Ranger Station is approximately 13km away from Limestone Gorge, and 56km south of Timber Creek (Fig 1).

Limestone Gorge is the valley of Limestone Creek, a tributary of the East Bains River, and extends east/west for approximately 3km. Base Camp was situated at the western end of the valley next to a permanent spring in the creek bed. Because of the large distances involved and nature of the terrain anyone planning to visit the area should have a 4WD vehicle carrying spare water, tyres and fuel. Access to the caves is gained via the Conservation Commission of the Northern Territory.

Climate

The climate in Gregory National Park is subtropical monsoonal giving rise to two major seasons, the wet summer (November-March) and the dry winter (May-September). The other months are humid with little or no rain. As most of the annual rainfall of 618-813mm falls in the wet season when the temperatures are often over 45°C, it makes for a very hot, humid environment.

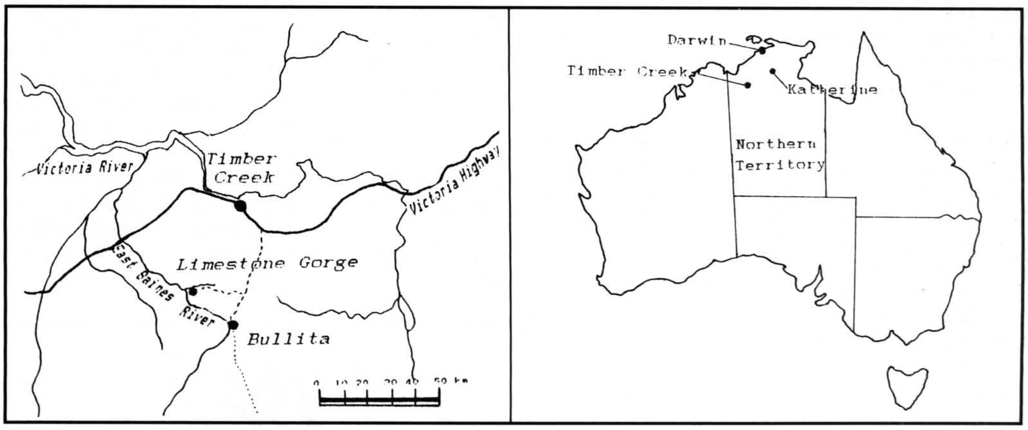
The rain generally falls in heavy bursts, which present two problems to the prospective caver; all the roads may become impassable and the caves become prone to flash floods and flooding; a visit during the wet season is inadvisable. During the dry season virtually no rain falls; the weather only presents the problem of high temperatures during the day, making the terrain very dry and dusty with fire as a potential hazard. With the evening and night time temperatures dropping to a relatively cold 10°C, a sleeping bag is required. All travellers, both above and below ground, need to carry water.

Geology

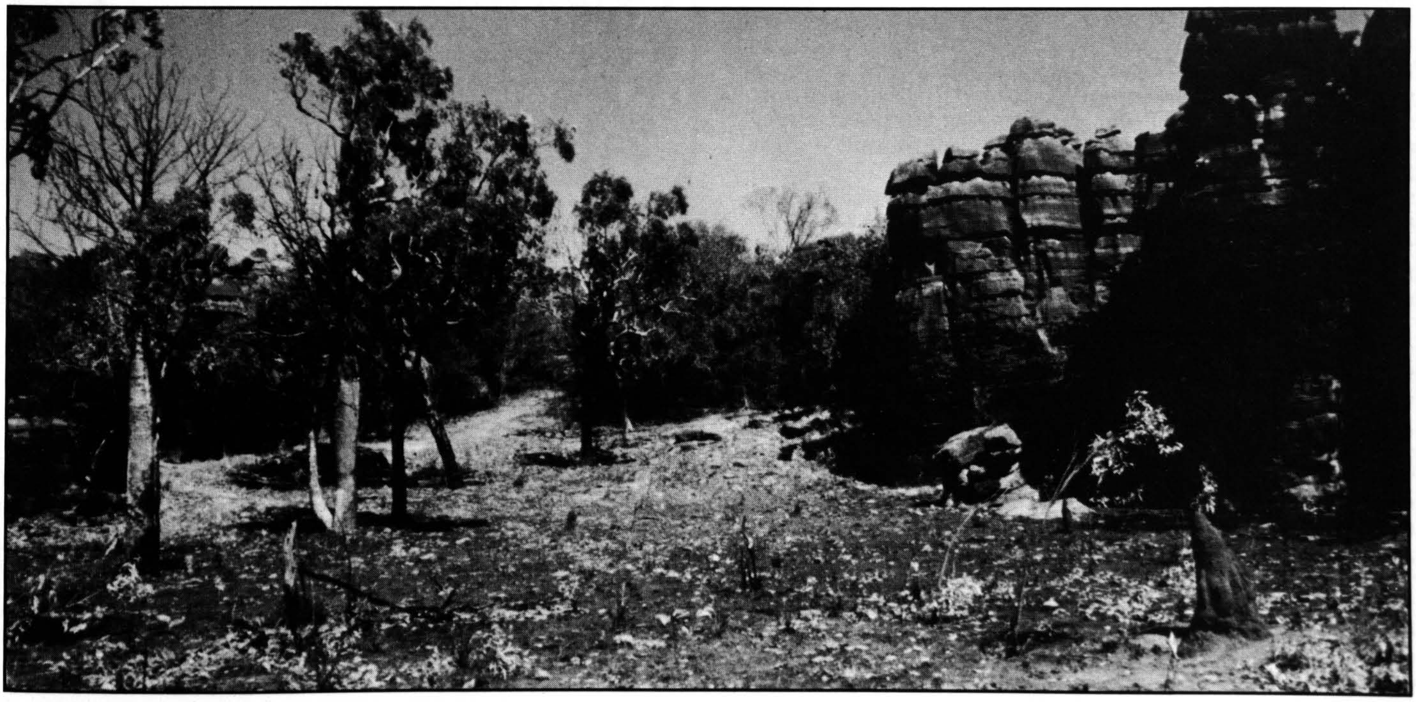
Gregory National Park is situated in the Victoria River basin. During the Precambrian era, cycles of marine deposition laid down the limestone in a shallow lagoon sea, later to be covered by massive beds of sandstone, now heavily eroded.

The predominant surface geology of the Limestone Gorge area is highly fractured thinly bedded dolomite, with thin beds of

Figure 1. Location maps.



Limestone escarpment near Claymore Cave.



Stromatolites in Birthday Cave.

dolomite, siltstone, minor sandstone and chert, providing an environment unsuitable for the formation of caves. These rocks dominate the topography of this area, giving rise to low plateaux and steep valleys. The valley sides are formed with alternating beds approximately 1m thick of limestone, creating small escarpments, and beds approximately 3.5m thick of sandstone, siltstone and limestone forming fractured slopes. Fortunately, due to the varying depositional environments within the Precambrian sea, there are isolated reefs of massive fine to coarse dolomite, with stromatolitic beds giving rise to escarpments up to 25m high; these provide an environment for the formation of caves and are the sites of all the explored caves.

Vegetation

The typical vegetation which dominates Limestone Gorge and the surrounding area falls in to the Tanmurra Land System (established by Stewart *et al* in 1970) with deciduous spruce, low woodland on calcareous desert soil or shallow skeletal soils with outcrops of limestone. The vegetation can be arranged in three 'strata' according to their height; being purely an arbitrary scale it gives an indication of physical size and position within the ecosystem. The categories include a lower stratum I (grasses etc.), a middle stratum II (woody shrubs & woody trees) and an upper stratum III (trees) and are outlined in table one. Limestone Gorge and the surrounding area are covered by open low woodland with dusty soil and grasses. The trees provide shade and somewhere to rest. The grasses on the other hand are far from hospitable, they are armed with spikes, spears and sharp edges so trousers or gaiters are recommended for trekking, depending on the length of the grass. The grass can be above head height and therefore can present a navigation problem as well as being a hostile obstruction. The obstacle of the grass may be greatly reduced if it has been burnt by the ranger or by natural fire.

Open low woodland (valley bottoms and plains)

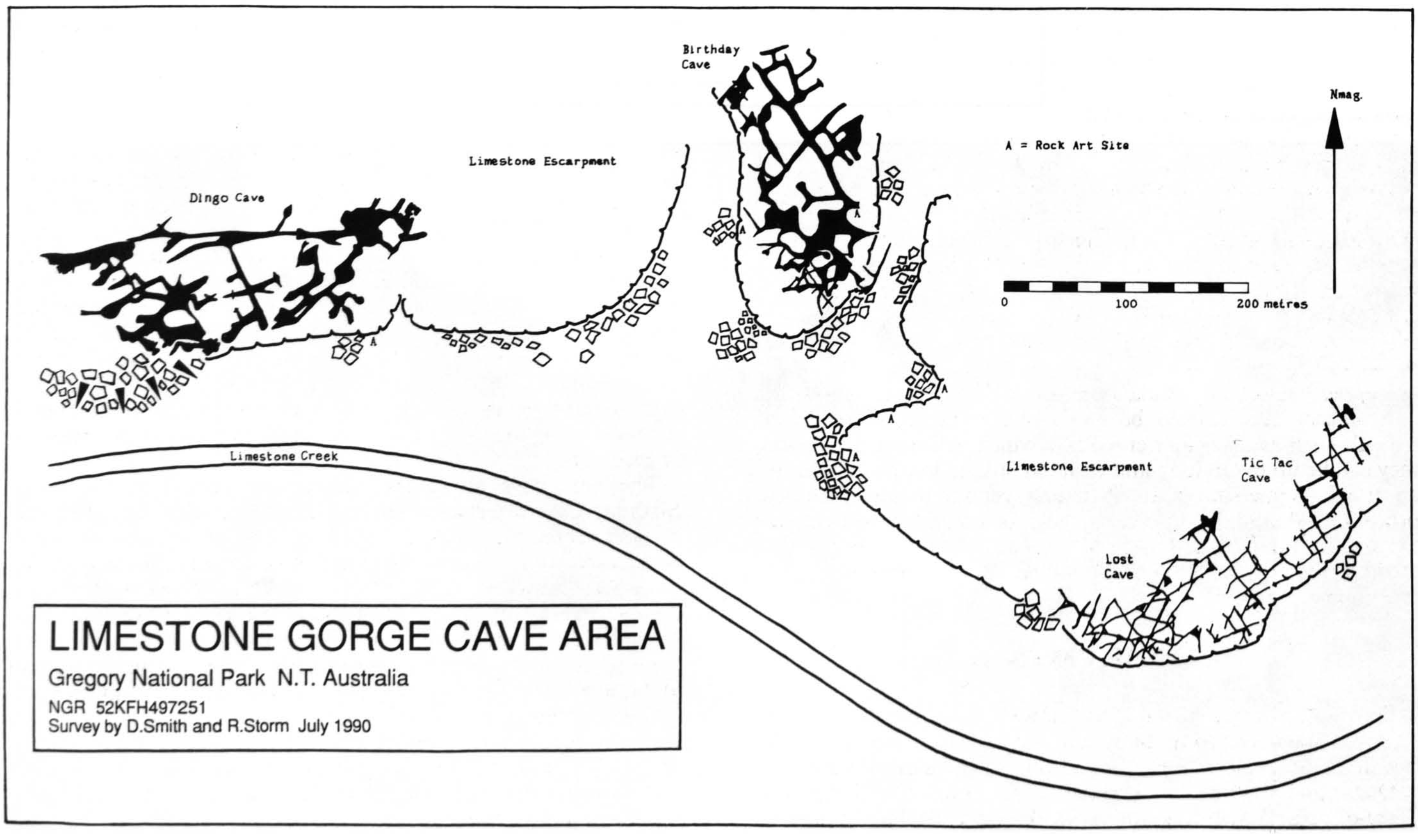
Strata	Species	Common Name
III	*Adansonia gregorii*	Boab
	Terminalia Arostrata	Nut wood or crocodile bark
	Eucalyptus terminalis	Plains Bloodwood
	Eucalyptus tectifica	Darwin/Grey box
	Hakea arborescens	Common Hakea
	Lysiphyllum cunninghamii	Bauhemia
II	No significant species	
I	*Thenseda australis*	Kangaroo grass
	Heteropogan contortis	Black speargrass
	Sorghim plumasum	

Limestone ridge (cave area)

Strata	Species	Common Name
III	*Cochluspermum fraseri*	Cotton tree
	Gyrocarpus americanus	Stinck wood
	Eucalyptus terminalis	Plains Bloodwood
	Grevellia demidiata	
	Celtis philippinersis	
	Strychnos lucida	
	Ficus leucotricha	Rock fig
II	No significant species	
I	*Heteropogan conturtis*	Black speargrass
	Triodia pungens	Spinifex

Table 1. Vegetation types in the main land ecosystems.

Figure 2.



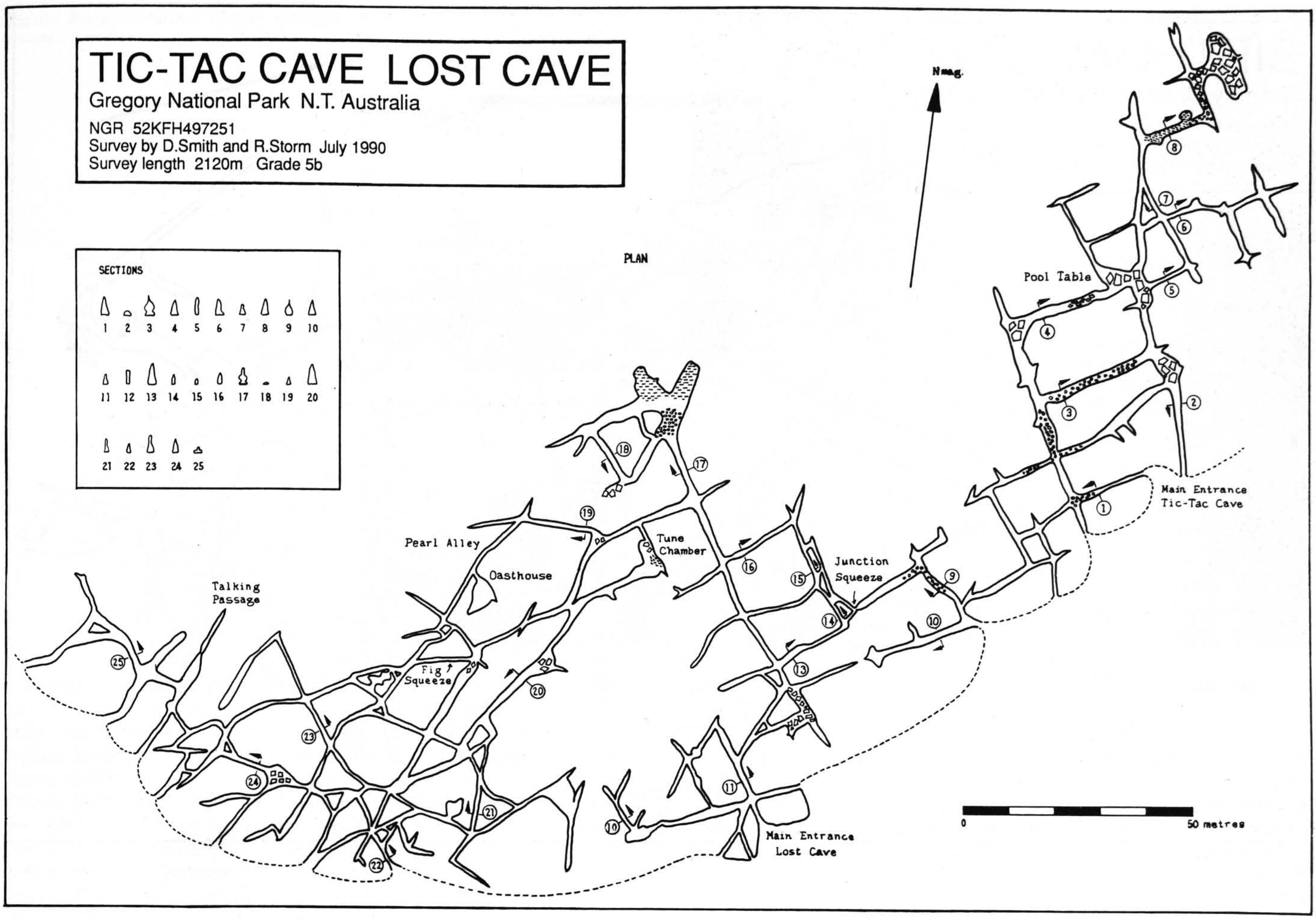


Figure 3.

Wildlife

Apart from the migratory population of cavers the region has a great profusion of wildlife both indigenous and introduced. A large population of feral cattle, donkeys and horses roam free and can prove hazardous to unwary drivers. Due to overgrazing and trampling, they have caused excessive erosion, warranting their control by park rangers. One benefit of this erosion is the creation of paths and tracks through the vegetation. Other interesting animals to be encountered include a variety of wallabies which will generally avoid humans, dingoes that will keep their distance but may cause a few sleepless nights with their eerie howling, spiders which may be large and venomous, thousands of flies that will annoy all visitors until dusk or underground, a wide variety of colourful birds, and an even wider variety of insects.

The caves support a healthy population of spiders, crickets and other insects. Apart from these residents, the caves are used by pythons sleeping off a meal, ringed tree snakes hunting the bat populations, and other small creatures. The bats identified were the common bent wing *(Miniopterus schreibersii)* and the hoary bat *(Chalinolobus nigrogriseus)*. Othe cave users identified were dingo, short-eared rock wallaby *(Petrogale brachyolis)*, agile wallaby *(Macropus agilis)*, antelopine walleroo *(Macropus antilopinus)* and short beaked echidna *(Tachyglossus aculeatus)*.

A special note should be made about the most hazardous animals such as salt water crocodiles which will travel far inland; they can be up to 6m long and travel at 30kph; few people survive an attack. Some snakes are extremely venomous and treatment procedure should be known by all, as correct treatment can prevent fatalities. Most snakes will not attack unless provoked so avoid contact; local advice should be sought concerning both snakes and crocodiles.

THE CAVES

During the period of the expedition six caves were discovered, explored and surveyed to their limit; further caves were discovered but not fully explored or surveyed due to the lack of time.

Our initial search was restricted to the Limestone Gorge (Fig. 2) and proved fruitless for a week, only finding numerous entrances that choked after 10-20 metres. Our labours proved more fruitful when our search moved to the northern side of the Gorge, soon after finding our first cave, Tic Tac Cave with a surveyed length of 500 metres (Fig. 3). Bats, spiders, crickets, and snakes were inhabitants of the cave. The bats were the most conspicuous and would fly around narrow corners straight into the unsuspecting and unsuspected caver. The development of the caves appeared to be by the enlargement of fractures in the rock by slow-moving phreatic waters and not by vadose stream development. On plotting the survey data, it was obvious that the majority of the maze-like systems owe their patterns to the bed rock fractures.

The second cave to be surveyed and completed was further along the northern escarpment, to the west of Tic Tac Cave. The cave was given the name Lost Cave due to its discoverers becoming temporarily lost. Lost Cave with a surveyed length of 1600 metres (Fig. 3), is of a similar nature to Tic Tac Cave, having narrow triangular passages some of which break through to the surface, allowing the odd shaft of light in to the cave. The floors have very little variation in level and consist of mud and rubble; calcite formations were found, including cave pearls. From the survey of Tic Tac Cave and Lost Cave it is apparent that the caves only extend approximately 100 metres into the escarpment at their extremes and generally follow the line of the escarpment, which suggested that the gorge has a role in the formation of the caves or vice versa.

The next cave along the escarpment was given the name Birthday Cave after some aboriginal rock art first thought to be a birth scene, but later discovered to be of a scene probably carried out nine months previously (we think!). Birthday Cave, having a surveyed length of 1750 metres (Fig. 4), was the first cave discovered to have large chambers and passages more than three metres wide. The passage section suggested a similar origin but in a more advanced state of development, with extensive erosion along a weaker bed of highly fractured siltstone and limestones, giving an oblong section to the lower portion of the passage. The passages break to the surface allowing some light in to the cave and they appear to run along fracture lines. The cave also has stromatolites that are well defined on some boulders in the area marked on the survey.

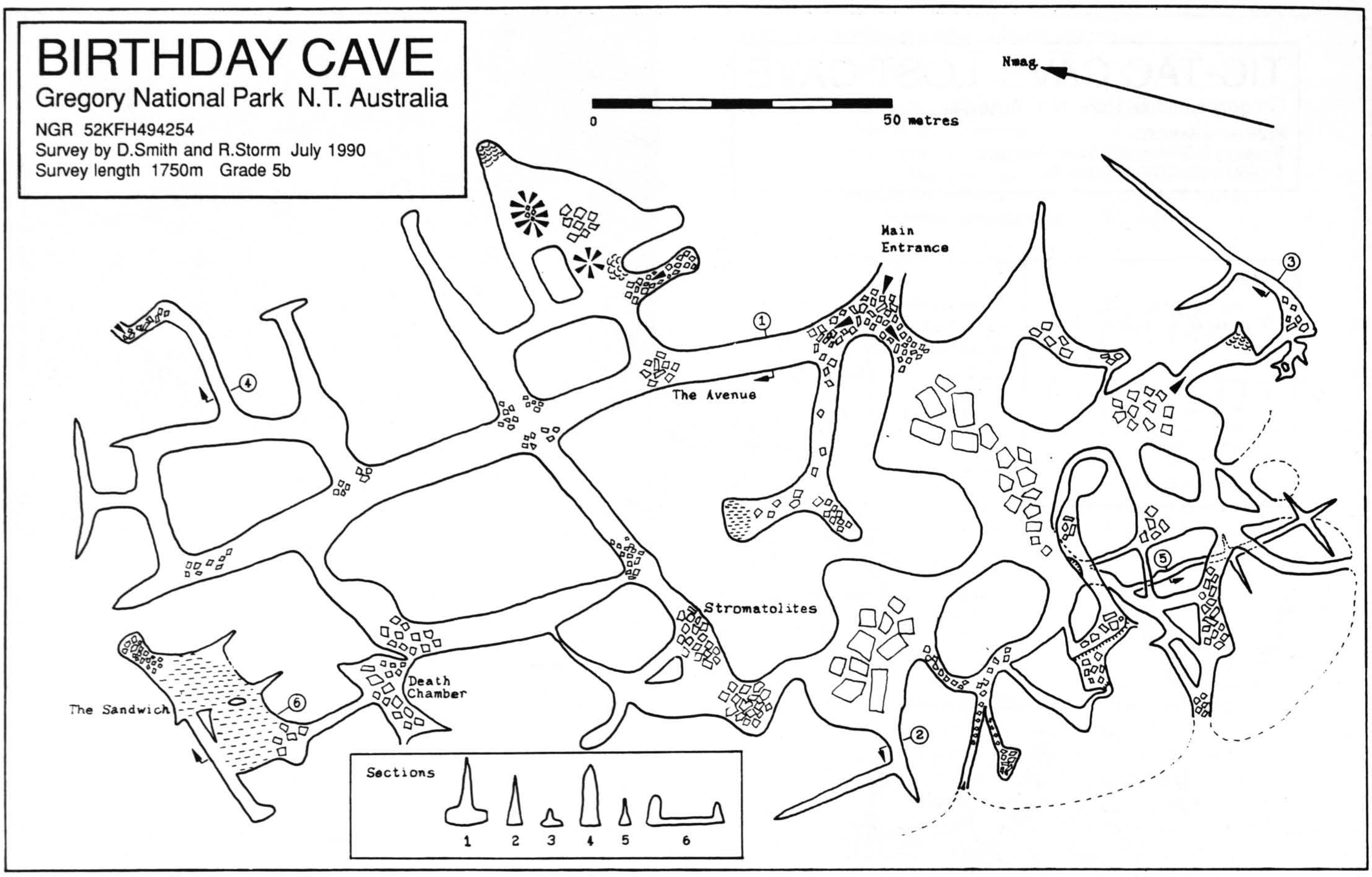
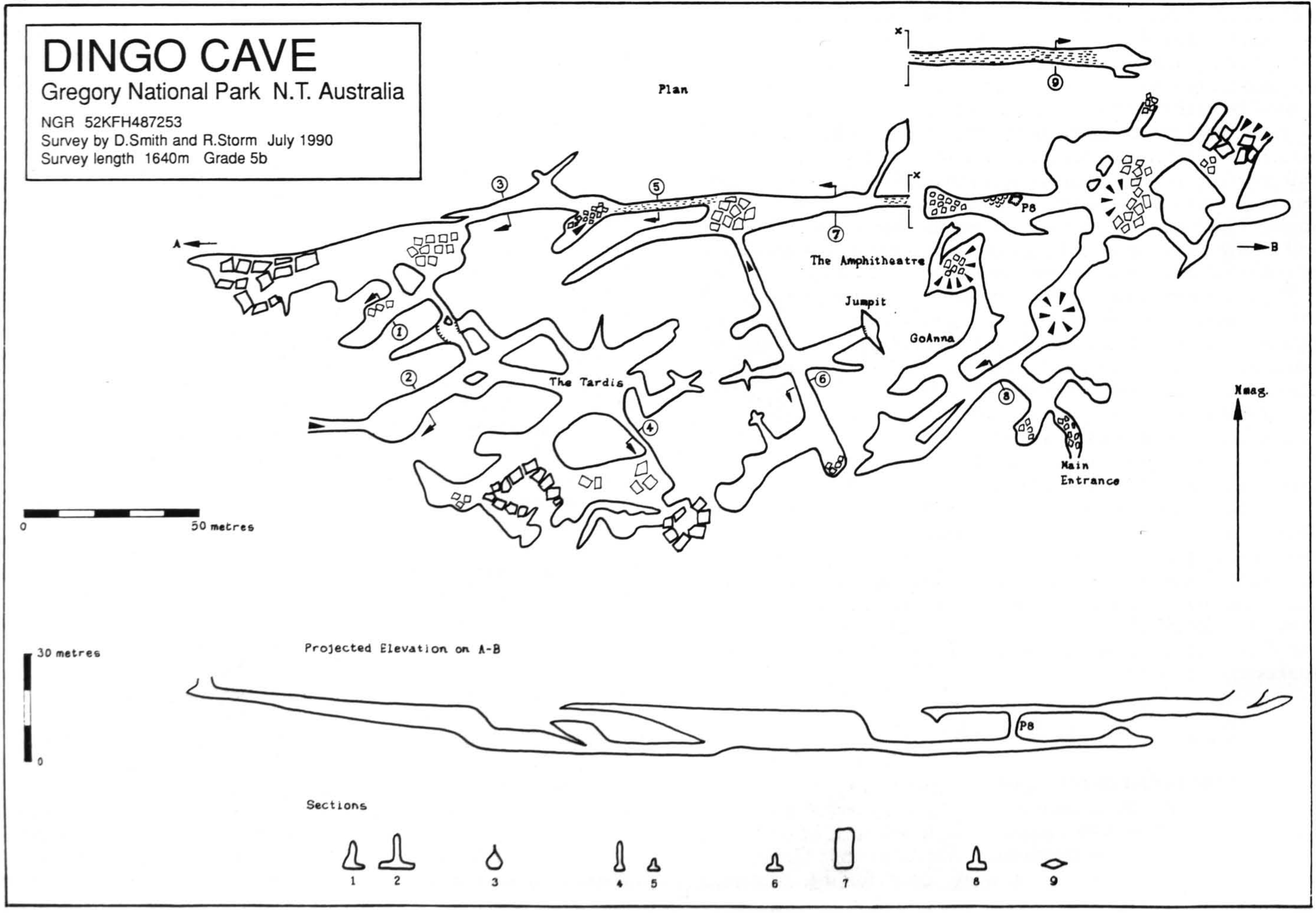
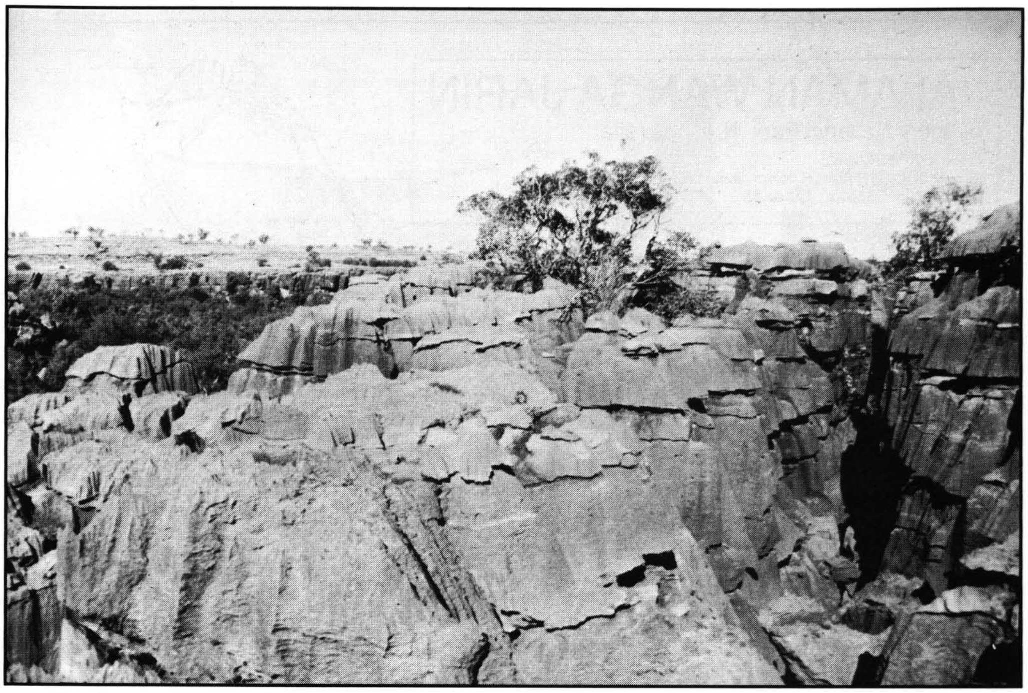


Figure 4.

Figure 5.



Typical limestone outcrop showing the sharp weathered surface.



Dingo Cave was named after the rock art near the entrance, and has a surveyed length of 1640 metres (Fig. 5). This cave was the only one found to exist on two levels, the entrance being on a higher level than the other main passages. An 8m pitch drops down to the same level that all the other caves seem to lie on. It should be noted that the cave is under an escarpment higher than the others thus allowing for the higher level. The cave is notable for having large chambers and solution passages, the upper chambers have formed by the extensive erosion of a bed of fractured limestone and siltstones giving a pattern comparable to the regular pattern of pillar and stall mining.

During the surveying of Lost and Tic Tac Caves, more caves were found approximately 7km south of Limestone Gorge in the valley of the East Baines River. Jalaman Wangar Jarin (aboriginal for East Baines Limestone Cave) has a surveyed length of 1340 metres (Fig. 6) and is of similar nature to the other caves but with some vadose solution passages running between Dolly Tubs and Root 66.

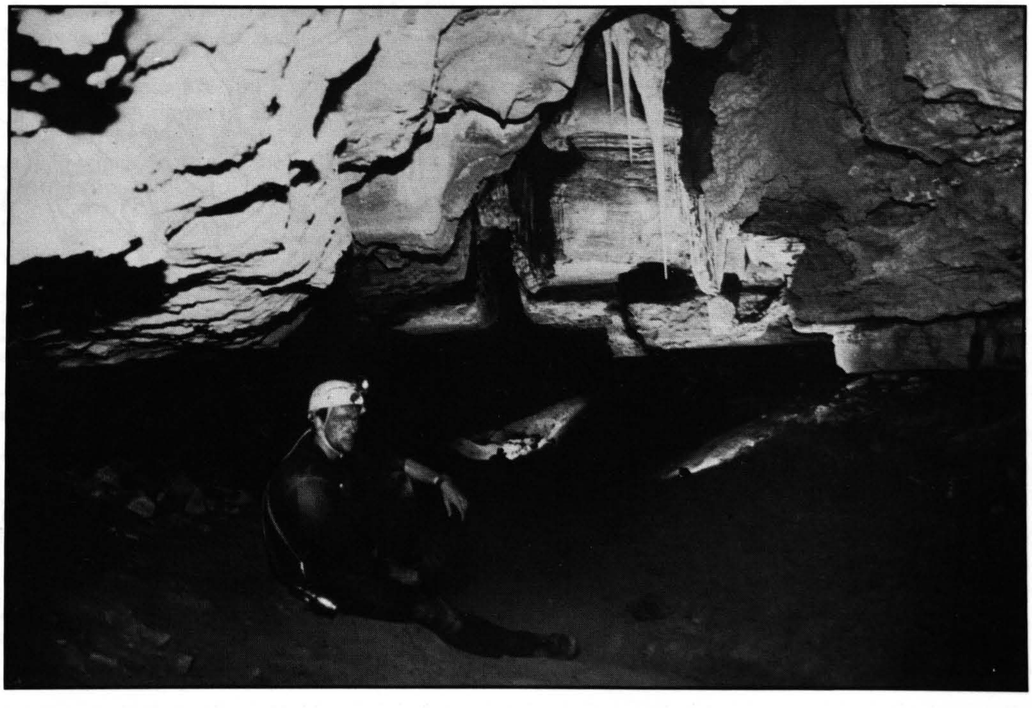
The next cave to be found was to the south-east of Jalaman Wangar Jarin. Claymore Cave, with a surveyed length of 6200 metres (Fig. 7), is the largest cave, and exhibits most of the features found in the other caves, having a large area of collapse chambers between isolated rock columns very much like a pillar and stall mine, with a mix of narrow and wide passages. Claymore Cave proved to have the finest formations including an area of cave pearls, making it the most interesting as well as the most extensive.

CAVE DEVELOPMENT

The features common to all the caves discovered are: they are largely bounded by and follow an escarpment; they all terminate in mud-floored and choked beddings; passages follow fracture patterns of intersecting joint systems; and they have few water-worn streamways, but have a maze of passages with triangular sections, locally breaking through to the surface at their apex.

The caves have developed initially by slow-flowing phreatic waters and then have been enlarged and modified by faster moving vadose water. The development of the caves has been by the enlargement of existing fractures within the bed rock, so the lines of the caves are dictated by these fracture lines. Therefore there will be areas that have a large cave density corresponding to areas of high fracture density. The possible mechanism for the formation of the valleys is the breakdown of these areas. Evidence for this mechanism can be seen in Tic Tac Cave; the area devoid of cave passage within the system corresponds to the interface of two fracture systems of different orientation. This leads to a high fracture density, leading to high cave density, now collapsed. The surface above this area is marked by a large depression half filled with boulders, the possible beginnings of a valley. Once the

The Catacombs in Claymore Cave.



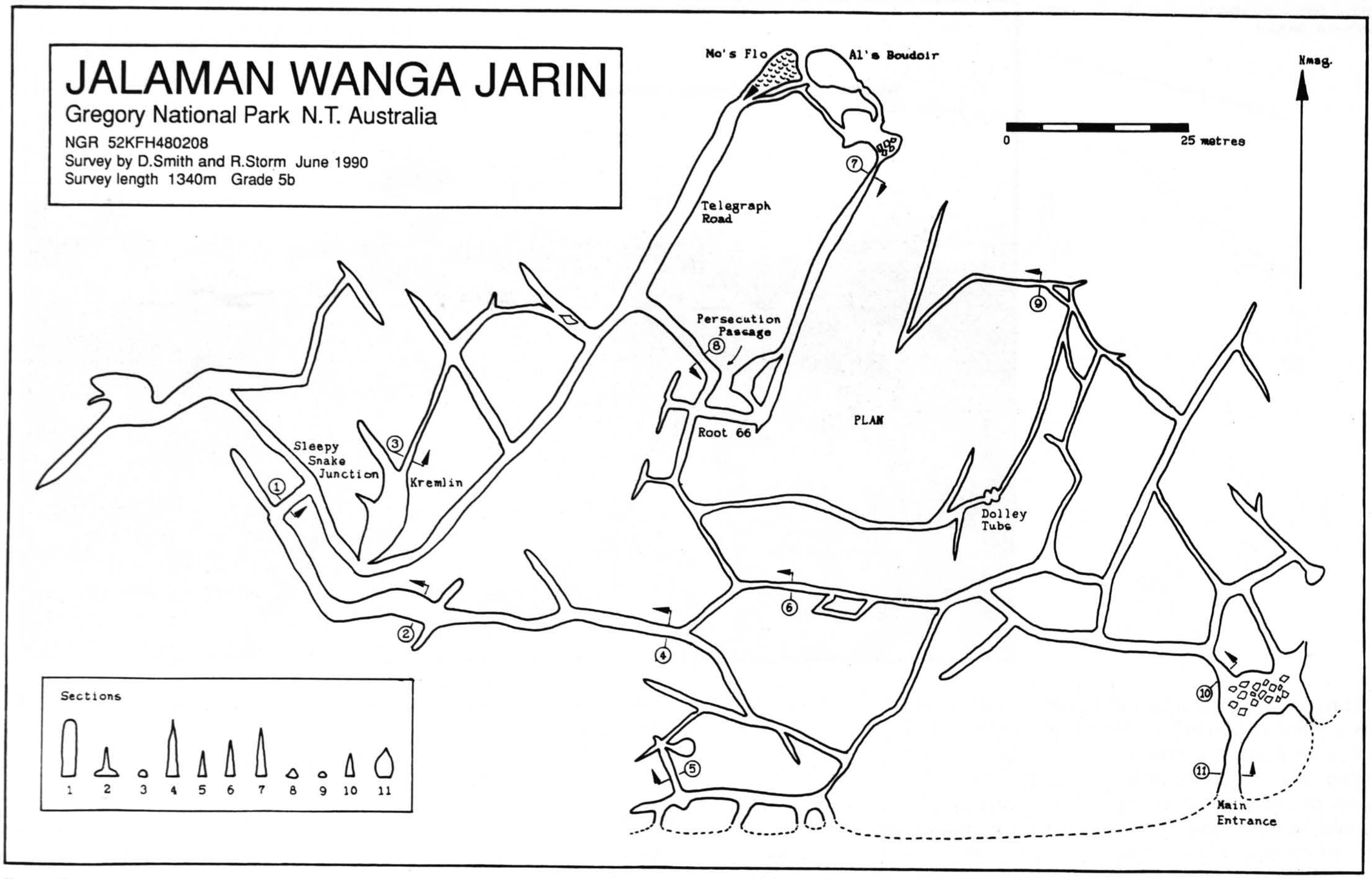
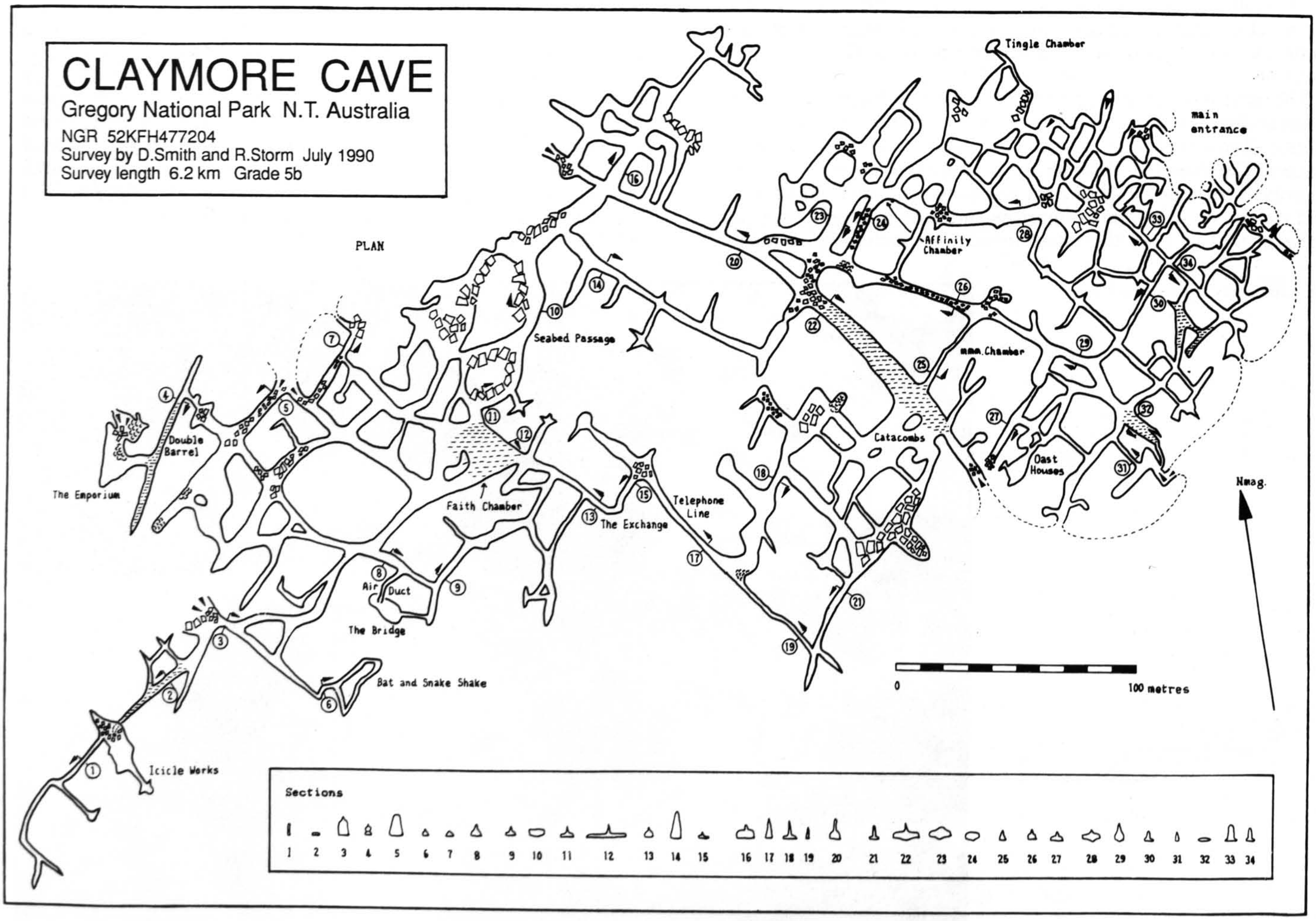
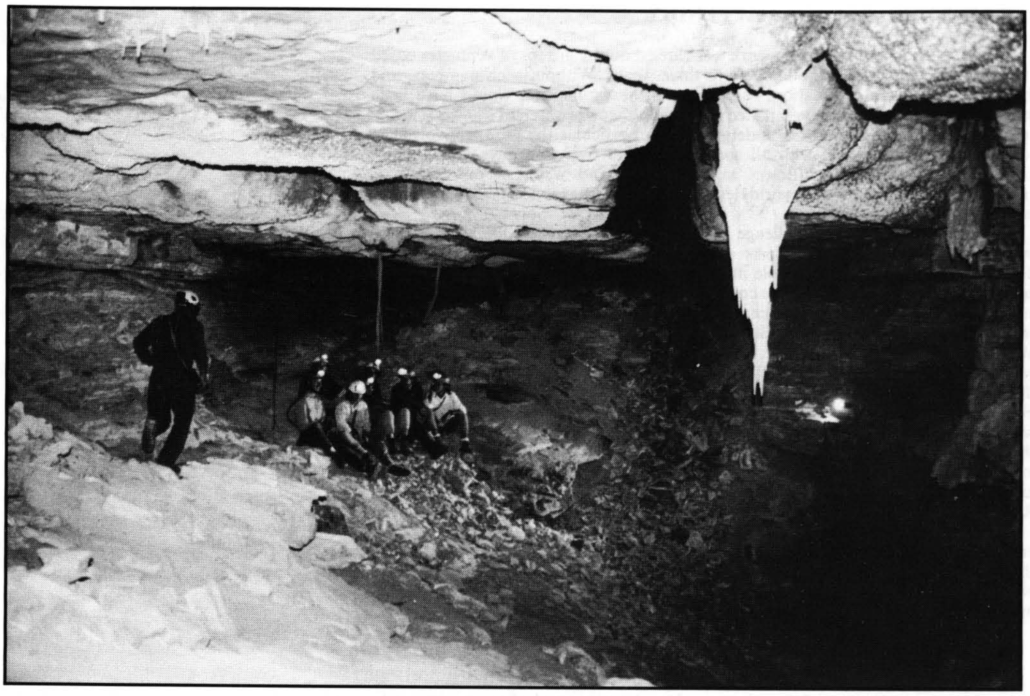


Figure 6.

Figure 7.



Dingo Cave.



forming valleys were able to provide more drainage to the caves, faster moving waters could cause the formation of the solution passages found. Once the valleys had formed, relaxation movement of the rock masses towards the valleys may have also contributed to the cave development.

Other features of the cave system included botryoidal calcite deposits that adorn the walls and roof of the passages, fig tree roots that stretch down from the surface through the passages in search of water like discarded hose pipes, the highly polished or smoother reddish calcite on the rocks, areas of phytokarst producing fingers of rock pointing towards the sun, and Aboriginal rock art in some of the entrances.

Cave Surveying

All the caves were surveyed using Suunto compasses, clinometers and 30m fibreglass reinforced tapes. The first surveying trip demonstrated the problem of using a northern hemisphere compass in the southern hemisphere, as the magnetic disc tips in such a way as to jam on the compass body when held horizontally. Although accurate bearings can be taken with care, the problem was solved by obtaining a Suunto compass adjusted for use in the southern hemisphere. Surveying was carried out employing the leap-frog technique to reduce errors. All the caves are complex mazes which meant that large numbers of survey legs were necessary; the Claymore Cave survey has nearly 600 legs in 6.2km of passage. Most of the passages formed parts of loops which allowed misclosures to be detected and removed, often by resurveying. It was necessary to tag cairns to keep track of the extent of the survey. The tags were later removed.

The data was processed in the field using a Casio FX 700 P computer running a modified version of a programme in the Descent Yearbook 1987/8 by D. J. Martin and M. H. Bonwich. This enabled surveys to be drawn in the field which could then be taken back to the cave to check passage detail.

Aboriginal Rock Art Man

ACKNOWLEDGEMENTS

Thanks to the Conservation Commission of the Northern Territory and the Top End Caving Club for their help and support during the expedition; a special thanks should be given to Keith and Sal Claymore for the extra support they gave us during and after the expedition; thanks to Helen Moxon for her general support, Guizhou 89 and Nottingham Polytechnic Caving Club for the loan of equipment, Tony Waltham for help in preparation of this report, and of course thanks to all the caving crew.

The caving crew included:

Group K: Marina Barns, Clare Barton, Big Al Graham, Little Al Coleman, Richard Steel, Mark Oxby, Jez Lester.

Group N: Laura Brocklebank, Margo Lawrence, Janet Morris, Kirstie Patten, Mat Carpenter, Jason Cooke, Neil Garfield, Luke Halestrap.

Group F: Gill Brown, Rosey Ferguson, Jo Lewin, Lucy Quinlan, Antony Kingston, Gordon Laptain, Edward Shaw, Rob Walton.

Group J: Noleen Mandrill, Jill Marsden, Jennie Robinson, Gail Urquhart, Rob Beman, Paul Brandon, Gary Cook, Gareth Joel.

Group C: David Bar, Mike Guyomar, Ian Lawson, Matt Nelsen, James Marsh, Kathy Mackay, Anna Shelbourne, Octavia Templer, Shauna Wilson.

Special thanks should be given to Mo and Jennie for doing much of the data processing which we hated so much.

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APPENDIX

The exploration and surveying work was carried out by groups of venturers based in Limestone Gorge for periods of up to three weeks. Without such numbers, and their hard work and dedication, the scope of the exploration would have been severely restricted. All members pulled more than their own weight despite dangers and fears of prolonged periods underground, in particular the groups involved in surveying Claymore Cave, who all spent periods of over two days continuously underground, being self sufficient in light, food and water. Many had little experience of an underground world, let alone the bats, snakes and large spiders that reside there.

Caving was not the only challenge met by the caving crew, as life at base camp meant isolation from the comforts of modern life. Good self organisation and discipline maintained an enjoyable atmosphere without destruction of the natural environment. At base camp certain comforts were kept by the ingenuity of crew, such as a fully-fitted kitchen, bathroom with matching bath boiler and shower and a separate WC/Barby pit, built a discrete distance from camp! Such luxuries were abandoned whilst out bush proper, either looking for caves or trekking to the remote cave areas. This meant carrying full packs, containing food, water, and caving gear, through the heat of the day whilst in a potentially dangerous environment. Fortunately there were no serious accidents during the expedition, even though there were a few minor hazards that could have been more serious without the resourceful thinking and actions of the crew. The minor accidents and dangers faced by the crew included two fractures, rope burns, loose rocks, sprains, heat stroke, two small explosions, wild animals, group J, snakes and spam! All were coped with in true Raleigh style.

The expedition successfully fulfilled its objective of exploring a region where cave entrances had been seen but not explored and thereby added to the knowledge that the C.C.N.T. had of the area. This will enable them to plan the management of the new national park, especially with regard to the increased access for tourists with minimal damage to the environment.

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Limestone Karsts of the Annapurna Region, Nepal Himalayas

Tony WALTHAM

Abstract: The Annapurna region contains three units of limestone and karst — the Nilgiri Limestones of the high summits, the Jomosom Limestones further north with the famous holy springs of Muktinath, and the Holocene Pokhara limestone further south with its substantial cave development. The Pokhara caves are formed in limestones little more than 500 years old. Brief new observations add to the data documented by the British expedition in 1970.

Annapurna and Dhaulagiri are two of the world's 14 summits which reach over 8000m high. They are both formed of a very thick sequence of Ordovician carbonates, known as the Nilgiri Limestone after the 7061m summit lying between them. Except for a slice of limestone forming the summit pyramid of Mount Everest, the Nilgiri Limestone has the highest altitude carbonate outcrop in the world. Furthermore they can be traced down to the floor of the Kali Gandaki Valley, between Dhaulagiri and Nilgiri, providing a vertical range of about 5500m in the outcrops. This situation was enough to attract a British expedition to the Kali Gandaki Valley in 1970 (Waltham, 1971), but they found only impure limestones, limited karst and almost no caves.

There are also other limestones in the Annapurna region. North of the main range, Jurassic limestones form a series of ridges and outcrops around Muktinath, and south of the range there are Holocene limestones in the floor of the Pokhara Valley. Both these have been found to exhibit karstic features, with substantial caves in the latter (Waltham, 1971).

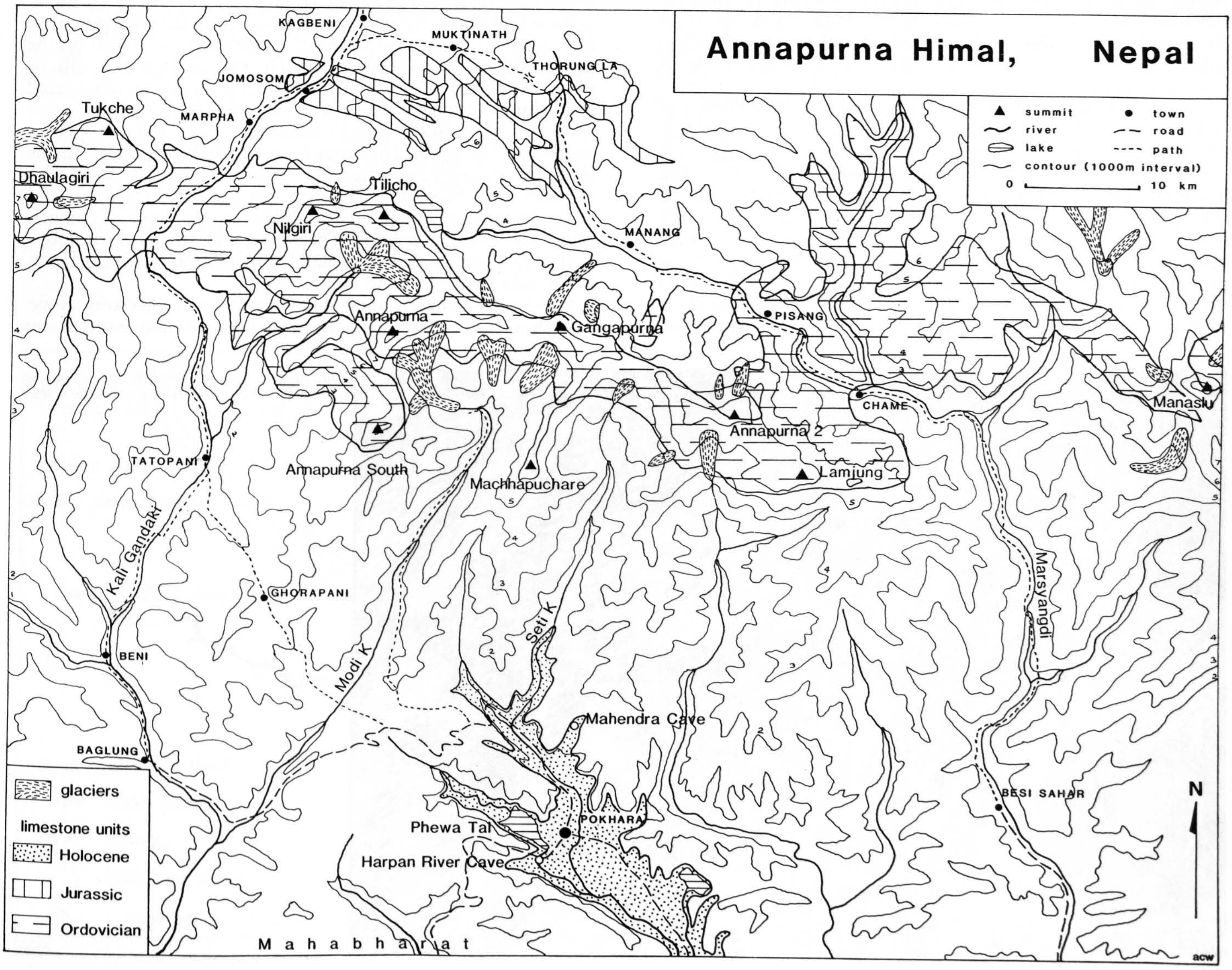
A recent walk round the Annapurna massif provided a further opportunity for brief observations of the limestones and karsts, including the outcrops in the Marsyangdi Valley and around Muktinath which were politically inaccessible in 1970.

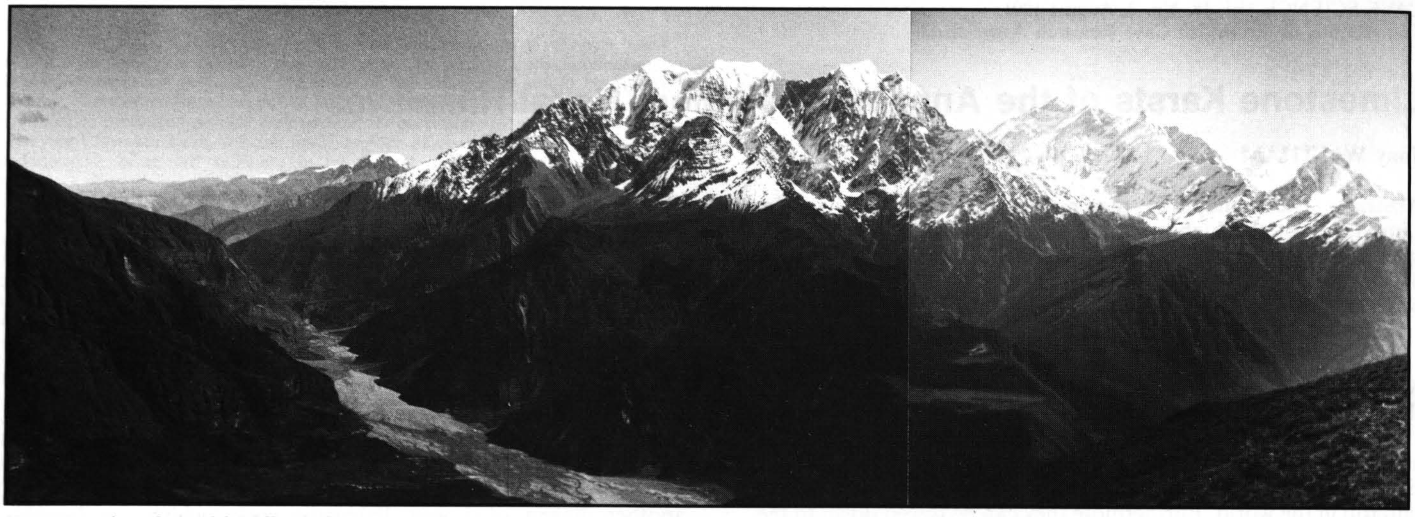
THE NILGIRI LIMESTONES

The Nilgiri Limestone is a 2000m thick unit of dominantly carbonate rocks, largely impure limestones and dolomitic limestones; it is of Ordovician age, and has been lightly metamorphosed with some recrystallisation. It is underlain by another 1000m of Lower Paleozoic rocks which are largely limestone but with thicker bands of reddish sandstone and more slatey facies; these were known partly as the Larjung Limestone (Bordet *et al,* 1967), but are later referred to as the Yellow Formation of Annapurna (Bordet *et al,* 1981). The boundary is not easily recognised in the field, and the two units are grouped together on the map (figure 1).

The main outcrops dip steeply north with massive recumbent folding; this repeats the strong limestones by stacking, to form huge thicknesses in the mountains of Dhaulagiri, Tukche Peak, Annapurna and Annapurna South (Waltham, 1972). These outcrops are breached by the graben faults of the Kali Gandaki, whose effect on the outcrop patterns is barely distinguishable at the scale of the geological map in figure 1. Further east, the limestones form the high ridge including the peaks of Gangapurna, Annapurna 2 and Lamjung, before a downfolded

Figure 1. Geological map of the Annapurna limestones. Topography largely after Mandalla trekking maps; geology largely after Bordet et al, *1981.*





View across the Kali Gandaki Valley, looking north and east, with Nilgiri (centre) and Annapurna (right) seen from the southeast shoulder of Dhaulagiri. Most of the viewed area is located on the Nilgiri limestones — except the lower right slopes on the underlying gneisses, and the far distant sandstones of the Mustang basin just left of the distant snow peak formed of the Jomosom Limestone.

zone is breached by the Marsyangdi River just above Chame. East of the Marsyangdi, the limestone outcrops are more convoluted as they reach to the summit of Manaslu (another over 8000m high) where they are cut out by a Tertiary intrusion of granite. The map (figure 1) is largely based on the published work of the French geological mapping programme (Bordet *et al,* 1981).

Karst features on the Ordovician limestones (both the Nilgiri and the Annapurna) are severely restricted for three main reasons: the carbonates are mostly impure with insolubles ranging from 15 to 35%; there is minimal vegetation on the high altitude outcrops, so that both carbon dioxide levels in percolation and run-off waters and also solutional activity are reduced; and, perhaps most importantly, the Pleistocene tectonic history of the Nepal Himalayas leaves outcrops only recently exposed in areas of extremely high surface erosion rates. These facts were all recognised in 1970 from field data collected in the Kali Gandaki Valley, and observations in the Marsyangdi Valley serve to confirm the concepts.

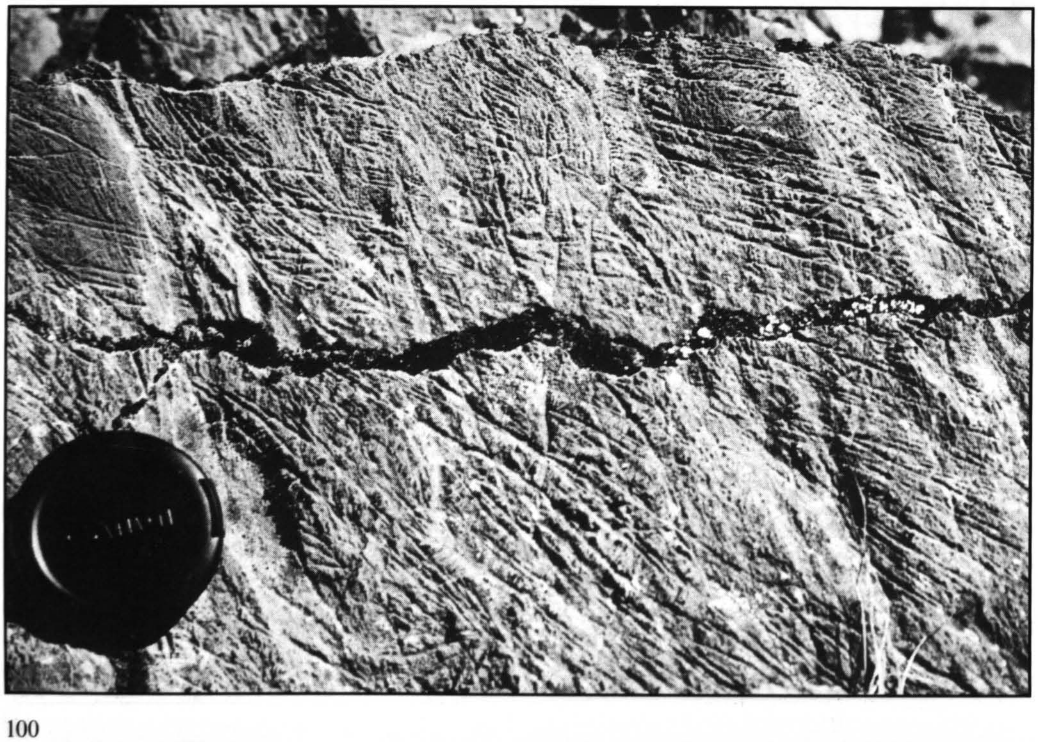
Between Chame and Pisang the limestones form high buttresses and steep walls along the Marsyangdi Valley. The tributary Nar Khola emerges from a limestone gorge of impressive dimensions, but no signs of karst are visible from the main valley. The limestone is massive but impure, and no karren were seen on the steep rock outcrops. Some Quaternary valley infills do have a tufa cement. One substantial resurgence was seen across the valley below Pisang; water pours from a small exit in the valley fill and probably emerges from a tufa cave similar to those at Kursangmo above the Kali Gandaki (Waltham, 1971). The likelihood of finding caves in the eastern outcrops of the Nilgiri and associated limestones seems to be as remote as it is in the Kali Gandaki Valley.

THE MUKTINATH LIMESTONES

North of, and stratigraphically above, the Nilgiri limestones, the Tibetan facies of various Mesozoic rocks are complexly folded and faulted behind the wedge of older rocks rising along the convergent plate boundary. The most conspicuous carbonates are the Lower Jurassic Jomosom Limestones, mapped by the French teams, forming a series of high rocky ridges rising to nearly 6500m just south of the Thorung Pass (figure 1).

Except for a few small fossil phreatic rifts exposed on the ridges above Jomosom (Waltham, 1971), no caves have yet been found in these limestones. Very small karren occur on the same outcrops, and microkarren were observed at an elevation of 5000m on the eastern slope of the Thorung Pass. The microkarren have rills, or solution grooves, only about 1mm wide; some are closely spaced with sinuous courses downslope, but others form more open networks at various angles across inclined surfaces cut in undisturbed bedrock. They may form largely by capillary tension related to evaporating water fronts; they characterise karst with minimal rates of solutional activity at high altitude or in arid zones, though they have been found in a wide range of climates (Ford and Lundberg, 1987). The Muktinath area is essentially a cold desert, almost devoid of natural vegetation or organic soils, in the rain shadow of the Himalayas.

Muktinath Temple stands below the end of a limestone ridge. At its heart lies the famous burning spring — a karst fissure issues



Intersecting sets of microrills on a sloping bedrock surface of the Jomosom limestone high on the Thorung Pass.

The karst rising from the limestone scree behind the temple at Muktinath; the resurgent water is channelled into the 108 carved spouts around the temple.

a small but steady flow of water (less than a litre per second), and from the same fissure natural jets of methane support small but perpetual flames. The water drains from the limestone ridge behind the spring, and the gas originates from carbonaceous animal remains in the adjacent Upper Jurassic black shales. The emergence of gas and water together is a coincidence guided by the rock permeabilities. Not surprisingly, the combination of earth, fire and water is held in some regard, and a small temple now sits on top of the spring (which is still visible below an image of Shiva). This is a major Hindu shrine attracting pilgrims from all over India, and the site also holds on adjacent Buddhist gompa. The common occurrence in shale nodules of golden (pyritised) fossil ammonities, known as saligrams, adds to the reverence accorded Muktinath.

Just 100m north of the burning spring, a larger spring supplies the water trickling from 108 carved spouts around the temple of Jiwala Mayi; with a flow of around 50 litres per second, this is also karstic, but no cave is visible, as the water emerges from an extensive scree at the foot of the limestone cliff.

The many cave openings in the valley sides around Muktinath, Kagbeni and Marpha, and further south in the Kali Gandaki Valley, are all only artificial excavations in the Quaternary valley sediments.

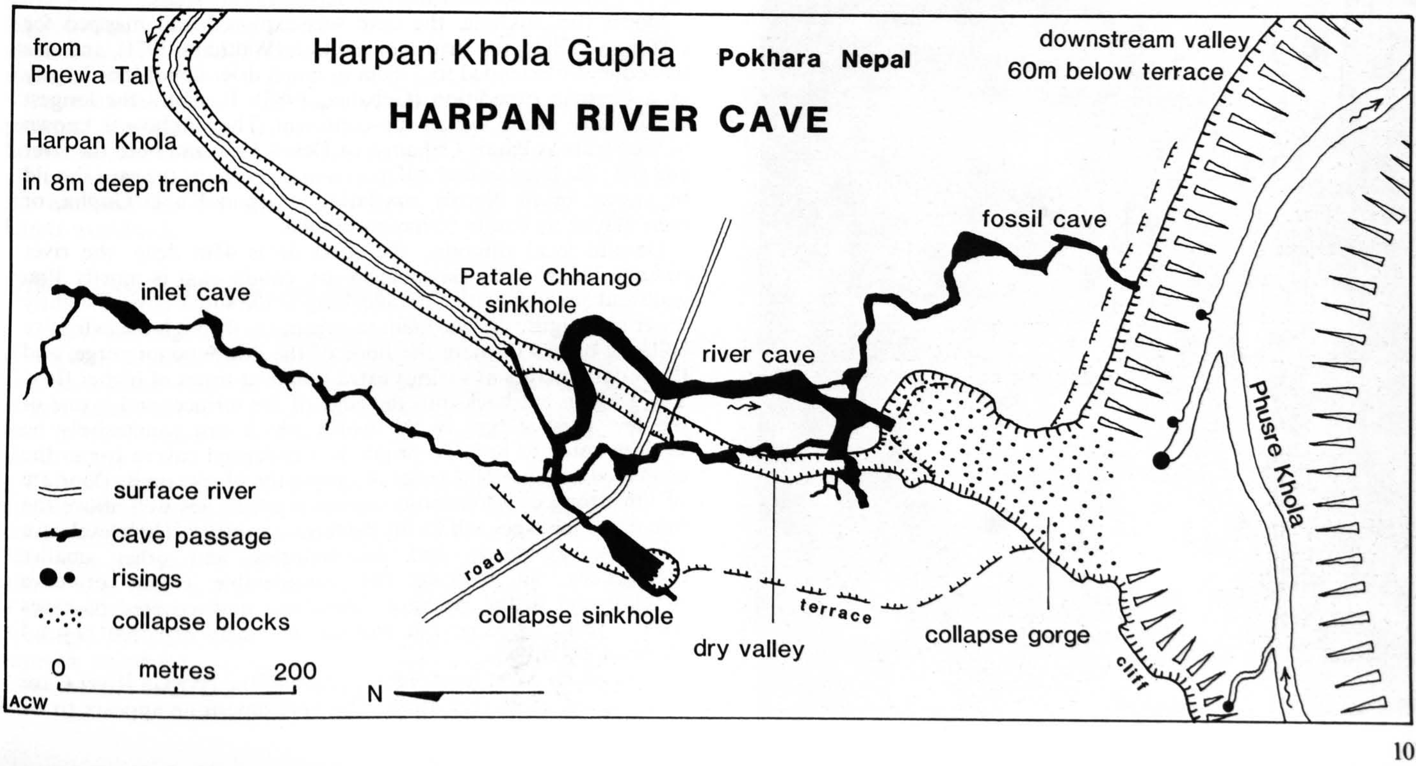
THE POKHARA LIMESTONES

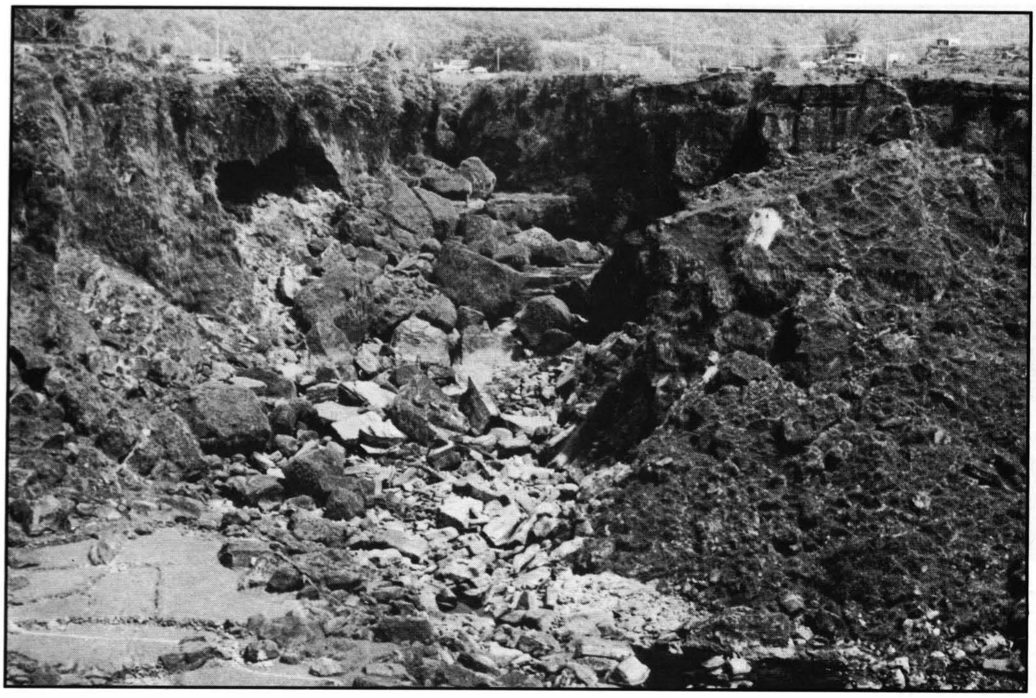
South of the Nilgiri limestones, bedrock is a complex series of metamorphic rocks, dominated by gneisses and schists but including bands of quartzite, marble and limestone. A small tourist cave is now advertised in an area of limestone crags along the Pokhara to Kathmandu road just south of Dumre; the Hinko Cave on the trail up the Modi Khola is however just a shelter beneath a massive boulder. The karst interest of the area is largely within the youngest sediments.

Quaternary sediments are features of most of the Himalayan valleys. Locally great thicknesses have accumulated behind Pleistocene moraines and later landslides. The greatest accumulations of all are behind the Quaternary uplift zone of the Mahabharat ranges, which the main rivers have to traverse between the Himalayas and the Ganges plain. The Pokhara basin was infilled by sediments from the Seti Khola and its tributaries. Subsequent incision and rejuvenation has left broad terraces in the Pokhara valley; the most extensive of these is the youngest and highest — the Pokhara Terrace, on top of the Pokhara Formation, which includes the Pokhara limestones (figure 1).

The detrital limestones of the Pokhara Formation have the visual appearance of sandstones, along with ripple-marking and

Figure 2. The Harpan River Cave and its collapse gorge. After surveys by Waltham, 1971, and Gebauer, 1982.



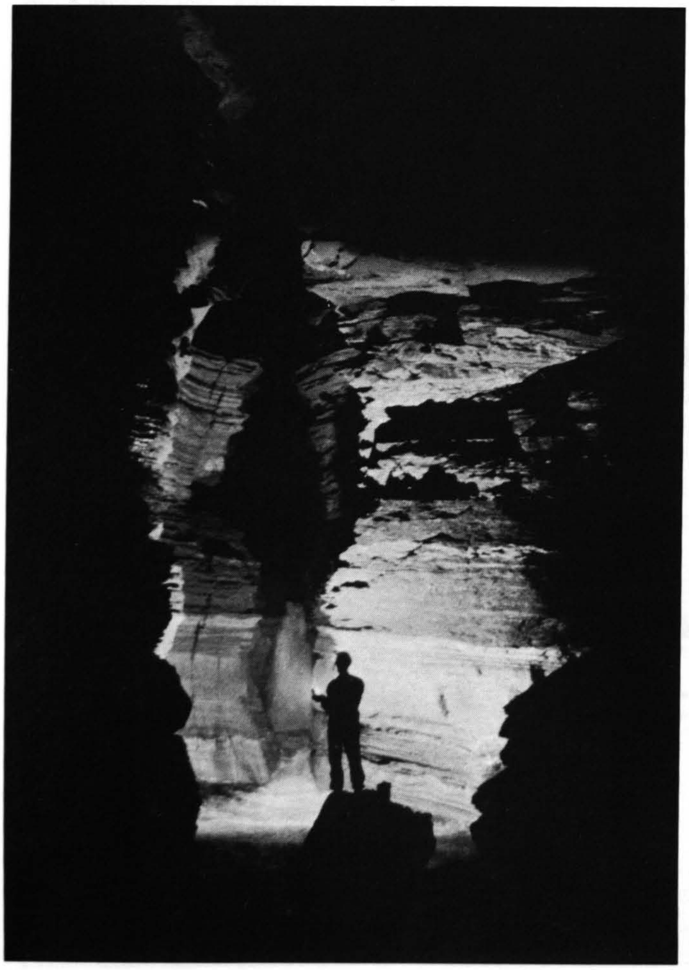


The collapsed cavern forming the downstream gorge at the Harpan River Cave, with the risings in the lower foreground.

cross-bedding and conspicuous conglomerate horizons. Though of very variable grain size and often poorly sorted their calcite contents are 45-80% (Waltham, 1971; Sharma, 1975) with little variation across the size ranges of the components. They are lightly lithified with secondary calcite cement, but are still very porous. The Pokhara limestones have an exposed thickness of at least 60m, and lie almost horizontally.

The Pokhara Formation appears to represent a fanglomerate of torrential debris flows, derived from the outcrops of the Ordovician limestones in the upper basin of the Seti Khola between Machhapuchare and Annapurna 2. Radiocarbon dating (eight analyses in three different laboratories) has yielded ages of 400-1100 years B.P. from included wood and peat (Fort, 1987). There is no recognisable age contrast between top and bottom of the bed, and it appears that the Pokhara limestones were formed in a catastrophic event. A seismicly induced failure of a debris dam upstream of the Seti Khola gorges, perhaps during a recorded 1464 earthquake, could have released huge volumes of saturated landslide and morainic material originally derived from the steep limestone slopes of the Annapurna range (Fort, 1987). Rapid filling of the Seti Khola valley would have impounded lakes in the tributary valleys around Pokhara; and this matches the historical legends of drowned villages now beneath Phewa Lake.

Main rift at the foot of the sinkhole in the Harpan River Cave.



The Harpan River Cave

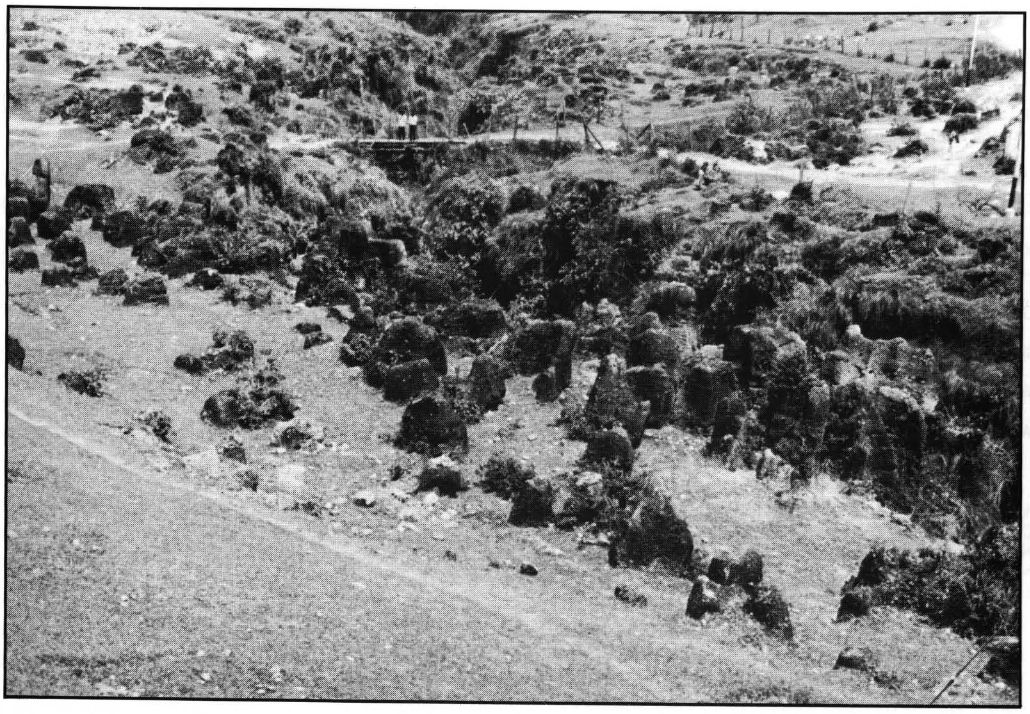
The largest cave in the Pokhara limestone is the Harpan River Cave, located just downstream of the spectacularly beautiful Phewa Lake, now fringed by the Pokhara tourist quarter (figure 1). The lake outlet flows for two kilometres through a shallow ravine cut in the upper conglomeratic limestone of the Pokhara Formation, and then plunges into a deep sinkhole beside the main road south out of Pokhara. The sinkhole is a tremendous sight when the river is in flood during the monsoon, but has only a small cascade down it for most of the year, since the lake water has been diverted through the Pokhara hydro-electric power station. It is now a tourist site, with an admission fee of three rupees, entered between lines of Tibetan craft stalls.

Down the sinkhole, the cave was explored and mapped for 1480m in 1970 by the British expedition (Waltham, 1971), and was subsequently extended to 2960m in much drier conditions largely by a German expedition (Gebauer, 1983). It is still the longest known cave in the Indian sub-continent. The sinkhole is known to the locals as Patale Chhango or Devi's Fall, and both the river and the cave have several different names; perhaps the cave should be known by its Nepali translation, Harpan Khola Gupha, or even maybe as Patale Chhango Gupha.

Despite local rumours, the sinkhole is 45m deep; the river passage below (only passable in dry conditions) is mostly 10m wide and 5m high, with a parallel loop to the south only of slightly lesser size (figure 2). The main resurgence is through the extensive collapse blocks forming the floor of the downstream gorge, and the water emerges at various extra points at times of higher flow. The gorge is cut back into the edge of the terrace, and is one of the few karst gorges in the world which can conclusively be demonstrated to have an origin as a collapsed cavern (or as the coalesced collapse of a series of caves); the blocks on its floor are of the strong conglomeratic limestone which lies well above the main cave passages and forms the terrace caprock. High level cave passages, tributaries and distributaries, and other smaller resurgences, all indicate the considerable extent of cave development in the Pokhara limestones; undiscovered passages almost certainly exist, but will not be easily explored beyond zones of collapse.

Perhaps the most remarkable feature of the Harpan River Cave is the speed of its formation. The host limestone appears to be

Dissected clints and pinnacles in the conglomeratic limestone of the Pokhara terrace; just beyond is the Seti Khola gorge, with the two men standing on the footbridge 50m above the river.



little more than 500 years old; the minimal lithification was probably almost immediate. Erosion started very soon after, concurrent with drainage and runoff into the open valley downstream of the debris mass in the Pokhara basin. Water in the Phewa valley ponded until it filled the lake, which survives until today, and then overflowed onto the limestone surface. Underground flow was initiated due to the very high primary permeability of the fanglomeratic limestone, perhaps aided by vertical desiccation or landslip fissures. The poor sorting of the granular limestone would also have permitted piping to take place, with fines washed out from between coarser particles. Solution of the limestone appears to have played no more than a subsidiary role in both the initiation and development of the cave.

Passage enlargement, within this time-scale, to diameters in excess of five metres, must have been largely mechanical. It is commensurate with the mean incision rates of over 100mm/year exhibited by the nearby Seti Khola over the 500 years of erosion in the debris flow limestone. The multiple levels and parallel passages within the cave system were probably formed almost contemporaneously. Incision of the Phusre Khola gorge downstream of the cave was initially rapid; once the cave outlet was close to its present level, the river passage would have taken the great majority of the flow, and is hence so much larger than the higher loops and distributaries. The relative depths of the surface trench above and below the Patale Chhango sinkhole suggest that continuous surface flow was maintained for only about half the erosional history; the cave appears to have reached maturity within 200-300 years of its initiation.

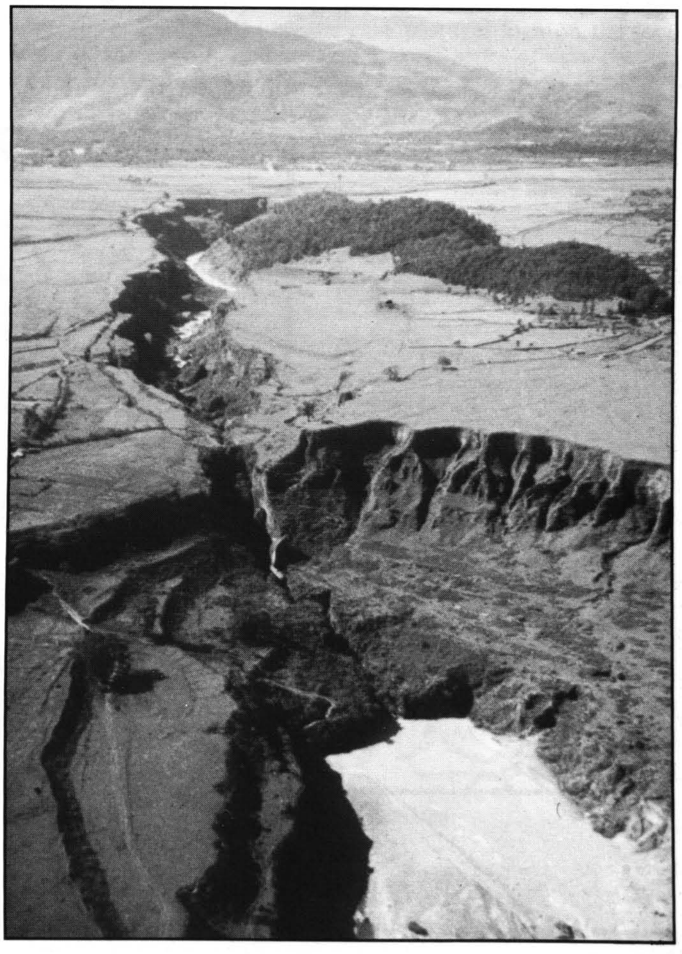
For both the extent of the cave system and the size of the main passage, the Harpan River Cave is probably the youngest limestone cave in the world. However, although the cave passages are of conventional morphology, both the limestone geology and the erosional environment are notably untypical of limestone karsts worldwide.

Other caves in the Pokhara valley

Caves are recorded elsewhere in the Pokhara limestones (Gebauer, 1983); all are only fossil passage fragments. Mahendra Gupha, located north of Pokhara (figure 1), has 240m of passage largely accessible as a showcave, and the Power Station Caves, east of the Harpan River Cave, have a total passage length of about 400m.

East of Pokhara, a series of rivers cross the main terrace and all are incised to various depths in the detrital and conglomeratic limestones. The Seti Khola is the largest river, and has cut a gorge 3km long just east of the airport. This increases in depth from about 30 to 60m, and is a remarkably narrow karstic slot gorge; a footbridge only 8m long spans it over 50m above the river. Sections of the river are invisible beneath huge blocks of fallen caprock conglomeratic limestone, and the lower end (seen only from the air) is very narrow, almost certainly with the river in a cave with a bedrock roof for about 100m. By analogy with the Harpan River, caves may well exist in the deeper recesses of the gorge, but none has yet been seen from the rim. Any exploration would be suicidal during the summer monsoon, and, being downstream of the town, could be medically hazardous in the dry season; there must be better caving elsewhere. Near the footbridge, the conglomeratic limestone along the gorge rim has been carved into a heavily dissected karst pavement, with some remnant clints and pinnacles standing up to 5m high. All the gorges further east appear to be much smaller, and certainly have less depth where crossed by the Kathmandu road; more caves may exist, but outward signs offer little encouragement.

Air view of the downstream end of the Seti Kola gorge, where the river appears to go underground for at least a short distance.



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The Karst of the Anamas Daglari, Anatolia, Turkey

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Abstract: During the summer of 1989, ten members of Sheffield University Speleological Society made a reconnaissance of the Anamas Daglari in southern Turkey. The area was found to contain numerous karstic features and much small-scale cave development, including Civ Magara which reached −238m, the eighth deepest cave in Turkey. The following report results from studies which attempt to relate the present day topography with long-term speleogenesis.

The Anamas Daglari comprises a series of mountain peaks rising to over 2300m asl, situated about 100km north of Antalya. They form the northern-most reaches of the Taurus Mountain Range, bounded to the east by the flooded polje of Beysehir Golu and to the west by Egridir Golu. The small tourist town of Egridir situated on the lake's southern shore serves as the access route into the expedition area. The road climbs from here up through pine and cedar woods passing through small cultivated plateaus, with the 1500m Anamas Daglari forming the backdrop to the east.

The small village of Aksu lies at the entrance to Zindan Gorge which cuts up into the flanks of the mountain. The road deteriorates to a stony track as it follows the river in its deep gorge. An ancient stone bridge leads over the river and to the entrance of Zindan Magara, a local tourist attraction. One of our new friends took us on a typical torch-lit trip into the cave, telling us the usual stories of near catastrophe as locals and tourists were taken unawares.

The Aksu plains and Zindan Gorge are cultivated by the villagers. In the summer months, according to long tradition, nomadic families return to grazing pastures on the high plateaus (yayla) on the Anamas Daglari, thus escaping the searing heat on the Anatalyan coast. The scene is idyllic, especially as the people are some of the most gregarious and relaxed imaginable. Life is beautifully simple and as such, luxurious.

Geological setting

The Taurus Mountains were uplifted during the Hellenide orogeny associated with the closure of the Tethys Ocean in Late Miocene times. Thrust slices form a southward concave configuration of tectonic units, known as the 'Isparta Angle' (fig.1). The study area is situated near the northern tip of this structure. In this region the basinal Mesozoic sedimentary rock slices are stacked up against the south-west edge of the carbonate massif that forms the mountain karst of the Anamas Daglari (fig.2). The massif was thrust south-westerly during the Eocene, over-riding the earlier thrust nappe in a period of renewed crustal compression (fig.3). This latter thrusting caused widespread folding and faulting in the already well-consolidated sparry limestone block, and spectacular deformation within fine-grained clastics of the lower Jurassic. The karst in this region exhibits a number of distinct forms, related to the regional geology and Quaternary climatic change.

RIVER VALLEY KARST

Platform edge limestones of thrust sheet A are dissected by three NW-SE fault orientated valleys. The interveining mountain peaks are steep with slopes of up to 65°. Two of the valleys are dry hanging valleys, relics of the earlier drainage pattern of the area.

The third valley is down-cut a further 100m. It is developed along a prominent fault with a downthrow to the east of at least 200m, separating the River Valley Karst from the Mountain Karst to the east of this fault. Two tributaries of the River Zindan have carved a narrow gorge. The northward flowing tributary is dry during the summer, though obviously carries much greater volumes during the spring thaws. The second tributary flows abundantly all the year round fed by resurgences rising along the east side of the large alluvial plane of Sorkein Alani (low lying plane). The lake that once was contained in the Sorkein depression may have been pro-glacial, drained during the regional lowering of water-table associated with the onset of a more temperate climate. The rapid down cutting of the river following the breach of the lake wall and its bisection of the former valleys indicate that the passage of the waters were barred by ice and that the discharge spread over the broad area which is now the head of the Zindan Valley. Later fluvial erosion has cut gorges truncating many small phreatic cave passages high on the rock walls of the canyon, and causing a lower series of cave passage and by-passes to develop in other systems (figs. 4, 6).

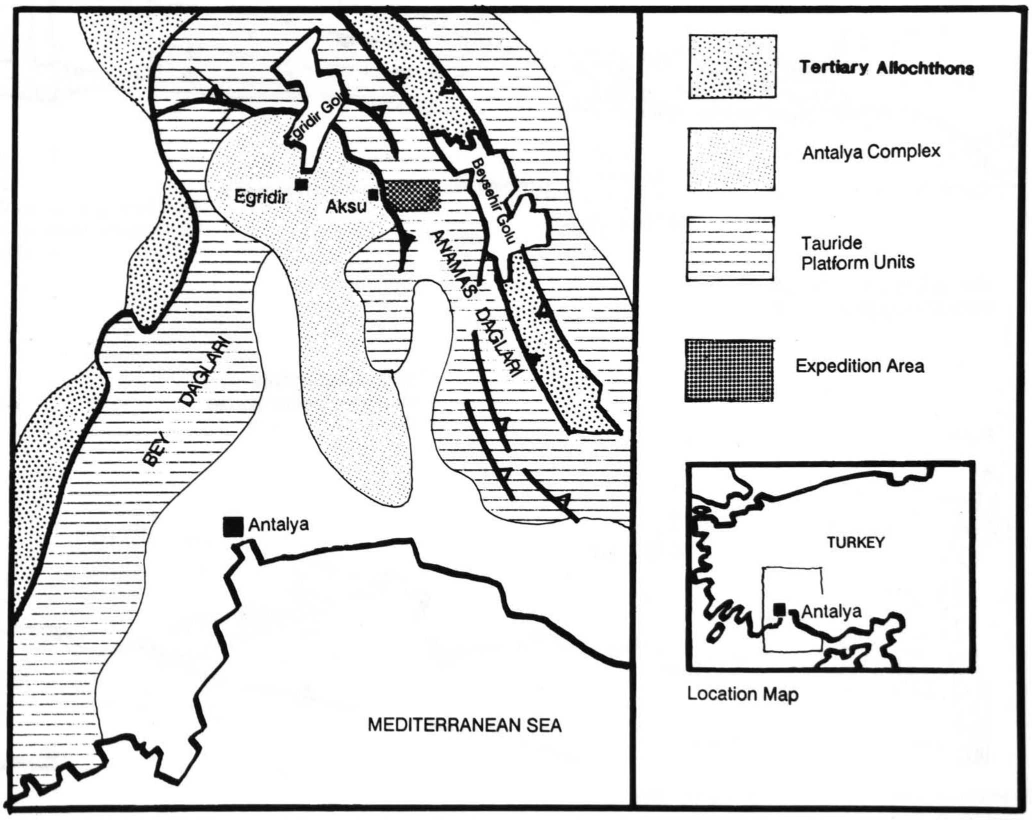


Figure 1. Structural units of the Isparta Angle.

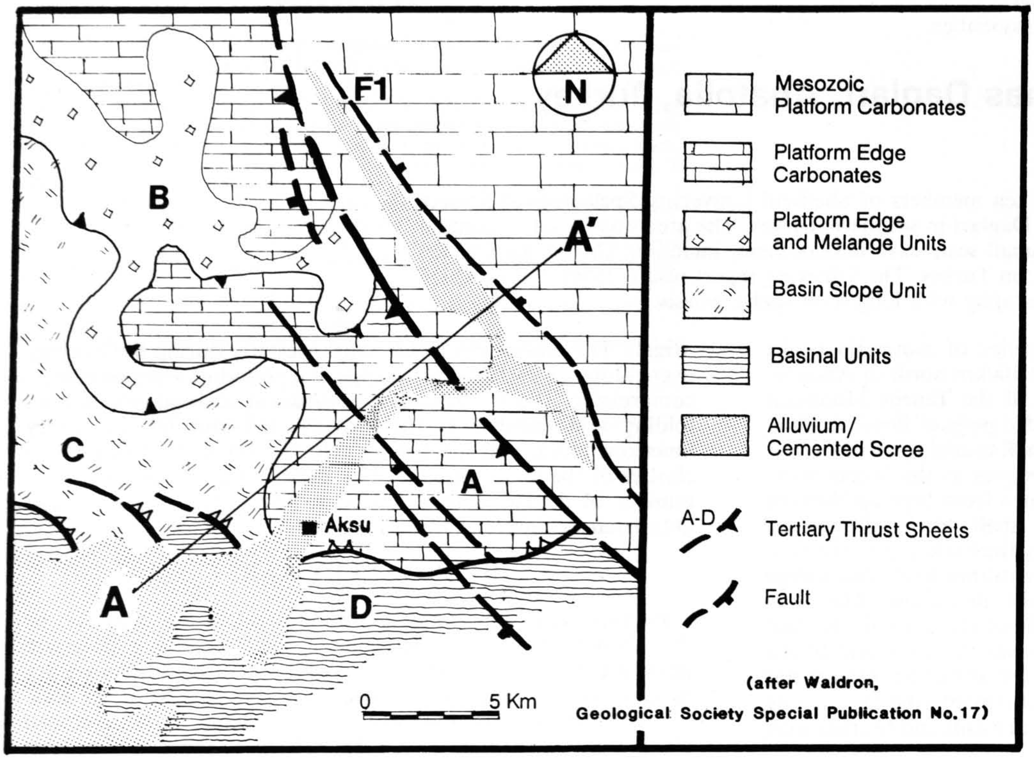


Figure 2. Simplified tectonic units of the Aksu region.

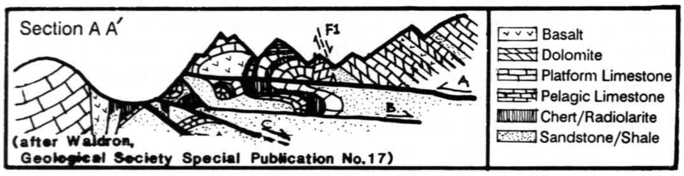


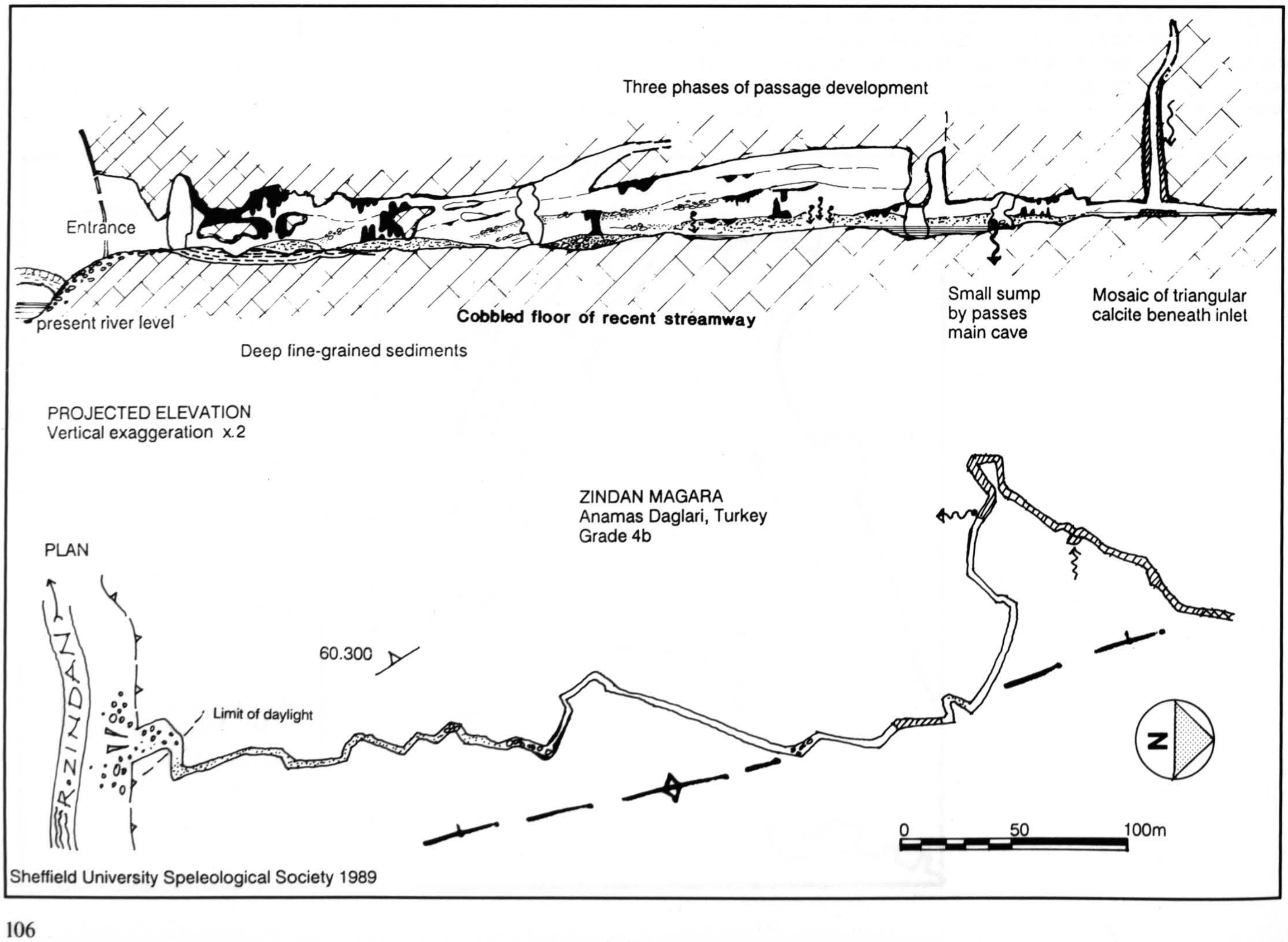
Figure 3. Diagrammatic section along the line A-A' on Figure 2.

Speleogenesis in River Valley Karst

All the caves seen in this area are resurgence caves with entrances 5-8m above the present water/plane level. Small springs seep into the river less than one metre above the summer water level.

Cliff terraces and patches of cemented scree indicate that the water-table lowered to its present level in a number of discrete stages perhaps associated with a more active hydrologic regime than present. The river-valley caves show three or more stages in

Figure 4. Plan and elevation of Zindan Migara, Anamas Daglari, Turkey (survey by Sheffield University Speleological Society 1989).



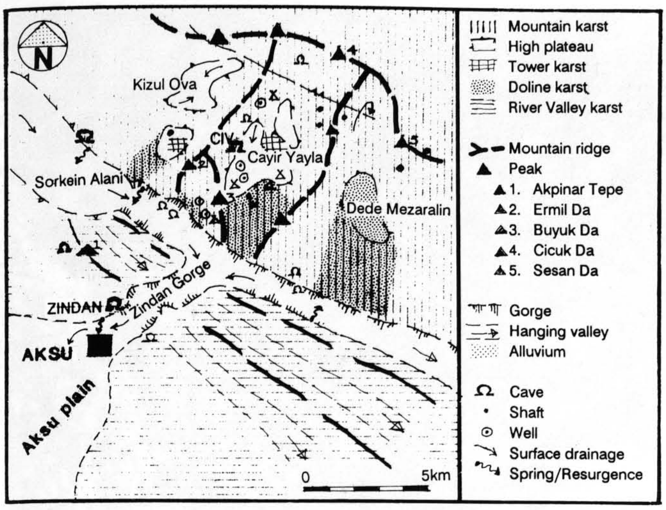


Figure 5. Sketch map of the geomorphological features of the Aksu region.

vadose passage development in post-glacial times, as seen in Zindan Magara (fig. 4). The latest stage in Zindan Magara is that with the falling water-table and the diminished volumes of water flowing through the system in Quaternary times, the stream in Zindan Magara now sinks close to its aven inlet, entering a renewed phreatic stage effectively fossilizing the vadose section of the cave. Sorkein Magrasi (fig.6) shows much less vadose rifting, though it too cuts down sharply to resurge on the plane.

MOUNTAIN KARST

The Anamas Daglari mountains reach over 2300m asl and correspond to the up-thrown eastern block of the large valley fault (F1, fig. 2). The moderate hillslopes reflect the homogeneous nature of the platy platform limestones that compose the mountain range. The bedrock is often exposed as heavily dissected pavement, with a slabby scree cover less common.

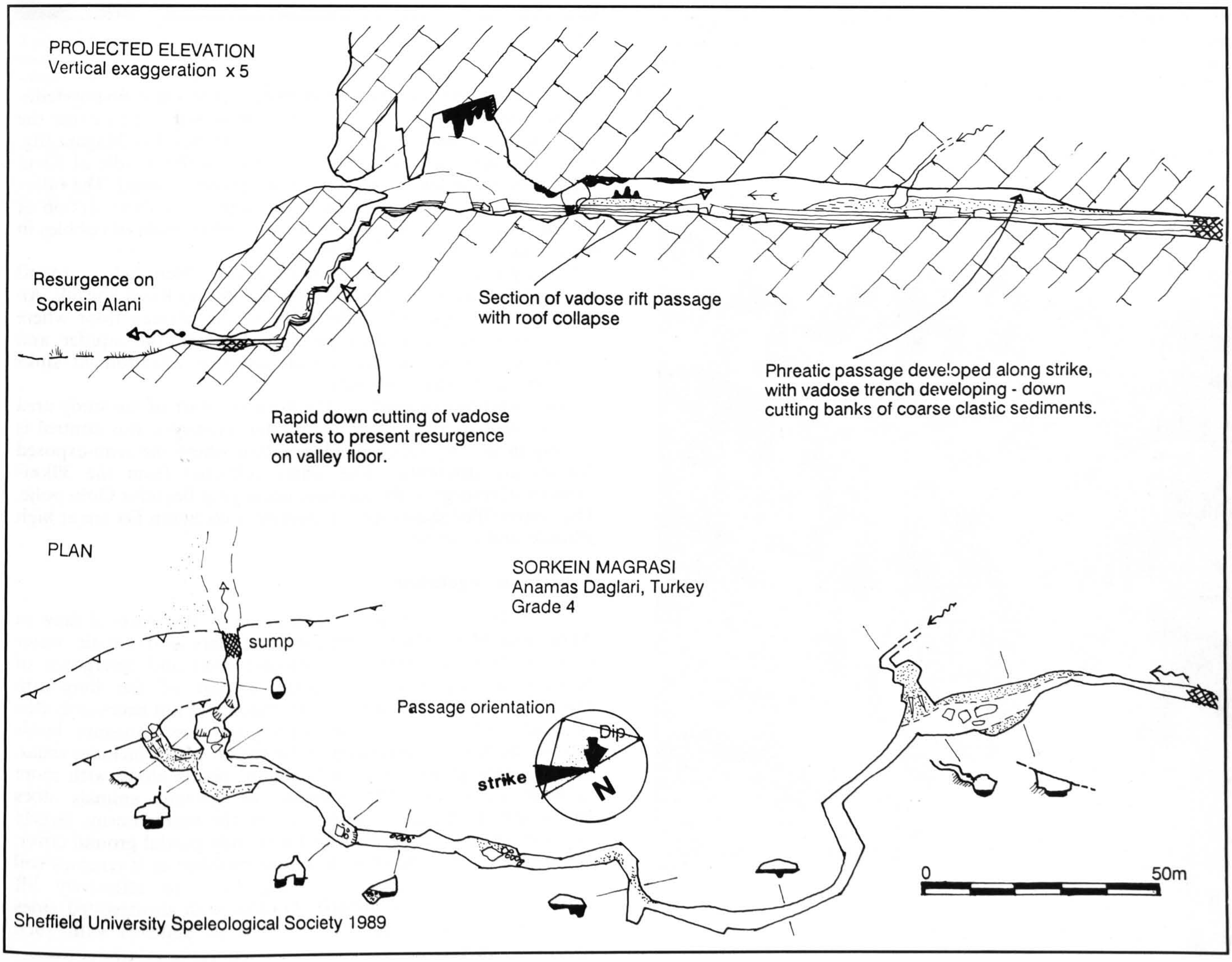
High plateaus ('yayla') lie amongst the gently rising lines of peaks. They tend to be linear features up to 10 square kilometres; apparently related to a single 8m ferruginous sandstone and conglomerate horizon, interbedded within the sparry carbonate sequence, known as the Cayir Sands. These clastic rocks are the main aquifer of the area and many wells mark its outcrop. The yayla have a red light textured soil cover, often developed for depths greater than one metre over the limestone bedrock. A variety of characteristic karstic features are exposed as erosion of the superficial layer proceeds.

Just beneath the plateau floor, close to the surface of the bedrock, is a network of small phreatic tubes of less than 20cm diameter which run along the plateau axis. There is no vadose trenching, implying that these conduits are only operational when the karstic water table is full; to carry massive surface run-off and spring melt waters. Courses of imbricated pebbles mark ephemeral streams which also run along plateau axes.

Infiltration of precipitated water etches a sub-surface pavement of clints and grikes, and individual blocks are separated by preferential erosion. Sub-aerial erosion of soil cover is speeded by the pressures of livestock, whose continual trampling and close grazing reduce the vegetative cover drastically, exposing the bedrock. Karren features, clearly sub-surface solutional erosion features, are modified by sub-aerial mechanical erosion which includes the pitting and fragmentation of raised pavement 'islands' on the plateau floor. Sub-surface solutional features are still very clear — perhaps indicating the speed at which the present plateau levels are being lowered.

As a continuation of these processes doline karst is developed within broad depressions, along mountain flanks and plateau margins. Doline fields seem to have developed in dolomitic limestones and strong conjugate joint-sets associated with the river valley fault (F1). Their formation may also be connected

Figure 6. Plan and elevation of Sorkein Magrasi, Anamas Daglari, Turkey (survey by Sheffield University Speleological Society, 1989).



with the glaciation of this upland region when ice sheets would have gouged and filled the valleys. The doline fields are seen up to 50m above the plateaus and 150m above the Zindan gorge.

Isolated groups of tors are seen in small plateaus or as intermediary features beween plateau and ridge. It would appear that jointing is less dense in these areas or that the limestones are generally less permeable and that deeper percolation of karstic waters has etched-out these large features. One particular group at the junction between Saralan and Kizul Kurulik yaylas shows two discrete top heights between 1-2 metres — that perhaps correspond to the successive stages of plateau floor lowering. Pavement islands are particularly prominent in their close proximity and it would seem that the islands are due to be future groups of tors, whose top height should be about 4m below the last set of tors to be formed.

The Saralan-Kizul Kurilik tors and Bykuk Da doline fields are at similar heights on the west and east ends of Saralan yayla. This relationship highlights the diminishing intensity of fracture away from the major valley fault.

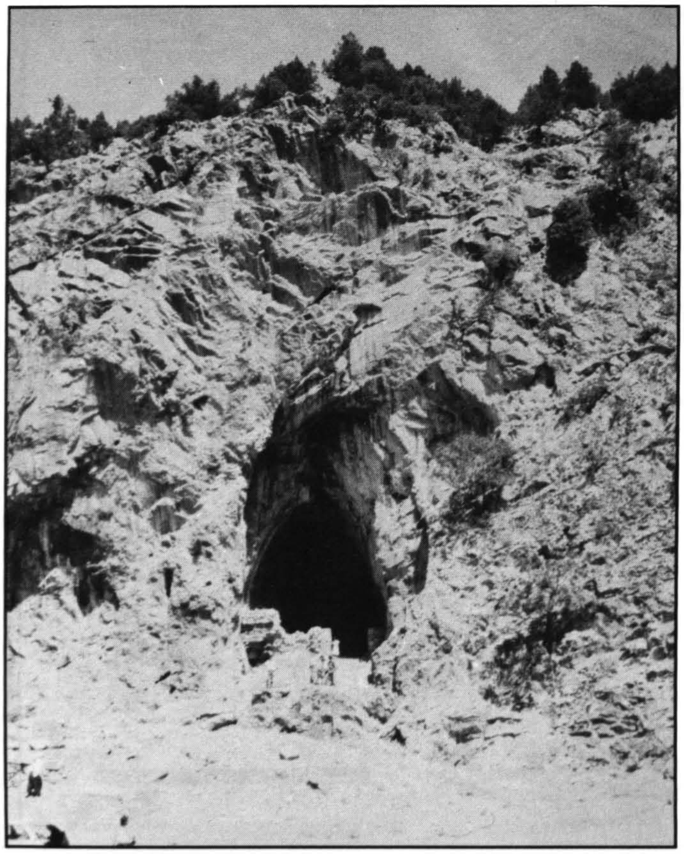
The exhumation of bedrock illustrates the topographic response to Quaternary climates. Dehydration is a prime characteristic of interior continental climate and is here accentuated by high altitude.

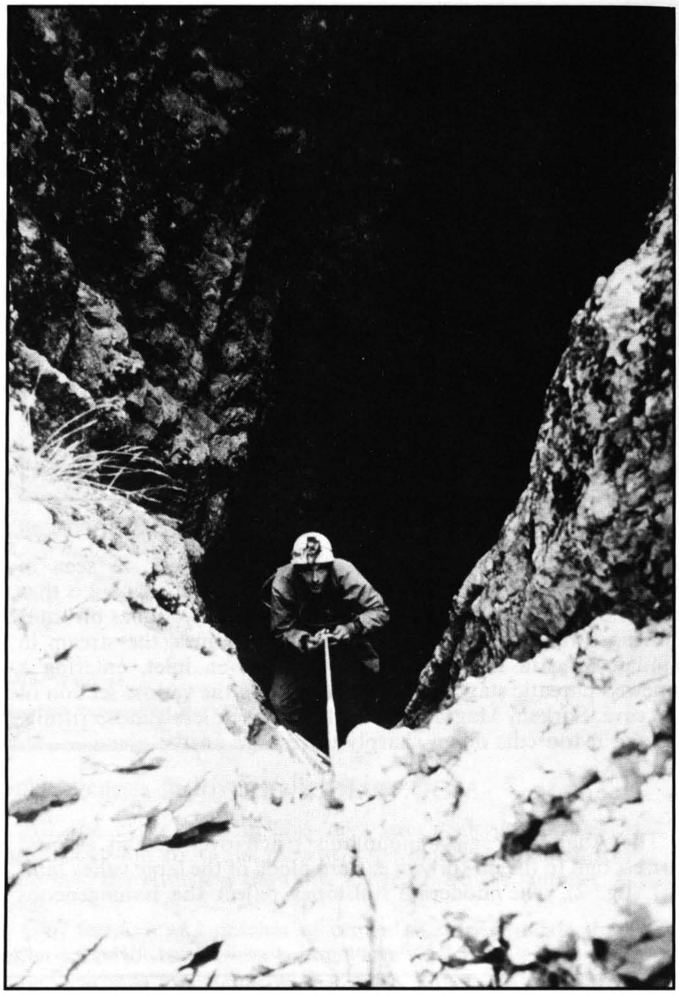
Speleogenesis in Mountain Karst

Truncated cave passages include large chambers approximately 2000m asl and are the remnants of the oldest cave systems of the area. Abundant decaying speleothem suggests a greater rock cover and/or soil cover and that they were formed when the topographic surface was considerably higher to accomodate drainage basins etc. Small rock-shelters and the remnant horizontal cave passages seen at the base of tors up to 3m above the level of the surrounding yayla are thought to be the phreatic stages of these high altitude caves. Shafts seen on Akbel Dag at similar altitudes do not seem to be active but may represent the earliest response to hydrological change.

The active caves of this region are found around 1800m asl and are characterized by vertical development as waters rapidly down cut to the karstic water table. The enlargement of passage is largely mechanical, occurring in the autumn and spring-times, when annual rains and thaws occur. Substantial snow traps are commonly found at the base of entrance shafts where a temperature inversion allows the snow to remain until late summer or even until the heavy rains of the autumn arrive. The persistance of these snow traps would seem to imply that the entrances are no longer the active entrances to these cave systems.

The entrance to Zindan Magara, with the ruins of the ancient Turkish baths.





Entrance pitch of Civ Magara.

The extent of the vertical development is impeded by either the Cayir Sands or underlying dolomitic limestones. Civ Magara (fig. 7) is the deepest of these pots, is situated in the middle of Kizul Kurilik yayla on the eastern side of an emergent island. The valley has a drain to the south, seen by scallops on a short section of ancient phreatic passage way and from imbrication of cobbles in ephemeral streams (fig. 7 inset).

Small phreatic tubes developed less than 20cm below ground level channel water to the sandstone aquifer on Kizul Kurilik. An 8m gash has appeared in the soils on the plateau floor where waters sink at the faulted junction between the aquifer and limestone. Above the active sink are two abandonded sinks perched on the steep hill-side.

The hydrology of much of the northern part of the study area is controlled by the sandstone aquifer. However, this control is lacking in the dry valley of Dedemezan where the semi-exposed dolines are dolomitic. The water collected from the 30km^2 depression resurge in the salt lake occupying Beysehir Golu polje. The debris filled shafts seen in pavement on Sesan Da are at high altitude and inactive.

A note on vegetation

The hydrological regime is dominated by the seasonal thaw in April and May which replenishes aquifers and karstic water reserves. General lowering of ground level and emergence of bedrock as limestone pavements is part of the long-term geomorphological evolution of the region and not necessarily due to over-grazing. High temperatures and low moisture levels dictate the natural vegetation of the region which includes cedar, juniper, wiry grasses and 'pin-cushion' plants along with more familiar calcicoles. The pressure of grazing animals does encourage an increased proportion of the more thorny, largely inedible xerophytic plants, which give only partial ground cover. Wind erosion then becomes a serious problem as it removes soil from around the plants, allowing them to effectively lift themselves out of the ground. Gulleys with unvegetated sides reaching several metres are observed in plateaus with such modified vegetation.

Gulleying and pin-cushion bushes blowing in the wind are then seen to indicate an instability — caused by sheep and goats exacerbating the delicate natural balance of the mountain ecology and shall not be discussed further here. The good agricultural management of the plateaus is vital to the livelihoods of the nomads (gocebe), so that the balance between human and slock requirements, and the natural resources is constantly under pressure. Small scale desertification is occurring on Cayir Alan yayla, where the limestone bedrock is exposed to the daily tramp of hundreds of feet during the dry summer. The imminent construction of a road over Cas Tas Dag will bring motorized vehicles onto this already unstable area. Once completed additional problems will arise from the increased numbers of people of the yayla, such as sanitation, litter disposal, but far more importantly the increased usage of the yayla will cause devastating erosion. The erosion will be to the great cost to the land and its people.

CONCLUSION

The high altitude mountain region of the Anamas Daglari marks the climatic border between Mediterranean and continental interior types. The topography was modelled by glaciation in Tertiary times, and has only been subject to this climate in recent times. Thus surprisingly the large-scale topography is the result of glaciation, with only surface weathering the result of the present climate. Cave surveys and altitudes add hydrological detail to the regional geomorphology.

ACKNOWLEDGEMENTS

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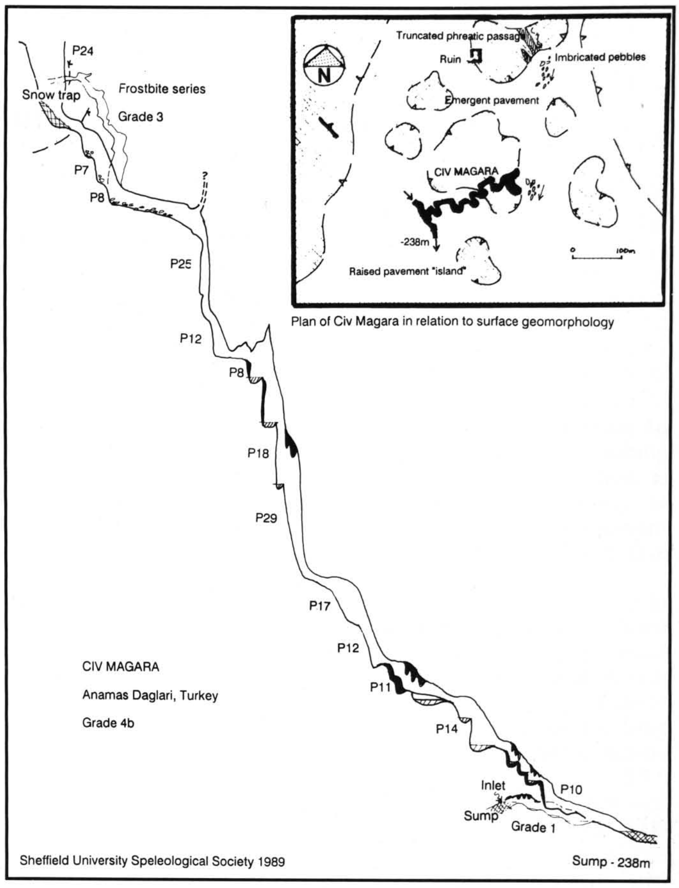

Figure 7. Elevation of Civ Magara, Anamas Daglari, Turkey; inset plan of Civ Magara in relation to surface geomorphology (survey by Sheffield University Speleological Society, 1989).

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Artificial Anchors for the Present and Future

John GANTER and William STORAGE

Abstract: Over the past 20 years, cavers have increasingly depended on artificial anchors ("bolts") for rigging points within caves. Many of these fixtures are now deteriorating. We consider the requirements for safe anchors, and present a tutorial on the mechanics involved. Corrosion and poor placement affect reliability, and are thus more important than initial strength. We show how the available anchors compare, and give suggestions for choosing among them. Finally, we discuss the ethics of artificial anchors and present some suggestions for consideration.

If caves are to be maintained in natural condition then visitors must try to minimize their impact. We tolerate minor exceptions to this rule that will return relatively large rewards in terms of more documented passage, or a reduction of hazard. The exceptions are most obvious in vertical caving, where either exploration or visitation may require artificial anchors to be placed for rigging. There are analogies to the physical infrastructure (roads, bridges, etc.) that is built and maintained for the common good. Our intent here is to provide some reliable advice on where and how these investments are appropriate and how they should be maintained. An important theme is that of false economy: cheap materials and/or laziness will waste effort, will result in more damage to the caves, and can result in hazard.

We began with three simple observations:

1. At some percentage of vertical drops there is no way to secure ropes to existing cave features to minimise abrasion, and thus artificial anchors must be installed;
2. Artificial anchors will deteriorate over time, particularly if they are not maintained properly;
3. Cavers can come to rely excessively on artificial anchors, placing them even where natural anchors exist;

From here we tried to assemble information that would help the caver to make responsible decisions. This is an account of exploration. What resulted was a complete re-assessment of both the published English-language literature and our own beliefs. The result is that we may have to reconsider how we build our infrastructure in the future, and regard past investments with increasing caution.

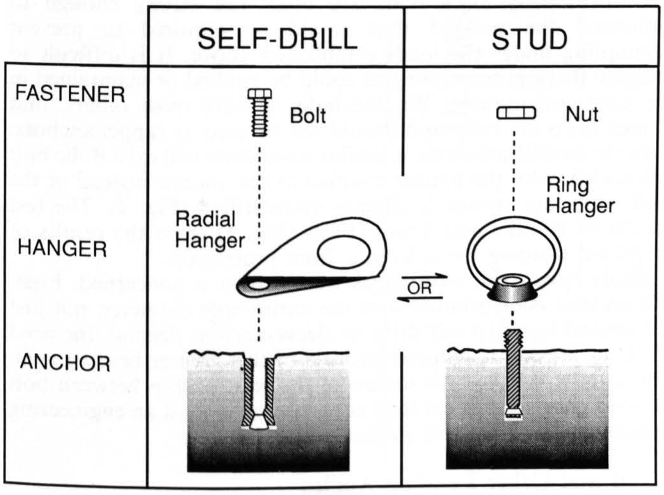
TRENDS IN ARTIFICIAL ANCHOR TECHNOLOGY

Why is the population of anchors increasing, and what will the effects be as this population ages? Which anchors will be most reliable for which applications? To consider these questions, we must first examine two trends.

The Increased Availability of Anchors and Hardware

Over the past 10 to 15 years there has been a gradual increase in the number of artificial anchors used in caving. The reasons are numerous. In part, we are pushing more difficult caves further. In part, we are more aware of expedition caving and aid climbing where artificial anchors have played a large role. And there is definitely a difference in availability: anchors, a variety of hangers, hammers, etc. are all available from caving equipment dealers. So there is much more chance that "Joe Caver" will have a "bolt kit" and use it.

Figure 1. The two basic categories of artificial anchors, and related terminlogy.



In the early 1970s increased availability resulted from interest in rock climbing. Petzl and Troll marketed products aimed specifically at cavers. To understand these effects, one must consider the vertical caving techniques of continental and British cavers. The earliest experiments with SRT occurred in France during the 1930s and 1940s, but ladders (and winches for long drops) were favored into the 1960s (Worthington, 1989). Alpine conditions, cold water and thinner ropes have since given SRT and artificial anchors a major role. This approach has allowed small teams to push cold, remote caves to depths of over 1000 meters. When the same approach has been attempted by less competent cavers in heavily-visited caves, there have been problems with poorly placed, deteriorating or simply unnecessary anchors.

Rechargeable Hammer Drills: Painless Drilling

The second important change is the introduction of battery-powered hammer drills. According to Peter Ludwig (1988) the original AC-powered hammer drill was developed by HILTI Company of Liechtenstein. This was superior to the traditional "impact drill" incorporating a rotating serrated disk that alternately pushes the drill bit forward as it turns. It was necessary for the user to push the impact drill hard to make it work. However, the hammer drill has a solenoid that operates a pneumatic cylinder to hammer at about 4000 impacts per minute (Hilti, 1989). It puts most of its energy into impacts (about 1 Joule each), and it does not have to be pushed hard by the user (Gebauer, 1986). After HILTI's patents expired, it was Bosch of West Germany who produced the first DC (battery-powered) hammer drills. Others, including HILTI, quickly followed.

Using a rechargeable hammer drill, a caver can set an anchor in less than a minute and a power pack will last for 10 to 20 holes (depending on various conditions like rock hardness, ambient temperature, etc.) Clearly this 4 kg tool has the potential to change the way in which we cave, because it makes placing artificial anchors so easy.

Effects of the Trends

The result of these two trends is that we have to re-examine what we know about anchors and how we use them. Due to the marketing and convenience, we have tended to use self-drill anchors over the past 10 years ("self-drill" refers to anchors which have drilling teeth on them; they are both a disposable drill and an anchor). For drilling holes by hand, self-drills are the choice of many experienced cavers. Other "sleeve-type" anchors with internal threads are also in common use. But these are all turning out to be more prone to deterioration than might have been expected. Interestingly enough, they have long been out of style for surface climbing. Now the hammer drill provides the opportunity to drill holes easily, even with awkward orientations. Should we set other anchors that will last longer? In what orientation should anchors be set? What hangers should be used?

Footnote: This is an adapted and updated version of an article that first appeared in the NSS News (National Speleological Society USA) 48:5, May 1990, pp.120-128.

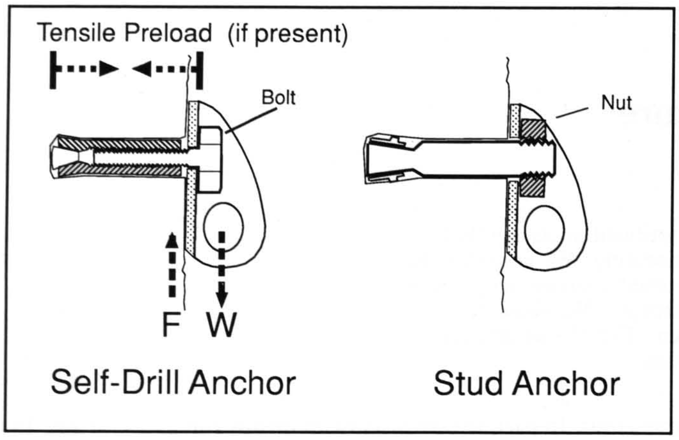


Figure 2. Idealised self-drill and stud anchors in tight holes. Axial preload enables the rock/hanger interface to oppose the load applied by the rope (W), with friction force (F). Note that the self-drill anchor is optimally placed just below the rock surface.

OBJECTIVES FOR ARTIFICIAL ANCHORS

What is an Artificial Anchor?

To begin, anchors fall into two broad classes. Each is a metal fitting that goes in a hole drilled in rock (Fig. 1). The self-drill has teeth that allow it to first be used as a drill. An expander cone is then placed in the open end, and the anchor driven home. A set screw, usually called a "bolt," attaches a hanger to the anchor and the rock surface.

Hangers connect the caving rope to the anchor. This is usually through a carabiner or Rapid-link, although some hangers support the rope directly. Hangers are of two basic types: those that are radially loaded and those that are omnidirectional.

The stud is driven into a hole drilled with a bit. Some type of protrusion then acts as a barb to keep it from being withdrawn. The end of the stud is threaded, and a nut is used to hold the hanger against the rock. There are variations and hybrids on these themes, but this is sufficient for general discussion. Later, we will give a more complete classification of anchors.

What is a Safe Anchor?

To be safe, an anchor must provide not just a place to hang the rope, but also for the avoidance of hazards. A good anchor allows the caver to be on rope while staying away from features of the cave which are judged to be hazardous: sharp and/or abrupt lips, loose rocks, water, etc. It should be strong enough to take the dynamic loads that would result from failures of other equipment or errors on the part of the cavers. And it should be reliable for users who do not know its history, and who may be less competent than those who installed it.

To be reliable, the placement must minimize susceptibility to deterioration if the anchor is left in place. Both the anchor design and the anchor placement must be damage tolerant. The strength of a newly placed anchor is almost irrelevant. More important is the strength of the aging anchor and the detectability of its deterioration.

How strong should an anchor be?

Anchors, artificial or natural, should be at least strong enough to hold the maximum loads that a caver could survive. Eavis (1981) suggests 1200 kgf as a maximum force survivable in a harness. (This force would be exerted by a 77 kg person taking a 15.5 g fall, i.e. decelerating at 15.5 times gravity). For very short durations, accelerations of 35 g's have been survived, but 15 g's is an accepted limit where the back bends forward to limit motion (Damon and Stoudt, 1966).

A BRIEF MECHANICS TUTORIAL

Loading

Judging the quality of an existing anchor requires some knowledge of the mechanics of the system. When the anchor (except for the adhesive types discussed below) is secured in its hole, a large compressive force is developed along the anchor-rock interface. This force provides the friction that resists pullout (axial direction, tensile force). The importance of a tight fit for pullout loading is thus obvious.

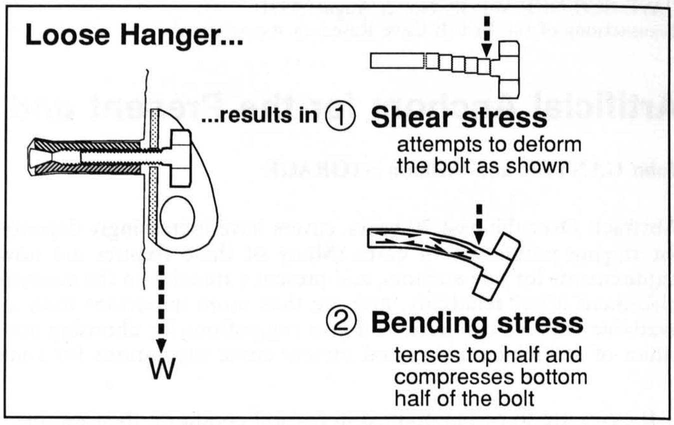


Figure 3. A self-drill anchor with a loose hanger resulting from a lack of preload. The hanger bears on the bolt directly. If the hanger is thin, the bearing stress is very high. Shear and bending stress also occur, and result in extension and compression within the screw. There is no pure axial tension.

The rock stress from this compressive force exists with no applied load. If an axial load is applied, the rock stress increases until the rock breaks along a conical plane of maximum stress. Shear loads will cause a slightly different failure shape.

Most small anchors are stronger in the pullout direction than in the perpendicular or radial loading (shear force) which is more common in cave use. This applies for both anchor failures and rock failures. Still, there are several reasons radial loading is preferred. While undesirable, it is possible to use a radially loaded anchor which is loose (Brook, 1965), with the hanger bearing directly on the anchor or bolt. Many combinations of anchors and hangers result in the hanger being coupled fairly tightly to the wall. Thus minimal bearing occurs and in normal loading the "shear" loading actually results in little applied shear stress to the anchor. Tables of anchor shear strength are thus often misapplied. A common misconception (e.g. Seddon, 1986; Meredith and Martinez, 1986) is that the stress due to applied shear loading and torquing are directly additive.

In most anchor systems, a nut or bolt is torqued down, squeezing a hanger against the flat rock surface (Fig. 2). This squeezing is called tensile preload, since it is a tension or pull induced in the anchor before it is loaded by the caving rope. This preload results in a frictional interface between the hanger and rock wall, which supports part of the load. As long as this coupling is maintained, the only significant force (and resulting stress) in the anchor is the tensile preload.

Unfortunately, maintaining this coupling requires that the preload, resulting from torquing, be somewhat higher than the applied load. A fall, the failure of another anchor, or possibly high loads during ascending may result in decoupling the hanger from the wall. This results in the hanger bearing down on the bolt or stud directly. A much different stress state then exists.

The new stress state is complex, a combination of shear, bending and compression (bearing). Shear stress, from the radial loading, attempts to deform the anchor as shown in Fig. 3. Bending stretches the top half of the anchor, adding axial tension.

Unfortunately 8mm bolts are often not strong enough to withstand the preload that would be required to prevent decoupling under the loads established above. It is difficult to imagine that optimum preload could be applied or maintained in the cave environment. We conclude, as have most others, that ¼ inch bolts are risky and should not be used as rappel anchors.

In the case of self-drills, a similar stress state will exist if the bolt is torqued, with the hanger coupled to the anchor instead of the wall when the anchor is slightly underdrilled (Fig. 4). The test results of Brindle and Smith (1983) (Fig. 5) show the results of increased bending stress from a 2mm protrusion.

Studs have some advantages where stress is concerned. First, the preload is distributed over the entire hole diameter, not just the central bolt in a self-drive or sleeve-anchor. Second, the need for high preload is reduced because of this greater bearing area. For a more detailed discussion of the relationship between bolt preload, stress and shear load capacity, we suggest an engineering design textbook such as Juvinall (1983).

Axial and Other Loading Angles

In cases where various load angles are basically directed at the head of the bolt (Petzl Clown and Petzl Ring, for example) the

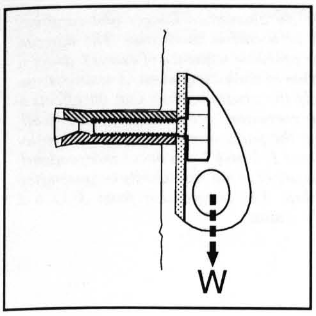


Figure 4. A self-drill that is underdrilled, but has a torqued bolt. Since a preload exists, it experiences only axial tension, bending, and shear.

anchor strength will vary predictably between that achieved in radial and axial loading. Some older hanger designs cause leverage tending to increase anchor loads as mentioned for axial loading. The newer Petzl designs greatly reduce this tendency. On the basis of our stress analysis, and testing by Brindle and Smith (1983), small variations from straight radial loading do not significantly affect anchor strength.

Because radial loads are always applied at some small distance from the wall, there is a tendency for the hanger to pivot about its bottom end. This results in leverage and some axial (pullout) component to any applied radial (shear) load. Lawson (1982) and Brindle and Smith (1983) have noted that the minimum net axial force will result from load application at some angle between radial and axial directions. This varies from straight axial by 15 to 40 degrees depending on hanger geometry. We agree with their observations on minimum net axial force but disagree with the conclusion that they represent "optimum loading angle." Loading at these angles will result in minimum stress only if no shear or bending is present in the anchor/bolt. Achieving such an "optimum loading angle" in caves would often mean placing anchors in overhanging walls where drilling is difficult and the consequences of poor placement are severe. We support Lawson's contention that increasing the load angle beyond "optimum" rapidly increases stress to dangerous levels, and feel that this is a further argument for anchor placement that results in loading which is close to straight radial.

Adhesive Anchors: A Special Case

Adhesive anchors, discussed in detail below, consist of a stud glued into a hole. Manufacturers of adhesive anchors claim that no expansion stress is placed on the rock and that true bonding of the anchor to the rock occurs. Their strength testing in weak concrete supports this. Until a load is applied to adhesive anchors, induced rock stress around the hole is essentially zero. This obviously leaves a larger percentage of the rock's strength to withstand applied loads.

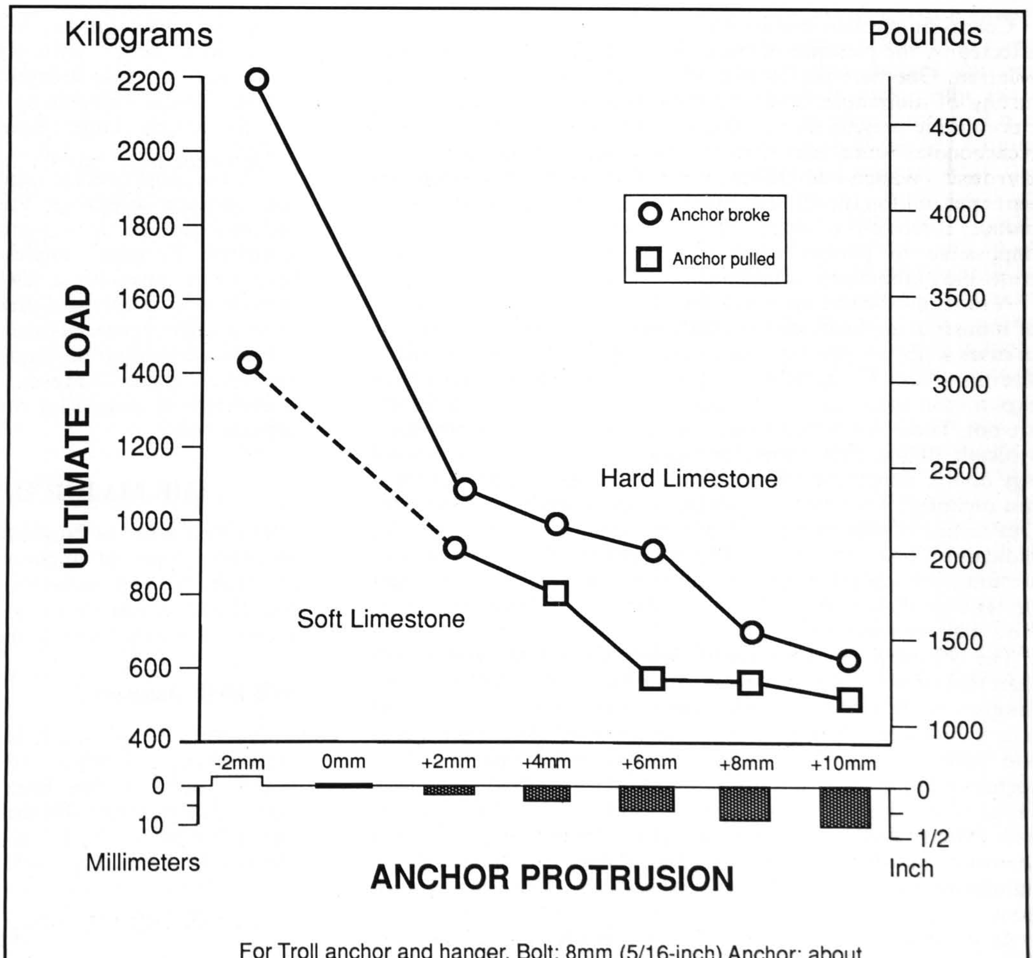
UNDERSTANDING CORROSION

Some popular corrosion fallacies exist in caving circles; one of these is stress corrosion. Stress corrosion cracking is a well known phenomenon where some metals, in a state of high mechanical stress, undergo accelerated electrochemical decay. The mechanism is complex and interesting, but largely irrelevant to caving. Stress corrosion is not observed in the combinations of alloys, heat treatments, stress levels, and environments encountered when commercial anchors are used in caves (ASTM Committee on Wrought Stainless Steels, 1978; Scharfstein, 1977).

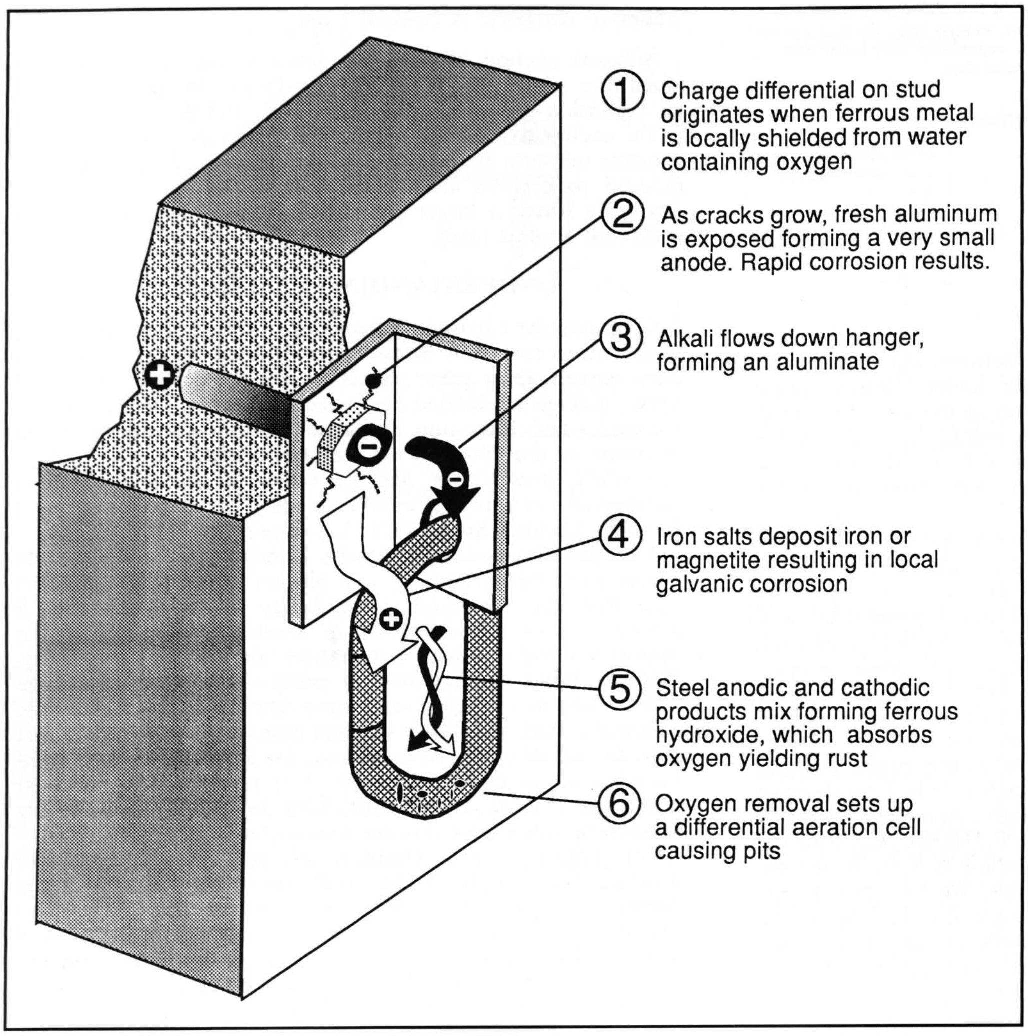
Another corrosion myth results from the table of electrode potentials found in chemistry and physics books. It is commonly held that the corrosion susceptibility of an anchor is a consequence of the difference in electrode potentials of the various materials (bolt or nut, hanger, anchor, etc.) (e.g. Riley, 1984a,b). While combinations of greatly different materials are undesirable, this belief is inaccurate. On the basis of electrode potentials, steel pivot pins in aluminum carabiners should not corrode, but they do. The conditions for which the table is valid (film-free metals in solutions with their normal activity of ions) rarely exist in cave environments. While beyond the scope of this article, the reasons for this are well documented (Evans, 1960).

For fasteners in caves, electrical cells may be set up even if all materials are the same. An electrical current may result when the portion of the anchor buried in rock limits the flow of water and oxygen to the metal surface. Oxygen exhaustion creates a small anode and the large exposed anchor surface becomes a cathode; corrosion follows (Evans, 1960). In such situations, the presence of grease is beneficial because it reduces ionic activity.

Figure 5. How strength decreases in an improperly placed anchor.



For Troll anchor and hanger. Bolt: 8mm (5/16-inch) Anchor: about 12mm (1/2-inch). Source: Brindle and Smith, 1983



① Charge differential on stud originates when ferrous metal is locally shielded from water containing oxygen

② As cracks grow, fresh aluminum is exposed forming a very small anode. Rapid corrosion results.

③ Alkali flows down hanger, forming an aluminate

④ Iron salts deposit iron or magnetite resulting in local galvanic corrosion

⑤ Steel anodic and cathodic products mix forming ferrous hydroxide, which absorbs oxygen yielding rust

⑥ Oxygen removal sets up a differential aeration cell causing pits

Figure 6. An aluminium hanger and carabine attached to a carbon steel stud. The diagran shows the probable sequence of events leading t degradation of each component. A stainless stu would help the situation. Note that the effects o "galvanic corrosion" are secondary; electricall insulating the parts would not reduce corrosio rates. Items 1, 2 and 3 can occur independentl — the sequence is not necessarily a cause-effec relationship. The progression from 3 to 6 i definitely causal.

Corrosion mechanisms are intricate. Corrosion rates are greatly affected by the presence of trace quantities of salts and metals in solution. One part per 50 million of copper in water will cause pitting of aluminum, when calcium bicarbonate, oxygen and a chloride are present (Porter and Hadden, 1953). Carbonates and bicarbonates sometimes inhibit and sometimes facilitate steel corrosion (Wallen and Olssen, 1977). It has been found that 100 parts per million (ppm) of calcium carbonate in groundwater can reduce corrosion of mild steel (Coburn, 1978). It is almost impossible to predict what will occur outside of carefully controlled laboratory conditions.

A more productive approach for cavers is to employ the history of industrial applications for guidelines. The majority of anchors in caves today are pre-expanded studs, self-drills and other similar sleeve anchors. Conservation considerations aside, for short-term exploration these may be adequate; for longevity they definitely are not. These fasteners are zinc plated or galvanized carbon steel, typically 1020 or 1030 alloys. Industrial experience tells us, beyond any doubt, that these will eventually corrode. The mechanism is not complex. They just rust away, progressively losing strength. Our testing of old pre-expanded studs from a rock climbing area indicates a loss of strength directly predictable from the loss of section thickness (Storage, 1980). It is inevitable that a significant percentage of anchors will be unsafe after 10 to 20 years of service. How old are they now?

The corrosion of aluminium hangers is much less predictable than that of steel bolts and anchors used in caving. We have some samples with uniform, multicolored corrosion products and others with a few deep pits. Several alloys used for hangers (2000 and 7000 series) corrode severely in cave environments. Stress corrosion at low stress levels is observed in these alloys even under surface conditions. The corrosion may be intergranular in nature, with extensive subsurface damage. The presence of steel anchor corrosion products accelerates the aluminium corrosion. A significant loss of strength can accompany a negligible loss of mass.

As is often the case, the strongest alloys are among the worst in terms of corrosion susceptibility. It is ironic that our single-minded quest for high strength has sometimes left us with inferior products. Conscientious manufacturers have selected weaker alloys with better corrosion resistance, despite competitive pressures to increase strength. We conclude that, while their light weight is useful for some applications like aid climbing, even the best aluminium hangers have no place in permanent rigging.

Since carabiners are left with fixed rigging in some parts of the world, the same concern applies. They are designed for strength, not corrosion resistance. Thin anodizing is merely ornamental, and probably accelerates aluminum corrosion rates where it is scratched. We have samples of deeply pitted carabiners which have sat in caves for a few months (Fig. 6). Steel rapid-links corrode more evenly and predictably, and thus we consider them to be a safer choice. Stainless steel rapid-links are even better.

From a corrosion position alone, stainless steel seems to be the obvious choice. However, strengths of materials must be considered. A discussion on balancing strength and reliability appears below.

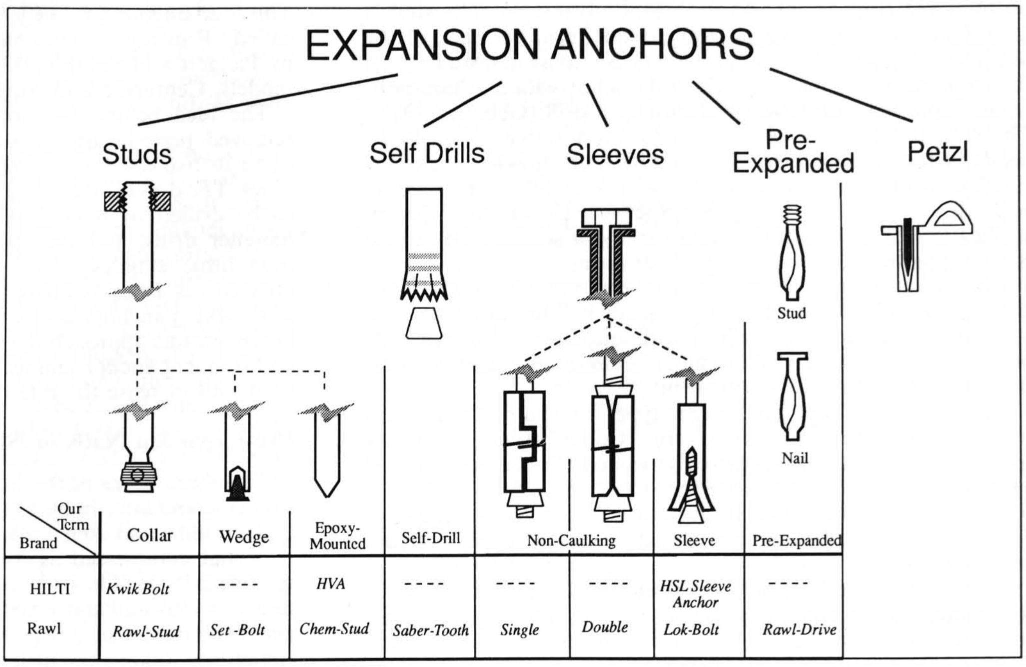
THE MAJOR OPTIONS IN ANCHORS

The first order of business is to agree on a vocabulary. There are many types of anchors available for a range of uses in construction and industry. Brand names only add to the confusion, because they tend to be inconsistent. Here we will use generic names that refer to the way that the anchor works (Fig. 7).

Self-Drill Anchors

Overview: Rock is hard. It can only be drilled by tools made of even harder steel, which even then become dull fairly rapidly. A popular solution has been the "self-drilling" anchor, which carries its own disposable drill. Once set, the anchor accepts a bolt and a hanger to which a carabiner or rope is rigged. Although marketed for securing machinery and other fixtures to masonry, this has been seen as a reasonable system for artificial anchors in caves. The "overhead" is a hammer and a driver to hold the anchor so that it can be hammered. The supply of sharp anchors is whatever the cavers want to carry. Instructions on setting self-drill anchors appear in a variety of publications.

Figure 7. Anchor types and terminology. All illustrations are stylised to demonstrate how the anchors work. The products of two widely-available manufacturers are given as examples.



Brand \ Our Term	Collar	Wedge	Epoxy-Mounted	Self-Drill	Non-Caulking		Sleeve	Pre-Expanded
HILTI	*Kwik Bolt*	----	*HVA*	----	----	----	*HSL Sleeve Anchor*	----
Rawl	*Rawl-Stud*	*Set -Bolt*	*Chem-Stud*	*Saber-Tooth*	*Single*	*Double*	*Lok-Bolt*	*Rawl-Drive*

Underdrilling and Overdrilling: Occasionally one will see the results from a caver who apparently got tired in the middle of drilling a hole and set the anchor anyway. The assumption seems to be: Half in means half as strong and that's plenty. This is completely wrong. Unfortunately the placement will probably hold for the fool that set it, and then lie in wait for the naive caver who comes along later. This underdrilling leaves the anchor and hanger sticking out from the wall, resulting in a tremendous increase in bending stress. As can be seen in Fig. 5, underdrilling by just 2mm can cut the strength of the whole system roughly in half (Brindle and Smith, 1983). Strength is also reduced if the lip of the hole is irregular and cone-shaped.

The other extreme is overdrilling. Fortunately, an anchor that is placed too deep produces less serious consequences. Assuming that the expander cone is still well in place, the loss of strength is due to loss of contact between anchor and screw. In these situations, high thread stress contributes to thread damage, an increasing concern in Britain (George, 1990).

How much torque?: Lawson (1982) warns that one should not "overtighten the bolt since doing so can drastically reduce the load it can support." This concern is valid, although it seems unlikely that bolt yielding and loss of strength would occur without being obvious (i.e. the bolt head twists off). Jim Smith (pers. comm.) reports that several ¼ inch bolts have been broken in Sistema Huautla by overtorquing. Our testing supports Smith's observations. However, we were unable to break 8mm or larger bolts with the spanners that we use underground.

Small diameter bolts are not strong enough to take the preload (and torque) necessary to maintain hanger/wall coupling and prevent shear and bending stress. Large diameter bolts can withstand the shear and bending, so the preload is unnecessary for stress considerations. Considering the difficulty of knowing what torque is actually applied under cave conditions, this is another argument against small self-drill anchors.

Reports of Failure: While some anchors are unreliable to begin with and some are visibly deteriorating, reports of failures have been scarce until recently. The majority are almost certainly unreported. Most that are reported seem to be non-catastrophic, i.e. a caver noticed the problem before loading the anchor and removed and/or replaced it.

In a rare reported instance of short-term failure, cavers had chosen to do a pitch despite "all the signs of [it] having been rigged by a half asleep caver in the middle of the night" (Warild, 1988). After exploration to −945 metres, the cavers were ascending quickly through water when an anchor pulled out, dropping one a short distance onto a ledge. The caver above repaired things, then he in turn fell 2 metres and "just above him swung the belay, a football-sized rock still attached by the tie-off sling." Clearly errors due to caver fatigue and time constraints played a major role in this situation.

Reports of failure in older anchors that are used heavily are beginning to appear. Apparently, threads are suffering in high-traffic caves where each party installs their own bolt and anchor. Nigel Robertson (1990) had passed beneath a rebelay in Rowten Pot when the bolt pulled out of the anchor, dropping him 2 metres and resulting in a broken back. In subsequent testing, the bolt "jumped the threads" when tightened into the anchor. Robertson concludes that "this damage seems to be caused solely by abuse (i.e. gross negligence and irresponsibility). Overtightening of bolts, using bolts with dirty or damaged threads will all damage the threads in anchors." While warning against these same practices, Dave George (1990) also states that "Many of the existing anchors have been in place for over 10 years and are simply wearing out."

The problem undoubtedly stems from both causes. Anchors rust over time. Rusty anchors are more susceptible to damage. A single negligent or inexperienced group can seriously damage the entire set of anchors in a cave, destroying the investment of time and money they represent.

We believe that no self-drive anchor can withstand the repeated insertion and removal of bolts in these high-traffic caves. Even stainless studs will suffer from the abuse to their threads. Perhaps the best solution would be to install anchors such as the Petzl P38/P39 (discussed below) which have a captive hanger. While more expensive at the outset, these anchors will neither require nor permit any fiddling or abuse by subsequent visitors. While the technology is available, a change in mindset will be required on the part of cavers if this investment in new infrastructure is to succeed. If there is an anchor in the cave, it might as well be of stainless steel with a highly reliable hanger affixed permanently to it. This tiny difference in visibility and aesthetic appearance must be balanced against the inevitable alternative: multiple, rusting anchors, abandoned holes, failures and accidents. Surely in high-traffic caves there can be little debate over which is the lesser of these two evils.

Maintenance: Like most things, anchors will last longer and be more reliable if they are maintained. This is particularly important in the case of self-drills since lubricant will reduce deterioration of low alloy and carbon steel dramatically. To service an existing anchor, the bolt should be carefully removed. The threads in the anchor can then be blasted out with a jet of spray lubricant. This will remove rock dust and rust, displace water and penetrate into the inner parts of the anchor. The anchor should then be squirted full of grease (Elliot, 1985). This can be petroleum jelly in a squeeze tube. Heavy bearing grease is even better. This can be loaded by using a spatula to fill a hypodermic syringe (with an enlarged nozzle) and then squirting this into the squeeze tube for transport into the cave.

Of course it is even better to grease the anchor when it is first installed. Sealing with silicone when the anchor is inserted may also be effective in protecting the metal/rock interface from deterioration. The best solution by far is to use stainless steel anchors, thus avoiding the need for grease altogether.

Studs

The stud anchor is an opposite approach to the self-drill; it provides a protruding threaded shaft for the hanger, which is held on by a nut (Fig. 1). There are several advantages. The stud is monolithic; a single piece of steel extends from the back of the hole to the hanger. The result, generally, is that a 6mm stud equals the strength of a 12mm OD self-drill anchor with an 8mm bolt. In addition, the stud is never abused as a drill (Gebauer, 1986). The stud has no internal opening to allow water to reach the inside of the anchor, nor will it fill with mud or other sediment. Finally, studs are available in 302, 303, 304 (all roughly equivalent) or 316 (a more expensive form for marine applications) stainless steel from a variety of sources. This alone is an important advantage over self-drill anchors.

The disadvantages are that a drill bit must be carried for drilling the holes. Since diameter control is often critical to the strength of the anchor, drilling with an impact hammer will produce better results. Drilling must be done very carefully with the manufacturer's recommended bits.

Collar Studs: There are several types of studs. Those used commonly in caving are what we term "Collar" studs. Expansion comes from a collar which encircles the stud. The collar is spread by the cone-shaped portion of the stud just above the base. Depth control is not critical, and in fact the hole can be intentionally overdrilled so that the stud can be hammered in to close off the hole after use.

Wedge Studs: Wedge studs are expanded like self-drills. Unlike collar studs, depth control is critical. For a given diameter, these anchors have nearly the same strength as collar studs. We are not aware of any available in stainless steel.

Adhesive-Mounted Studs

Another option is to make custom studs from stainless steel bolts or rod which do not expand in the hole. Alan Brook (1989) has a set of these anchors, made from ½ inch rod, which are in good condition after 10 years at the entrance to Jingling Pot. Alan uses industrial-grade Araldite Epoxy Resin (Ciba-Geigy Plastics) to secure the studs. The epoxy is not affected by water and most chemicals; Alan remarks that it is used to secure roof bolts in mines. Given a source of fairly cheap stainless steel rod, this appears to be an attractive option for high-traffic caves. Petzl offers a "Ring" (P40) that apparently is set with an epoxy (Petzl, 1988?).

Most manufacturers of expansion anchors now market adhesive anchor systems to be used with $\frac{3}{8}$ to ½ inch rod or bolts. In very soft rock (under 900 kg/cm^2) these anchors offer markedly increased strength, due to the more even load distribution along the buried portion (Raleigh, 1989). A $\frac{3}{8}$ inch by 2 inch adhesive mounted stud, properly placed in 3400 kg/cm^2 rock can withstand shear loads of over 2700 kg.

To use these anchors, a hole slightly larger in diameter than the stud is drilled and then a glass capsule is inserted. The capsule contains the correct proportions of epoxy (vinylester or polyester resin), sand and hardener in separate chambers. The stud, with a properly beveled end, is then used to fracture the capsule and mix the contents. This must be done very rapidly by using a hammer drill (with the impact turned off) to spin the stud.

Some suppliers also market the adhesives separately. These can be used to seal and reinforce normal expansion-type studs. Although discouraged by the manufacturer because of the tendency for the adhesive to splatter everywhere as the stud is driven into the hole, this combination will greatly reduce water seepage, corrosion and rock deterioration.

Petzl Long-Life Anchor System (P38/P39)

Petzl has recently introduced a combination anchor/hanger made of stainless steel. The P38 requires a 12mm hole, the P39 a ½ inch hole. The P37 is a double-expansion version for soft rock which requires a 14mm hole. Strengths are high (2100 kg). While somewhat expensive and requiring large holes, these anchors are very well engineered, with obvious forethought into minimizing bearing and bending stresses. A spanner is not required for installation and no parts are removable after placement. For high-traffic caves where artificial anchors are proliferating, these appear to be excellent choices to provide long-term reliability.

Non-Calking or "Sleeve" Anchors

When an anchor expands into its hole, it is said to "calk" (e.g. Rawl, 1981). This refers specifically to the placement of soft metal (typically lead) anchors which greatly deform in the hole and are *not* safe for life support. Here we use the term "non-calking" to refer to anchors that are removable after they have been placed. This is an attempt to clarify terminology: in Britain these are often called "Rawlbolts." They have also been called "sleeve anchors" by Padgett and Smith (1987). Montgomery (1976) describes two models, Centurion and Austin McLean.

The idea behind the non-calking anchor is that it may be removed periodically, inspected and greased (Brook, 1985). In some British caves, cavers provide their own anchors for existing holes. The disadvantage to this is that the large holes (½ inch) had to be drilled by hand. Today the holes could be drilled with hammer drills, and the anchors have performed well, but the monolithic stainless steel studs are certainly more attractive alternatives. In cases where rapid rock deterioration is a concern, non-calking anchors can be removed for periodic hole inspection. However, this approach does nothing to prevent hole weathering and frequent anchor removal in soft rock will undoubtedly cause wear and increase the rate of deterioration.

Pre-Expanded Nails or Studs

These were some of the earliest and most popular anchors used in caving and aid climbing. They are simple, a one-piece stud split in the middle and then hardened so that two opposing flanges are bent and compressed as it is driven into the hole. The stud is threaded; the nail has a head and is not removable. Again, these terms are misused and interchanged often in the literature. These anchors have declined in popularity because they tend to pull out, sometimes under very little force (Davison, 1977). The problem seems to arise in several ways. Some limestones may not be hard enough to fully depress the flanges. While tests in granite gave very good results (Montgomery, 1976), data from Molly (Emhart, 1989) indicates extremely low pullout loads in soft concrete. In other cases weathering and solution, sometimes after the anchor is placed, may make the rock too soft to hold the anchor. Dozens of climbing accidents have occurred from use of these anchors (Leeper, 1977). Thus pre-expanded studs are not recommended for long-term placements.

CHOOSING ANCHORS: BALANCING STRENGTH AND RELIABILITY

Having established a reasonable working load for anchors of roughly 1200 kg earlier ("What is a Safe Anchor?"), we must now think about how to actually achieve this goal with confidence underground. Margins of safety are used in design for two main reasons. The first involves the level of confidence that the strength of an individual item is the same as the samples that were tested and analyzed. Obviously, we have limited confidence in the rock strengths. The second reason involves deterioration and reduced strength as the item ages.

Fastener manufacturers, such as ITW Ramset/Redhead (1989), recommend 25% of measured ultimate (breaking) load as a safe working load, to account for strength scatter and imperfect placement. The International Congress of Building Officials (1988) recommends an additional 50% reduction where inspection is impossible.

These recommendations result in a desired safety margin of 8 (or a theoretical 9000 kg capability). This would require unacceptably large anchors; a 1 inch self drive drilled deep into very strong rock, for example.

Redundancy is a better approach. If parallel redundancy, or shared loading as described in a variety of publications is used, the applied load to each anchor is halved. The probability of simultaneous failures is low, and the likelihood of either failing is reduced because of the divided load.

We feel that two anchors, each intended to be capable of taking the 1200 kg load, is a safe system, provided that they do not suffer significant loss of strength over time.

In general this means a 10mm stud of a suitable stainless steel, placed properly. The strength of smaller SAE grade 8 (a stronger material than stainless) bolts may be adequate, but these corrode quickly. Since self-drives cannot be made from stainless (it generally cannot be heat treated), studs have a clear advantage for long-term placements.

The preference for stainless steel eliminates many studs from consideration. The wedge stud design is acceptable, but they do not seem to be available in stainless. Stainless sleeve studs are available, but for a given hole diameter they will always be weaker than collar or wedge studs. Sleeves offer somewhat better load distribution than collars in soft rock, but nowhere near that of adhesive-mounted studs. Stainless collar studs and adhesive-mounted studs emerge as obvious winners for permanent placements.

THE ETHICS OF ARTIFICIAL ANCHORS

Anchors beget more anchors. Cavers sometimes place them poorly and even the best deteriorate. The next cavers come along, don't like the placements or deterioration or sizes, and set still more anchors. Where does it end?

Perhaps the most serious problem is somewhat unobvious; the decline of good caving skills. Cavers who learn that caving is pounding in anchors, or get in the habit of seeing them at every drop tend to lose the ability to recognize and use natural anchors. Dave Elliot (1983), a caving instructor who is a major proponent of artificial anchors, has said, "In contrast to the fertile imaginings of the purists among us, there are in fact very few natural belays in caves suitable for SRT, artificial anchors are necessary on almost every pitch." Clearly a judgement has been passed; don't bother looking because you won't find anything. Once these beliefs about how drops are to be rigged spread, they can go to ridiculous lengths. Paul Lydon (1986) has reported finding two easy 4-foot climbs rigged from an anchor. Dave Brook (1987/88) remarks in reviewing Elliot's rigging guide for the Yorkshire Dales that "the authors love messing about on rope, but don't like certain aspects of caves such as climbs, crawls and especially water."

The other side of the story comes from the Oxford cavers (Rose, 1983) who have descended numerous deep systems in Spain using artificial anchors on less than half the pitches. Kevin Downey (1987) reports on trips to several deep European systems that have been rigged using rebelay techniques, but with no artificial anchors. Explorers of Mexico's Sistema Huautla have noted that about 70% of its roughly 600 pitches have been rigged with natural anchors.

Naturally a lengthy and heated debate has ensued, but to us some points seem worth noting. Anchors can be thought of by less-experienced cavers as "hard core" and applied indiscriminately. Anchors can be hammered in (often badly) by anyone who can buy a kit. Terry Raines (1986) has noted that Sotano de la Golondrinas was descended regularly for 16 years before the first anchor was placed. Now there are over a dozen. An anchor is a permanent defacement of the cave, so poor technique affects everyone.

Some drops unarguably require anchors to be descended safely. In other cases, it is a judgement call and the skilled caver can manage with careful use of natural anchors, rope pads, etc. Steve Foster (1986) gives a good introduction to natural rigging, and more articles on this topic are needed in the caving literature. Like mountaineers and rock climbers, we may begin to see separate ethics for artificial aid near home and far away (Mitchell, 1983). On Everest, just about anything goes; on the local climbing face, a single anchor might be considered very poor form. Too much technology can destroy the experience of caving. As Mike Boon (1980) has observed, "How many bolts are needed before the exercise becomes pointless is a matter for individual judgement." Ultimately it is a question of using technology to enhance, but not overwhelm, the aesthetic experience of working within the challenges of nature.

SOME SUGGESTIONS FOR CONSIDERATION

- Learn to find and use natural anchors safely
- Set anchors responsibly, as an investment for the caving community
- Use stainless steel studs
- Use stainless steel hangers and bolts for existing self-drives, and sleeve-anchors where anchors are removed.
- Use grease on all self-drill anchors
- Anchors, bolts and hangers should be placed well and left in place. Subsequent visitors should not remove the bolts and hangers.
- Don't use ¼ inch anchors or studs
- Don't leave aluminium hangers in caves

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B.C.R.A. Research Funds [illegible]

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[illegible]

B.C.R.A. Research Funds and Grants

THE JEFF JEFFERSON RESEARCH FUND

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

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

The award scheme will not support the salaries of the research worker(s) or assistants, attendance at conferences in Britain or abroad, nor the purchase of personal caving clothing, equipment or vehicles. The applicant(s) must be the principal investigator(s), and must be members of the BCRA in order to qualify. Grants may be made to individuals or small groups, who need not be employed in universities, polytechnics or research establishments. Information and applications for Research Awards should be made on a form available from S. A. Moore, 27 Parc Gwelfor, Dyserth, Clwyd LL18 6LN.

GHAR PARAU FOUNDATION EXPEDITION AWARDS

An award, or awards, with a maximum of around £1000 available annually, to overseas caving expeditions originating from within the United Kingdom. Grants are normally given to those expeditions with an emphasis on a scientific approach and/or exploration in remote or little known areas. Application forms are available from the GPF Secretary, David Judson, Rowlands House, Summerseat, Bury, Lancs. BL9 5NF. Closing date 1st February.

SPORTS COUNCIL GRANT-AID IN SUPPORT OF CAVING EXPEDITIONS ABROAD

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

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

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

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