Cave and Karst Science

The Transactions of the British Cave Research Association

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BCRA

Papers presented at the International Symposium on Changing Karst Environments, Oxford and Huddersfield, September 1994

Cave and Karst Science

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

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

2. Development Articles
Shorter papers, normally 500-3,000 words, on aspects of karst/speleological science listed above, or more descriptive material such as caving expedition reports and technical articles. These will be reviewed by the editorial board unless the subject matter is outside their fields of expertise, in which case appropriate expert assessment will be sought.

3. Forum
Personal statements of up to 1,000 words on topical issues; discussion of published papers and book reviews. Statements should put forward an argument and make a case, backed-up by examples used as evidence.

4. Abstracts
Authors (or supervisors) of undergraduate or postgraduate dissertations on cave/karst themes are asked to submit abstracts for publication. Please indicate whether the thesis is available on inter-library loan. Abstracts of papers presented at BCRA and related conferences or symposia will also be published.

Manuscripts may be sent to either of the Editors: Dr. D J Lowe, British Geological Survey, Keyworth, Nottingham, NG12 5GG, UK, and Professor J Gunn, Limestone Research Group, Department of Geographical and Environmental Sciences, The University of Huddersfield, Queensgate, Huddersfield, HD1 3DH, UK. Intending authors are welcome to contact the Editors, who will be pleased to advise on manuscript preparation.

NOTES FOR CONTRIBUTORS

These notes are intended to help the authors to prepare their material in the most advantageous way so as to expedite publication and to reduce both their own and editorial labour. It saves a lot of time if the rules below are followed.

All material should be presented in a format as close as possible to that of *Cave and Karst Science* since 1994. Text should be typed double-spaced on one side of the paper only. Subheadings within an article should follow the system used in *Cave and Karst Science*; a system of primary, secondary and if necessary, tertiary subheadings should be clearly indicated.

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

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

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

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Tables: These should not be included in the text but should be typed, or clearly handwritten, on separate sheets. They should be numbered in sequence, and a list of captions, if necessary, should be submitted on a separate sheet.

Approximate locations for tables, plates and figures should be marked in pencil in the manuscript margins.

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

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

We prefer articles to be submitted on disk if possible, although paper copy is also acceptable. We can read most PC based word processing packages but if in doubt please consult one of the Editors. Apple Mac disks are accepted as a last resort!

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

Cave and Karst Science

TRANSACTIONS OF THE BRITISH CAVE RESEARCH ASSOCIATION

Volume 21 Number 2 March 1995

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Cover photo:
An example of a vertical shaft with no associated doline development, Khodzha-Akcha-Burun plateau, Central Asia. Photo by J. Zimels (see article by Alexander Klimchouk).

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EDITORIAL

John Gunn and David Lowe

When we agreed to take over the editorship of Cave and Karst Science we were under no illusions that it would be an easy job. Even so, the first six months have proved more arduous than we expected. Production of our first issue was relatively easy, as it consisted solely of abstracts. The current issue has involved much greater editorial input and the development of new production methods. We are extremely grateful to Jean Reeve, who has undertaken the desk top publishing for this issue, and who is already working on the next. We apologise to those who have been waiting and wondering when Volume 21, Number 2 would appear. Now we have overcome various problems, issue Number 3 will follow in 2 to 3 months. We hope to produce the first part of Volume 22 shortly afterwards, and will be working hard to get publication back on schedule. Whether we achieve this aim will depend on potential contributors maintaining the flow of good quality material.

This issue is made up entirely of papers presented at the International Symposium on Changing Karst Environments (see Volume 21, Number 1). The Symposium was sponsored by the Commission on Environmental Changes and Conservation in Karst Areas of the International Geographical Union, by the Karst Commission of the International Association of Hydrogeologists and by UNESCO International Geological Correlation Programme Project 299 (Geology, Climate, Hydrology and Karst Formation). Hence, this issue of Cave and Karst Science represents a contribution to the work of these three groups. As such, it contains material on a wide range of themes from around the globe, a trend that we hope to continue in future issues. Inclusion of so many papers in this issue has meant that we have been unable to include the Forum and Abstracts; these have been held over to the next issue. Our thanks to those who have provided Forum submissions and thesis abstracts. We would welcome more of these, particularly abstracts of undergraduate dissertations, which are often forgotten. Even if the project did not turn out as you intended, or the report cannot easily be obtained, it is useful to record what has been attempted.

Finally, as many readers will be aware, Marjorie Sweeting, one of the best known figures in international karst science, died in December 1994. Obituaries have been published in the UK national press and in many caving journals, including Caves and Caving, the Bulletin of the British Cave Research Association. Although, sadly, illness prevented her attendance at the meeting, Marjorie played a major part in the organisation of the International Symposium on Changing Karst Environments. For this, and for her numerous other contributions during many years of karst research, this issue of Cave and Karst Science is dedicated to the memory of Marjorie Sweeting.

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Chemistry of the water in the Nerja Cave System (Andalusia, Spain)

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Abstract: The main physical-chemical characteristics of the drip water in the Nerja Cave (southern Spain) were monitored on an approximately monthly basis between 1991 and 1994 at ten different points. The water from precipitation and from the saturated zone of the aquifer was similarly monitored. The chemistry of the drip water can be explained basically both by the climatic concentration in the soil of the components dissolved in the rainwater, and particularly by the dissolution of the highly-fissured Triassic dolomitic marble in which the Cave has developed. The considerable number of visitors, some 500,000 per year, causes significant variations in the temperature, humidity and CO_2 content in the interior atmosphere of the Cave. This is also reflected in the different physical-chemical characteristics of the drip water in the chambers open to the public, as compared with those which remain closed: slightly higher values of mineralisation and equilibrium pCO_2, and lesser of temperature and SI, are found in the visit area, as well as a higher variability of the measurements. Another anthropogenic effect is the percolation of water pumped out of the saturated zone, used for watering the gardens, in the sector of the Cave closest to the entrance. This drip water presents the highest mineralisation and pCO_2 values of the cave system.

INTRODUCTION

The Nerja Cave is situated in the south of Spain, some 50 km to the east of Málaga (Andalusia). It was discovered in 1959 and was opened to the public in the following year. Since then, it has been one of the most visited natural attractions in Spain, with approximately 500,000 visitors a year. The majority of these come during holiday periods (Easter and summer), when daily maximums of around 4000 are attained. Its popularity is influenced by its location in a major tourist zone (Costa del Sol), and naturally, by the beauty of the chambers and speleothems that can be found there.

The Cave extends through a series of chambers and galleries to a total distance of almost 5 km, having a height of 70 m and occupying a volume of over 800,000 m^3 (Sociedad Excursionista de Málaga, 1985). Its shape is relatively simple - elongated in a more or less N-S direction (Fig. 1). The cave entrance is situated at an altitude of 158 m, and is less than 1 km from the sea. Tourist visits are restricted to the third of the cave nearest the entrance (Fig. 1).

The mean annual temperature of the air outside the Cave is 16.5°C (January 11.4°C; August 24°C) and the mean rainfall is slightly under 500 mm yr^{-1}. The climate is Mediterranean with a fairly marked dry season from May to October. Since the end of the 1970s, a general tendency to below average rainfall has been recorded, excepting only the years 1983-84 and 1989-90. Indeed, the period 1991-93, when most of this research was carried out, was abnormally dry. These climatic conditions, together with repeated forest fires, are the principal reasons why the vegetation and cover soil above the Cave are currently scarce. The mean annual actual evapotranspiration is in the order of 425 mm; the excess water available for infiltration is therefore very limited. Direct data regarding the partial pressure of CO_2 in the soil do not exist; however, from the mean value of evapotranspiration, it can be estimated to be of about $10^{-2.5}$ atm (0.3% vol.) (Brook et al., 1983). This value has been corroborated by way of hydrogeochemical modelling in a nearby sector with fairly analogous characteristics (Cardenal et al., 1994).

Preliminary studies based on the content of Rn-222 in the air of the Cave indicate that the air in the zone open to the public is replaced every 5 days on average (Dueñas et al., 1993). This rate is, for instance, higher than that found in the Carlsbad Caves, USA (Wilkenings and Watkins, 1976) and in the Altamira Cave, Santander, Spain (Fernández et al., 1986).

Although previous -but discontinuous- data exist on the main atmospheric parameters inside the Cave, it is worth noting that since 1991 a systematic monitoring has been introduced. This was carried out on a daily basis until the end of 1993, since when continuous recording sensors - of temperature, humidity and CO_2 content in the Cave air - have been in place. Some of the first data from this record will be presented later on. The research is complemented by monitoring of the physical-chemical characteristics of the water inside the Cave and at various key locations outside it. This paper deals mainly with the results of that hydrochemical monitoring.

GEOLOGICAL AND HYDROGEOLOGICAL SETTING

From a geological point of view, the Cave is situated in the Alpujarride Complex (Internal Zones of the Betic Cordillera). This complex has two lithological formations. The lower formation is of a metapelitic nature (schists and quartzites), and is thought to date from the Palaeozoic. The upper formation is carbonated: dolomitic marble towards the base and calcareous marble towards the top, with discontinuous metapelitic intercallations, dating from the middle-upper Triassic. The Cave is developed over the dolomitic marble which presents a dense microfissuration. In some places the rock appears completely shattered, giving rise to a typical saccharoidal texture, with grains made up of single dolomite crystals. Outside the Cave, discordant detrital Neogene deposits appear over the Alpujarride materials (Fig.1).

Although the structure of the Alpujarride Complex is highly complex on a regional scale, in the immediate surroundings of the Cave it is fairly simple: the marble has an almost tabular arrangement, dipping 15-20° to the south. The existence of normal and/or strike-slip faults with a NW-SE direction is worth noting, these having caused significant vertical movements since the Pliocene.

The Triassic carbonate materials constitute an aquifer of regional importance whose recharge is produced mainly by the infiltration of precipitation on the mountainous outcrops to the north of the Cave, where the peaks reach almost 1800 m. Surface karstic forms (karren, dolines, sinkholes, etc.) hardly exist in these carbonate materials, in which, on the other hand, a fairly well-developed surface drainage system does exist, favoured by the considerable slopes in the terrain, as well as by the local loose lithological texture of the dolomitic marble.

The discharge of the aquifer, apart from wells, is produced by a series of springs, among which the Maro spring is of particular significance, situated less than 1 km to the east of the Cave (Fig. 1), at an altitude of

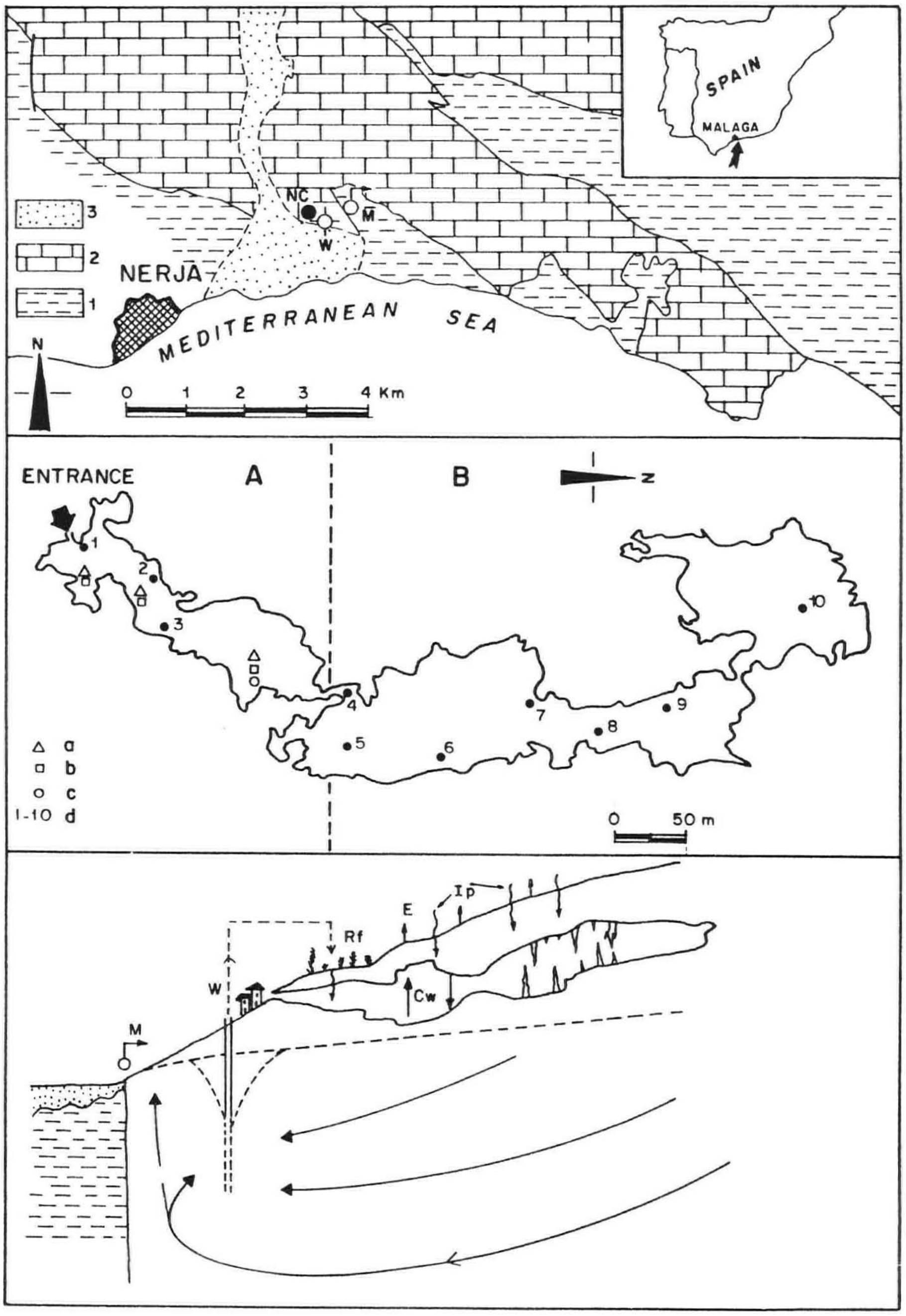


Figure 1. Situation and geological sketch of the Cave of Nerja.
Above. 1: metapelites, 2: carbonates, 3: Pliocene and Quaternary deposits. NC: Cave entrance, M: Maro spring, W: Cave well.
Middle: location of the monitoring points inside the Cave. a: air temperature, b: humidity, c: air CO_2 content, d: drip water sampling point. A: area open to the public, B: area closed to the public.
Below: cross-sectional sketch (not to scale) showing the main processes influencing the water chemistry inside the Cave (see text for more details).

120 m. The lowest parts of the Cave are situated approximately 10 m above the spring. The mean outflow of this spring is a little under 200 l s^{-1}. From the available data, it is not possible to talk of very significant oscillations in the outflow, given that the highest values, measured before the monitoring initiated by this study after periods of precipitation of certain significance, are of 650 l s^{-1}. Although the absence of adequate records prevents an in-depth analysis of this aspect, it is worth pointing out here that the majority of the springs which drain Alpujarride carbonate aquifers are characterised by a marked hydrodynamic inertial behaviour, which has caused the corresponding aquifers to be classified as of a fissured type rather than karstic in the strict sense, with predominantly diffuse flow systems, a fact which is also corroborated when analysing the hydrochemical variability in their natural discharge, which is generally very low.

Endokarstic forms of a certain significance are fairly rare in the Alpujarride carbonate aquifers. The Nerja Cave is a major exception. The karstification process which gave rise to the Cave occurred throughout the Pliocene and the Pleistocene, as a result of the combined action of subterranean waters, climatic changes and neotectonic activity. It is precisely this last factor which provides the main reason why the Cave is currently to be found in the unsaturated zone of the aquifer. During the temperate and hot periods of the Quaternary Age (Durán et al., 1993) enormous quantities of calcite or aragonite deposits were generated, which constitute the Cave's main attraction.

MONITORING POINTS : METHODOLOGIES

Hydrochemical monitoring of three types of water has been under way since March of 1991: (1) precipitation outside the Cave, (2) drip water from the roof within the Cave itself and (3) samples from the saturated area around the Cave. The samples of rainwater were obtained immediately after periods of precipitation, from a pluviometer situated next to the entrance to the Cave. The quantity of water collected was not always enough to carry out all the analyses.

Until March 1993, monitoring of the drip water inside the Cave was undertaken using samples collected on a monthly basis at 10 points, the locations of which are shown in Fig.1. Subsequently, after a preliminary analysis of the findings obtained (Carrasco and Andreo, 1993), the network was reduced to three points (1, 3 and 7), considered as representative of the chemistry of the various types of water found, which will be discussed later on. Samples were taken every 15 days at these points. Between October 1991 and March 1993, the drip water flow was also monitored at the 10 points mentioned above, with the same frequency with which the samples were taken. Additionally, the drip water flow has been measured daily from April 1993 to date at point 3. The values recorded are, in every case, under 2 cm^3 min^{-1}.

The third group of samples were taken from the Maro spring, and from a well forming part of the Cave's installations (Fig.1), intended for watering the gardens and cleaning. The sampling frequency was virtually monthly.

In each sample of water, the temperature, pH and electrical conductivity (E.C.) were measured "in situ". In the laboratory, the alkalinity by volumetry with H_2SO_4, and Ca^{2+} and Mg^{2+}, by complexometry, were measured on the same day as the sample was taken. Subsequently, but always within a week, the following were measured: Cl^-, by argentometry with $AgNO_3^-$; SO_4^{2-}, by gravimetry; SiO_2 and NO_3^-, by spectrophotometry, and Na^+ and K^+ by flame photometry. Once the ionic concentrations were available, analyses with balance errors of over 5% were not considered. The program SOLUTEQ (Bakalowicz, 1984) was applied to the physical-chemical findings obtained, in order to calculate the equilibrium partial pressure of CO_2 (pCO_2) and the saturation indexes for calcite (SIc) and dolomite (SId).

Fig. 1 shows the location of sensors which measure the humidity, temperature and CO_2 content of the air inside the Cave, at hourly intervals, to assess the impact of visitors on the microclimate in the Cave.

RESULTS

Table 1 shows a statistical summary of the results obtained from the hydrochemical monitoring up until June 1994. The mineralisation of the rainwater, although relatively low (some 100 μS cm^{-1}, on average), is highly variable: between 15 and 330 μS cm^{-1}, with a coefficient of variation of 64%. With the exception of Cl^- (45%), the variability of each chemical constituent is quite high (values from 90% to 130%). The water is of a HCO_3 Cl-Ca type.

The temperature of the air inside the Cave ranges from 18 to 21°C. It increases with the distance from the entrance. Its variability follows the opposite trend. The relative humidity inside the Cave varies between 50% and almost 100%, the latter value being recorded in the summer months, coinciding with the greatest number of visitors and is mainly produced by human transpiration. It is also during these periods that the highest concentrations of CO_2 in the Cave atmosphere are reached. As an example, the weekly variations recorded in the concentration of CO_2 at two different times of the year are shown in Fig.2. In the last week of January 1994, when there were few visitors (1880), the maximum concentration of CO_2 recorded was 450 ppm. On 27th January, no variation occurred in the CO_2 concentration, as the Cave remained closed. On the other hand, during Easter week of 1994 (end of March - beginning of April), which may be considered a period of maximum visitors (16800), values of near 1200 ppm were reached.

The drip water collected in the Cave is of two types. That from point 1 is HCO_3-SO_4 Ca-Mg, with relatively high mineralisation, between 850 and 1500 μS cm^{-1} (1160 μS cm^{-1}, on average) which corresponds with its

Table1. Statistical summary of the physical-chemical data registered in the monitoring network.
n: number of measurements taken,
m: arithmetic mean,
V: coefficient of variation,
Chemical content in mg/l,
pCO_2 in %vol.,
temperatures in °C,
E.C. in μS/cm^{-1}.

Point		pH	t	E.C	Ca2+	Mg2+	Na+	Cl-	SO42-	Alk.	NO3-	SiO2	pCO2	SIc	SId
P	n =	19	3	30	16	16	30	33	15	20	21	20			
	m =	6.81	16.33	103.83	7.67	3.05	2.26	12.52	11.98	27.51	3.05	1.69			
	V (%) =	4.81	18.93	64.42	122.11	124.26	90.58	44.26	93.44	99.97	108.13	98.37			
1	n =	29	29	29	30	30	30	30	30	30	30	30	29	29	29
	m =	7.88	18.83	1164.41	131.91	70.58	29.82	81.05	287.68	364.88	18.23	14.76	0.43	0.85	1.66
	V (%) =	2.34	4.11	9.12	19.28	9.66	31.40	23.81	14.23	9.31	23.90	9.76	46.03	21.17	21.03
2	n =	13	13	13	14	14	14	14	14	14	14	14	13	13	13
	m =	8.35	18.68	531.46	41.36	41.57	7.67	25.07	14.69	300.03	2.31	7.15	0.13	0.85	1.92
	V (%) =	2.65	6.62	11.33	28.91	15.28	18.78	18.98	24.03	13.73	39.42	16.01	71.24	30.35	24.63
3	n =	32	32	30	33	33	33	32	30	33	32	31	32	32	32
	m =	8.33	19.18	520.77	35.05	44.96	9.02	28.68	18.55	299.44	4.86	9.49	0.13	0.73	1.82
	V (%) =	2.21	4.40	10.38	33.91	12.28	22.16	41.02	30.45	11.01	59.29	19.10	53.56	29.58	18.79
4	n =	17	17	17	17	17	17	17	17	17	17	17	17	17	17
	m =	8.31	20.40	529.12	44.93	42.26	8.46	29.74	17.42	304.79	6.14	10.81	0.18	0.85	1.93
	V (%) =	3.27	0.94	4.99	16.37	11.06	9.01	14.48	14.92	6.20	26.90	11.68	133.88	30.76	26.49
5	n =	8	8	8	8	8	8	8	8	8	8	8	8	8	8
	m =	8.49	19.06	521.63	40.13	42.85	9.39	32.81	20.99	297.99	3.71	8.60	0.08	0.95	2.17
	V (%) =	1.45	4.13	4.37	16.66	7.26	9.50	1.86	12.86	2.35	55.93	22.15	24.57	7.21	8.66
6	n =	15	15	15	14	14	14	14	14	14	14	14	14	14	14
	m =	8.37	19.07	504.47	48.31	40.25	5.79	21.22	11.04	317.78	8.87	8.55	0.13	0.93	2.03
	V (%) =	1.77	2.15	8.53	23.86	13.63	8.46	12.99	26.95	7.52	37.29	25.13	37.86	16.10	12.52
7	n =	40	40	40	40	40	40	40	40	40	40	40	40	40	40
	m =	8.28	19.21	465.33	42.95	37.06	6.50	25.74	18.33	279.61	5.44	7.54	0.14	0.77	1.71
	V (%) =	2.49	2.84	13.87	13.51	10.44	17.12	60.80	30.50	5.49	78.21	14.61	61.21	25.05	22.97
8	n =	14	14	14	14	14	14	14	14	14	14	14	14	14	14
	m =	8.66	19.34	392.07	19.02	42.46	8.38	26.62	16.23	233.18	3.06	9.51	0.05	0.70	2.00
	V (%) =	1.48	1.13	11.24	18.10	5.32	7.66	12.49	16.29	2.93	20.63	10.26	32.26	13.17	9.20
9	n =	10	10	10	10	10	10	10	10	10	10	10	10	10	10
	m =	8.55	19.51	417.50	22.29	42.75	6.90	26.90	13.46	251.22	2.39	7.23	0.06	0.71	1.95
	V (%) =	0.93	1.20	6.14	13.01	3.23	13.28	13.48	26.76	3.94	25.00	15.78	18.57	11.31	8.51
10	n =	11	11	11	10	10	10	10	10	10	10	10	10	10	10
	m =	8.39	19.61	482.73	43.96	38.54	5.50	20.63	13.74	304.72	2.23	7.07	0.10	0.95	2.09
	V (%) =	1.46	3.05	6.58	12.99	6.83	18.18	4.47	27.77	7.30	40.11	11.53	26.60	4.43	4.67
M	n =	17	17	17	16	16	15	15	16	15	15	15	15	15	15
	m =	7.71	19.18	718.06	108.79	29.79	9.11	28.45	222.23	199.87	0.89	14.48	0.34	0.41	0.50
	V (%) =	2.69	2.71	11.34	17.62	31.78	34.85	16.96	22.82	4.67	95.11	22.07	44.97	63.21	91.63
W	n =	17	17	18	17	17	17	17	17	17	17	17	17	17	17
	m =	7.38	21.32	667.56	82.26	36.04	12.36	33.91	93.43	291.20	15.92	12.12	1.14	0.17	0.24
	V (%) =	1.67	4.37	8.98	10.11	16.37	29.94	19.45	18.74	11.42	44.94	12.18	29.95	90.80	142.03

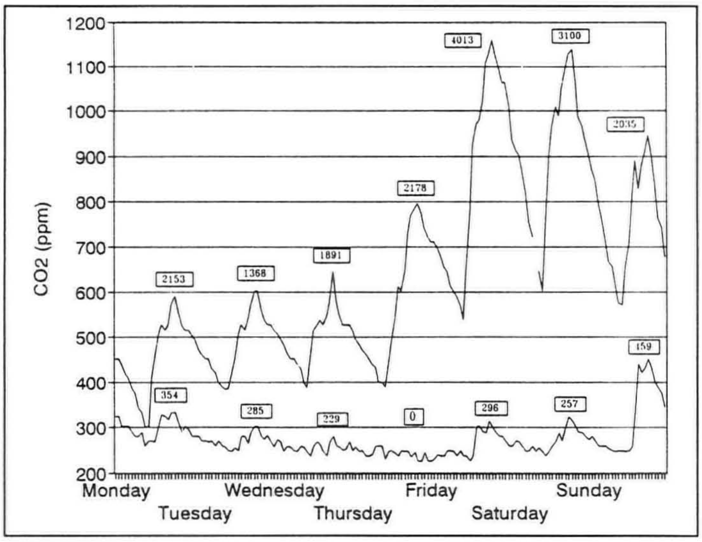


Figure 2. Evolution of CO_2 content in the Cave atmosphere during two different weeks in 1994. The higher values correspond to Easter Week (end of March-beginning of April). The lower values correspond to the last week in January. The number of daily visitors is indicated above each peak.

higher content in all the constituents analysed; its pCO_2 values are the highest recorded among all the drip water sampled (0.4%, on average). The water at the other points is of HCO_3 Mg-Ca type with conductivity values of between 350 and 670 µS cm^{-1}. The most mineralised waters in this group broadly correspond to the points situated in the area open to the public, or in those immediately adjacent to it: 520-540 µS cm^{-1} as opposed to 390-510 µS cm^{-1} which are the characteristics of the sectors with restricted access. The same can be said about the mean pCO_2 values: 0.1-0.2 % (open area) and 0.05-0.15 % (closed area). The mean temperature of the drip water is higher in the area closed to the public (19 - 20.5°C) than in the part which is open (18.5 - 19.5°C). All the samples collected from the drip water indicate conditions of oversaturation in calcite and dolomite, with mean values of SIc between 0.7 and 1.0 and of SId between 1.7 and 2.2. The highest values of SI correspond to the area closed to the public.

Analysis of the seasonal evolution of the electrical conductivity and chemical constituents dissolved in the drip water does not show significant variations. This is due to an important effect of chemical homogenization with respect to the precipitation input data, as is also clear from the values of the coefficients of variation: less than 15% for the E.C.. However, the relative greater variations of mineralisation are recorded at points in the area open to the public. The relative maximums tend to appear around the summer months, an aspect which is also apparent in the evolution of the pCO_2 (Fig.3). This figure also shows that, besides the difference in the absolute values, the evolution recorded at point 1 is slightly different from the general pattern of points 3 and 7. The coefficient of variation of pCO_2 values is higher (50 to 135 %) in the visit area than in the closed area (25 to 65%). The variability of temperature is also higher in the area open to the public.

The seasonal variations in the flow of the drip water are difficult to interpret from the available data. Even from the most detailed recording (Fig.4), a clear response to precipitation does not appear to exist. In fact, after the rainfall in October and November 1993, the drip water was interrupted; indeed, significant rainfall occurred during the period in which no drip water was recorded. The humidity inside the Cave, related in turn to the number of visitors, seems to have a more direct influence in this respect (Fig.4).

The samples taken in the saturated zone of the aquifer (points M and W, Fig.1 and Table I) are of a HCO_3-SO_4 Ca (M) and HCO_3 Ca-Mg (W) type. Their E.C.values range from 500 to 800 µS cm^{-1}, with values slightly higher at point M than at point W (720 µS cm^{-1} and 660 µS cm^{1}, respectively, on approximate averages). The mean temperature at point M is 19.2°C, whilst that at point W is 21.3°C. The appreciable difference

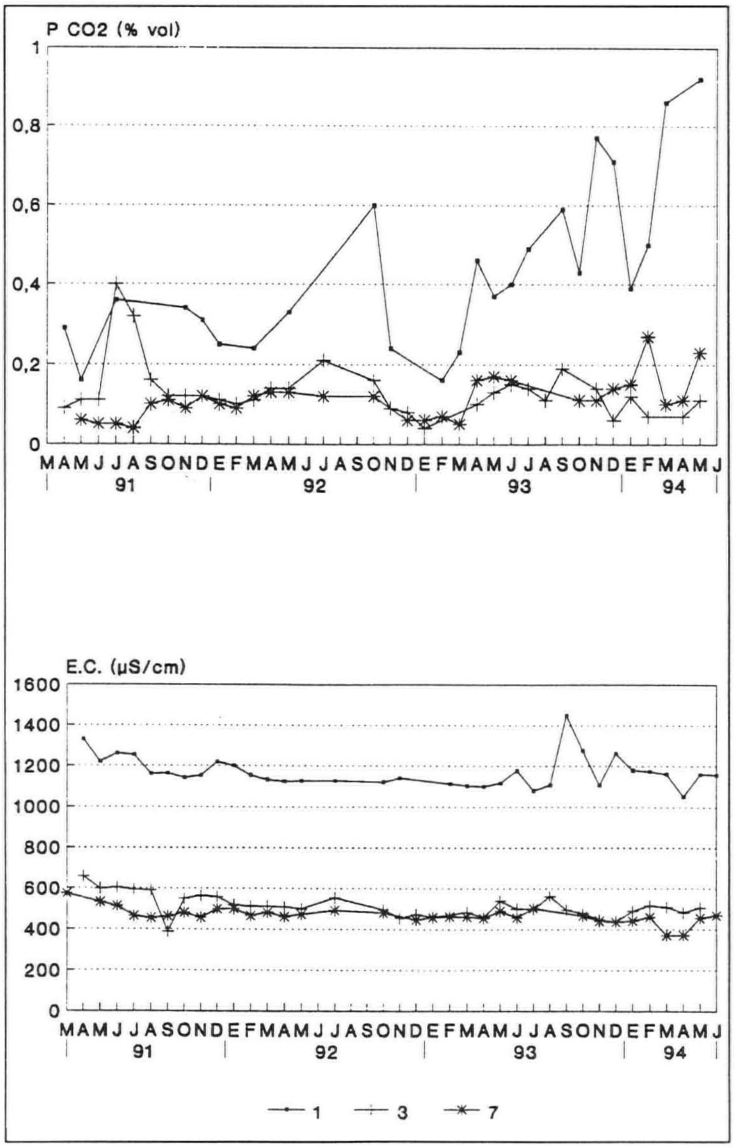


Figure 3. Evolution of E.C. and pCO_2 in three representative sampling points of drip water inside the Cave.

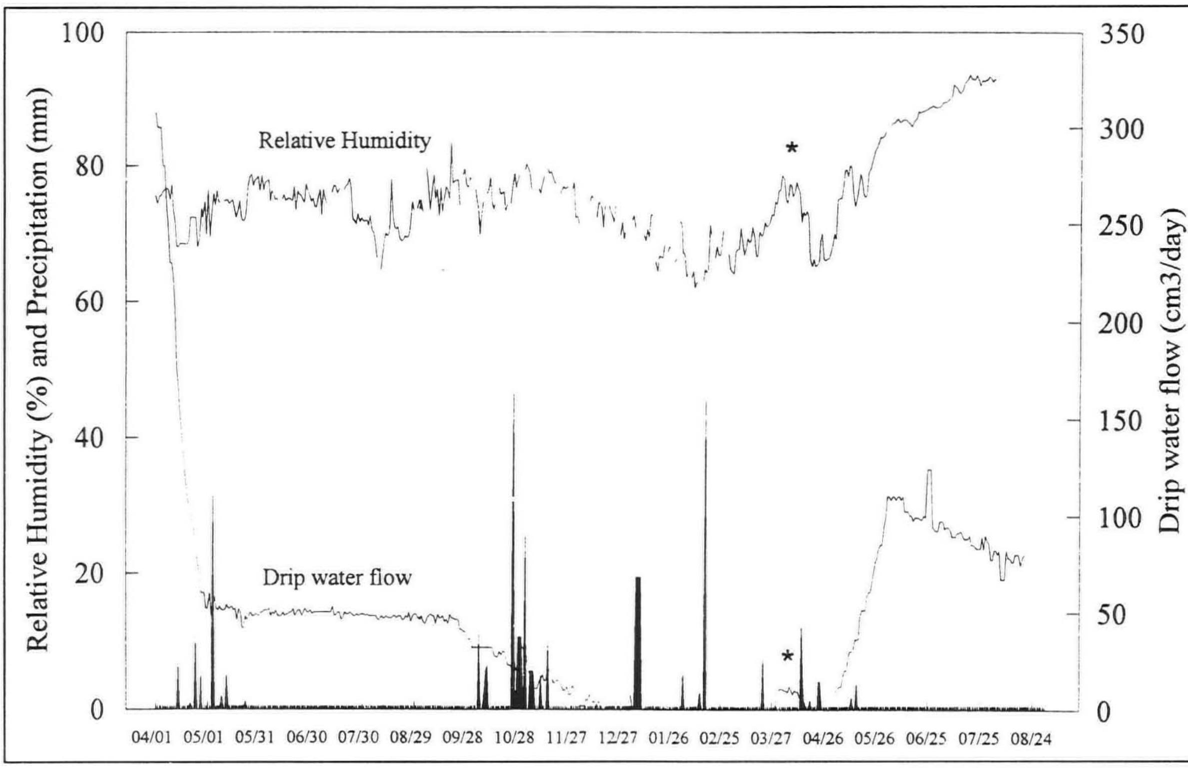
which both points show regarding the mean values of pCO_2 is worth noting: around 0.4% (point M) as opposed to 1-1.5% (point W). In both cases the water is slightly oversaturated as regards calcite and dolomite, although in the case of point W they are closer to equilibrium. The seasonal hydrochemical evolution recorded at these points indicates that, following the main rainy episodes, and in addition to the increase in the discharge, a reduction in the E.C. can be detected (Fig.5). This is accompanied by decreases in the values of SIc and SId.

DISCUSSION

The physical-chemical characteristics recorded in the rainwater are explained both by the short distance between the sea and the sampling point, and by the possible influence of certain nearby industries, such as marble quarries. The sampling procedure itself may mean that dry deposition could have a significant influence on the samples taken, especially after prolonged periods without any precipitation, as "wet-only" type sampling devices (Galloway and Likens, 1978) were not available.

With the exception of point 1, the chemistry of the drip water collected in the Cave must basically proceed from the relatively slow infiltration of rainwater through fissures in the marble. This process is indicated by Ip in Fig. 1. On the one hand, this permits a concentration (by way of the evapotranspiration in the soil zone: E, Fig. 1) of chemical components of

Figure 4. Evolution of the relative humidity, flow of drip water at sampling point 3 and precipitation, from April, 1993 to August, 1994. Note the local increase of humidity and flow during Easter holiday period (*).



meteoric origin (Cl^-, Na^+, particularly) and, on the other hand, causes dissolution of the marble until it becomes saturated in calcite. Subsequently, because of degassification of CO_2, this mineral precipitates and forms speleothems. This process induces an increase in the Mg/Ca ratio observed in the drip water in relation to the expected stoichiometry of dolomitic marble dissolution (Appelo and Postma,1993). In any event, the encrustant nature of this water is currently apparent from the formation of calcite precipitates around various objects (wires, containers, etc.). These conditions of SIc >0 in drip water have been observed in many other caves where diffuse infiltration through the vadose zone is the predominant process (White,1990).

The differences in the physical-chemical characteristics between points 2, 3 and 4 and the other drip water, must be related to the location of the former three in the area of the Cave open to the public, an aspect which is particularly highlighted by the data regarding the pCO_2. The seasonal evolution of this parameter seems to reflect natural fluctuations of soil CO_2 content in temperate climates, with low values in winter and high values in summer. This cycle is also observed in cave atmospheres (Troester and White, 1984). Apart from this, anthropogenic source of CO_2 from human respiration must influence the observed evolutions.

The drip water flow must be influenced to a certain extent by the water which comes from the condensation of the humidity in the air inside the Cave (Cw in Fig. 1), especially during periods in which this variable reaches values close to saturation point. In any event, the possible mixture of this condensation water with that from infiltration was already suspected when estimating the coefficient of infiltration over the carbonate materials, by using the climatic concentration factor with regard to the content of chlorides in the precipitation. Although it is necessary to apply this method with caution in areas with a relatively dry climate such as that studied (Lerner et al., 1990), the percentages of infiltration obtained (a little under 30%) seemed excessively high with regard to the actual conditions, which could reflect a diluting effect on the content in Cl^- of the infiltration waters. This effect is thought to be induced by condensation water which comes mainly from transpiration of the visitors. In order

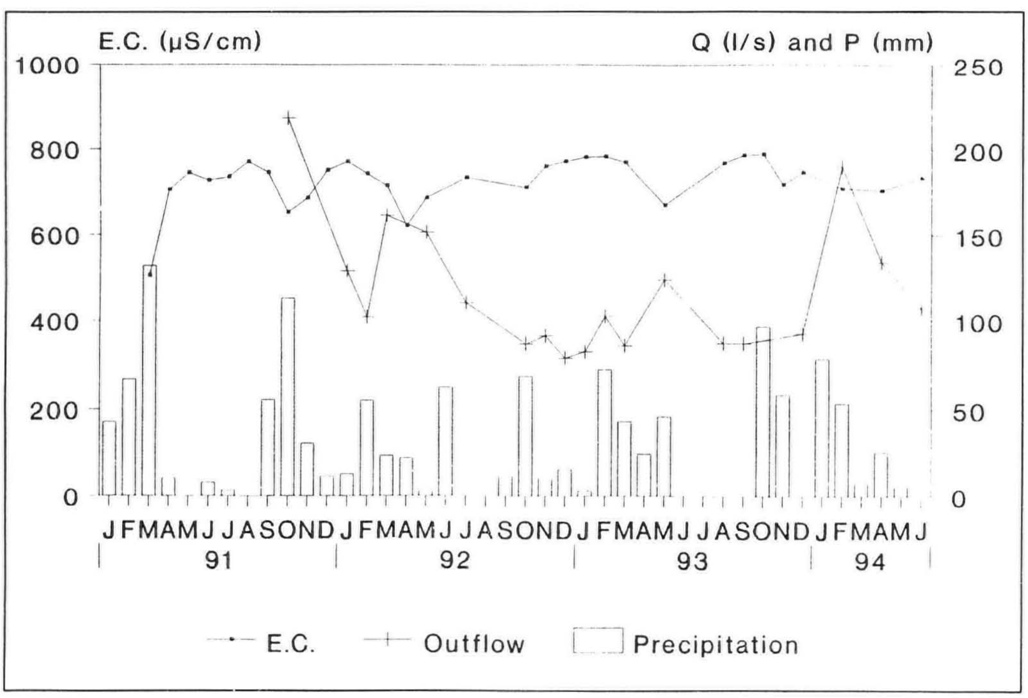


Figure 5. Evolution of outflow (Q) and E.C. in the Maro spring.

to try to evaluate the relative importance of this process, measurements of stable isotopes (Oxygen 18 and deuterium) are currently being undertaken both from rainwater and drip water.

With regard to the particular hydrochemical characteristics observed at point 1, these must be due to its situation below the gardens of the Cave, watered with water from well W. The drip water chemistry at this point is thus affected by a return flow effect (Rf, Fig.1). The climatic concentration effect must also be taken into account as regards the composition of this water, as well as the increase in the pCO_2 values due to the effect of the vegetation and the presence of a thicker layer of soil than that existing above the other rocky outcrops. This would also explain its relatively anomalous evolution.

The differences observed in the samples from the saturated zone must be due to the existence of two different flow systems within the same hydrogeological unit. In the flows which feed the well of the Cave, deeper paths than those which characterise the natural drainage towards the spring must predominate (Fig.1). The explanation of the relatively high content in sulphates and calcium in this type of water could be related to the dissolution of gypsum, whose presence in the Alpujarride carbonate formation is well-known in similar massifs situated further East. In these massifs, water of a SO_4 Ca type is predominant, to the extent that even processes of dedolomitisation can be identified (Cardenal et al., 1994). However, in this sector of the cordillera, owing to a higher degree of metamorphism, petrographic studies reveal the absence of such an evaporitic mineral. Thus, it could be considered that its origin is related to the oxidation of metallic sulphurs (pyrite, galena, etc.), which also exist within the aquifer materials. Although the sampling frequency is not ideal for illustrating this aspect, the chemograph for the Maro spring (Fig. 5) seems to indicate a certain degree of functional karstification. This is reflected in the behaviour following the rainy episodes, when the influence of more diluted - and with lower SI values - water is detected.

CONCLUSIONS

As in the majority of caves open to the public, the considerable number of visitors to the Nerja Cave causes thermal, chemical and biological changes in the subterranean environment (see Huppert et al., 1993, for a comprehensive review of the most common problems in touristic caves). From an isotopic study of the speleothems, Reyes et al (1993) suggest that the mean temperature in the Cave may have risen by almost 2°C since its opening to the public. The first available results from the continuous monitoring of temperature, humidity, and CO_2 content in the atmosphere of the Cave, set out in this paper, clearly show the influence of the visitors. The physical-chemical and flow data of the drip water, which constitute the main aspect of this study, also seem to confirm this influence. As regards the biological changes, the development of flora on the speleothems has already been the subject of previous studies (Ruiz-Sanchez, I. et al., 1991) and steps are being taken to minimise its impact (modification of lighting system, cleaning etc.).

Apart from local phenomena identified in the sector closest to the entrance, it would be interesting to find out in what way the chemical composition of the drip water could affect the speleothems. In a preliminary study, Reyes et al (1993) consider that CO_2 contents in the Cave atmosphere of above 750 ppm may facilitate the alteration of the carbonate material, providing that the humidity is also appropriate. This aspect is currently being investigated using different techniques, including hydrogeochemical modelling. In fact, crusts caused by weathering of the speleothems, which crumble easily, have been identified in some points. It is essential to study and control these effects for the conservation of the Cave.

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REFERENCES

Apello, C.A.J. and Postma, D., 1993, *Geochemistry, groundwater and pollution. Balkema.* 536 pp. Rotterdam.

Bakalowicz, M., 1984, Water chemistry of some karst environments in Norway. *Norks. geogr. Tidsskr.*, 38, 209-214.

Brook, G.A., Folkoff, M.E. and Box, E. O., 1983, A world model of soil carbon dioxide. *Earth Surf. Proc*, 8, 79-88.

Cardenal, J., Benavente, J. and Cruz-SanJulián, J.J., 1994, Chemical evolution of groundwater in Triassic gypsum-bearing carbonate sequences, (Las Alpujarras, Southern Spain). *J. Hydrology*, 161: 3-30.

Carrasco, F. and Andreo, B., 1993, Características geoquímicas del agua de infiltración de la Cueva de Nerja (Málaga). *Geogaceta*, 14, 9-12.

Dueñas, M.C., Fernandez, M.C., Carretero, J. and Pérez, M., 1993, Estudio de la ventilación de la Cueva de Nerja mediante la concentración de Radón. IN Carrasco, F. (ed) *Geologia de la Cueva de Nerja - Trabajos sobre la Cueva de Nerja*, 3: 253-263.

Durán, J.J., Grün, R. and Ford, D.C., 1993, Dataciones geocronológicas absolutas (métodos E.S.R. y series de Uranio) en la Cueva de Nerja y su entorno. Implicaciones evolutivas, paleoclimáticas y neosismotectónicas. IN Carrasco, F. (ed.) *Geologia de la Cueva de Nerja - Trabajos sobre la Cueva de Nerja*, 3, 233-248.

Fernandez, P.L., Gutierrez, I., Quindos, L.S., Soto, J.and Villar, E., 1986, Natural ventilation of the Paintings room in the Altamira Cave. *Nature*, 321, 6070, 586-588.

Galloway, J.N. and Likens, G.E., 1978, The collection of precipitation for chemical analysis. *Tellus*, 30, 71-82.

Huppert, G., Burri, E., Forti, P. and Cigna, A., 1993, Effects of tourist development on caves and karst. *Catena supplement*, 25, 251-268.

Lerner, D. N., Issar, A.S. and Simmers, I.,1990, Groundwater recharge. *Int. Contrib. Hydrogeol.*, 8, I.A.H.

Ruiz-Sanchez, I., Marín-Girón, F., Ojeda, F., Marín-Olalla, F., Berros, J. and Marín-Olalla, E. (1991), Estudio macroscópico "in situ" y microscópico-ecológigico de pequeñas zonas de flora verde (algas verdes y verdeazuladas) del interior de la Cueva de Nerja. IN Marín-Girón, F. (ed.) *Investigación Biológica y Edafológica - Trabajos sobre la Cueva de Nerja*, 2, 113-125.

Sociedad Excursionista de Málaga, 1985, La Cueva de Nerja. *Sociedad Grupo de Espeleólogos Granadinos*, 87 pp.

Troester, J.W. and White, W.B., 1984, Seasonal fluctuations in the carbon dioxide partial pressure in a cave atmosphere. *Water Resources Research*, 20, 153-156.

White, W. B., 1990, Surface and near-surface karst landforms. *Geol. Soc. of America*, Special Paper, 252, 157-175.

Wilkenings, M. H. and Watkins, O. E., 1976, Air exchange and Rn-222 concentration in the Carlsbad caverns. *Health Physics*, 31, 139-145.

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Cave Conservation Plans: The Role of English Nature

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Abstract: Cave conservation is concerned with the safeguard of caves as both static repositories of scientific information and as naturally evolving dynamic landforms. English Nature, as statutory advisors to the Government on nature conservation issues in England, is responsible for a network of protected cave sites. These sites can be threatened by both internal cave users and by external activities such as quarrying and agricultural practices. External threats are usually countered by English Nature through the statutory planning process, but internal threats need to be addressed by those who use the underground cave systems. English Nature would therefore like to see cave users and owners taking more responsibility for management and conservation of these sites. In order to do this, English Nature is advocating the use of cave conservation plans and is currently facilitating caving groups in producing trial plans. These plans will help to safeguard England's cave resource into the future.

INTRODUCTION

In Great Britain, there are separate government conservation agencies for England, Scotland and Wales. In England, the body charged with responsibility for the safeguard of wildlife and natural features is English Nature. At present, a site based approach to nature conservation is used and under the Wildlife and Countryside Act 1981 English Nature has the power to notify land as Sites of Special Scientific Interest (SSSI) which it considers to be "of special interest by reason of any of its flora, fauna, geological or physiographical features". English Nature is also obliged to inform the local planning authority of every SSSI in their area and the local authority must consult English Nature over any planning applications which affect these sites. This legislation has resulted in a network of some 3000 SSSIs throughout England. Included in this figure are many sites notified for their importance as cave and karst features (Nature Conservancy Council 1990). These cave and karst features were selected by a nationwide process known as the Geological Conservation Review (GCR).

In England, caves are protected by English Nature for both their nature conservation interest and their geology and geomorphology. There are 36 cave Sites of Special Scientific Interest (SSSIs) in England selected by the Geological Conservation Review for geological reasons. Including caves notified for biological reasons, there are 813 cave SSSI in total. In reality, however, there is obviously a great amount of overlap between these designations since the GCR sites may also contain significant populations of many cave biota. The cave GCR sites were selected with the advice of local caving groups, national bodies such as the National Caving Association (NCA) and scientific groups such as the British Cave Research Association (BCRA). The results of this exercise are summarised by Waltham (1983).

Britain's caves

Caves are an often forgotten part of our natural heritage. Yet the underground environment of cave systems, their internal natural features and their wildlife are an exciting and beautiful part of the natural landscape. Caves are valuable as a scientific, aesthetic and recreational resource. There are six main areas of cavernous limestone in Britain and Ireland: in County Fermanagh, the Northern Pennines, the Peak District, County Clare, the Mendips and South Wales (Fig. 1). Current estimates give the total length of mapped passage in Britain and Ireland at a figure of around 800 km (Chapman 1993). This figure is probably an underestimate - with continued cave exploration the length of known passage is always on the increase, whilst the figure only includes those passages which are accessible to man. There are also many hundreds of kilometres of cave passage below human dimensions which remain unexplored.

Figure 1. The location of the six main areas of cavernous limestone in Great Britain.

The majority of accessible caves in Britain are formed by the natural solution of limestone along cracks and joints, creating an underground network of caverns and passages. Due to differences in geological history, climate and topography, the rates of cave formation are not uniform and may vary even over relatively short distances. Within the cavernous areas of Britain and Ireland these caves are all at different stages in their 'life cycle' and therefore represent a series of distinct habitats which may be exploited by a variety of biota. Cave conservation seeks to safeguard the many different geological and geomorphological features and biological species which are found underground.

In terms of their geology and geomorphology, caves are a unique repository of information about past climates and landscape change. The information contained in speleothems and clastic sediments are used by scientists studying subjects as diverse as mineralogy, palaeontology, hydrology and geomorphology. Cave entrances have long been used as shelters by both man and animals, and are therefore also rich in archaeology. Animal and plant remains washed into cave systems through these entrances are used by palaeontologists to reconstruct past environments. Fossils found in caves and cave entrances yield information about the species which lived above ground. Scientists can also date the formation of cave passages and cave systems using information obtained from decorations such as speleothems and cave muds. Caves also provide an important habitat for wildlife, including protected species such as bats (Glasser and Key, 1995). They are also home to various species of invertebrates, such as the freshwater crustaceans (shrimp-flea and water-flea -like creatures) which inhabit underground water. Of these, the shrimp-like Niphargellus glenniei is not found anywhere in the world other than in a handful of cave streams and river gravels in Devon and is probably endemic to Britain.

THREATS TO THE UNDERGROUND HERITAGE

Internal and external threats

The main threats to our underground heritage can be divided into those originating from internal and external pressures. Internal pressures arise from the use and exploration of caves and cave systems by scientists and recreational cavers. Over-use of a cave can result in damage to individual passages, to fragile cave sediments and cave decorations, and disturbance to cave wildlife such as bat roosts or insect habitats. It is estimated that up to 30,000 people in Britain may go caving, based on the total membership of caving clubs (Ford, 1990). Activities such as blasting or digging have obvious detrimental effects on the pristine cave environment and its habitats. External threats are presented by activities which change the internal composition of the cave system through alterations to water levels, chemical content or sediment supplies. Any such activity within the hydrological catchment can affect the cave, including changes in groundwater flow, run-off, pollution incidents, agriculture and quarrying. The effects of these activities vary between catchments and are reviewed in more detail by Hardwick and Gunn (1993).

Countering threats

Many of the external threats to cave SSSI are countered through the statutory planning process. Statutory consultees such as English Nature and the National Rivers Authority can take steps to ensure that potentially damaging operations are controlled, and that caves and cave systems are not adversely affected by development. Combating the internal threats is more difficult since it is not possible to "police" threatened areas of cave passage. In cases where there is restricted access, this can be used to limit the size and number of parties using the cave. The key to successful cave conservation is education and several documents have been produced with this aim in mind (NCA 1986; Price and Wright, 1990, 1991). Our underground heritage will only be fully safeguarded with the full acceptance that cave conservation lies with cave users as individuals. These individuals, along with their parent caving clubs, must take more responsibility for cave conservation if internal threats are to be tackled with any success. The involvement of external parties is also important, since if cave conservation plans are to succeed they also need the support of the cave owners.

CAVE CONSERVATION INITIATIVES

Cave conservation plans

In order to do this, English Nature is promoting the use of cave conservation plans. The fundamental principles behind these plans have already been explained and are accepted by the majority of cave users (Price and Wright, 1990, 1991). Cave conservation must take account of two fundamentally different aspects of caves. Firstly, caves are dynamic and evolving landforms in which natural processes can be studied. Secondly, caves are natural repositories of more static features such as speleothems and sediments which provide evidence of climate change and landscape development throughout the Quaternary.

Cave conservation plans involve a four stage process of:

- documenting the scientific interest of the cave, including the type of interest, location and current condition.
- describing the pressures and threats to the cave system, including both internal and external threats. Consideration must be given to their effects on the scientific interest of the cave.
- recommending action to protect the cave from any of the threats noted above. These must be practical conservation measures which can realistically be implemented.
- monitoring the cave to assess the effectiveness of the conservation measures. This allows any problems or deficiencies to be identified and addressed.

The progression of a cave conservation plan through these stages is shown in Fig. 2.

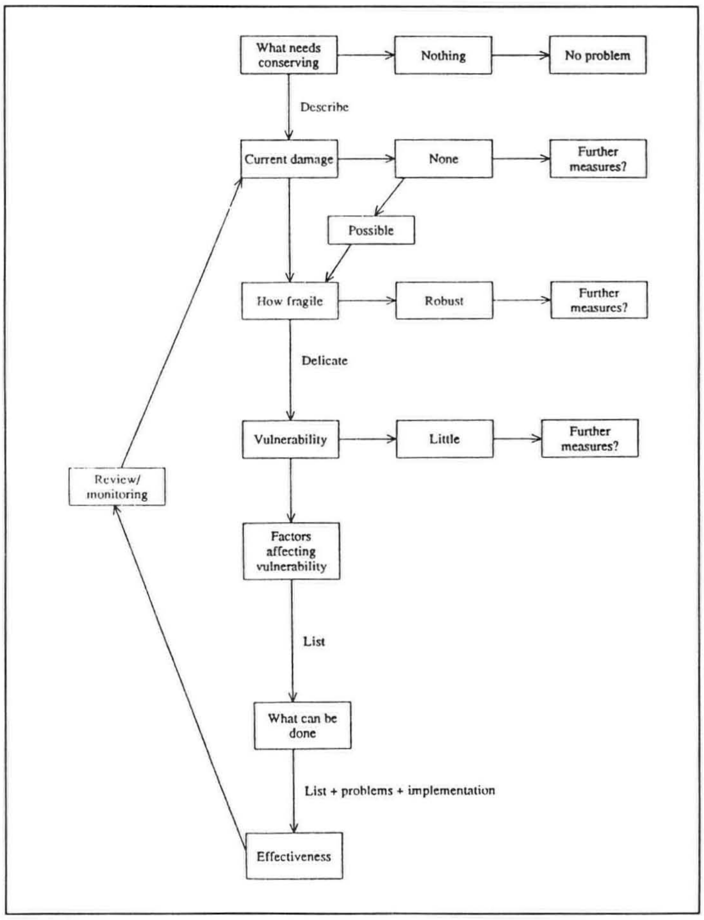

Figure 2. Flow diagram illustrating the main stages in the formulation of a cave conservation plan.

The concept of producing cave conservation plans is central to the newly-published National Caving Association (NCA) cave conservation policy (NCA 1994). Together with the NCA, English Nature is promoting the concept of the plans within the caving community by encouraging their production for cave SSSI. One way in which English Nature is doing this is by helping to fund caving groups in the production of cave conservation plans. Four plans have already been produced, with the specific aim of obtaining a spread of caves in different geographical regions. This allows the whole spectrum of different cave types, different pressures, different threats and different users to be identified as a model for future plans.

Cave Conservation plans - a working example

The production of a cave conservation plan is best illustrated by using the example of Knock Fell Caverns (KFC) in Cumbria. This cave system was first discovered in 1979 and explored (with the full consent of the landowner) over the period 1980-84. For a number of reasons the cave has not been subjected to the same visitor pressures as other caves in the area;

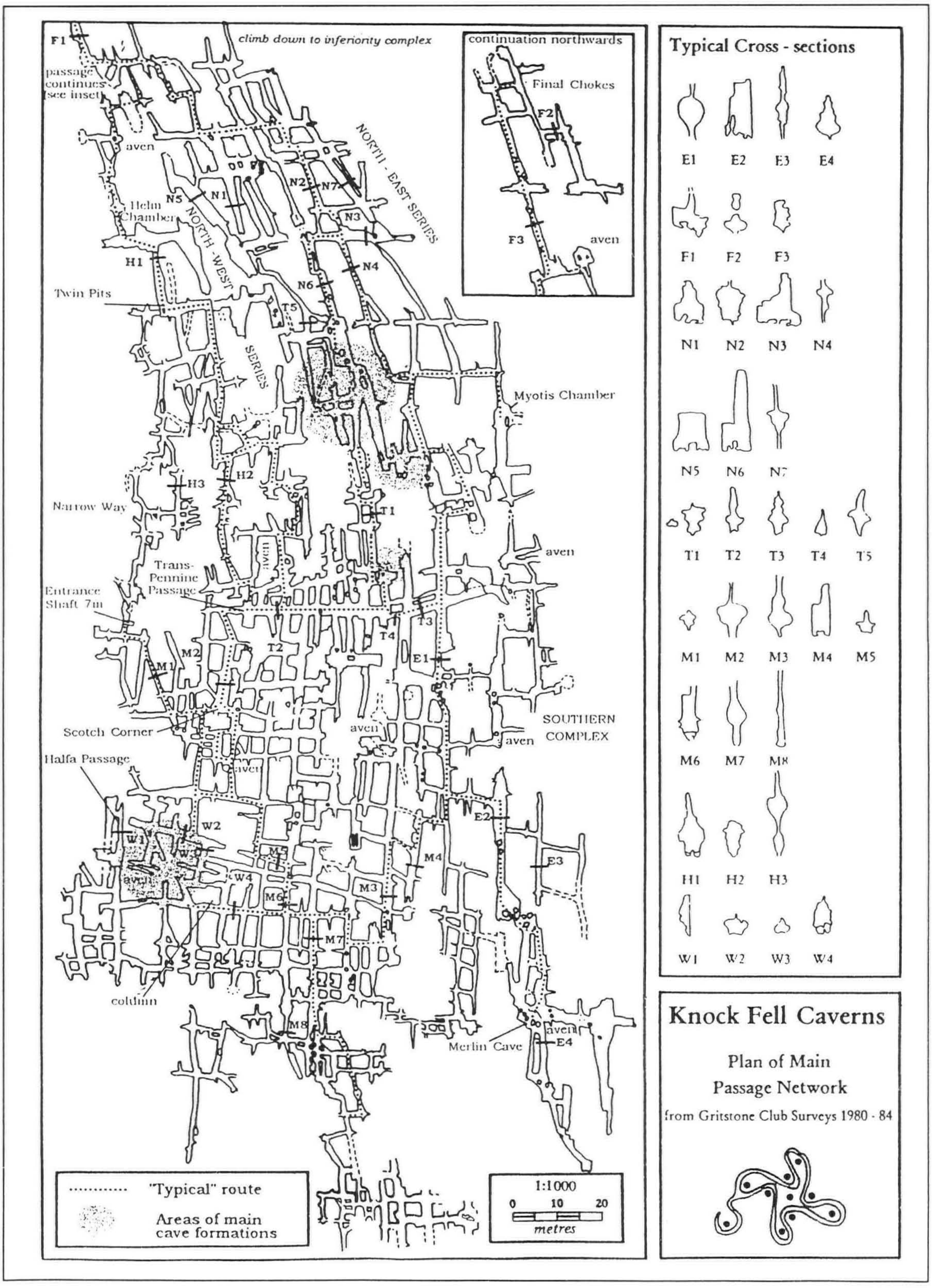

Figure 3. Annotated cave survey from Knock Fell Caverns cave conservation plan. The survey is designed to illustrate areas of areas of sensitive cave formations and a typical visitor route.

it is in an isolated and relatively inaccessible location, it has no great depth but large passage length, and its time of discovery means it is not included in the guide book for the area. Few cavers are aware of the existence of the cave.

In recent years the landowners have gated the cave in the interest of public safety, and permission to enter the cave has been restricted. This raised the issue of access to Knock Fell Caverns amongst the caving fraternity. Together with the imminent update of the caving guide to include the site, this situation needed to be addressed. An access agreement for the site was required and this needed to consider conservation of the cave. From this background a cave conservation plan for the site was drawn up by some of the original explorers, members of the Gritstone Club. This project was funded by English Nature.

The cave conservation plan is now complete and includes a study of the cave, its location, and the internal and external threats which it faces (Fig. 3). Since the cave is situated in a National Nature Reserve managed by English Nature, external threats are easily addressed. Internal threats are associated with caver access and use, and the study has identified those parts of the cave which may prove sensitive to the passage of cavers. The recommendations of the Knock Fell Caverns conservation plan include:

1. A permit-only access agreement should be instituted which will give English Nature and the National Caving Association the opportunity to control and monitor use.

2. Access should be restricted to experienced cavers and should prohibit its use by novice and outdoor activity groups.

3. Access documentation given to visitors should include information on the status of the cave, access restrictions and dangers.

4. Documentation should also include a survey which shows the normal visitor routes recommended for safety and conservation reasons, and highlights both the dangerous and sensitive areas of the cave.

5. Sensitive features in the cave should be taped off to prevent accidental damage. These features have been recorded and photographed as part of the cave conservation plan in order to act as a baseline for monitoring.

6. Monitoring will use not only the information in the plan, but also use the access procedures to monitor numbers and groups using the cave. This information can be used to examine the effects of access on the conservation interest of the site.

The proposals of the conservation plan have been openly discussed and generally welcomed by cavers. The move towards educating cavers on their responsibilities in conserving Knock Fell Caverns has started by using the cavers to produce the plan themselves. With the ownership of the plan, it is hoped that any of its restrictions will be seen as acceptable and therefore complied with.

THE FUTURE

In order to conserve caves successfully there is still a need for a change in attitude towards cave conservation. Quarry and mineral extraction companies must avoid prime areas of karst, and landowners and cavers must be aware of the consequences of their actions on the surface and underground. Cavers and caving organisations must become more active in the sphere of cave conservation. English Nature takes a lead in protecting caves. Impacts from developments requiring planning permission are carefully assessed and steps are often taken to influence surface land management practices where it may adversely affect a cave SSSI. Cave conservation plans will form the basis for tackling many of the outstanding issues facing the future management of England's underground heritage. The aim is to produce these plans initially for all cave SSSI, and then to widen their scope to include non-statutory cave sites. The plans will integrate management of caves for geology with management for wildlife. Hopefully, this process will help to safeguard the nature conservation value of our caves.

REFERENCES

Chapman, P., 1993, *Caves and Cave Life*. London, Harper Collins.

Ford, T., 1990, Caves and conservation. *Earth Science Conservation* 28, 6-8.

Glasser, N.F. and Key, R., 1995, Managing caves for nature conservation. *Earth Heritage* 3, 7-9.

Hardwick, P. and Gunn, J., 1993, The impact of agriculture on limestone caves. *Catena Suppl. 25 Karst Terrains: Environmental Changes and Human Impact*, 235-249.

National Caving Association, 1986, *Protect Our Caves*. NCA leaflet.

National Caving Association, 1994, *Cave Conservation Policy*. National Caving Association, Bristol.

Nature Conservancy Council, 1990, *Earth Science Conservation in Great Britain - A strategy*. Nature Conservancy Council, Peterborough.

Price, G and Wright, J.R., 1990, Cave Conservation - a joint NCC/NCA initiative. *Earth Science Conservation* 28, 9.

Price, G. and Wright, J.R., 1991, Taking cave conservation into the 21st Century: A joint NCA/NCC initiative. *Descent 98*, 31.

Waltham, A.L., 1983, A review of cave conservation sites in Britain. *Trans. Br. Cave Research Assoc.* 10, 46-54.

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Regional Mapping of Karst Terrains in Order to Avoid Potential Environmental Problems

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Abstract: The Oklahoma Geological Survey will prepare a map of the State at a scale of 1:500,000 to show karst terrains and associated environmental problems in Oklahoma. Surface and near-surface carbonates (limestone and dolomite) comprise about 6% of the surface area of the State, whereas sulphates (gypsum and anhydrite) comprise about 4% of the State. Areas of carbonates and sulphates will be differentiated and mapped separately as two zones: in zone 1 they are 0-6 m deep, and in zone 2 they are 6-30 m deep. Areas underlain by bedded salt (halite) within 300 m of the surface comprise 14.6% of the State, and they will be mapped as zone 3.

INTRODUCTION

This is a brief paper describing the plans of the Oklahoma Geological Survey (OGS) for preparing a map and text showing the karst terrains and associated environmental problems in Oklahoma, in the southwestern U.S.A. (Fig. 1). Such a program is needed to show the distribution of karst features in the State so that engineering, construction, and ground-water-related projects can be prepared to solve or avoid problems related to development in karst terrains. The regional map and text will not replace the need for site-specific geotechnical and/or hydrogeological investigations where projects may be impacted by location in or near a karst terrain. We believe that all terrains in which carbonate, sulphate, or chloride rocks crop out or are in the shallow subsurface are probably some type of karst. In the case of carbonates and sulphates in Oklahoma, we believe that karst features can cause significant problems in areas where the soluble rock is as much as 30 m below the land surface; and for chlorides (halite, or rock salt), karst features can be significant where salt is as much as 300 m deep.

GEOLOGIC SETTING

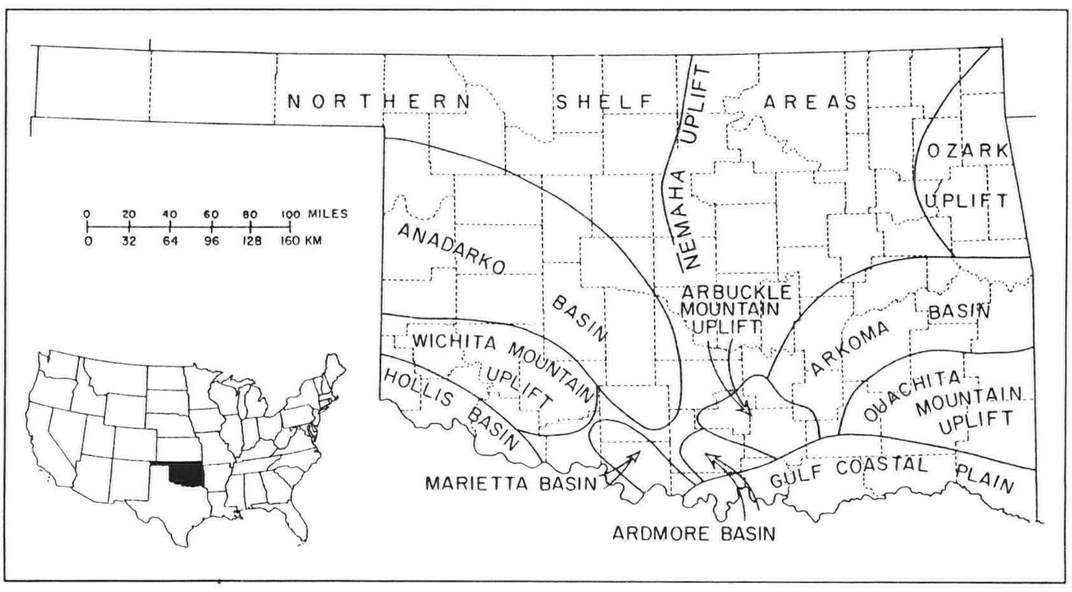
Sedimentary and low-grade metasedimentary rocks comprise about 99.5% of the outcrops in Oklahoma (Fig. 2), and Palaeozoic strata are as much as 6000-9000 m thick in the depocentres of the major sedimentary basins (Figs. 1 and 2). Carbonates and evaporites make up a significant portion of the outcrops and shallow-subsurface rocks in several of the geologic provinces, and thus the known and potential karst regions of the State are quite widespread. Carbonates, mostly limestone and minor dolomite, crop out chiefly in the Arbuckle Mountains, Wichita Mountains, and Ozark uplift (Fig. 3): they occur in units 15-2000 m thick and are of Late Cambrian through Early Pennsylvanian age. Pennsylvanian and Early Permian limestones, 2-15 m thick, occur in the northern shelf areas; and Cretaceous limestone, about 6 m thick, crops out in the Coastal Plain of southeast Oklahama. Permian evaporites are important in, and are restricted to, western Oklahoma (Fig. 3). Outcropping gypsum beds typically are 2–30 m thick, and five major subsurface salt (halite) units are each commonly 30–150 m thick and consist of shale interbedded with salt beds that are 1–10 m thick.

Within Oklahoma's area of 180,000 km^2, limestone and dolomite crop out, or are no more than 30 m deep, in about 10,700 km^2 (6% of the State); gypsum and anhydrite crop out, or are no more than 30 m deep, in about 7100 km^2 (4%); and salt is within 300 m of the land surface in about 26,300 km^2 (14.6%).

MAPPING PROCEDURES

The OGS has been involved for many years in a long-term programme of geologic mapping. Mapping has been done by OGS staff members, university faculty, or supervised graduate students. Field mapping normally is conducted through a coordinated program involving stereoscopic examination of aerial photos and field study. Carbonate and sulphate rocks in Oklahoma can be mapped easily; they commonly form conspicuous topographic highs because annual precipitation is rather low, ranging from about 50 cm in the west to about 125 cm in the east. At present, about 40% of Oklahoma's surface geology has been mapped at a scale of 1:62,500, or larger, and this is adequate to enable delineating areas where soluble rock units crop out or are in the shallow subsurface.

Figure 1. Map showing major geologic provinces of Oklahoma.



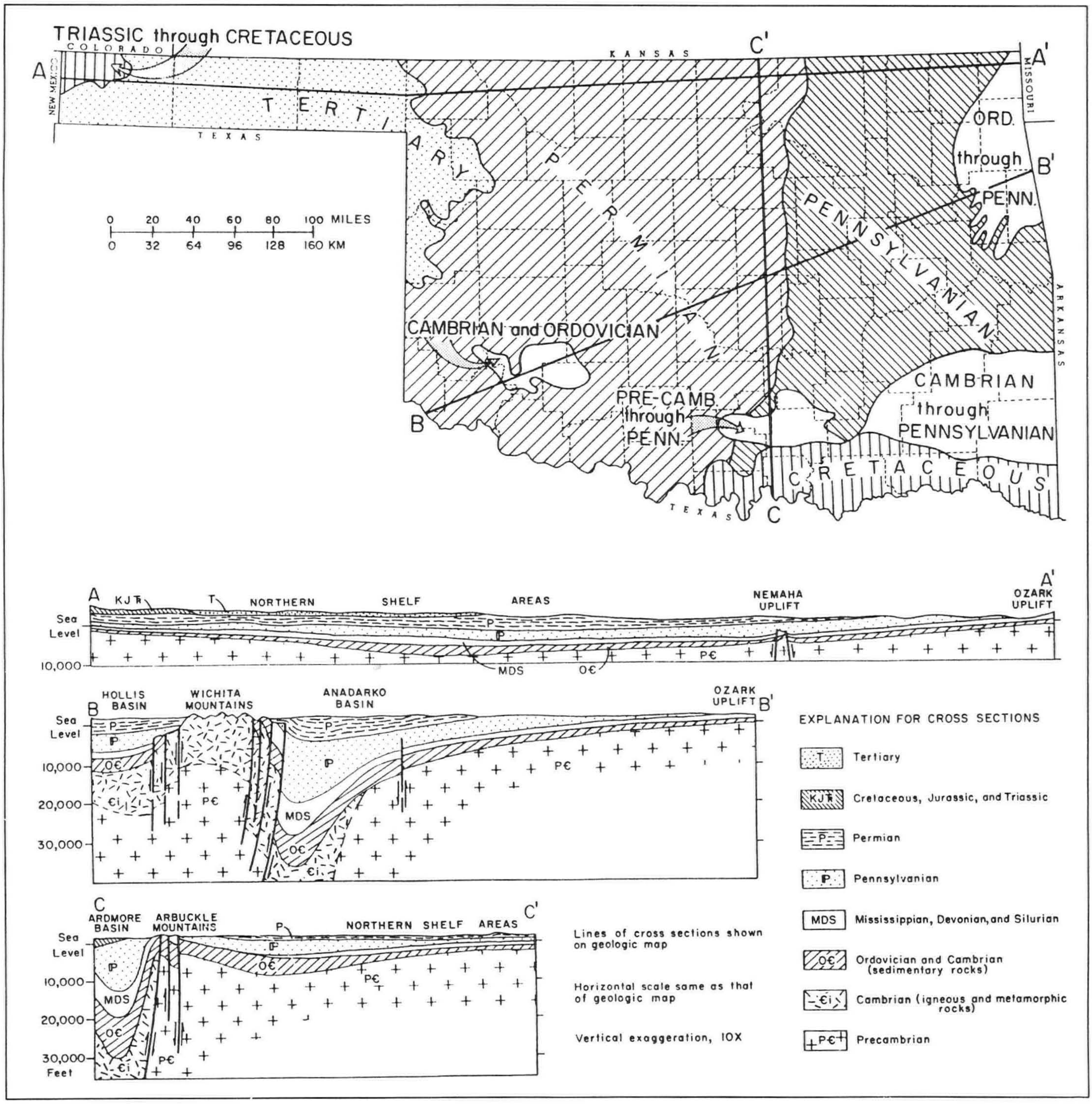


Figure 2. Generalized geologic map and cross sections of Oklahoma.

Fortunately, most of the counties or regions containing karstic rocks are among those already mapped, and compilation of reconnaissance-level data for karst areas in unmapped terrain will be carried out by stereoscopic photo examination and field checking.

Using geologic maps and aerial photos, we will outline the areas where carbonates and/or sulphates are at least 1 m thick and are less than 30 m deep. Furthermore, we will divide those areas into two zones (Fig. 4): in zone 1 the karstic rocks crop out, or are as much as 6 m deep, and areas in this zone normally represent the greatest potential for karst development and associated environmental problems; in zone 2, the top of the karstic rocks is 6–30 m deep, and areas in this zone normally represent a somewhat lesser (yet real) potential for karst development and associated problems. These two zones will be shown separately on the final map, and the areas of carbonates and sulphates will be differentiated (i.e., carbonates, zones 1 and 2, and sulphates, zones 1 and 2). The depths of 6 m and 30 m are somewhat arbitrary, but reasonable: any significant construction/engineering project in Oklahoma is likely to excavate, and/or directly deal with, bedrock karst units to a depth of 6 m; and karst development in the range of 6-30 m deep should be sufficiently widespread and may have an adverse impact on a construction/engineering project. Karst also develops in Oklahoma carbonates and sulphates at depths greater than 30 m (probably as deep as 50-100 m, locally), but it is much more sporadic, is less well developed, and its potential to cause environmental problems is probably quite low.

Areas underlain by shallow salt deposits are well known, as a result of interpretation of geophysical logs available for a great number of oil and gas tests drilled throughout Oklahoma. We will delineate those areas of western Oklahoma where the top of the shallowest salt is within 300 m of the land surface, and show those areas as zone 3 on the karst map. Salt does not crop out in Oklahoma, but it does occur at depths of only 10-15 m in several localities. The depth of 300 m for salt karst is also arbitrary, but reasonable. Active, natural dissolution of salt in Oklahoma

Figure 3. Map showing general distribution of karst terranes in Oklahoma.

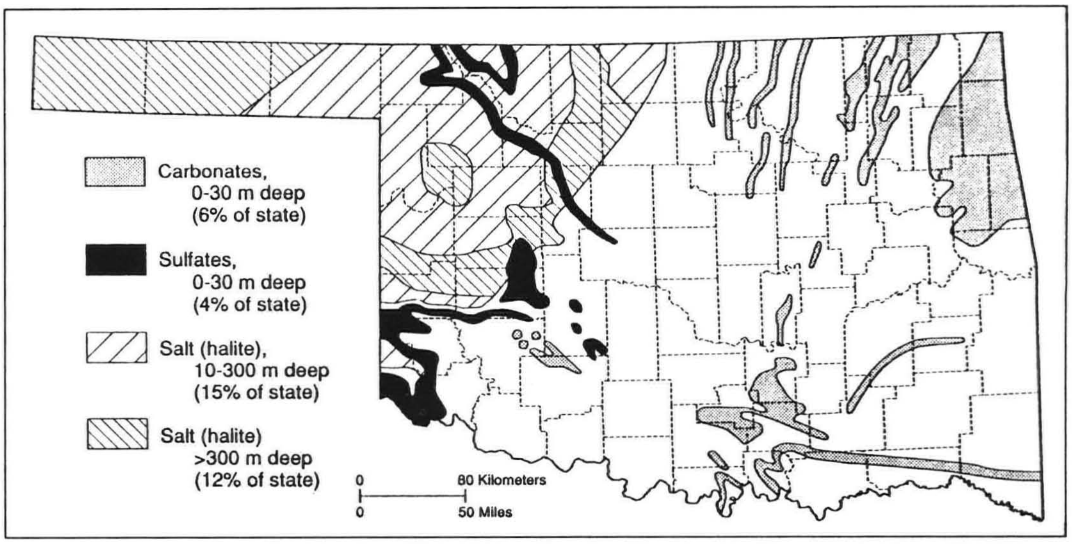
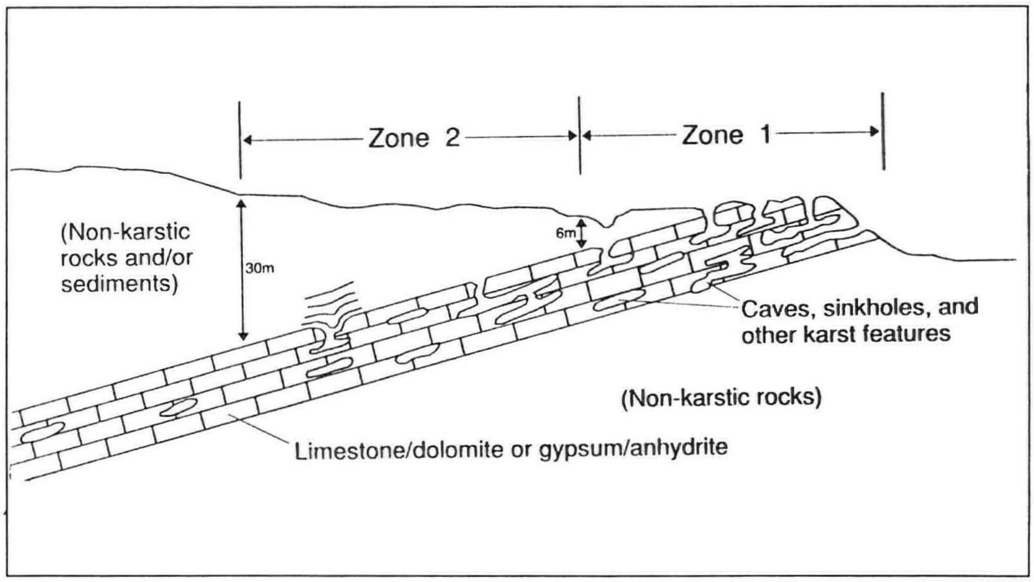


Figure 4. Schematic diagram showing proposed karst zones 1 and 2, which are related to the depth of karstic carbonates and sulfates in Oklahoma.



occurs locally at depths of 10-150 m, and anthropogenic dissolution of salt and consequent collapse, associated with boreholes (due to salt-cavity development and to petroleum activity), has occurred at several places in the United States where the salt beds are as much as 300 m below the surface. We are not aware of any natural dissolution of salt in Oklahoma at depths greater than 300 m.

Depth ranges described above for zones 1, 2, and 3 are considered reasonable for karst development in Oklahoma, at this stage of our study. We will, however, evaluate these depth ranges as work progresses, and will modify them if warranted. The final map will be prepared at a scale of 1:500,000. The base will show the land grid (townships and ranges), counties, towns, highways, railroads, and principal surface-water features. The map will delineate areas of limestone/dolomite karst and gypsum/anhydrite karst (zones 1 and 2), and will outline areas where shallow salt deposits (zone 3) can cause karst problems. An accompanying text will describe the geology and nature of karstic rocks in Oklahoma, and will discuss the known and potential hazards associated with karstic rocks and karstic terrains.

SUMMARY AND CONCLUSIONS

Owing to the importance of assessing the significance of karst in engineering and environmental problems in Oklahoma, the OGS will prepare a statewide map showing karstic terrains and a description/discussion of known and potential karst-related problems in the State. The map will be compiled at a scale of 1:500,000 from existing geologic maps and reports, and from stereoscopic aerial-photo examination in areas not yet mapped in detail. Areas of limestone/dolomite and gypsum/anhydrite will be differentiated, and each will be divided into two zones (0-6 m deep, and 6-30 m deep). Areas where salt is within 300 m of the surface will be mapped as a third zone. These depths are considered reasonable for Oklahoma, at this stage of our study, but they will be further evaluated (and perhaps modified) as the work progresses. These data, and the accompanying text, will aid in the planning of engineering, construction, and ground-water-related projects, and should reduce the adverse impact of environmental problems associated with karstic terrains. Detailed studies will also be needed, however, to evaluate the specific relationship between a proposed project and the local karst conditions.

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Kannosui Spring and Endokarstification of the Hokezu mountains, Western Shikoku, Japan - A Case Study of Human Impact on a Limestone Aquifer

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Abstract: This case study makes use of a man-made tunnel to examine the endokarst system and spring outflow. The study area, the Hokezu mountains, is situated in the western part of Shikoku at the southern margin of the Sambosan Belt bounded by the Butsuzo tectonic line. Limestone of Triassic age is the most frequent rock of the endokarstification in this area. Previous hydrogeologic studies accepted that the famous ascending-vauclusian karst spring Kannonsui was excavated by meteoric water descending through the weathering zone. During the period 1976-1980 the maximum outflow from the Kannonsui spring was approximately 20.4 times the lowest discharge. Geological data obtained during construction of the Yoshida aqueduct tunnel revealed that the endokarstification of the Hokezu mountains extends to a depth of some 300 metres and is controlled by fault tectonics.

INTRODUCTION

The study of deep karst phenomena can be very important for tunnel construction. It is necessary to have information about the location of limestone aquifers at the depth of the tunnel so as to avoid inflow and collapse accidents. The Kannonsui spring in the karst region of the Hokezu mountains, western Shikoku has been famous for at least 400 years. It has an average discharge of about $100 l s^{-1}$ and the waters are used for irrigation, fish-breeding and drinking. At the Nanyo Irrigation Project, the 6348 m long Yoshida aqueduct tunnel planned to cross the Hokezu mountains and topographic constraints meant that the tunnel had to pass relatively near to the Kannonsui spring. When the tunnel reached 2827-2829 metres from its lower entrance there was a a great inrush of karst water as the Kannonsui spring was emptied into the tunnel passage.

GEOLOGY AND CLIMATE

The study area is situated in the western part of Shikoku, southwest Japan on the southern margin of the Sambosan Belt (Fig. 1). The Hokezu mountains range in elevation from 200 to 700 metres above sea level. The Itagatani Formation of the Sambosan Belt is distributed in the Hokezu mountains along the northern side of the Butsuzo tectonic line. The formation consists of sandstone, slate, chert, limestone and basalt-pyroclastic rocks. The formation is Triassic to Jurassic in age. The clastic Cretaceous (Albian) Hokezu Formation of the Shimanto Belt is also present and it is located on the southern side of the Butsuzo tectonic line. The climate is semihumid warm. The mean annual temperature is 14.6°C, the highest monthly temperature is 26.2°C in August and the lowest 3.6°C in January. The annual average precipitation is 1914 mm (last 30 years) and varies within the range of 1657-2481 mm.

ENDOKARST

In the small-scale karst area of the Hokezu mountains, the endokarst phenomena are represented mostly by caves and springs. The horizontal caves (Ananogozen Cave, Umenoki-do Cave) and the vertical caves (Chigeo-do Caves, Karimata-ana Cave) are sporadically distributed. Of these, the vertical style caves which mark an ancient karstification level, are located at 500-660 metres. The other endokarst phenomenon in the Hokezu mountains are represented by two springs, the Kannonsui spring and the Shiramizu spring. Geomorphological studies suggest that uplift occurred in two stages, the first one in the late Pliocene which formed the uplifted peneplain of the summit and the second in the middle Pleistocene which formed the river terraces of the Uwa river.

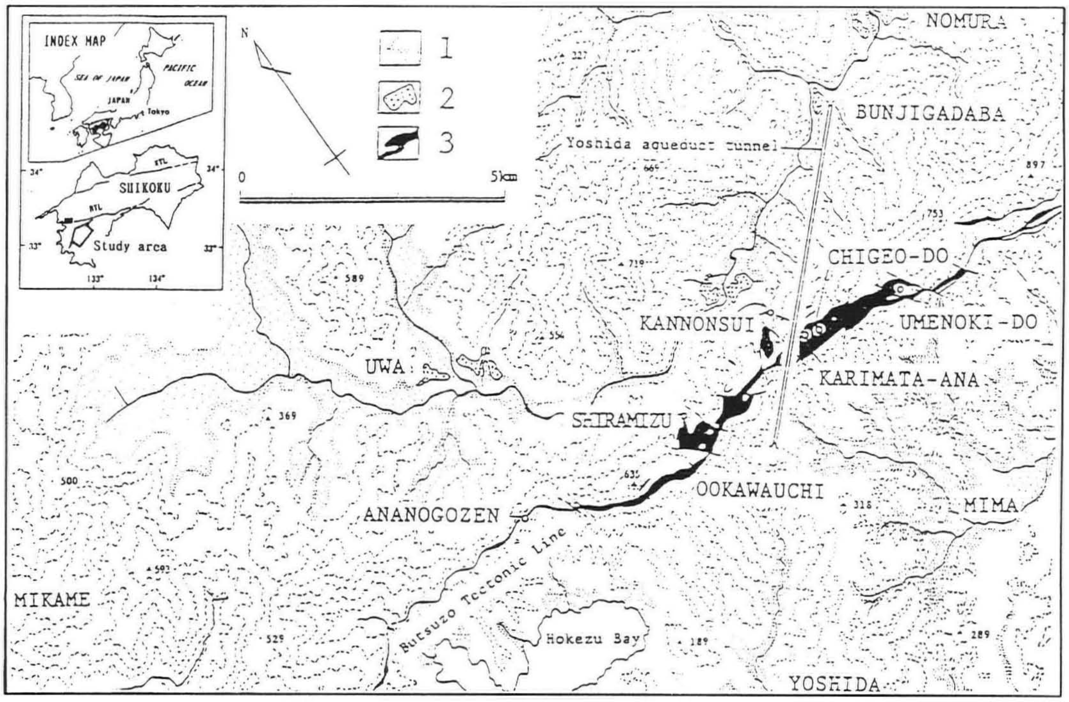


Figure 1. Index map of study area, the location of the karst features and the Yoshida aqueduct tunnel in the Hozeku mountains, western Shikoku, Japan. MTL: Medium tectonic line. BTL: Butsuzo tectonic line.

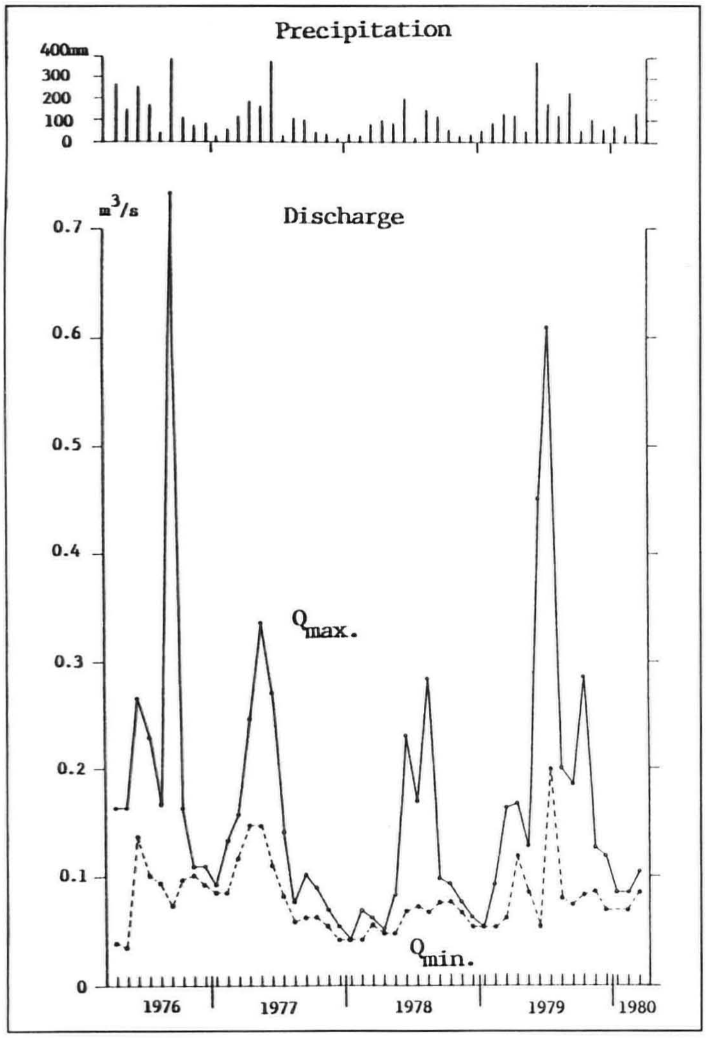


Figure 2. Monthly discharge of the Kannonsui spring and precipitation histogram for the period 1976-1980 (after Nanyo Agricultural Irrigation Office).

KANNONSUI SPRING

The Kannonsui spring is located on the north side of the Hokezu mountains at about 312 m above sea level. The limestone in the Kannonsui spring area is dolomitized and silicified pelagic biomicrudite and megalodont-bearing biomicrite. The water of Kannonsui spring drains from a small cave with an average outflow of about 100l s^{-1} and a range of 36-736.6l s^{-1}. Fig. 2 shows the monthly discharge of the Kannonsui spring and the precipitation for 1976-1980. The Kannonsui spring can be classified into ascending-vauclasian type spring. The surface drainage basin of Kannonsui spring is 0.382 km^2 but water balance studies suggest that the real catchment (watershed) area is about 1.521 km^2.

YOSHIDA AQUEDUCT TUNNEL

The Nanyo Irrigation Project is to provide the irrigation water for a 7200 ha orchard and to supply water for 170,000 inhabitants of the Nanyo region. It is intended that up to 4.0 m^3/s be taken from the Nomura Dam, which is constructed on the Hiji river, to two cities and seven towns. This project started in 1974 and is scheduled for completion in 1997. It is intended that the Yoshida aqueduct tunnel (6348 metres long and invert elevation from 138.5 m to 130.6 m) crosses the Hokezu mountains and topographic constraints meant that the tunnel had to pass relatively near to the Kannonsui spring. The tunnel route intersects the Butsuzo tectonic line and the limestone aquifers which feed water to the Kannonsui spring.

At the initial investigation stage of the Yoshida aqueduct tunnel, it was of the utmost importance to obtain information concerning the depth of the karstification zone. A seismic refraction survey and a borehole survey were used to explore the endokarstification zone in the limestone. The karstification zone in limestone which indicates the depth of limestone weathering was identified by seismic refraction profiles of the low velocity zone (below 900-2000 m s^{-1}) and observation of karstic solution fissures and cavities using three drilling cores (ES-3, N501 and N502) from a same line of seismic measurement (Fig. 3). Based on these investigations, it was estimated that the depth of karstification in this area was about 130 metres from, and parallel to, the land surface. During tunnelling operations through the limestone many clay filled cracks were encountered together with a paleo-cave system about 25 metres long (Fig. 4) containing unconsolidated sediments which are markers of ancient karstification level. Large quantities of groundwater entered the tunnel at high pressure (15-27 kg cm^{-2}) but these phenomena have no apparent relationship to the Kannonsui spring.

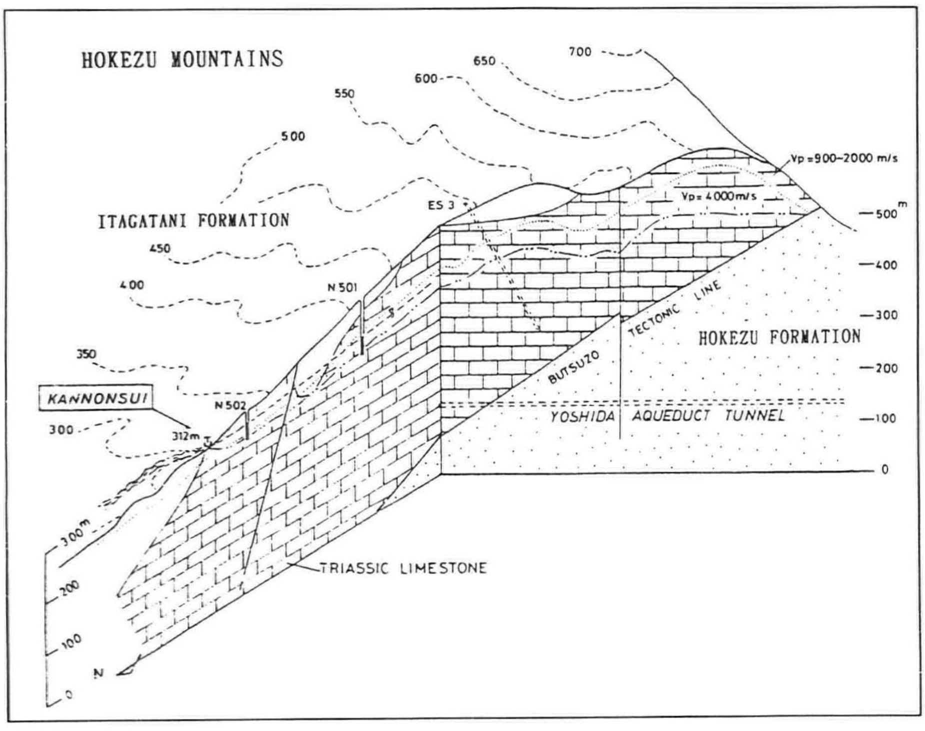


Figure 3. Block diagrammatic view of the karstification zone on the Hozeku mountains crossed the Kannonsui spring and the Yoshida aqueduct tunnel (after Nanyo Agricultural Irrigation Office, 1975).

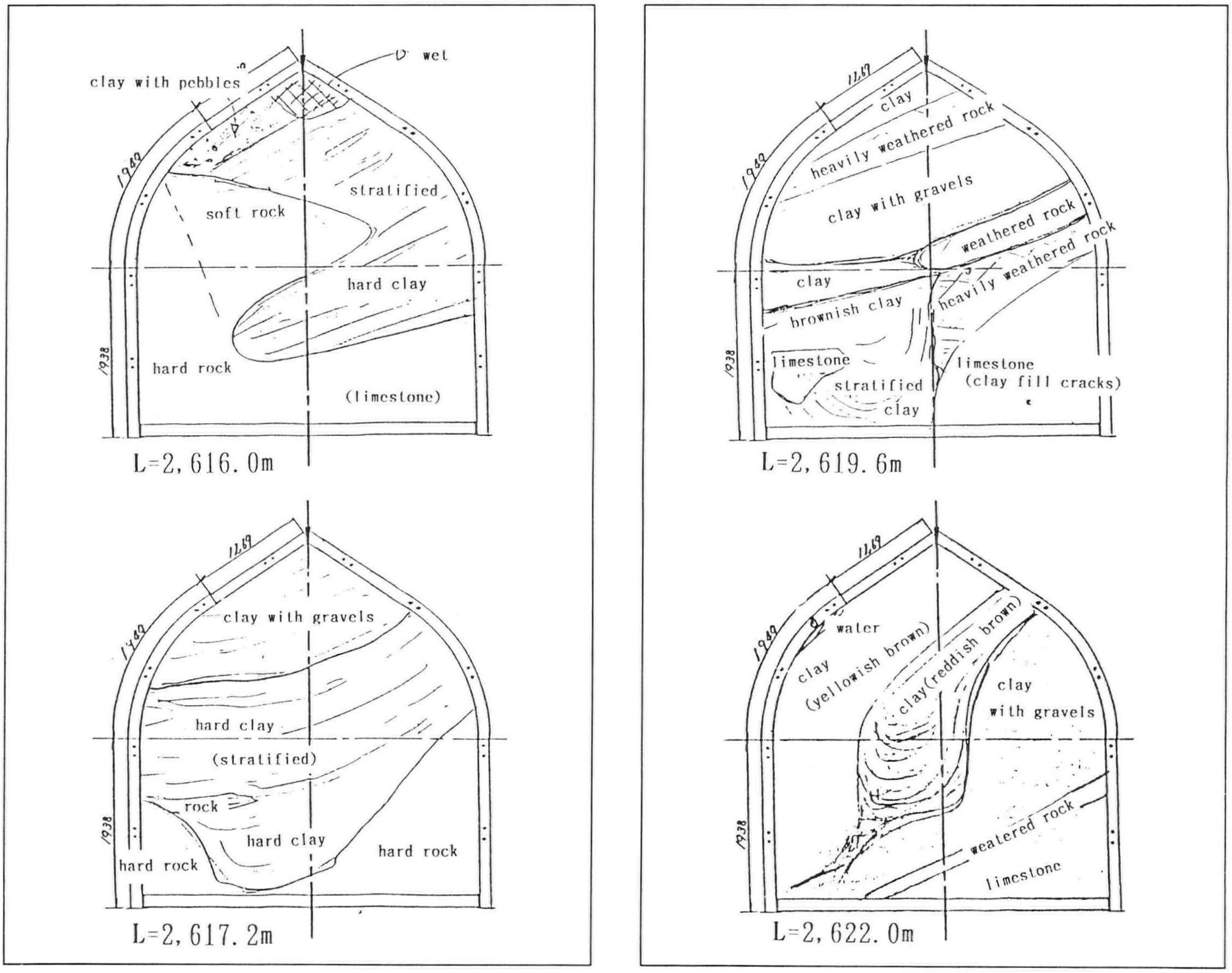
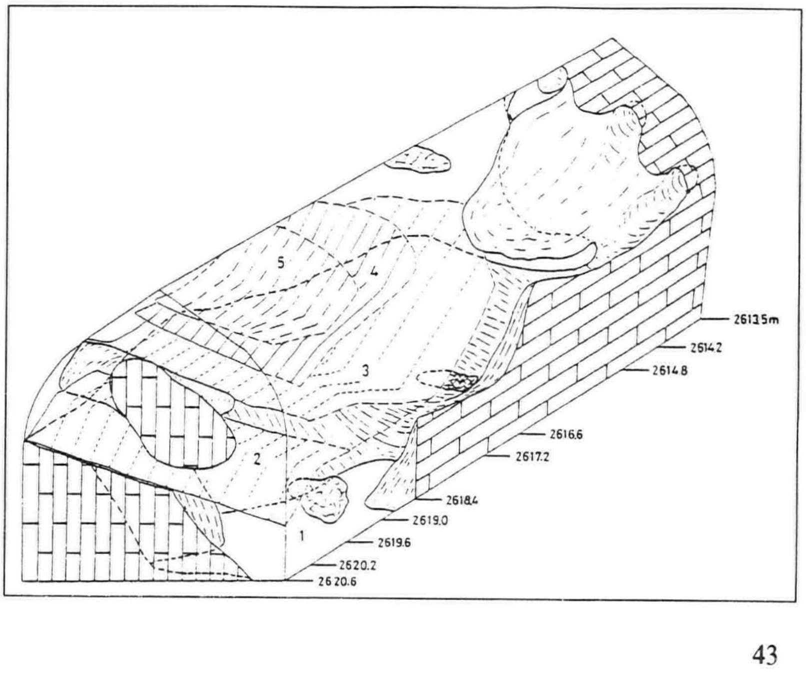


Figure 4. Tunnel cross cut wall sketches of the Yoshida aqueduct tunnel (L=2616.0 m; L=2617.2 m; L=2619.6 m and L=2622.0 m) (after Nanyo Agricultural Irrigation Office).

Figure 5. Block diagram illustrating the paleo-cave with unconsolidated sediments in the Yoshida aqueduct tunnel.
1. *Stratified clay bed.*
2. *The base plain of reddish purple clay bed.*
3. *The base plain of clay bed with gravels.*
4. *The base plain of heavily weathered rocks.*
5. *The base of clay bed.*



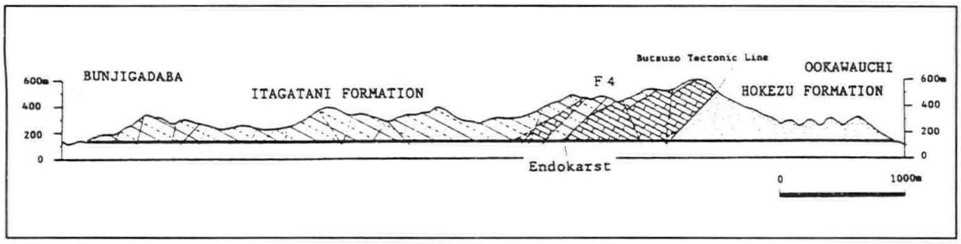


Figure 6. Geological profile through the Yoshida aqueduct tunnel.

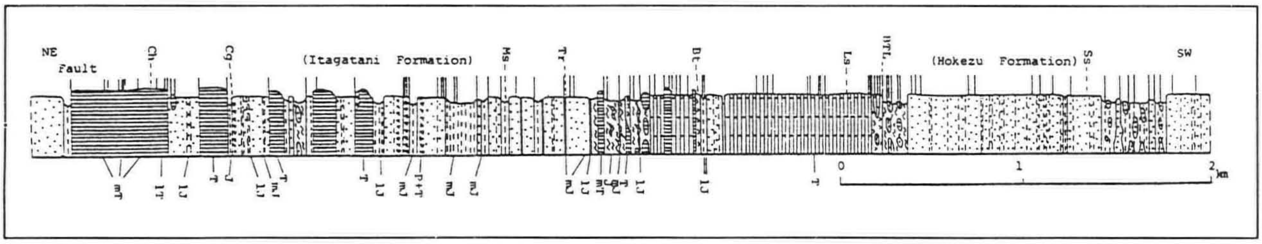


Figure 7. NE-SW cross sectional column through the Yoshida aqueduct tunnel.
Ss : sandstone; Ms : mudstone; Cg : Conglomerate; Bt : basalt-pyroclastics; Ls : limestone; Tr : radiolarite.
BTL : Butsuzo tectonic line.
l : late; m : middle; P : Permian; T :Triassic; J : Jurassic.

Fig. 5 shows the paleo-cave in the Yoshida aqueduct tunnel. Figs. 6 and 7 show the geological profile and a NE-SW cross sectional column through the Yoshida aqueduct tunnel based on the investigation of both side walls of the tunnel. At 2827-2829 m from the lower entrance the tunnel intersected a fracture zone in the limestone aquifer and a great quantity of karst water (about 2600 l s^{-1}) entered the tunnel. This resulted in a complete cessation of flow at Kannonsui spring. Back filling and sealing operations were undertaken and two months later the spring was completely restored.

CONCLUSIONS

1. The Yoshida aqueduct tunnel provided an excellent example of the nature of endokarst/paleokarst.

2. The Kannonsui spring forming the endokarst system in limestone aquifers was emptied during tunnelling operations.

3. At the present time, the endokarstification in this area is probably developed around the fracture zones, the fault system extending diagonally to the basic structure of the Butsuzo tectonic line.

ACKNOWLEDGEMENTS

The writer gives grateful thanks to the staff of Nanyo Agricultural Irrigation Office and Okumura-Gumi Company for help in carrying out this investigation. He wishes to thank Professor Jiro Takahashi, Department of Geology, Faculty of Education, Ehime University, for assistance in field works.

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REFERENCES

Kashima N., 1969, Stratigraphical Studies of the Chichibu Belt in western Shikoku. *Mem. Fac. Sci., Kyushu Univ,.* [D], XIX, 387-436.

Kashima N., 1993, Discovery of radiolarian fossils from the Hokezu Block at the northern area of Uwajima, Shikoku (in Japanese with English abstract). *NOM. Spec.*, Vol. 9, 225-231.

Kashima N. and Miyahisa M., 1965, Geology of the so-called Sambosan zone of western Shikoku, with some consideration on the stage of fault-movements of the Butsuzo tectonic line (in Japanese with English abstract). *Mem. Ehime Univ.* [D], 5, 39-59.

Kashima N. and Takahashi J.,1987, *Geology of the Yoshida aqueduct tunnel (Sambosan-Shimanto Belts) for Nanyo Irrigation Project* (in Japanese). Abstract of the 94th Annual Meeting of the Geological Society of Japan, 233.

Kashima N. and Takahashi J.,1989, Endokarst of the Hokezu mountains in western Shikoku, Japan. (Geological studies of the construction of the aqueduct tunnels for Government operated Nanyo Irrigation Project - Part 6). (In Japanese with English abstract). *Mem. Ehime Univ., Sci.*, [D], 11, 31-40.

Kashima N., Mitusio T. and Nishijima T., 1991, *Environmental Geology of the drainage basin of the Hiji river* (in Japanese). Excursion guidebook, The 98th Annual Meeting of the Geological Society of Japan, 215-234.

Okumura-Gumi Company, 1986, *The Construction Report of the Yoshida aqueduct tunnel of the Nanyo Irrigation Projects* (in Japanese), 143pp.

Tanaka K. and Nozawa T., 1977, *Geology and Mineral Resources of Japan.* Geological Survey of Japan, 430pp.

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Karst Morphogenesis in the epikarstic zone

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Abstract: The epikarstic (or subcutaneous) zone forms the upper layer of limestone rocks and its specific properties are due to the processes of weathering which directly affect this layer. A summary of the structural peculiarities of this zone and of the major features of epikarstic hydrology is provided, and the morphogenetic evolution of karst forms at the top of a massif is considered. A model of morphogenesis in the epikarstic zone is suggested which involves speleogenic development at its base. The role of condensation processes in epikarstic morphogenesis are also briefly considered.

INTRODUCTION

During the last two decades the enormous importance of the immediate subsurface zone in karst has been recognised by karst workers (Table 1), and specific hydrologic and morphogenetic processes have been studied which occur in the very top of karstifiable rock exposed to the surface. This zone is referred to as the subcutaneous or epikarstic zone.

Recognition and study of the epikarstic processes and their significance in karst hydrology and morphogenesis (main referrences)

Authors	Major books on karst hydrology and geomorphology (summarization)	Structural prerequisites and conceptual models of karst systems (karstic reservoirs)	Specific consideration of epikarstic processes and their significance	
			Hydrologic processes	Morphogenetic processes
Droque, 1979		+	+	
Droque, 1980		+	+	
Droque, 1992		+	+	
Mangin, 1973		+		
Mangin, 1975		+		
Williams, 1983		+	+	+
Williams, 1985		+	+	+
Gunn, 1978			+	
Gunn, 1981			+	
Gunn, 1983			+	
Bacalovicz, Blavoux, Mangin, 1974			+	
Bonacci, 1987	+	+	+	
Ford & Williams, 1989	+	+	+	
Klimchouk, Stotland, Lomaev, 1979			+	+
Klimchouk, Rogozhnikov, Lomaev, 1981			+	+
Klimchouk, Stotland, 1983				+
Klimchouk, 1987		+	+	+
Klimchouk, 1989		+	+	+
Klimchouk, Jablokova, 1989			+	

Table 1. Recognition and study of the epikarstic processes and their significance in karst hydrology and morphogenesis (main references).

MAJOR FEATURES OF EPIKARSTIC HYDROLOGY

Epikarstic processes are preconditioned by the contrast in jointing density and hydraulic conductivity between the uppermost layer of the karst rock and its bulk mass in the depth (Fig. 1). This contrast forms due to weathering processes affecting the uppermost layer. This layer can be developed as a zone several meters thick, which is highly fissured and diffusely karstified. Because of its high and quasi-uniform hydraulic conductivity the epikarstic zone receives diffuse recharge from the surface. As jointing density and diffused karstification rapidly diminish with depth, permeability also rapidly decreases in this direction (Fig. 2). Beneath the epikarstic zone the rock mass is much less uniformly fractured, and is divided by major joints and faults into large blocks, so that infiltration into the top of the epikarstic zone is much easier than drainage out of it (Williams, 1983). Considerable distinction in the structure and permeability between the epikarstic zone and the underlying block zone brings about an important percolation threshold, and causes an aquifer to form within the epikarstic zone. This aquifer is perched above the vadose zone (at the top of block zone) and leaks into it along major tectonic joints and faults which possess high hydraulic conductivity. Water stored in the epikarstic zone flows centripetally toward such joints, according to the relief of the epikarstic water table (Fig. 3). The peculiarities of the permeability structure and flow at the top of a karst massif bring about two major features of epikarstic hydrology: water storage and flow concentration.

Epikarstic storage

The epikarstic zone can store significant amounts of water which leak slowly into the underlying block (vadose) zone. The store maintains shaft flow along major joints and conduits, and the base flow of springs. The volume of the epikarstic store depends on the "maturity" of the zone and the contrast in hydraulic conductivity between the epikarstic zone and the underlying vadose zone. Storage in the epikarstic zone results in a significant delay in the through-flow of diffusely absorbed precipitation.

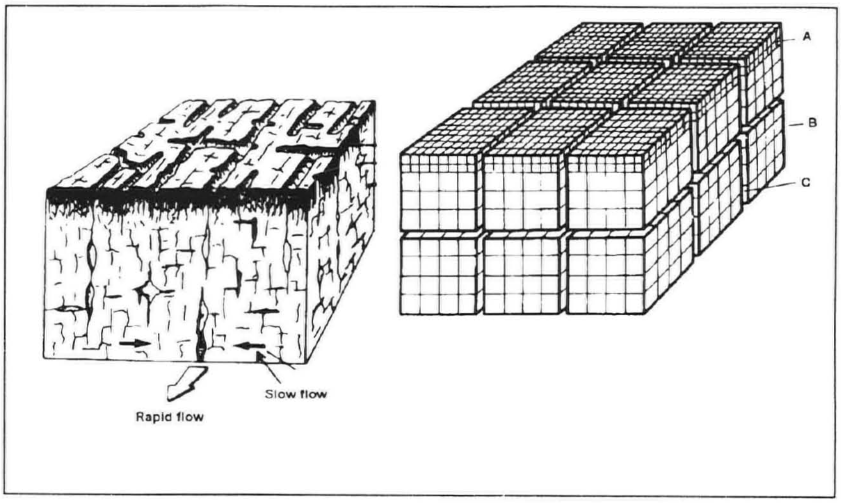


Figure 1. Geometrical representation of karstic storage structure. A - upper zone which is weathered and highly permeable, enhancing infiltration of water; B - block with networks of low-permeability cracks in which slow flow occurs; C - major joints and karst conduits with rapid flow which drains aquifer. (From Drogue, 1992).

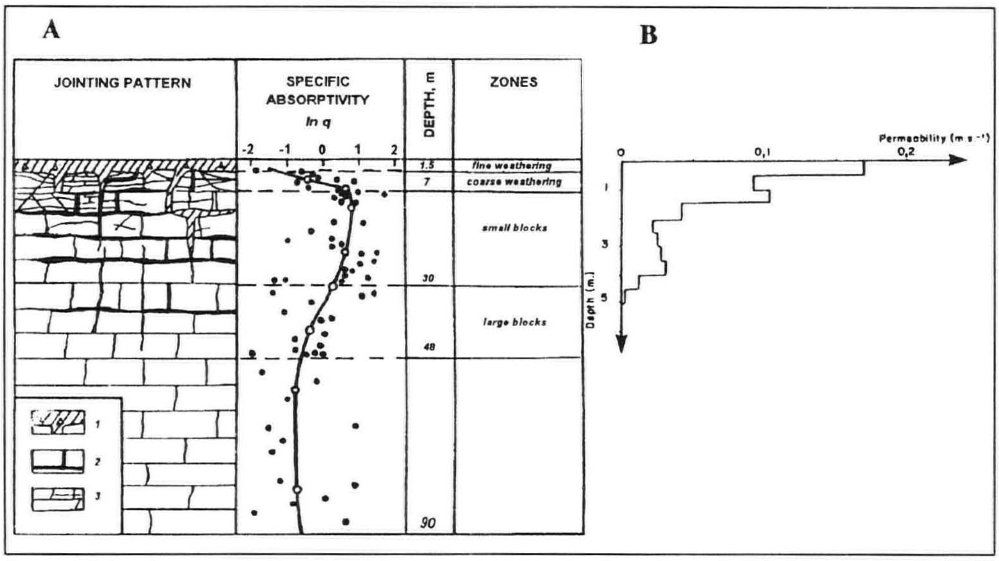


Figure 2. Changing of permeability with depth. A - Ust'-Ilym site, Siberia (From Chernyshev, 1979); B - Corconne site, France (From Drogue, 1992).

Regime studies by Gunn (1983) in the Waitomo District, New Zealand, and by Williams (1983) in Carlsbad Cavern, New Mexico showed that such delay can be as long as 2 to 14 weeks. Evidence of epikarstic storage and through-flow delay has been obtained also from $^{16}O/^{18}O$ isotope studies in the Arabika massif, West Caucasus (Klimchouk and Jablokova, 1989). Meltwater from small snow deposits in dolines which survive the summer period display no variations of $\delta^{18}O$ values, the average being -12.0 ‰ (Fig. 4). Shaft flow also has no variations ($\delta^{18}O$ = -12.0 ‰) and has the same isotopic composition as snow meltwater despite there being negligible snow melting recharge in August. Shaft flow does not normally show a rapid response to rain events but a heavy storm event in August, with rainfall $\delta^{18}O$ of -5.4 ‰, caused a flood response in shaft flow in Kujbyshevskaya cave. However, there were no associated variations in the isotopic composition of shaft flow during the flood, or within 10 days after it. These data clearly show that shaft flow is maintained by water stored in the epikarstic reservoir for rather long periods. Rapid response of shaft flow to the storm event was due to the transmission of a pulse wave, but flow consisted of "old" snow meltwater stored in the epikarstic zone since early summer (when massive snow melting occurs). Hence, the flow-through time is in the order of 2-3 months.

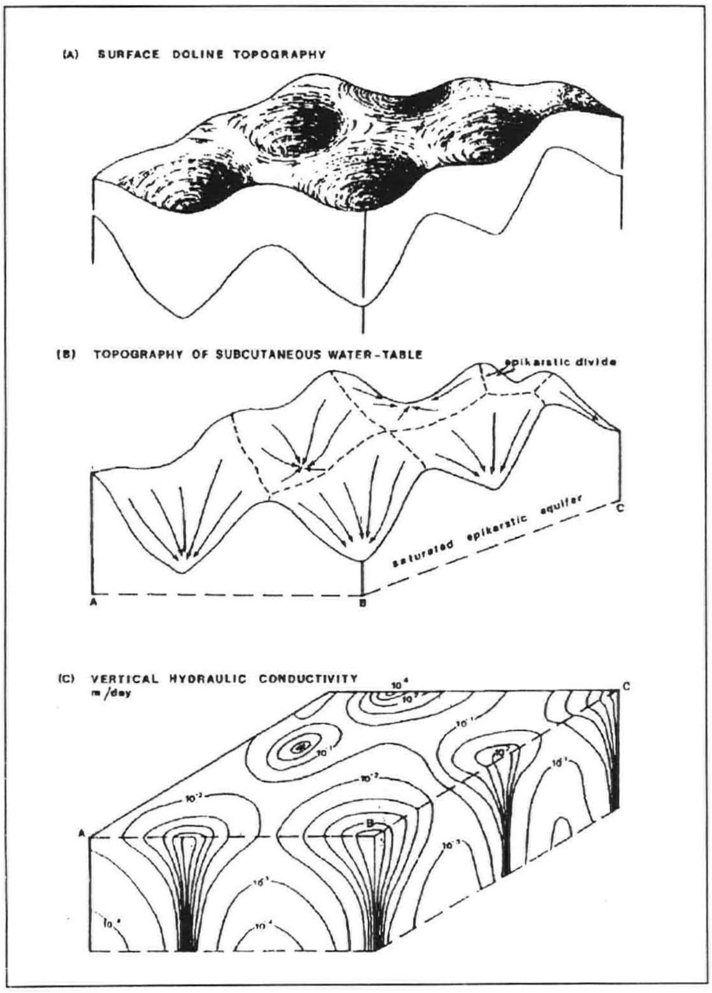


Figure 3. The relationship between (A) surface solution doline topography, (B) underlying relief on the epikarstic water table, and (C) vertical hydraulic conductivity near the base of the epikarstic zone. (From Williams, 1985).

Flow concentration

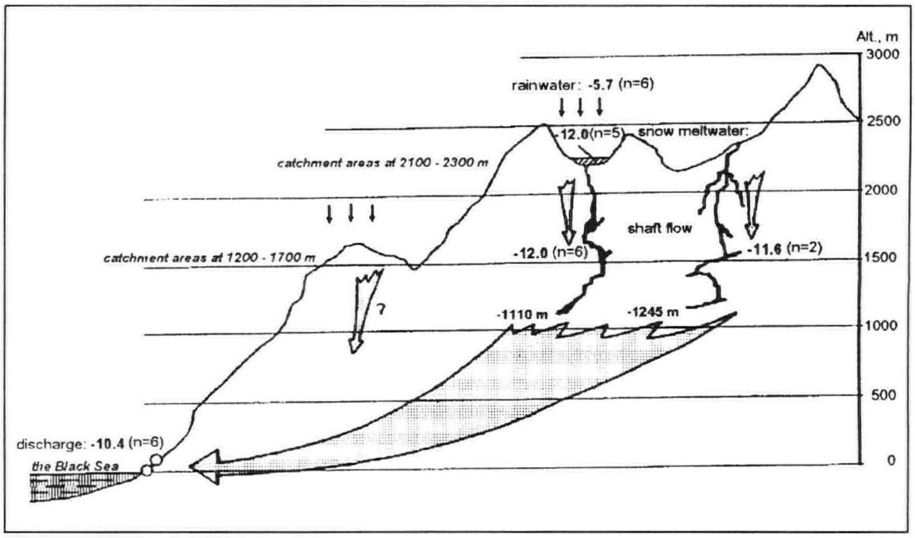
Initially diffused flow in the epikarstic aquifer focuses along major joints and faults which act as leakage paths to the vadose zone. A percolation threshold at the base of the epikarstic zone causes flow concentration to occur whilst passing from the epikarstic zone to the underlying block zone (Fig. 5). This feature is of great importance in karst morphogenesis. Even when a doline landscape has developed on the surface, overland flow is still unimportant, and epikarstic flow has been shown to remain the dominant concentration mechanism (Gunn, 1983; Fig. 6).

KARST MORPHOGENESIS

Epikarstic mechanisms are responsible for the initiation of closed depressions at the surface even if autogenic diffuse recharge prevails and no overland concentration of flow and corrosion occurs. Williams (1983) has suggested that dolines are initiated due to more intense dispersed corrosion within the drawdown cones in the epikarstic water table, which develops around major joints (leaking paths). As the surface lowers such areas begin to obtain topographic expression as solution dolines (Fig. 7). Once a doline is established, positive feedback will encourage its further development because of the centripetal focus of flow and hence corrosion (Williams, 1985).

Another model of epikarstic morphogenesis has been suggested which incorporates speleogenic development along the paths of leakage from the epikarstic zone (Fig. 8; Klimchouk et al., 1979, 1983; Klimchouk, 1987, 1989). The focus point of epikarstic flow and hence corrosion is located at the base of the epikarstic zone, at some depth under the surface (Fig. 8-A). From this point intense widening of a major joint occurs, progressing downwards and resulting in the formation of a vertical shaft which has no open entrance to the surface (Fig. 8-B). A karren field may form at the surface with a diameter corresponding to the diameter of the cone of depression in the epikarstic water table. The progressive increase of shaft diameter and isolation of boulders in the roof eventually results in collapse (Fig. 8-C) and an open entrance to the shaft. Further development rapidly leads to the formation of a cone-shaped depression

Figure 4. Oxygen isotope composition ($\delta^{18}O$‰) of rainfall, snow meltwater, shaft flow and spring discharge in Arabika massif, Western Caucasus, August 1984-85. (From Klimchouk and Jablokova, 1989).



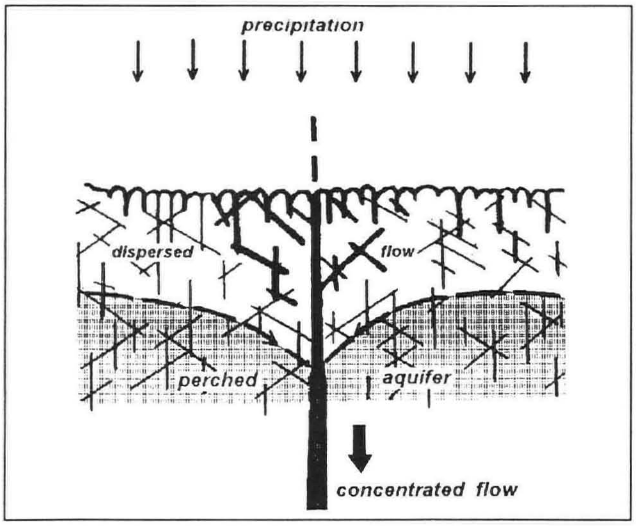


Figure 5. Diagram explaining flow concentration at the base of the epikarstic zone.

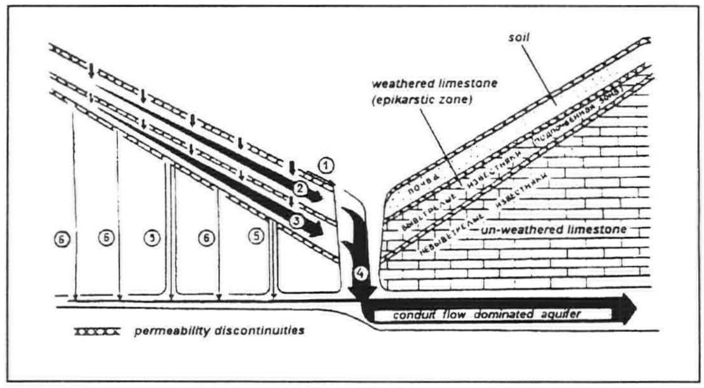


Figure 6. Flow concentration and input mechanisms in a closed depression. Arrows proportional to flow in Waitomo area, New Zealand. Concentration mechanisms: 1 - overland flow; 2 - throughflow; 3 - subcutaneous (epikarstic) flow. Input mechanisms: 4 - shaft flow; 5 - vadose flow; 6 - vadose seepage. (From Gunn, 1983)

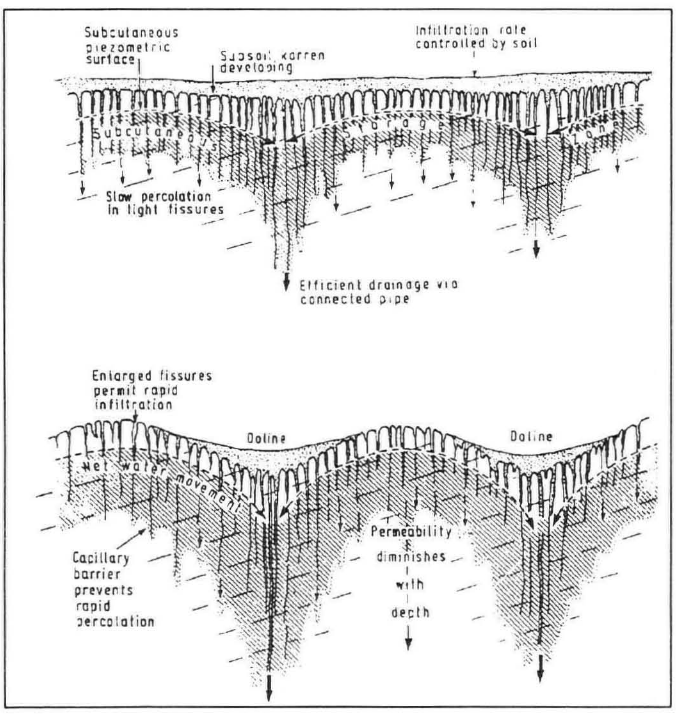


Figure 7. Model of solution dolines initiation in the epikarstic zone. (From Williams, 1983).

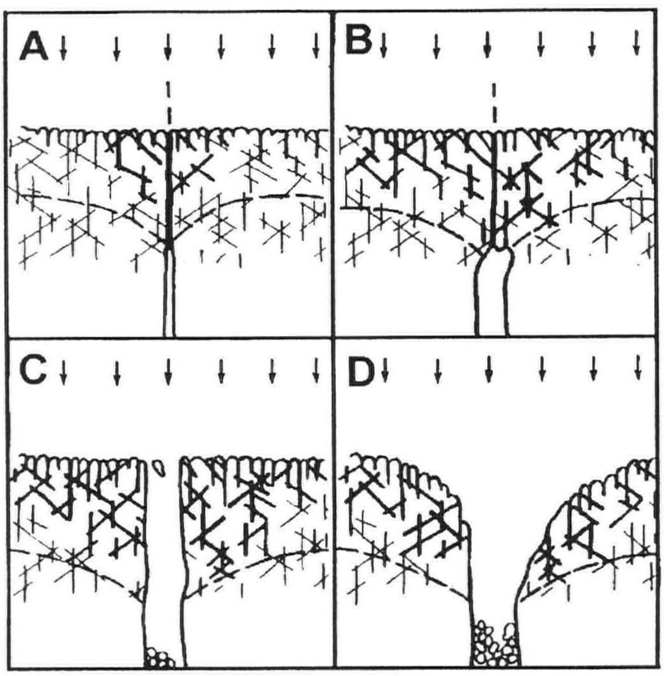


Figure 8. Model of the evolution of karst features in the epikarstic zone. A-D - different stages, see explanations in the text. (From Klimchouk et al., 1979, 1981).

as a ready made, highly karstified and disconnected rock mass surrounds the shaft entrance (Fig. 8-D). If a shaft is not deep and the bottom is infilled with collapse boulders and slope wash, then the hole can assume the bowl shape of a solution doline. Thus, epikarstic morphogenesis can result in "hidden" speleogenic development. In this case the dolines on the surface can be formed not only through solutional lowering, but also through the collapse stage. This model explains well the conjugate development of karren fields, shafts, collapses and closed depressions as different stages of the epikarstic morphogenetic process. One of the typical features of many karst areas well explained by this model, is the presence of vertical shafts which have no associated dolines around their entrances. Instead, such entrances are often located in the centre of karren fields (Klimchouk et al., 1981; front cover photo). Fig. 9 shows examples of such shafts from Kyrktau plateau, Zeravshan Ridge, Central Asia. Moreover, in many cases it is possible to reach well developed "hidden shafts" via enlarged cracks within a karren field (Fig. 10).

The epikarst is a zone of dispersed karstification which is most typically expressed in the formation of grikes, or Kluftkarren. The focused appearance of most other karst features of small to intermediate scale (like dolines or shafts) is largely a reflection of the subsurface localisation of flow and corrosion occurring at the base of the epikarstic zone. So, the plan pattern of major joints in the depth of rocks which determines the structure of internal karstification, is manifested to the surface through the epikarstic processes and accounts for the focused appearance of the surface karst landscape (Klimchouk, 1989). The morphology of surface karst features depends on the age of the surface, or the "maturity" of the epikarstic zone. In "mature" karsts doline landscapes prevail, as most of epikarstic focuses have passed the "karren fields" stage of "hidden speleogenesis", and collapse shaft entrances have eventually developed into dolines. But epikarstic morphogenetic mechanisms may restart again at the earliest stages where the mature karst landscape had been scoured away by glacial activity, as, for instance, in the high mountainous karsts of West Caucasus and other regions of the Alpine geosyncline, or in the Yorkshire Dales of England and the Burren of County Clare, Ireland.

Formation of the initial contrast in the permeability structure between the top layer of a rock and its bulk mass at the depth, as well as further development of the epikarstic zone, is controlled by both lithology (textural and structural properties of the rock) and climate. Climatic control is very important as the top layer of rock is directly affected by weathering processes. Climatic conditions, through many specific controls, determine the relative significance of solution and other agents of rock decomposition; the type of weathering products; the rate of epikarstic zone formation and, eventually, the structure, thickness and permeability of the epikarstic zone and the morphological appearance of surface karst features. It does not seem an overestimation to state that climatic variety of weathering processes is a key to the problem of the formation of the epikarstic zone and of climatic differences of karst morphology. The way to the global correlation of karst morphology lies through deep study of weathering (or, more specifically, epikarstic) processes.

THE ROLE OF CONDENSATION PROCESSES IN EPIKARSTIC MORPHOGENESIS

Some studies have shown that condensation recharge can be significant in the water budget of karst massifs, as well as in speleogenesis. According to calculations provided by Dubljansky et al. (1983, 1984), condensation processes contribute from 0.7 to 2.6 $l\ s^{-1}\ km^{-2}$ to average annual flow in the low altitude karst massifs of Crimea and West Caucasus, and from 3.8 to 4.7 $l\ s^{-1}\ km^{-2}$ in the high mountainous karsts

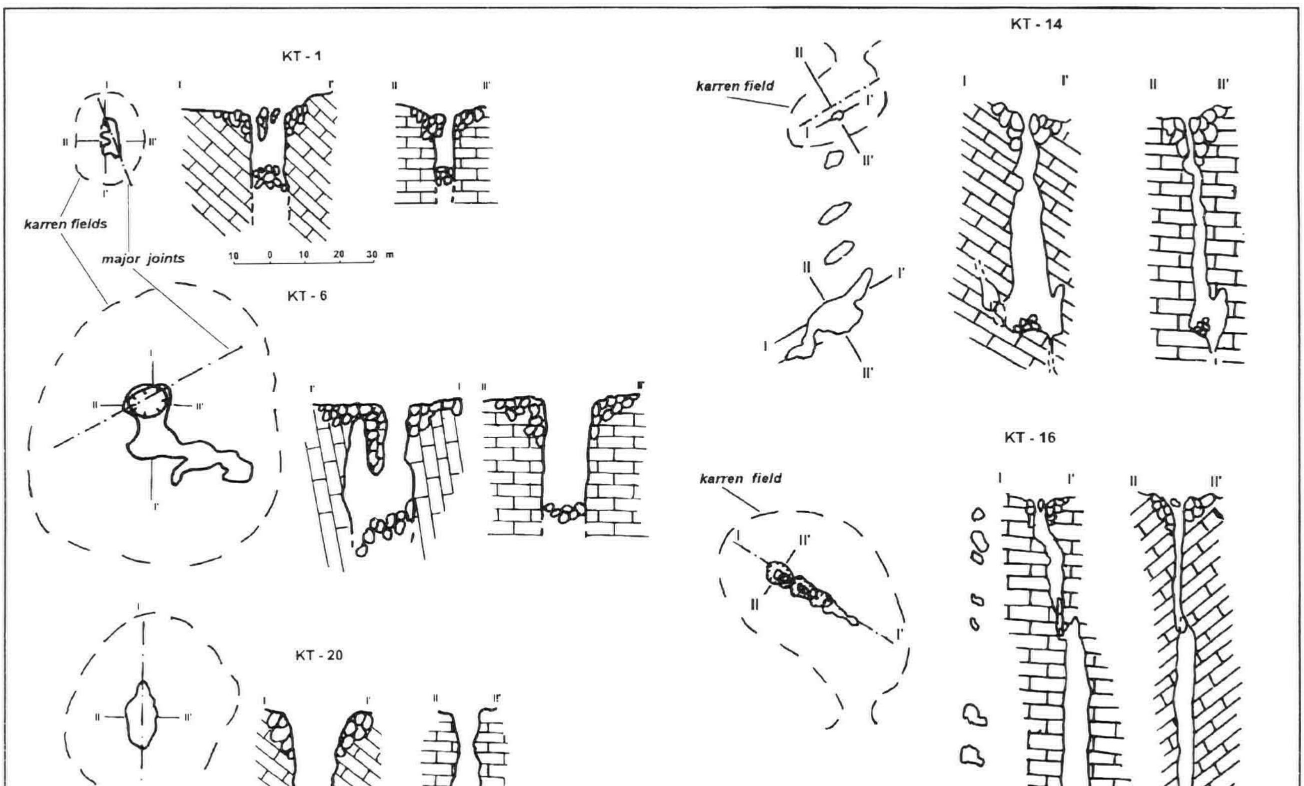


Figure 9. Typical examples of vertical shafts with no associated dolines around entrances, located within well localised karren fields, Kyrktau plateau. Central Asia. (From Klimchouk et al., 1981).

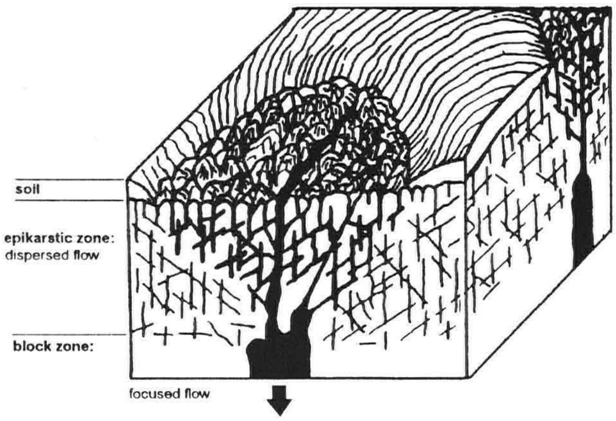


Figure 10. Typical occurrence of a shaft underneath a karren field, Kyrktau plateau, Central Asia.

of West Caucasus (Arabika and Bzybsky ranges). Because condensation recharge is active only during the warm season (Fig. 11), flow produced by condensation processes is much higher if calculated for this specific season: from 1.4 to 6.1 $l\ s^{-1} km^{-2}$ for low altitude mountains, and from 7.9 to 9.7 $l\ s^{-1} km^{-2}$ for high mountains (Dubljansky and Kiknadze, 1984; Dubljansky et al., 1983).

During warm periods in mountainous karst massifs, air inflow from outside prevails through upper entrances on the plateau surface, and condensation recharge takes place contributing to karst flow. It can be assumed that it is just the epikarstic zone where most active condensation occurs, as this zone is the transitional one in terms of equilibrium conditions of the outside and inside atmospheres. During the cold period air outflow prevails from the interior of the karst massif through upper entrances (Fig. 12), but no moisture outflow occurs, as the epikarstic zone is the zone of cooling, so that moisture from ascending cave air condenses on reaching the epikarstic zone (Fig. 13). Although they provide little contribution to karst flow from a massif as a whole, during the cold period condensation processes can contribute considerably to corrosion development of shafts at the base of the epikarstic zone. This preliminary consideration shows that, besides specific infiltration processes, condensation processes can be also of great significance in karst morphogenesis in the epikarstic zone and, in particular, in speleogenesis at its base. This supposed role should be further assessed by analytical and experimental studies.

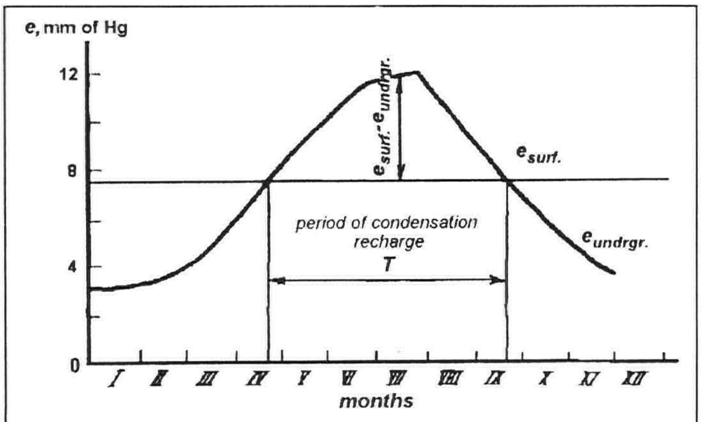


Figure 11. A year course of condensation processes in low altitude karst massifs of Western Caucasus. (From Dubljansky, V. and Kiknadze, T., 1984).

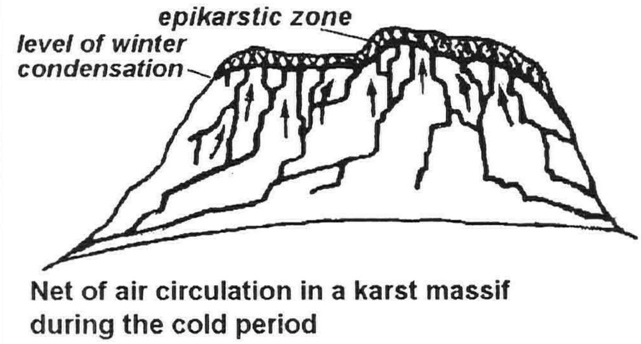


Figure 12. Net of air circulation in a karst massif during the cold period.

CONCLUSIONS

1. The epikarstic zone is characterised by specific hydrologic and morphogenetic processes which occur both within it and at its base. Dispersed flow and karstification prevail within the epikarstic zone. The contrast in hydraulic conductivity between the epikarstic zone and the underlying vadose zone causes flow concentration to occur at the base of the epikarstic zone. It means that corrosion also focuses at the certain depth below the surface.

2. The suggested model of epikarstic morphogenesis incorporates speleogenic development of major joints at a certain depth below the surface. Dolines at the surface can be formed not only through solutional lowering, but also through collapse of the roof of a shaft formed at the base of the epikarstic zone. The focused appearance of most karst features of small to intermediate scale (like dolines or shafts) is largely a reflection of the subsurface localisation of flow and corrosion occurring at the base of the epikarstic zone.

3. Climate is one of the major controls on weathering processes and formation of the epikarstic zone. Study of climatic variety of the weathering processes and the epikarstic zone formation is the key to an understanding of climatic differences in karst morphology.

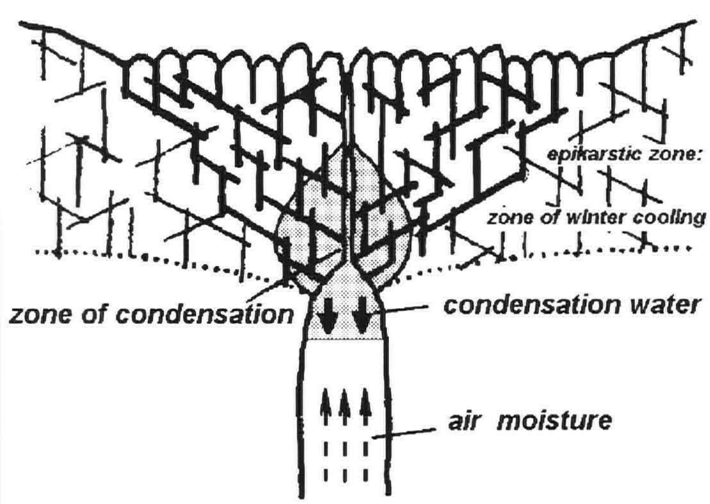


Figure 13. Condensation of air moisture at the base of the epikarstic zone during the winter period.

4. Condensation processes are assumed to play an important role in speleogenesis at the base of the epikarstic zone. Condensation within a karst massif is concentrated mainly in the epikarstic zone during both warm and cold periods.

REFERENCES

Bakalowicz, M., Blavoux, B. and Mangin, A., 1974, Apports du tracage isotopique naturel a la connaissance du fonctionnement d'un systeme karstique-teneurs en oxygene-18 de trois systemes des Pyrenees, France. *Journal of Hydrol.*, 23, 141-158.

Bonacci, O., 1987,. *Karst Hydrology, with special reference to the Dinaric karst.* Berlin - Heidelberg, Springer-Verlag. 184pp.

Drogue, C., 1979, Structure du milie et organisation des ecoulements dans la zone non saturee d'un aquifere karstique. Etudes sur perimetre experimental. *Le Reun. annu. sci. terre, Lyon*, 145-153.

Drogue, C., 1980, Essai d'identification d'un type de structure de magasins carbonates fissures, Application a l'interpretation de certains aspects du fonctionnement hydrogeologique. *Mem. Soc. Geol. France*, n.11, 101-108.

Drogue, C., 1992, Hydrodynamics of karstic aquifers: experimental sites in the Mediterranean karst, Southern France. IN Back, W. (Ed-in-chief.) *Hydrogeology of Selected Karst Regions.* Hannover, Heise, 133-149.

Dubljansky, V.N., Kiknadze, T.Z. and Kolomietz, A.L., 1983, Vertical zonation of condensation in the fissure-karstic collectors of Western Georgia. *Bull. of the Acad. of Sci. of the Georgian SSR*, 110 (2), 333-336. (in Russ., abs. English).

Dubljansky, V.N. and Kiknadze, T.Z., 1984, *Hydrogeology of Karst of the Alpine Folded Region of the South of the USSR.* Moscow: Nauka, 127. (in Russ., abs.English).

Ford, D.C. and Williams, P.W., 1989, *Karst Geomorphology and Hydrology.* London, Unwin Hyman. 601pp.

Gunn, J., 1978, *Karst hydrology and solution in the Waitomo District, New Zealand.* PhD. Thesis, Univ. of Auckland, Auckland.

Gunn, J., 1981, Hydrological processes in karst depressions. *Z.Geomorph.* 25(3), 313-331.

Gunn, J., 1983, Point recharge of limestone aquifers - a model from New Zealand karst. *Journal of Hydrol.*, 61, 19-29.

Klimchouk, A.B., 1987, Conditions and peculiarities of karstification in the near-surface zone of carbonaceous massives. *Caves of Georgia, v.11.*, Tbilisi: Metzniereba, 55-65. (in Russ., abs. English).

Klimchouk, A.B., 1989, The Significance of the Subsurface Zone in Karst Hydrogeology and Morphogenesis. *Kiev: Inst. of Geol. Sci.*, 43. (in Russ., abs. English).

Klimchouk, A.B., Rogozhnikov, V.Ja. and Lomaev A.A., 1981, Karst of the Kyrktau massif (Zeravshansky Range, Tjan-Shan). *Kiev: Inst. of Geol. Sci.*, 54. (in Russ.).

Klimchouk, A.B., Stotland, A.B. and Lomaev, A.A., 1979, Karst and speleological investigations in the Kyrktau plateau (Zeravshansky Range, Tjan-Shan). *Izvestija VGO*, v.111, n.5, 442-448. (in Russ.).

Klimchouk, A.B. and Stotland, A.B., 1983, Forms of karst landscape of the Kyrktau plateau (Tjan-Shan). *Proc. of the Europ. Regional Conf. on Speleol.*, Sofia, v.2, 171-176. (in Russ.).

Klimchouk, A.B. and Jablokova, N.L., 1989, Evidence of hydrological significance of the epikarstic zone from study of oxygen isotope composition of water, Arabika massif, Western Caucasus. *Proc. of the 10th Intern. Congr. of Speleol.*, v.III, Budapest, 798-799.

Mangin, A., 1973, Sur la dynamique des transferts en aquifer karstique. *Proc. of the 6th Intern. Congr. of Speleol.*, Olomouc, v.4, 157-162.

Mangin, A., 1975, *Contribution a l'etude hydrodynamique des aquiferes karstiques.* DES thesis, Univ. Dijon, France.

Williams, P.W., 1983, The role of the subcutaneous zone in karst hydrology. *Journal of Hydrol.*, 61, 45-67.

Williams, P.W., 1985, Subcutaneous hydrology and the development of doline and cockpit karst. *Z.Geomorph.*, 29(4), 463-82.

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Anthropogenic impacts on karst polje morphology in Slovenia

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Abstract: In Slovenia there are from 15 to 20 karst poljes and not one is preserved in an entirely "natural" state. In the last 200 years various ameliorations were done changing the morphological features and hydrological function of the poljes or their parts (resurgences, superficial beds, swallow holes). In some places single works were done; in others complex changes to the entire background of a bigger karst spring (Krka). The paper presents the plans, their realization and actual intentions.

INTRODUCTION

In Slovenia there are from 15 to 20 karst poljes (the number depends on the definition, criteria respectively). A whole series of types exists depending on how frequently they are flooded, or how long the water remains on them. They range from seasonal lakes (such as Cerknisko jezero, flooded in average 8 to 10 months per year) to dry poljes (such as Dobrepolje, which is flooded on average once every 10 to 15 years). As everywhere on karst, on karst poljes there is either too much or too little water as floods and droughts alternate. To secure life on karst poljes and to make better economic use of them, man has tried to change their water regime. In Slovenia, the first such works date from the Roman period when Strabo records attempts to dry up Lugeon (Lugeus) Palus. However, it is not certain if the name "Marshy Lake" denoted the actual Lake of Cerknica or Ljubljana Moor which is not a karst polje. The first reliable account of human intervention on karst is Valvasor (1689). When describing the annual processions to "sacred caves" (the majority of them were on Dolenjska and Notranjska where at the time, according to reports wizards and witches lived) he tells that at the end each participant must grab the biggest rock or branch, with respect to his physical strength, and throw it into the pothole to "stuff the devil's way out of the underground".

DRAINAGE WORKS

The type of amelioration depends on the type of polje. On karst poljes where the floods are frequent or water remains so long that it has a negative influence on use or crops, people have tried to abolish the floods, to lower the water level and to shorten the length of floods, mostly by increasing the outflow from the poljes. Methods used include:

- increasing the capacity of the existing ponors (cleaning, widening, opening of swallow holes and underground channels);
- increasing the number of swallow holes (opening and digging new ones);
- lowering the ponor places; and
- increasing the runoff velocity (levelling river beds over the karst poljes and digging artificial river beds).

In addition to these active defences against floods, passive responses included construction of dams and artificial elevations, and in particular by suitable land use adapted to floods. Initially the houses in villages and the main fields corresponded exactly with the level of the highest average flood. This was changed first due to agrarian pressure and later due to industrialization in the 19th century and in the first half of the 20th century. The farmers wanted to take advantages of the favourable surfaces more intensively (plains, enough thick cover of soil) for fields while the industry wanted the, at the beginning less valuable surfaces. Poorer classes started to inhabit the belt exposed to floods in particular because this landscape was common - "gmajna".

From the first half of 19th century we know a project about preventing the floods on Cerknisko polje (Schaffenrath) and soon after there are notices about the realization of modest ameliorations and experiments in preventing extremely high (catastrophic) floods. The peasants of Cerknica installed catching rakes in front of bigger swallow holes and organized the cleaning of these rakes, swallow holes and even accessible cave passages behind them (Kebe, 1860). At the end of 19th century a series of big and long lasting floods occurred on the karst poljes of Notranjska and this was enough for the government in Vienna to react. In 1886 the Ministry for Agriculture entrusted to V. Putick (1856-1929) the preparation of projects to abolish the floods on the karst poljes of Carniola. Putick set on the extensive explorations which rank him as one of the pioneers and the greatest Slovene speleologist. He proposed a project "Generalproject zur unschadlichen Ableitung der Hochwasser aus den Kesselthalern von Planina, Zirknitz und Laas-Altenmarkt in Innerkrain" (Putick, 1888), but it was not adopted. Nevertheless some proposals were realized under his direction during the 1890's and as late as 1920. The main obstacle was the concerns of the inhabitants on the downstream poljes, on Ljubljana Moor and in the town itself, that the augmented outflow of flood waters from karst poljes might increase or cause the floods at them. In 1901-1906 according to Putick's plans big technical works were done on Losko polje: digging of new riverbed, construction of rakes and grids and at the end of the riverbed a tunnel, 15 m long into the lower parts of Golobina ponor cave (Habic, 1987).

Local people from Cerknisko polje were not satisfied with rejection of Putick's original plan and repeatedly asked for help. In 1920 a "water community" was formed and up to the 2nd World War they executed smaller ameliorations with the help of public funds: ponors to Velika and Mala Karlovica were lowered, some syphons were blown up, rakes installed and other ponors cleaned and enlarged. They regulated almost 8 km of channel including the Strzen stream, stream-beds leading toward ponors, and the beds of the tributary streams Zirovniscica, Lipsenjscica, Tresenec and Goriski potok. The results were as follows: catastrophic floods were moderated, middle and high waters drained away more quickly and sweet grass began to grow on ameliorated lands (Jenko et al., 1954; Kranjc, 1986; Kranjc, 1987). There were no serious reports or complaints that subsequent floods on lower lying poljes or Barje were larger or more frequent. The works done by the "water community" are now almost invisible as they are "covered" by at least two series of later works.

Planinsko polje is one of the smaller karst poljes in terms of surface area (10 km^2 of flood surface) but the most extensive amelioration works were done there. The interventions were the most radical which is reflected in height and duration of floods (Gams, 1981). There the Unica riverbed is regulated from the first sinkholes downstream. The sinkholes in the riverbed or close to it are regulated (walled, covered by grids, the fissures widened, artificial canals leading to them). The biggest work is done in the corner Pod Stenami where the sinkhole part of the polje was regulated as a uniform complex. The so-called Putickove stirne (The Putick's Wells) constructed in 1894, are particularly interesting. These are two catavotres in the form of walled wells, 10 m deep and 4 m in diameter, covered by a metal grid (Putick, 1889).

On Ribnisko-Kocevsko polje the sinkholes in the northern part of Ribnica polje were regulated as a defence against the floods that threatened Ribnica and the swallow holes of the Bistrica and Ribnica brooks in the central part of the polje, the swallow holes of Prednja Rinza (the floods in Lozine) and Rinza, the last flooding the Kocevje town. The amelioration elements are similar to those elsewhere: opening, widening, walling and protecting the ponors with grids, among them some made in a type of small catavotres, walling and deepening of the riverbeds and the digging of new riverbeds to the ponors, for example between the riverbed of the Bistrica brook and Tentera swallow hole. This one engulfed the flood waters of Bistrica only after the digging of a 655 m long canal; the waters of medium level of Bistrica flow into Tentera (Slabe, 1993). A general principle of the regulation is that it is meant to engulf the low and medium flood waters into the swallow holes into which the high flood water sank when they were in their natural state (Putick, 1892).

Very extensive and complex works were done in the immediate catchment area of the Krka springs (including three poljes: Radensko, Zalnsko and Lucki Dol) where the intention was not the amelioration of a particular karst polje but the regulation of the entire catchment area including sinking streams and swallow holes, ponor caves, catavotres, karst springs and even an attempt to widen and clear the syphons. The works were conceived and led by engineer J. V. Hrasky (Brencic, 1993).

Nevertheless, in spite of extreme wishes and demands none of the Slovenian karst poljes has been completely drained, as has happened, for example, at Popovo polje in Hercegovina.

WORKS TO RETAIN THE WATER

Not everyone wanted the water to drain off quickly or the riverbeds of brooks and sinking streams to remain dry for a long time. For example, mills at sinking streams on karst poljes or on their borders had permanent problems, except at floods, because of lack of water. Thus the millers filled up the swallow holes in the beds of Zgornja Pivka. Along Reka, on Zalnsko polje, before the miller started work he had to walk around the riverbed upstream of the mill and stuff the swallow holes. The Brdavs's mill upstream of the Rascica sink was abandoned between the two wars due to severe lack of water.

Proof of how the sinking of karst streams advances on the border of the poljes or blind valleys even without a human impact is a swallow hole (5 m wide and (27 m deep) which suddenly opened in 1982 in the Reka river bed, 6 km upstream of Skocjanske jame and swallowed all the Reka water at discharges smaller than $0.8 m^3 s^{-1}$ (Habic et al., 1989). Another example is offered by the village Skocjan near Turjak: in Valvasor's work (1689) we see the drawing of a mill at the end of the brook in the middle of the village, close to the ponor. Today there is not a trace of a mill or swallow hole nor of the brook through the village.

Following the intensification of industry, particularly after the Second World War, and the consequent diminishing of the importance of agriculture, the value of flood prone areas on karst poljes changed. The value of the landscape suitable for agriculture was reduced and more income was promised in energetics, tourism, fishing, hunting; activities which demanded more water on the poljes, longer times of flood and even permanent "lakes".

Vicentini's (1875) plan to prevent the floods on Cerknisko jezero already assumed the accumulation - retaining basin (Zadnji kraj) would help to prevent the floods on other parts of the polje. During the 20th century there were more plans to change Cerknisko polje into a lake or water accumulation: F. Schenkel's (1912) and two between the world wars. Soon after it V.Slebinger proposed a hydro-electric power plant at Gornje jezero; accumulations on the lower part of the polje and an underground tunnel towards Rakov Skocjan valley. Jenko's plans from 1954 proposed accumulation on the upper part of the polje and ameliorated - drained land at its lower part. In 1965 he proposed "The permanent Cerknisko jezero lake experiment", which was accepted in the form of "experimental damming of the ponors", which should last 3 years (Jenko, 1965).

In the years 1968-69 the entrances to some ponors (including the biggest ponor caves Velika and Mala Karlovica) were closed by concrete and a (30 m long tunnel 3.7 m of diameter was made to allow the water to flow directly to the inner parts of Karlovica ponor cave, in front of which a 4 m x 4 m turnpike was constructed. However, the experiment has proved to be negative and inconvenient. Breznik's (1983) plan which proposed isolation of the ponor side of the polje by a dike and grouting curtain to make a "Multipurpose accumulation" in the upper part of polje also roused a lot of discussion.

One reaction to all these plans and works has been the proposal of a "Notranjski kraski park" and biosphere reserves with the Cerknisko polje as its centrepiece. The slogan of its proponents is "Cerknisko jezero back to natural conditions". Although some works from the "Permanent lake experiment" have been demolished, it is difficult to talk about "natural state" because it is just a return to the previous stage of ameliorations and not to a primary natural state. On the other poljes the situation is generally similar, although less pronounced than on Cerknisko polje.

CONCLUSION

When walking across the karst poljes of Slovenia and observing flat bottoms, riverbeds, terraces, swallow holes, and springs, sometimes full of water, other times completely dry, one can be sure that in most cases all these features have been changed in some way by human activity. Despite this, all the poljes are functioning in something which approaches a "natural" manner, although the details and everyday responses to droughts and heavy rains have been altered by man. Movement, aiming to preserve and to restore the nature of karst poljes cannot be regarded as "restoration" of natural stage but rather as a retreat to some previous stage. The idea to leave some poljes functioning by themselves alone, allows some optimism and we can hope that in the "Classical Karst" we will be able to preserve some "classical karst phenomena" as karst poljes are, in relatively unaltered form and function.

REFERENCES

Brencic, M., 1993, Jan Vladimir Hrasky. *Bilten Jamarskega kluba Zeleznicar*, 19-21.

Breznik, M., 1983, Vecnamenska akumulacija Cerknisko jezero. *Gradbeni vestnik*, 32, 1-2, 3-15.

Gams, I., 1981, Poplave na Planinskem polju. *Geografski zbornik*, 20, 9-29.

Habe, F., 1982, Ein plotzliches Verschwinden der Innerkrainer Reka (Slowenien). *Die Hohle*, 33, 73-81, Wien.

Habic, P., 1987, Ponorna jama Golobina na Loskem polju. *Acta carsologica*, 16, 35-49.

Habic, P. et al., 1989, Skocjanske jame speleological revue. *International Journal of Speleology*, 18, 1-42.

Jenko, F., T. Mrak, R. Tancik and N. Cadez, 1954, *Vodnogospodarska osnova porecja Ljubljanice*. Vol. 1-7, 1134pp, Projekt nizke zgradbe, Ljubljana, Manuscript.

Jenko, F., 1965, *Idejni projekt stalne ojezeritve Cerkniskega jezera*. Zavod za vodno gospodarstvo SRS, 1-116, Manuscript.

Kebe, G., 1860, *Popis Cerkniskega jezera*. Novice gospodarske, obertniske in narodne, 18, 267-268, 274-275, 283, 298-299, 308-309, 327-328, Laibach.

Kranjc, A., 1986, Cerknisko jezero in njegove poplave. *Geografski zbornik*, 25, 71-123.

Kranjc, A., 1987, Cerknisko jezero, An example of man's impact on karst hydrology. *Man's Impact in Dinaric Karst*, Guide-book, 65-79.

Putick, W., 1888, *Generalproject zur unschadlichen Ableitung der Hochwasser aus den Kesselthalern von Planina, Zirknitz und Laas-Altenmarkt in Innerkrain.* Arhiv Podjetja za melioracije.

Putick, W., 1889, *Die Katavotrons im Kesselthale von Planina in Krain. Wochenschrift des Osterreichischen Ingenieur- und Architekten- Vereines*, 46, 47, 1-7, Wien.

Putick, W., 1892, *Zur Entwasserung der Kesselthaler von Reifnitz und Gottschee. Laibacher Zeitung*, 51, 419-420, 52, 427-428, Laibach.

Slabe, T., 1993, Fasete, pomembna sled oblikovanja in razvoja kraskih votlin. *Acta carsologica*, 22, 139-177, Ljubljana.

Strabo, *Geographica*, lib. 7, fol. 211, lib. XLI; lib. 31; lib. 14.

Valvasor, J.W., 1689, *Die Ehre des Herzogthums Krain.* I. Th., 1-696, Laybach - Nurnberg.

Vicentini, R., 1875, *Bonificio della valli di Laas, Zirknitz, Planina e Lubiana. Arhiv Savskih elektrarn.*

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Differential diagnosis of paragenetic and vadose canyons

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Abstract: In speleogenetic analysis, paleo-watertables are generally reconstructed by locating the morphological transition between vadose and phreatic features. When seen as isolated features, meandering vadose and paragenetic canyons may superficially appear indistinguishable and confusing. Based on the fact that ideal, meandering vadose and paragenetic canyons comprise a pair of mirror images, a method is suggested for differential diagnosis between them. The two features can be distinguished by plotting flow directions of syngenetic scallops together with meander migration vectors (MMV) in a lower hemisphere stereonet. The test should be combined with 'common sense' and supplementary traditional criteria as discussed in the text. The method was successfully applied to a Norwegian marble cave where active vadose canyons exist together with a large, paragenetic canyon.

INTRODUCTION

Paragenesis, the corrosional and erosional rise of a passage ceiling above a detrital fill, is a phenomenon that is unique to the cave environment and certain subglacial situations (the formation of an esker may be regarded as paragenesis in an ice cave). The concept was originally used on karst systems by Renault (1968a, b) to describe any phreatic or watertable passage where the cross-section is modified due to accumulation of sediments. Later, extensive use of this term by English-speaking speleologists (Ford and Williams, 1989) has narrowed down the content of the concept somewhat. We may now define paragenesis as a speleogenetic process where corrosive fluid is forced to flow along the interface of the passage perimeter and a total or partial sediment fill. A speleogenetic process is in this context a passage-widening process. The result is the formation of linear or sinuous channels of various widths that are incised into the walls and ceiling of the pre-existing passage (Fig. 1, Plates 1-3).

Paragenetic features fall in several morphological groups, depending on their size relative to the passage and the extent of their development, see for instance Bretz (1942); Warwick (1976); Bögli (1978) and Ford and Williams (1989). These forms include a) wall and ceiling half-tubes, sometimes sinuous or "meandering"; b) anastomosing fields of half-tubes, often recognized through the negative pattern of interchannel residuals, rock pendants; and finally, c) single ceiling half-tubes forming vertical, inverted canyons above the primary passage (Bauer, 1961; Pasini, 1975). A subclass of category a) is perhaps the debated 'Wirbelkanäle' of Bögli (1978), which are not attributed to sediment contact, but solely to ascending airbubbles corroding a half-tube shaped trace, always situated along the apex of the passage ceiling. The morphological similarities between anastomosing rock pendant fields and bedding- or fracture plane anastomoses of the early stages of karstification, point to an essential aspect of the paragenetic process: local rejuvenation of the cave system. The sediment fill may obstruct the original passage so severely that the conduit returns to its proto-cave (anastomosis) state. Hardware simulation experiments (Lauritzen, 1981a) in plexiglass pipes and on plaster models have demonstrated two main aspects of the process. First, the sinuous, or 'meandering' tendency of paragenetic half-tubes is in part inherent in the fluid-sediment interaction along pipe walls; i.e. forced water flow through a completely water- and sediment-filled, sloping, cylindrical plexiglass tube develop a sinuous channel along its ceiling (Plate 4). Second, the corrosion process is concentrated where fluid flow rate is high.

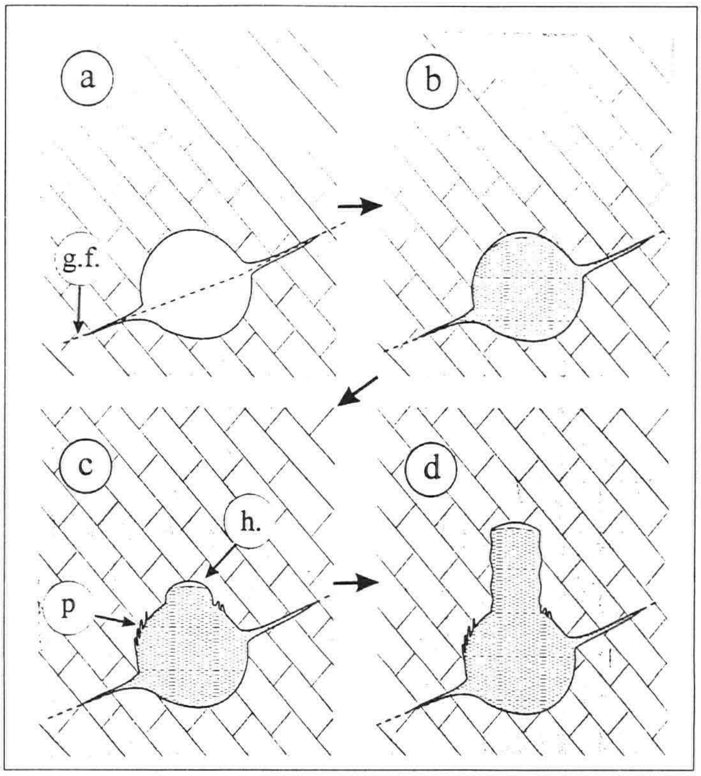


Figure 1. The concept of paragenesis.
a) Primary (phreatic) tube. (g.f. : Guiding fracture)
b) The tube becomes choked up with sediments. Post-depositional shrinking or eroson make enough space to sustain water flow between passage walls and the sediment fill.
c) Half-tubes of various size are formed along microchannel traces. Roof recession is compensated by sediment fill. p: Rock pendant field (anastomosing half-tubes), h: ceiling half-tube.
d) Further development of a ceiling half-tube creates a paragenetic canyon.

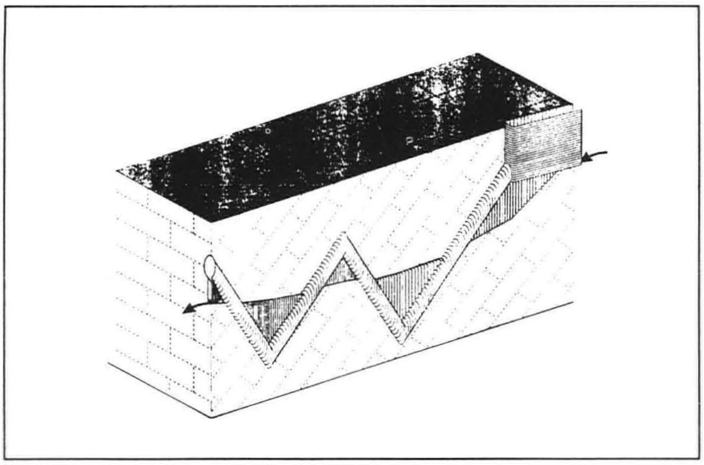


Figure 2. Paragenetic canyon erosion is a form of 'phreatic grading' towards an ideal water- table cave. See also Pasini (1975) and Ford and Ewers (1978). Paragenetic and vadose incision work towards the piezometric surface from below and above, respectively. Paragenetic canyons may therefore be used for paleo-watertable reconstructions in much the same way as vadose canyons are used.

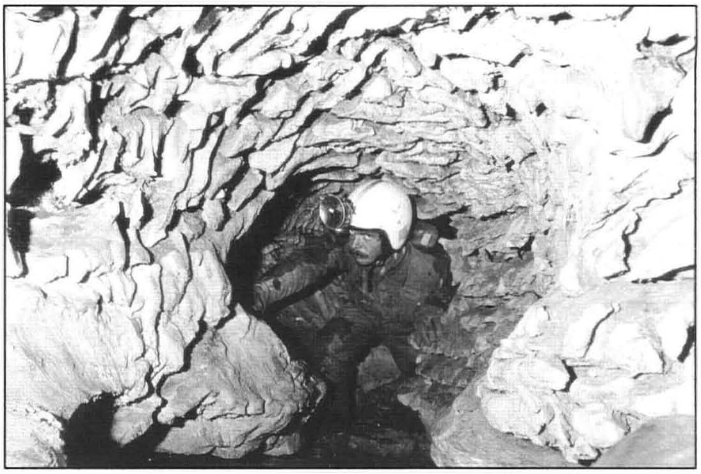
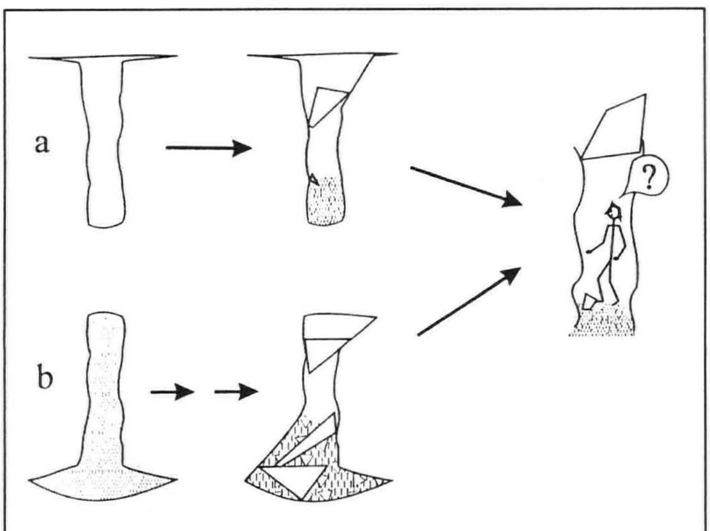


Plate 1. Anstomosing halftubes, forming a rock pendant field on ceiling, walls and in part on the floor of a phreatic tube. From Svartisen, N. Norway. (Photo: S. E. Lauritzen).

PARAGENETIC CANYONS

Classical examples of inverted canyon development are, among others, described by Pasini (1975), Bauer (1961), and Ford and Williams (1989), where paragenetic amplitudes may exceed 50 m. In particular, Ford and Ewers (1978) advocate the view that paragenesis is an important factor in "phreatic grading" of a cave system towards the ideal, water-table cave (Fig. 2).

Normal, vadose canyon incisions are extensively used in speleogenetic analysis to determine paleo- watertables. When traversing down through a relict karst system, the transition of passage characteristics from vadose canyon incision into phreatic or epiphreatic tubes, define the position of a local paleo-watertable. Several such observations may support inference about a regionally controlled water table and corresponding erosional baselevel. This relates speleogenesis to surface topography, which in turn permits important inferences to be made on erosion rates and landform development (Ford et al., 1981; Atkinson and Rowe, 1992). The basic assumption here is that the canyon is indeed situated physically higher than the associated phreatic features. On the contrary, this principle would be reversed for a paragenetic canyon, although the feature itself may define a paleo watertable; this time at or above its ceiling. It is therefore essential to find reliable criteria for differential diagnosis between vadose and paragenetic canyons. In a paleokarst setting, where subsequent erosion or collapse may have removed or obscured the ceiling, and where only passage fragments may be accessible, such criteria would be crucial for a correct interpretation of the paleowater table position. This situation is depicted in Fig. 3.



RELATION TO GUIDING FRACTURES

Vadose canyons develop from a pre-existing phreatic or epiphreatic passage, giving rise to the common hybrid key-hole cross-section. For invasion- type caves, the phreatic/epiphreatic phase may exist only for a very short time, leaving a phreatic lens (commonly named 'bedding plane' by explorers) or an anastomosis band along the primary guiding fracture. For a vadose canyon, there will always be a roof level void along a guiding fracture or bedding plane from where the process initiated. These features may be difficult to observe, especially in huge invasion canyons. Guiding fractures are not necessary for the subsequent vadose downcutting, although the canyon would exploit them if they are present. The same principle holds true for paragenetic half-tubes and canyons, but the sequence is inverted. A sufficient diagnostic feature of a paragenetic half tube or canyon is that it lacks a guiding fracture other than the passage (often below) from where it originated (Plates 1-3). This is, however, not a necessary requisite for a paragenetic feature, because any fractures or voids it intersect would be exploited. Paragenetic half-tubes may in some cases form as shortcuts between isolated ceiling fractures. The formation of bypass tubes at the expense of paragenetic canyons would then indicate that fissure frequency and connectivity has been sufficiently high to permit breakthrough closer to the piezometric surface. In spite of this, most paragenetic features are diagnosed by the following two criterions: a) They appear to have developed away from a mother passage, and b) at least for some distance, they lack any guiding fracture or void other than the mother passage itself.

Figure 3. A case where both a vadose (a) and a paragenetic (b) canyon would develop into the same ambiguous situation.

CURVATURE OF VADOSE AND PARAGENETIC CANYONS

The dynamics of 'meanders' in rock canyons are radically different from 'normal', alluvial meanders, because material can only be removed, and not redeposited. Similar conditions are found in channels cut in ice or peat. While an alluvial meander can move laterally by means of erosion and point-bar deposition, the rock 'meander' can only change its course as it cuts down. This leaves a sequence of subsequent courses at various levels in the canyon, which can be mapped separately. Observations of active canyons display water movements of the type depicted in Fig. 4, where water chutes tend to be deflected between the canyon walls, slightly out of phase, so that those parts of the concave walls facing upstream receive most of the erosion. This effect would expectedly decrease with decreasing discharge, but since both chemical corrosion and abrasion by suspended load increase with increasing flow velocity, the highest discharges will have the greatest impact on canyon shape. This would in turn result in a downstream migration (phase shift) of the meander bends with progressive downcutting. This effect is well illustrated by Ewers (1972), cited in Ford and Williams (1989), and reported by numerous other workers (Smart and Brown, 1981). This effect is most perfectly developed in entrenching cave meanders, less so in the so-called 'entrenched' canyons (dome-pit canyon) that work backwards from a vertical waterfall at a receding knick-point (Ford and Williams, 1989). In this case, the meander migration vectors (vide infra) would be vertical (Bretz, 1942), and the passage would display distinct, vertically fluted walls (cave karren). The tendency of downstream migrating meanders are also seen in other rock canyons, like many proglacial canyons cut into the thresholds of glacial troughs, where abrasion rates are high due to large discharges and a high content of suspended load. An outstanding example of this type is perhaps the canyons at Berekvam, western Norway, cut in soft phyllite (Holtedahl, 1967).

A paragentic canyon, eroding its way upwards through the rock mass, often in a sinuous pattern, may also display a progressive downstream phase shift. In this case, the meandering process would have a closer resemblance to alluvial meanders, as the (phreatic) streambed is controlled by the sediment fill beneath it. The meandering of paragenetic canyons (Fig. 5) was perhaps first recognized by Ewers (1972), cited in Ford and Williams (1989).

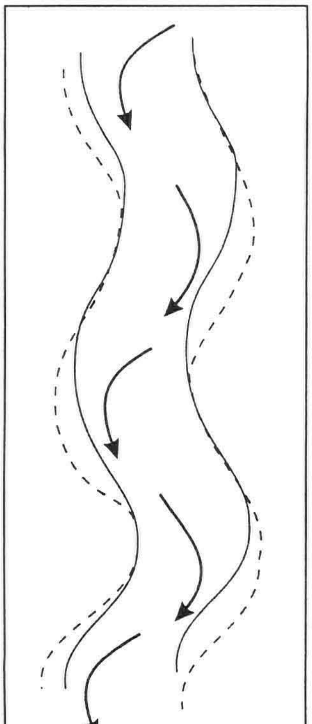


Figure 4. The movement of chuting water in a vadose canyon would cause downstream migartion of meander bends.

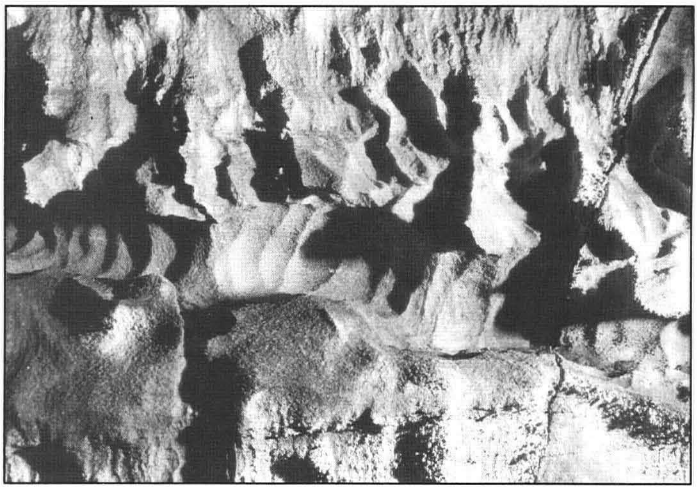


Plate 2. Scalloped half-tube incised into passage wall. Incipient pendant field above the tube. Half-tube diameter about 10 cm. From Svartisen, N. Norway. (Photo: S. E. Lauritzen).

SCALLOPING

Scallops are corrosional flow marks in solid rock, displaying both directional asymmetry (Coleman, 1949) and absolute size that is inversely related to flow velocity (Blumberg and Curl, 1974; Curl, 1974), see also reviews in textbooks (Bögli, 1978; Jennings, 1985; White, 1988; Ford and Williams, 1989). Both types of canyon can develop wall scallops. Due to rapid, free flow under vadose conditions, the scallops of vadose canyons tend to be quite small and sometimes elongated. Conversely, paragenesis is a phreatic process, with lower flow velocities, resulting in relatively large scallops. The crucial problem connected to the use of scallops as paleoflow indicators, is that they represent only the last flow of corrosive water in the passage, having a duration sufficient to remove older patterns if they were different (Lauritzen, 1982). It is essential that the scallops are syngenetic, i.e. formed together with the passage. A scallop pattern may, in principle, also reflect a late re-invasion phase of the system, as we may find in formerly glaciated areas. Scallop patterns should therefore be used with caution, and the pattern should be checked for consistency, preferably along the entire passage.

One interesting property of paragenetic canyons that develop above sand- and gravel- sized sediments, is that under ideal conditions there will be a balance between flow rate and sediment grain size. Sediment filling keeps pace with ceiling retreat and flow rate, so that sediments on transit through the system would either accumulate or become eroded and leave a lag. If the original sediment fill is sufficiently preserved in

Plate 3. Large scale phreatic canyon. The canyon roof is devoid of guiding fractures, excluding the possibility of a precursor tube at roof level. The profile is somewhat distorted by the wide-angle lens, and also modified by breakdown at the left-hand wall. From Kjøpsvik, N.Norway. (Photo: T. Storskjær).

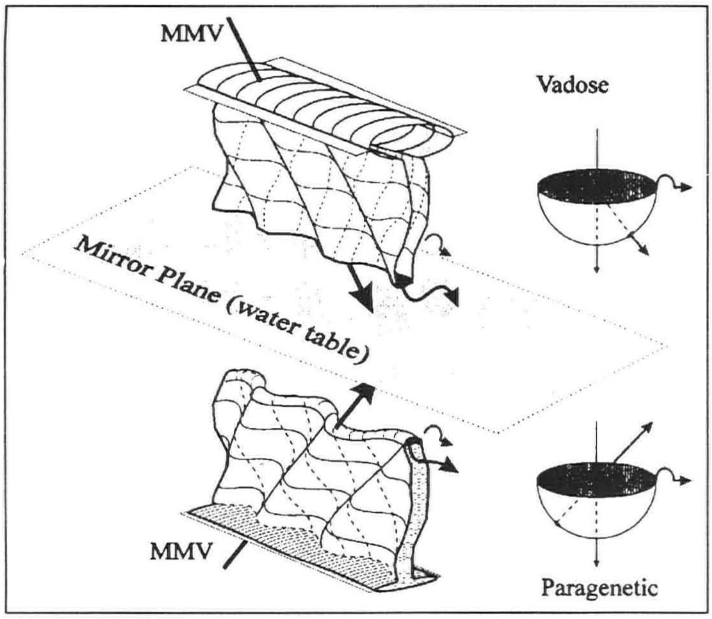


Figure 5. Vadose entrenching canyons and paragenetic canyons form a pair of mirror images. They are mirrored through the water table. The meander migration vector (MMV) is defined as shown, and can be determined from canyon walls and scallop flow direction. The two vectors would plot in the lower and upper hemispheres, respectively. Projected into a lower hemisphere stereonet, scallop flow direction and MMV pairs would plot differently for the two cases (right). See text for further discussion.

abandoned paragenetic galleries, we should expect the grain size to match the flow rate that can be deduced from local scallops in the ceiling above (Lauritzen, 1982).

AN ASSYMMETRY TEST FOR VADOSE AND PARAGENETIC CANYONS

The downstream phase shift of canyon bends may be characterized and measured by the slope and direction of the downcutting along the axis of a single curvature bend. We may call this the meander migration vector (MMV). The polarity of this vector is determined by the direction of flow. Vadose and paragenetic canyons are incongruent mirror images of each other; because the constellation of MMV and the gravity vector (i.e. down) cannot be superimposed for the two cases by simple rotation in space. The gravity vector is fixed as 'down', hence rotation is restricted to the vertical (z) -axis only. For a vadose canyon, the MMV will have a negative inclination (i.e. plunge in downstream direction), whilst for a paragenetic canyon, the MMV will have a positive inclination (i.e. rise in upstream direction) (Fig. 5). If the canyon walls are sufficiently scalloped to permit determination of flow direction (Lauritzen, 1981b), then the corresponding MMV polarity is uniquely defined. The test may be visualized as follows: If the scallop direction and the MMV trend are plotted together in a lower hemisphere stereonet, then both directions from a vadose canyon would plot within the same semicircle (often within the same quadrant). On the contrary, a data set representing a paragenetic canyon would plot in opposite quadrants (Fig. 5). Since scallop directions in a meander bend are oriented approximately tangential to the surface, meandering itself may introduce some scatter into the data when plotted by absolute declinations. The picture becomes clearer if each data pair is rotated to make all scallop directions to point the same way, which then becomes 'downstream', (Figs. 5 and 6). This corresponds to a change of variables resulting in a situation where one axis (the y-axis) becomes the thalweg of the cannel. The test is performed under two assumptions: first, that the canyon curve under consideration display distinct syngenetic scalloping, and second, that the canyon posesses sufficient curvature to allow determination of MMV. Moreover, the MMV's must also be significantly different from vertical.

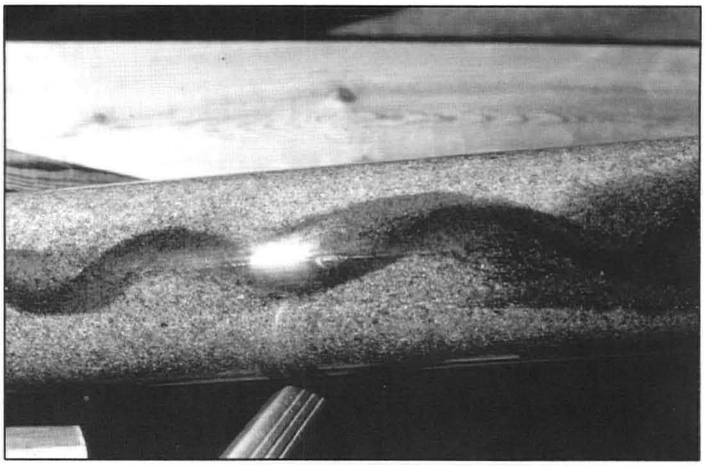


Plate 4. Simulation of aphreatic meander. Sinuous channel developed beneath the ceiling of a sand-filled plaexiglass tube. Flow from right to left, tube diameter 10 cm. From Lauritzen (1981a).

AN EXAMPLE FROM A MARBLE CAVE

The test was applied during re-surveying and speleogenetic analysis of Storsteinshola in the Kjøpsvik quarries, northern Norway (Lauritsen et al., 1994). The main passage forms a huge, canyon-shaped corridor, more than 10 m high (Plate 3). The floor is obscured by breakdown and glacigenic sediments. Where observable, the roof level of the canyon lacks guiding fractures as well as any signs of a primary roof level tube, thus excluding a classical key-hole situation. The presumed paragenetic canyon cuts across thick layers of amphibolite at roof level, indicating upward directed erosion. Where not obscured by breakdown or sediments, the cylindrical bends of corridor walls display scallops that were taken as syngenetic. The MMV were estimated by declination and inclination of a wooden beam that was aligned inside the semicylindrical wall concavities and measured with a compass. Moreover, several smaller, active vadose canyons were available at lower levels where similar measures could be taken. The results are shown in Fig. 6. As expected, the vadose canyon data plot within the same semicircle, whilst the suspected paragenetic canyon data plot in opposite quadrants. Combined with the other, independent morphological observation, we take this as confirming evidence for a paragenetic origin of the passage.

CONCLUSIONS

1. In order to perform confident speleogenetic analyses, for instance with respect to paleo-watertables, it is of crucial importance to distinguish between 'normal' vadose canyons and paragenetic canyons, which are vadose and phreatic features, respectively.

2. Due to phase shifts in their curvatures, vadose and paragenetic canyons form a pair of mirror images that cannot be superimposed by simple rotation in space.

3. The meander migration vector (MMV) is defined as the axis along which a wall curvature ('meander bend') moves as canyon deepening progresses. It may be measured by placing a suitable ruler inside semicylindrical concavities in canyon walls, which can be regarded as part of a 'meander' curvature.

4. A test for differential diagnosis of vadose and paragenetic canyons is suggested. The procedure is as follows:

   a) Determine a series of unambiguous MMV and scallop direction pairs in the passage under question.

   b) Plot scallop direction axes and MMV trends in a lower hemisphere stereonet.

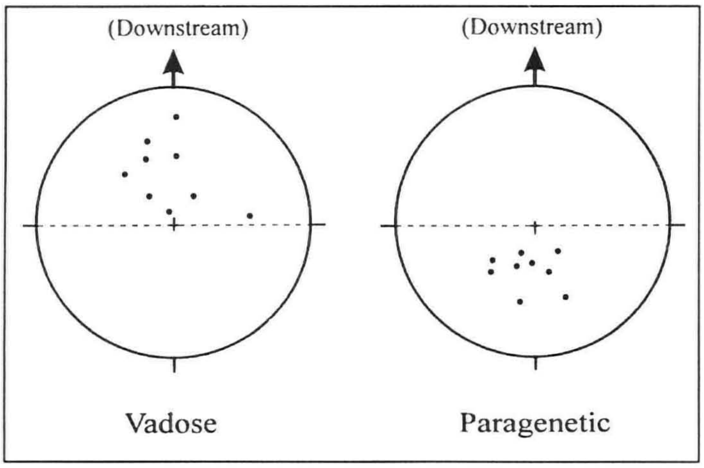


Figure 6. MMV plots from Storsteinshola, Kjøpsvik Quarries, north Norway. Left: Present-day active vadose canyon. Right: The suspected paragenetic corridor. They plot as indicated in Figure 5., and confirm the suspicion of a paragenetic origin for the passage. See text for further discussion.

c) Rotate each data set around the vertical axis so that all scallop directions point the same way in the diagram.

d) If the data pairs plot together in the same semicircle (or often the same quadrant), a vadose canyon is indicated. If the data pairs plot in opposite quadrants, a paragenetic canyon is indicated.

5. The result should be combined with common sense, in particular should lithostructural factors be taken into consideration (almost all speleogenetically significant morphologies are best developed in homogeneous rocks!). Another assumption is that the scallop pattern can be taken as syngenetic with the canyon, and not representing a later phase of invasion. Additional criteria that are sufficient, but not necessary for diagnosing a paragenetic canyon, are the independence of guiding fractures and lack of a precursor passage at roof level. Vadose canyons would almost always display a distinct precursor passage with guiding fracture at roof level, of either phreatic or epiphreatic origin.

6. The test worked favourably in an example from a marble cave in Norway, where a paragenetic gallery was suspected. The method needs further testing in other sites, and in particular at various scales.

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Financial support for hardware experiments were provided (1980) by Fridtjof Nansen and affiliated funds, later fieldwork by The Norwegian National Research Council (NFR) under the 'Klimbre' program (1991- 1994). Logistic support was provided by Tysfjord Kommune and A/S Norcem in Kjøpsvik. Members of Tysfjord Grotteklubb provided valuable enthusiasm and assistance during fieldwork, where Torbjørn Storskjær provided the photo in Plate 3. We profer them all our sincere thanks. This is contribution No. 32 of the Karst research Project in Norway.

REFERENCES

Atkinson, T.C. and Rowe, P.J., 1992, Applications of dating to denudation chronology and landscape evolution. IN Ivanovich, M. and Harmon, R.S. (Eds.) *Uranium-series Disequilibrium: Applications to Earth, marine, and Environmental Sciences*, 669-703. Clarendon Press, Oxford.

Bauer, F., 1961, Sedimentation und Konvakuationserweiterung in aufsteigenden Siphonstrecken. *Rassegna Speleologica Italiana*, 5, 171-175.

Blumberg, P.N. and Curl, R.L., 1974, Experimental and theoretical studies of dissolution roughness. *Journal of Fluid Mechanics*, 65, 735-751.

Bögli, A., 1978, *Karsthydrographie und physische Speläologie*. Springer-Verlag, Heidelberg. 292 pp.

Bretz, J.H., 1942, Vadose and phreatic features of limestone caverns. *Journal of Geology* 50, 675-811.

Coleman, J.F., 1949, An indicator of water-flow in caves. *University of Bristol Spelaeological Society, Proceedings* 6, 57-67.

Curl, R.L., 1974, Deducing flow velocity in cave conduits from scallops. *National Speleological Society*, Bulletin 36, 1-5.

Ewers, R.O., 1972, *A Model for the Development of Subsurface Drainage Routes along Bedding Planes*. MSc Thesis, Department of Geology, University of Cincinnati. 84 pp.

Ford, D.C. and Ewers, R.O., 1978, The development of limestone cave systems in the dimensions of length and breadth. *Canadian Journal of Earth Sciences* 15, 1783-1798.

Ford, D.C. and Williams, P.W., 1989, *Karst geomorphology and Hydrology*. Unwin Hyman, London. 601 pp.

Ford, D.C., Schwarcz, H.P., Drake, J.J., Gascoyne, M., Harmon, R.S. and Latham, A.G., 1981, Estimates of the age of the existing relief within the southern rocky mountains of Canada. *Arctic and Alpine Research* 13, 1-10.

Holtedahl, H., 1967, Notes on the formation of fjords and fjord-valleys. *Geografiska Annaler* 49A, 188-203.

Jennings, J.N., 1985, *Karst Geomorphology*. Basil Blackwell, Oxford, 293 pp.

Lauritsen,Å., Nese, H. and Lauritzen, S.E., 1994, Geomorphic and stratigraphic development of caves in the Kjøpsvik quarries, north Norway. *Cave and Karst Science* 21, 17.

Lauritzen, S.E., 1981a, Simulation of rock pendants - small scale experiments on plaster models. *Proceedings, 8th International Speleological Congress*, Bowling Green Ky, USA, 8, 407-409.

Lauritzen, S.E., 1981b, Statistical symmetry analysis of scallops. *National Speleological Society*, Bulletin 43, 52-55.

Lauritzen, S.E., 1982, The paleocurrents and morphology of Pikhåggrottene, Svartisen, North Norway. *Norsk Geografisk Tidsskrift* 36, 183-209.

Pasini, G., 1975, Sulli'importanza speleogenetica dell' 'erosione antigravitativa'. *Le Grotte d'Italia*, 4, 297-326.

Renault, P., 1968a, Contribution a l'étude des actions mécaniques et sédimentologiques dans la spéléogenèse. Les effects mécaniques a l'échelle de la cavité. *Annales de Spéléologie*, XXIII, 259-307.

Renault, P., 1968b, Contribution a l'étude des actions mécaniques et sédimentologiques dans la spéléogenèse. Les facteurs sédimentologiques. *Annales de Spéléologie*, 23, 529-593.

Smart, C.C. and Brown, M.C., 1981, Some results and llimitations in the application of hydraulic geometry to vadose stream passage. *Proceedings, 8th. International Speleological Congress*, Bowling Green 2, 724-726.

Warwick, G.T., 1976, Geomorphology and Caves. IN Ford, T.D. and Cullingford, C.H.D. (Eds.), *The Science of Speleology*, Academic Press, London, 61-125.

White, W.B., 1988, *Geomorphology and Hydrology of Karst Terrains* Oxford University Press, New York. 464 pp.

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The Hydrology of the Southern Cape Karst Belt, South Africa

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Abstract: The Cenozoic calcarenites of the South African Cape coastal belt host a complex surface karst. Few scientific studies of the karst hydrology belt are available with the exception of the eastern Cape, Alexandria karst, although a number of unpublished reports on water supplies have been produced. This paper reports recent research on a part of the southern Cape karst belt between 21°00 E and 21°50E. The karst comprises four distinct east-west belts. These belts are compartmentalised by south flowing allogenic rivers incised into the underlying Cape System impermeable basement rocks. Well developed karst is associated only with a 90 m - 150 m plateau and a case-hardened plateau above 200 m altitude, both developed on Pliocene Wankoe Formation calcarenites. Elsewhere karst development is poor. The Wankoe Formation contains the main aquifer. Borehole yields range from under $0.5 l s^{-1}$ to $25 l s^{-1}$. High yields are strongly localised. Springs provide an important water resource. The strongest springs merge at the coast or into dry valley systems tributary to the allogenic rivers. A map of the limestone/basement topography was constructed which shows a relatively smooth gradient to the coast, with some incision associated with the allogenic rivers and steepening inland associated with a marine transgressive notch. The topography of the piezometric surface diverged considerably from that of the limestone/basement surface. Higher piezometric surface levels occur inland of the coastal Cape System sandstone outcrops which are less easily planed by marine transgressions than the adjacent Bokkeveld shales. They serve to pond the groundwater. Both high yielding springs and higher production boreholes are strongly localised in these localities. High yielding areas can be correlated with steeper gradients in the piezometric surface and to ponding inland of the buried sandstone outcrops.

INTRODUCTION

Cenozoic calcarenite limestones of beach and aeolian provenace occur in three distinct areas along the Cape Province coast of South Africa: adjacent to Saldanha Bay in the west; between Cape Agulhas and Cape Blaise (Mossel Bay) in the southern Cape and in the Alexandria area of the eastern Cape (Fig. 1). This paper focuses on part of the southern Cape karst belt. Although the surface karst distribution and landform characteristics have been reported (Marker and Sweeting, 1983; Marker, 1987, 1993; Russell, 1989) no recent scientific study of the hydrology of the southern Cape has been made. The hydrology of the eastern Cape karst is, in contrast, better known. A piezometric surface map was presented as early as 1983 (Marker and Sweeting, 1983) and flow-through rates and water chemistry have also been investigated (Marker, 1988, 1994). This research anticipated that the methods utilised in the eastern Cape could be usefully applied to the southern Cape. The recent research reported here was concerned with underground karst water resources in that part of the southern Cape karst region lying between the Duivenhoks and the Gourits rivers (longitude 21°00E to longitude 21°50E). This particular portion was selected for investigation because the rural area is entirely dependant on underground water resources as boreholes, springs and shallow wells. Much of the karst area west of 21°00E is supplied by the Overberg Water Scheme which pipes water from the Langeberg mountains inland because karst sources are inadequate.

THE KARST CHARACTERISTICS

In the areas under discussion, Russell (1989) recognised four clearly defined karst belts, aligned east to west. From the coast to the interior they are: a narrow coastal belt on Pleistocene semi-lithified limestone with poorly developed doline karst partially overlain by more recent blown sands; a low 90-150 m plateau with simple doline development; a case-hardened plateau from 200-250 m altitude that carries a complex karst of large enclosed hollows and linear poljes; a karst border plain where residual limestone ridges rise from an open plain surfaced by thin limestone overlying Bokkeveld shales. Incipient drainage lines parallel the foot of the high plateau escarpment along the margin of the border

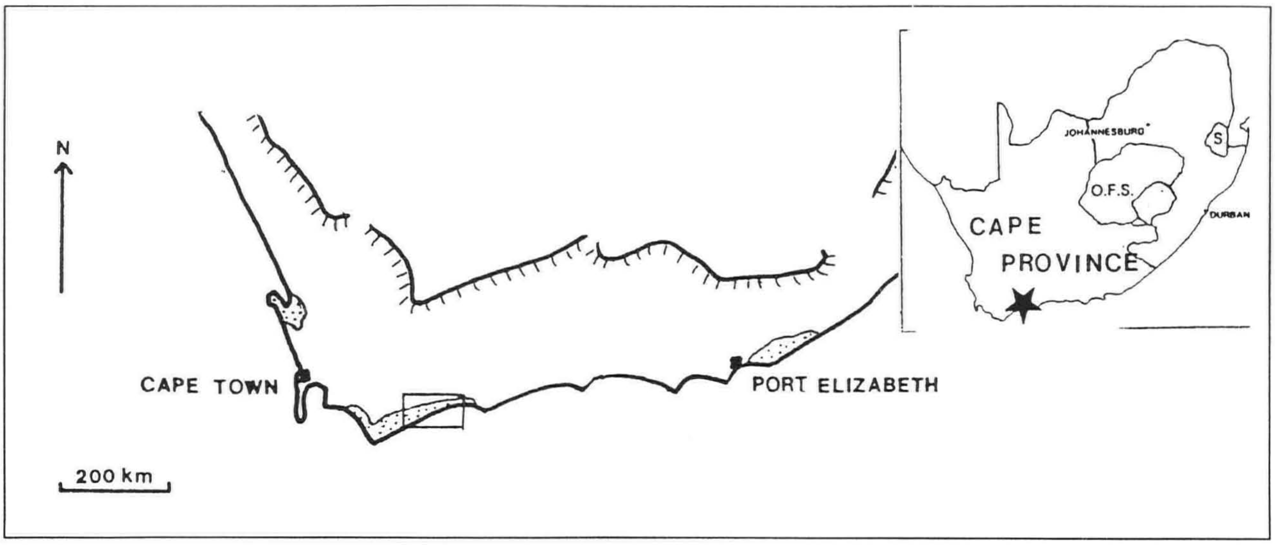


Figure 1. Location of the study area with Cenozoic calcarenite limestone outcrops in the Cape Province stippled. The extent is more continuous off-shore.

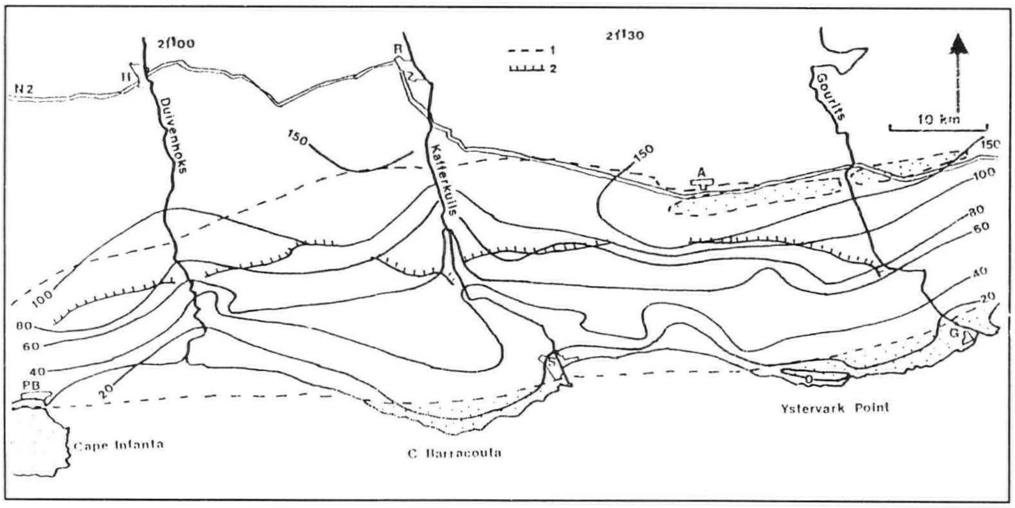


Figure 2. Topography of the contact between limestone and Table Mountain Group marine planed basement.
(Contours at 20 m intervals; Table Mountain sandstone stippled; 1 = geological boundaries; 2 = northern margin of the high karst plateau above the border plain; A = Albertinia; G = Gouritzmond; H = Heidelberg; PB = Port Beaufort; R = Riversdale; S = Still Bay).

plain. They flow now only after exceptional rain events. The border plain merges inland with remnants of the deeply weathered African surface which is believed to have been a coastal plain contemporaneous with the deposition of the limestone at the coast. The karst belts area compartmentalised by south flowing allogenic drainage lines such as the Duivenhoks, Kaffirkuils and Gourits rivers. Thus each interfluve acts as a separate karst aquifer since the allogenic drainage is incised into the underlying Table Mountain Group impermeable strata.

The southern Cape karst is believed to be syngenetic in origin (Russell 1989; Marker, 1993). It is characterised by linear poljes and enclosed hollows of variable dimensions aligned sub parallel to the present coast between former headland by-pass dunes. Fourth order dry valley systems feed to the present allogenic drainage. Caves are absent owing to the friable character of the limestone. The karst is hosted by Wankoe Formation Pliocene calcarenite except nearer the coast where markedly less lithified Pleistocene Waenhuiskrans Formation constitutes the substrate (Malan, 1990). Limestone thickness is closely related to topography. Case-hardened lithified limestones are restricted to an inner belt exceeding 200 m altitude. Surface sands of varying ages are another significant component. Precipitation infiltration is total.

These Cenozoic limestones rest on relatively planed impermeable Table Mountain Group strata of Bokkeveld shales and Table Mountain sandstone. The Bokkeveld shales occupy a syncline aligned east to west between two belts of more resistant Table Mountain sandstone. On the inland margin of the karst region, the Aasvoelberg, reaching an altitude of 490 m, is constituted of anticlinal Table Mountain sandstone. Along the coast a seaward dipping synclinal limb of Table Mountain sandstone extends east from the Potberg Range terminating in Cape Infanta, and underlies Cape Barracouta, Ystervark Point and Cape Vacca (Rogers, 1988). East of the Bree river, Table Mountain sandstone is visible only on the wave platforms. Inland it is overlain by limestone and the coastal contact is hidden by dunes. The Bokkeveld shales slope seawards as a marine cut surface. A break of gradient in this surface is interpreted as marking the inland extent of one phase of transgressive erosion (Russell, 1989). There is some evident that marine planation was less effective on the sandstone which is associated with a more irregular topography and probably forms a set of basement 'highs' (Rogers, 1988).

METHODOLOGY

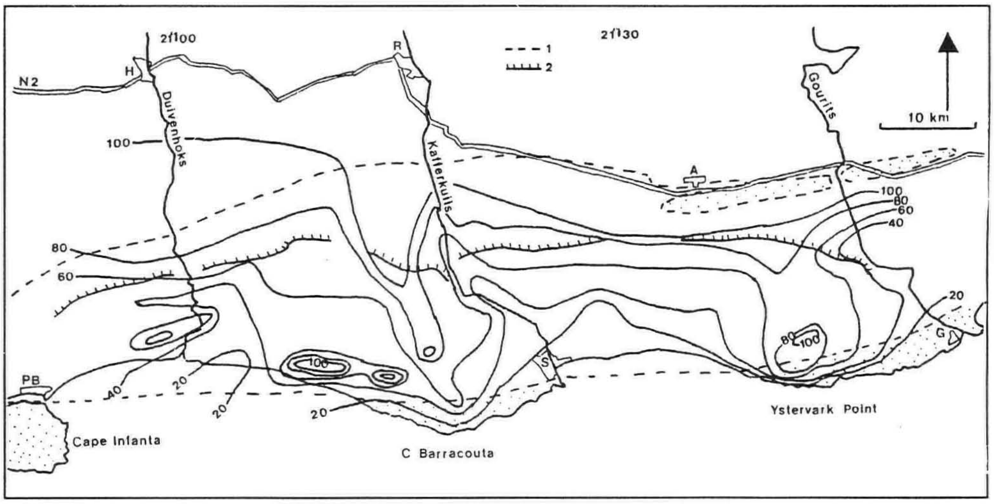
From experience gained from hydrological research in the eastern Cape karst region, it was anticipated that water should flow coastwards at the base of the limestone just above the contact with the impermeable Table Mountain Group rocks. In the eastern Cape, higher borehole yields are associated both with a conglomerate at the base of the limestone and with steepening of the hydraulic gradient above basement steps. There the piezometric surface closely resembles the limestone/basement topography (Marker and Sweeting, 1983). A similar situation was expected to obtain in the southern Cape. The present investigation began with the derivation of a limestone/basement contact map contoured at 20 m intervals a.s.l. The second stage was to construct a piezometric water surface map, also contoured at 20 m interval a.s.l. For the substrate map, data was collected from published depths (as De Bruin, 1969; Andersen and Muller, 1983; Russell, 1989; Meyer and Bertram, 1989), borehole records and by field recording of contact altitudes where exposed at the surface, particularly along the margins of the border plain, along valley sides of the three incised allogenic rivers and along the coast. At the coast the contact is only exposed as an irregular wave platform where Table Mountain sandstone outcrops exist. At Ystervark Point on Rein's Nature Reserve, the limestone has been eroded back by spring sapping to leave a cliff above a relict platform some 5 m to 15 m a.s.l. The sediments resting on this platform are not calcareous (Andersen and Muller, 1984).

The piezometric surface map has been constructed largely from data derived from farmers and from the municipalities of Albertinia and Still bay. The 2700 km^2 area of the Duineveld (essentially the karst area), not supplied by the Overberg Water Scheme, falls under the Riversdale Agricultural Extension office through which this survey was initiated. They furnished a list of resident farmers likely to have data. The area was settled early and has been considerably subdivided. Many small farms are now vacation homes or are held by inland farmers who utilise their karst farms chiefly in winter under a form of transhumance. Thirty four questionnaires were posted. Their return was followed by phone calls and by field visits, so that 75% response was obtained. Preliminary investigation had indicated that the area served by the Overberg Water Scheme which brings mountain water to that part of the limestone area lying west of the Duivenhoks river, should be excluded as there the limestone is so thin that karst water is unobtainable in sufficient volume. Three farms west of the Duivenhoks river covered by the survey confirmed the absence of adequate karst water resources and the importance of the water scheme to the area.

THE DATA

The limestone/basement contour map shows a general gradient seawards (Fig. 2) with some valley incision along the allogenic rivers. The gradient is more uniform west of the Kaffirkuils river. Nevertheless, even there some evidence of steepening between 100 m and 80 m a.s.l. is visible. East of the Kaffirkuils river, there is marked steepening south of the Aasvoelberg and considerable irregularity inland of Ystervark Point. The piezometric surface shown by the constructed map is markedly more irregular than the limestone/basement contact (Fig. 3). Piezometric surface highs exist inland of Ystervark Point and inland and west of Cape Barracouta. Both these areas have underlying Table Mountain sandstone rather than Bokkeveld shale. The piezometric surface gradient is particularly low west of the Duivenhoks river, an area into which the Overberg Water Scheme extends and where karst water availability is restricted. By combining topographic information with the

Figure 3. Piezometric surface with contours at 20 m interval above sea level. (Key as Figure 2).



data from the two constructed maps, it was possible to produce accurate north to south cross sections at three localities (Fig. 4). The effect of ponding behind the less planed Table Mountain sandstone barrier is apparent on all three sections. The ponding effect in the western section is attributed to the effect of the Table Mountain Sandstone outcrop off-shore continuing the alignment of Cape Infanta.

Fieldwork confirmed reports from the eastern half of the survey area of three groups of springs (De Bruin, 1969). Springs of variable output occur at low altitude in every dry valley tributary to the allogenic rivers. Seepage zones and low volume springs exist along the footslope of the northern margin of the high plateau and around limestone residuals on the border plain. Springs also occur along the entire coast just above or even below mean sea level. Large volume springs such as that at Jongensfontein, tapped to supply the local community, at Blombosstrand and east of Ystervark Point are localised. High yielding springs and shallow boreholes adjacent to the Aasvoelberg, supply the Albertinia Municipality. Rein's Nature Reserve has a number of smaller springs which are seasonal in flow. De Bruin (1969) reported that 83% of all springs in the area covered by his survey, east of the Kaffirkuils river, yielded less than 0.5 l s^{-1}. His survey excludes seepages and small seasonal springs. The present survey indicates that 50% of all springs fall into the low yield category (Table 1). Nevertheless, high yields also occur, particularly nearer to the coast as at Jongensfontein (28 l s^{-1}), at Langfontein and Botterkloof (both 12.6 l s^{-1}), Melkhoutfontein near Still Bay (10.7 l s^{-1}), Melkhoutfontein on the Gourits river (68 l s^{-1}) and Vermaaklikheid, formerly a notable irrigated grape producing area. Most farmers indicated that there was no seasonal difference in flow rate. This survey suggests that water available in sufficient volume to be utilised for farming exhibits little or no seasonality of flow. However, seepages and low yield springs do show reduced flow towards the end of the summer dry season, as is the case at Ystervark Point.

From boreholes, yields range from under 0.5 l s^{-1} to over 12.5 l s^{-1} (Table 1). High yielding boreholes are also localised, in the area known as Blombos west of Still Bay, south west of the Aasvoelberg and in a belt aligned approximately along the major linear poljes of Canca se Leegte and Wankoe (Fig. 5). The high yields reported by the Albertinia Municipality and from Rein's Nature Reserve boreholes must be excluded from this survey as the water is drawn from the Table Mountain sandstone aquifer rather than from the overlying limestone aquifer (Andersen and Muller, 1984; Meyer and Bertram, 1989). All the other boreholes investigated draw water from the limestone close to the basement contact and are representative of the karst aquifer. Boreholes associated with high yielding areas may be sub-artesian in character. Farmers in the Blombos and eastern Wankoe depression report up to 8 m rise in water level after water was struck. They also indicate that high yields are associated with basal gravels and with consolidated limestone. Sandy limestone, particularly within depressions (where solution has been concentrated) have lower yields.

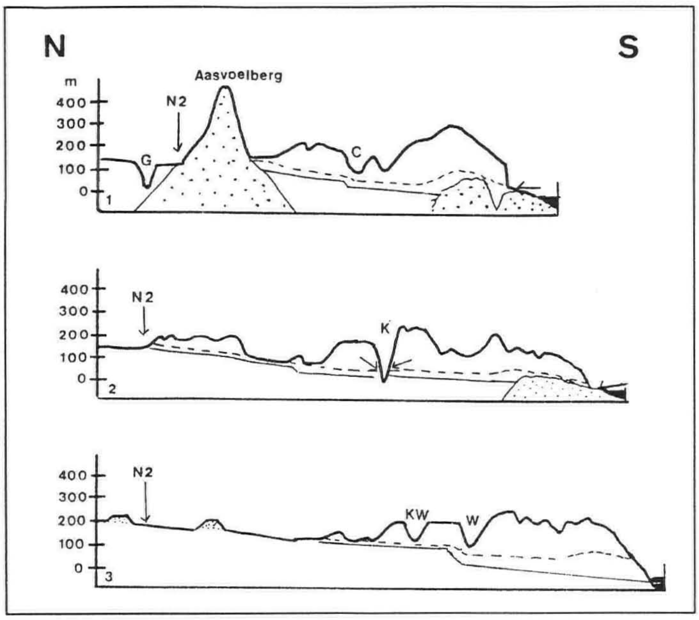


Figure 4. Measured north-south profiles across the limestone outcrop showing the basement contact and the piezometric surface as a broken line. Arrows denote position of major springs. Close stippling on plateaux denotes African surface weathering.
Profile 1 at 21°40E, G = Gouritz river; C = Canca se Leegte polje
Profile 2 at 21°20E, K = Kaffirkuils river
Profile 3 at 21°10E, KW = Klein Wankoe polje; W= Wankoe polje.

l s^{-1}	Boreholes	Springs
<0.5	18	13
0.5-1.4	3	2
1.5-2.9	11	2
3.0-5.7	6	4
5.8-12.5	6	3
12.6-25.0	10	1
>25.0	-	2
Total	54	27

Table 1: Water yields.
Data chiefly drawn from De Bruin, 1969; Meyer and Bertram, 1989; Ninham Shand, 1986.

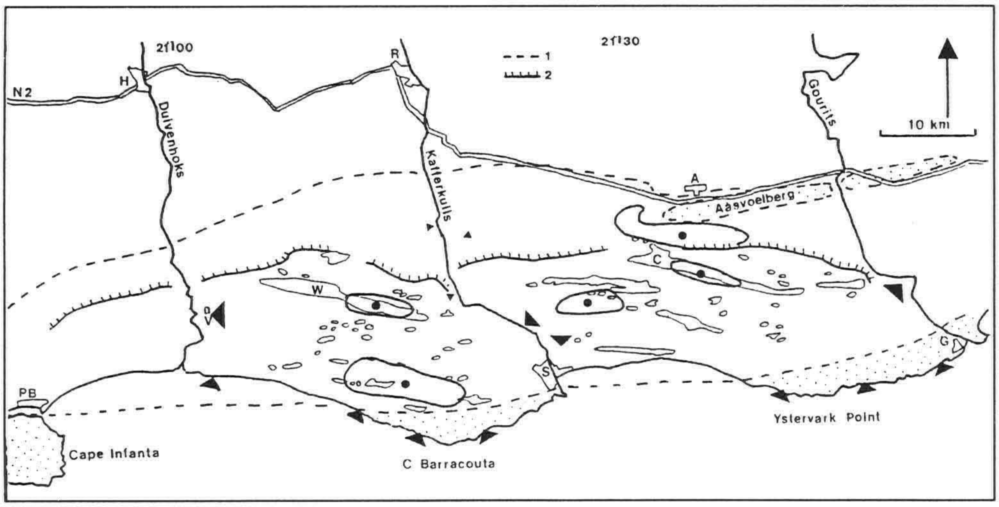


Figure 5. Major kaarst depressions (outlined lightly) and areas of high water availability (bold outline with black dot). Arrows denote positions of major springs. (Key as Figure 2).

No attempt was made to investigate water chemistry. However, published and local information suggest that the water is of high quality. Chloride contamination is a problem only close to the coast in shallow boreholes on the coastal footslope or in springs adjacent to tidal level. Calcium carbonate hardness ranges from 170 ppm at Driefontein, probably as a result of dilution with sandstone water, 230 ppm at Jongensfontien and 360 ppm at Gouritzmond. No other data have been obtained.

RESULTS

The area surveyed covers two separate aquifers, that lying between the Duivenhoks and Kaffirkuils and that between the Kaffirkuils and the Gourits rivers. With the exception of water entering from the Table Mountain sandstone in the vicinity of the Aasvoelberg, the aquifers are entirely dependant on rainfall. All water draining from the inland mountains flows into the allogenic rivers. Rain infiltration is rapid since much of the area is sand covered. All dolines and enclosed hollows carry thick sand infill. Annual rainfall ranges from under 400 mm y^{-1} to slightly over 600 mm y^{-1} only in a belt from Cape Barracouta to include the Kalkberge, the rise from the border plain (Fig. 6). Evaporation is high as the area is hot in summer and windy. Precipitation is seasonal with winter dominance when evaporation is lower. Most of the area is covered with indigenous lowland fynbos or grassland where that has been cleared, so the demands of the natural vegetation cover is moderate. Nevertheless, the volume of water derived from these karst aquifers is high considering the relatively low amount of annual rainfall available.

Only the aquifer between the Kaffirkuils River and the Gourits river receives input from springs draining into the limestone from the southern flank of the Aasvoelberg. This water ensures that the border plain behind the Aasvoelberg has adequate water. In contrast, the border plain west of the Kaffirkuils river is short of water. There, boreholes are extended into the underlying Bokkeveld shales to ensure adequate if somewhat saline supplies. The main aquifers are all associated with thicker limestones of the Wankoe Formation underlying the high 200-250 m plateau and the lower 90-150 m plateau nearer the coast. High yield areas can be classified into those immediately south of the Aasvoelberg, areas south and adjacent to the 100-80 m basement step where the piezometric gradient is steeper and to coastal areas where the piezometric surface is raised by ponding behind areas of more resistant Table Mountain sandstone. Major coastal springs are all located on the seaward steep gradient of such ponded zones. The high yielding springs associated with certain dry valleys are also located over areas of steeper gradient and therefore more rapid flow. Their association with high order dry valleys suggests that such gradients must have obtained throughout the evolution of the karst topography. In the eastern Cape incompletely planed quartzite ridges trending at an angle to the direction of flow seawards, explain the location of all coastal springs (Marker, 1988). The Table Mountain sandstone performs a similar function in the southern Cape karst belt and its alignment governs zones of higher yields of both boreholes and springs. Through-flow immediately east of the Duivenhoks river may be directed southeast, subparallel with the Bree river and probably explains the piezometric high between Cape Infanta and Cape Barracouta.

This paper has reported initial research in a little known karst area. Much further work is required to investigate water chemistry, flow-through rates and to explain variation in yields between adjacent dry valley springs and boreholes. Nevertheless, local evidence indicates that higher yields from both boreholes and springs is related to more consolidated limestone. Higher yields occur where the limestone is better lithified and does not break down to sand. It seems probable that sandy sites give rise to diffuse springs whereas consolidated limestone can accommodate larger conduits and therefore larger springs.

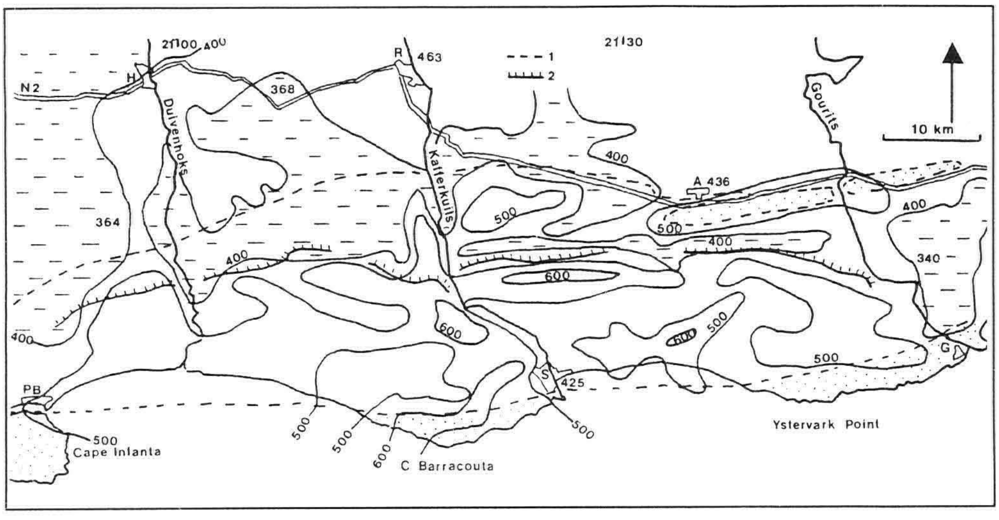


Figure 6. Rainfall variation over the karst area (after Dent et al, 1988).
Areas receiving more than 600 mm p.a. are shaded; those receiving less than 400 mm p.a. are shown by broken lines. Figures give rainfall amounts at selected farm recording stations. (Key as Figure 2).

CONCLUSION

The southern Cape karst belt between 21°00 and 21°50E is an important aquifer. Aquifers of similar importance are absent west of the Duivenhoks river and east of the Gourits river where the wide belt of high lying case-hardened limestone is also absent. Only in the area of the De Hoop Nature Reserve lying south and west of the Potberg Range are water yields again higher. This is also an area of well developed high-lying karst. The similarity of locations south and west of ranges Table Mountain sandstone may be significant. The ranges have certainly assisted in the preservation of the karst topography.

In the surveyed area, the piezometric surface is markedly more irregular than anticipated from earlier research in the eastern Cape. These irregularities serve to explain the varying yields from both boreholes and springs.

ACKNOWLEDGEMENTS

This research would not have been possible without the co-operation of the Riversdale Agricultural Extension office, initiated by Mr. F. Steyn, who provided the contact with farmers. Their help is gratefully acknowledged. The willingness of many local people to share their knowledge was a further factor and they are thanked. Partial financial assistance was received from the University of Cape Town.

REFERENCES

Andersen, N.J.P. and Muller, J.A., 1984, *Water borehole and monitoring borehole percussion logs with step drawn down and 36 hour tests.* Gouriqua Project Geological site selection programme Progress Report 16. Nuclear Development Corporation (Pty) Ltd., S.A.

De Bruin, C.G., 1969, *Boorgat- en fonteinopname Kafferskuil Gouritzrivier gebied, Distrik Riversdal.* Technical Report GH 1490. Water Affairs and Forestry, Pretoria.

Dent, M.C., Lynch, S.D. and Schulze, R.E., 1988, *Mapping mean annual and other rainfall statistics over Southern Africa.* Water Research Commission Report 109/1/1989. University of Natal Pietermaritzburg/ Water Research Commission.

Du Preez, J., 1987, *Verslag van Duineveld-boerderygebied.* Riversdale Voorligtingskantoor (area 271980Ha).

Malan, J.A., 1990, *The stratigraphy and sedimentology of the Bredasdorp Group, southern Cape Province.* M.Sc. dissertation (unpublished), University of Cape Town.

Marker, M.E., 1988, The hydrology of the Alexandria karst region, eastern Cape Province S.A. *21st IAH Conf. Proc. Karst Hydrology and Karst Environmental Protection*, 21 (1), 484-494. Guilin.

Marker, M.E., 1993, Syngenetic karst in the southern Cape, South Africa. *Cave Science*, 20, 51-53.

Marker, M.E., 1994, The application of a simple technique to monitor karst aquifer flow rates at Bushman's River Mouth, Alexandria, Eastern Cape, South Africa. *Fort Hare Papers* (in press).

Marker, M.E. and Sweeting, M.M., 1983, Karst development on the Alexandria Coastal Limestone, eastern Cape Province. *Zeitschrift fur Geomorphologie*, 27, 21-38.

Meyer, P.S. and Bertram, W.E., 1989, *'N kort geohudrologiese ondersoek vir Albertinia Munisipaliteit met 'n oorsig oor die verloop van die boorwerk en aanbevelings vir 'n verder ondersoek.* Tech. Rept. GH 3612, Director General Water Affairs.

Ninham S., 1986, *Jongensfontein: water voorsiening skema verslag oor die uitbreiding van die watervoorsiening skema.* Verslag, No. 1149/4334.

Rogers, J., 1988, Stratigraphy and geomorphology of three generations of regressive sequences in the Bredasdorp Group, southern Cape Province, South Africa. IN Dardis, G.F. and Moon, B.P. (eds) *Geomorphological studies in Southern Africa.* Balkema, Rotterdam.

Russell, L., 1989, *Karst surface landforms of the Cape Coastal Limestones.* PhD Thesis (unpublished), University of Fort Hare.

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The Morphology of shafts on the Trnovski gozd plateau in west Slovenia

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Abstract: On the high karst plateau of Trnovski gozd all precipitation penetrates immediately into the karst. Closed depressions, potholes and shafts are the dominant karst features. At least three types of shaft can be distinguished on the basis of morphology and genesis although most shafts show a strong tectonic influence. Other features such as big chambers or even collapsed dolines can form from shafts.

INTRODUCTION

Trnovski gozd is a karst plateau among the river valleys of Idrijca, Soca and Vipava in western Slovenia. It is one of a series of high karst plateaus which form the karstic part of the Dinaric Mountains on the Balkan Peninsula and which display rather similar superficial and underground geomorphological features. Large depressions which have been substantially influenced by glaciation are a characteristic superficial feature of this karst (Habic, 1978). In addition to these depressions there are collapse dolines. Potholes (caves made up predominantly of vertical shafts) are the dominant speleological feature on these plateaus. There are almost no horizontal caves or bigger active caves, and it seems likely that several dolines originated by breakdown of parallel shafts.

GEOLOGICAL AND TOPOGRAPHICAL RELATIONS ON TRNOVSKI GOZD

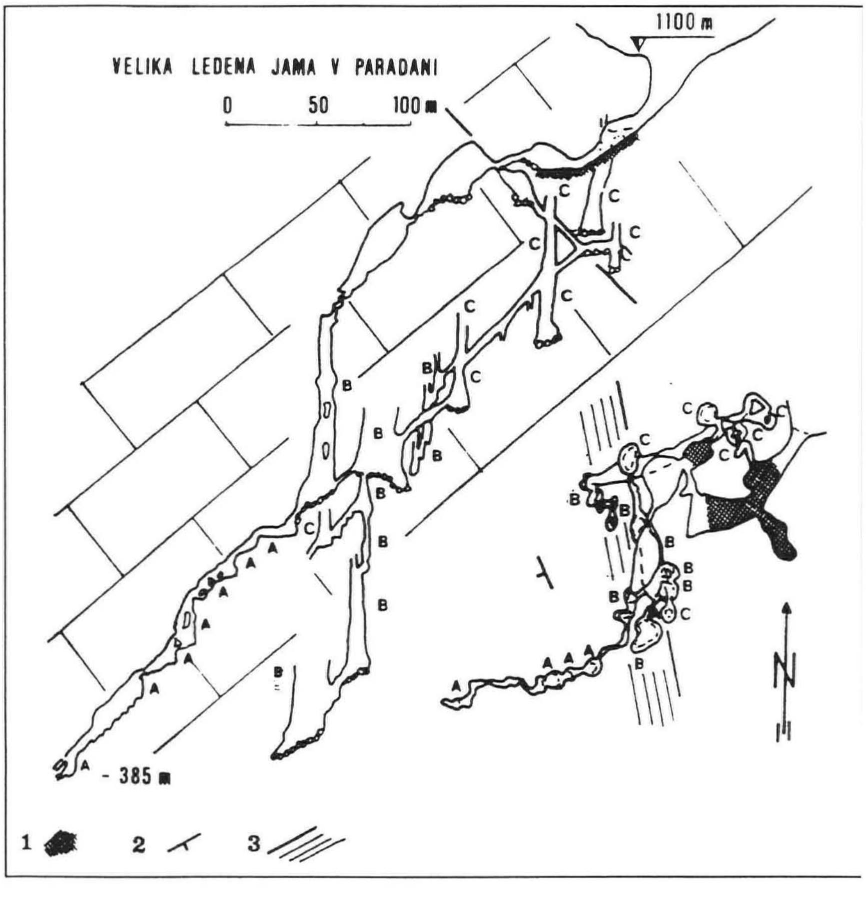
The surface of the Trnovska plateau lies between 600 and 1200 m a.s.l. and the springs at its border are between 100 and 219 m a.s.l.. Carbonate rocks cover the whole area, mostly limestone of Jurassic and Cretaceous age followed by Triassic dolomites and limestone. Structurally the area forms part of a huge regional overthrust of Mesozoic carbonate rocks over impermeable Eocene flysch rocks. The thrusted massif was later broken by right transcurrent faults in the direction NW-SE and by a series of secondary fissure zones (Placer and Car, 1974). These zones may be described as a series of parallel fissures where no displacements are seen. The distance between the fissures ranges from some 10 cm to several metres. The fissures may converge and create lens-shaped bodies. The fissure zones are well distinguished on the limestone pavement and frequently define the basic shape of potholes.

SPELEOLOGICAL PROPERTIES

The entire surface of Trnovski gozd drains through karst; there is no superficial flow on it. The main karst springs are at about 100 to 219 m; thus the vadose zone may be 800-1000 m in thickness. On about 120 km^2 of the surface there are 91 caves of which 69 are potholes and the others are inclined caves or caves much transformed by weathering. In spite of the large number of caves and relatively well prospected terrain there are no caves with horizontal passages within the area. The only accessible horizontal caves are those developed at Hubelj spring where there is a maze of passages along joints and fractures in non bedded limestone and dolomite. The oscillations at the spring may reach 50 m suggesting that the channels are not yet fully formed.

On the plateau most of the potholes are simple shafts. Forty-two are up to 50 m deep; 6 are deeper than 100 m and the deepest is Velika ledena jama in Paradana, 365 m deep (Habic, 1968). The majority of the pothole

Figure 1. Sketch plan of Velika ledena jama in Paradana.
A - Stepped shafts, B- Fissure zone shafts, C - Independent shafts.
1- cave ice, 2- dip of strata, 3- fault zone.



entrances are at about 800 m a.s.l. where the average annual temperature is about 4-6°C (Mihevc and Gams, 1976). Some entrance pitches are fundamentally modified and frequently they are wider than the interior parts. Numerous potholes are blocked by ice, snow or breakdown blocks. The original shapes of the potholes, not yet spoiled by superficial influences may be observed only in inner shafts.

The shapes of the shafts and their space distribution are best seen in Velika ledena jama in Paradana. This ice cave is developed in bedded Jurassic limestone and dolomites. Steady strike (SW) and dip (50°) of strata may be observed in the whole cave except in a strong vertical fault zone where the rock is crushed in some places and consolidated into tectonic breccia. In this zone, crossing the cave in a N-S direction most of the shafts are developed. Other parts of the cave follow the dip of the strata or are linked to rather rare separate faults. The shape of certain shafts does not indicate any connection with structure and simply means the break through the beds. In the entrance part of the cave there are three chambers where weathering processes are well expressed. Permanent ice remains in them indicating a strong surface influence. The inner parts of the cave are composed of shafts linked by short passages which are mainly narrow and high oxbows draining the water of the shafts or corrosionally widened fissures. Two passages only indicate a phreatic origin and they are in some places broken through by younger shafts. There are 33 inner shafts within the cave, the deepest being 98 m deep followed by 55, 40 and 35 m deep shaft. The total polygon cave length is 1610 m of which 710 m are shafts. Thus they represent the main building element of the cave (Fig. 1).

Three types of shafts may be distinguished on the basis of shape and, in particular, their mutual position and dependence on geological setting:

1. Stepped shafts

These occur either in series or originating in oxbows concordant to the dip of the strata. In the upper part the shafts are meander-wide but they widen downwards and have rounded bottom cross section. There are no chimneys, at the ceiling, at the top of the shafts respectively the oxbow ceiling continues. The bottom is mainly in bedrock with few stones, and somewhere, at the lee-sides, smaller quantities of sand are deposited (Mihevc and Zupan, 1988). The characteristic feature is arches among the shafts due to deepening of a part of the shaft's bottom which lies directly below the water jets, vertically below the inflow point at the top of the shaft. The water finds new way among the bedding planes towards the next lower shaft and one part of the shaft's bottom stagnates. The initial shape of these shafts is oxbow, with irregularities some centimetres or more in size at the bottom of the oxbow passage.

2. Independent shafts

This type does not show any impact of bedding or dissection in its accessible or even major part. Obviously these shafts were deepened out of initial discontinuity planes. Bottom deepening is the dominant and most important process in the shaft, the main conditions being the initial water fall, the permanent point of water inflow and the possibility of drainage out of the bottom. On some of the walls narrow, mostly impassable, oxbows which were the former water conduits are preserved. The discovery of such shafts is usually accidental where they break through older passages.

3. Fissure zone shafts

These are shafts along fissures within the fault zone. Upwards they narrow into fissures from where the water flows, the bottom is mostly covered by break-down blocks and for the most part they resemble the spindle-shaped shafts described by Maucci (1975). In cross-section they are lens-shaped and remain such towards the bottom too. The only ones where strong water jets were observed are more rounded downwards. Sideways shafts or parallel shafts arranged in a series along the same fissure or one above the other are characteristic. Their origin is obviously contemporaneous, probably by vertical initial openings developed along the fissured zone in phreatic conditions. Most of the shafts belonging to this type developed within the fault zone in the central part of the cave on the ground plan of 70 x 30 m. Between the top of the highest and the bottom of the lowest there are 350 m of denivellation. The shafts are parallel one to the another within a short distance and their total volume is 36,000 m^3. The same type of shaft with the same cavernosity probably continues downwards below the accessible parts of the cave.

In terms of volume, stepped shafts are the smallest and fissure zone shafts are the largest (Fig. 2). The shafts are so close to one another that there are a lot passages among them and break-down of the in-between walls frequently occurs.

Other caves on the plateau display similarly shaped interior shafts and one may presume that the entrance parts have the same origin due to lowering of the surface (Maire, 1990). The walls and the dimensions of

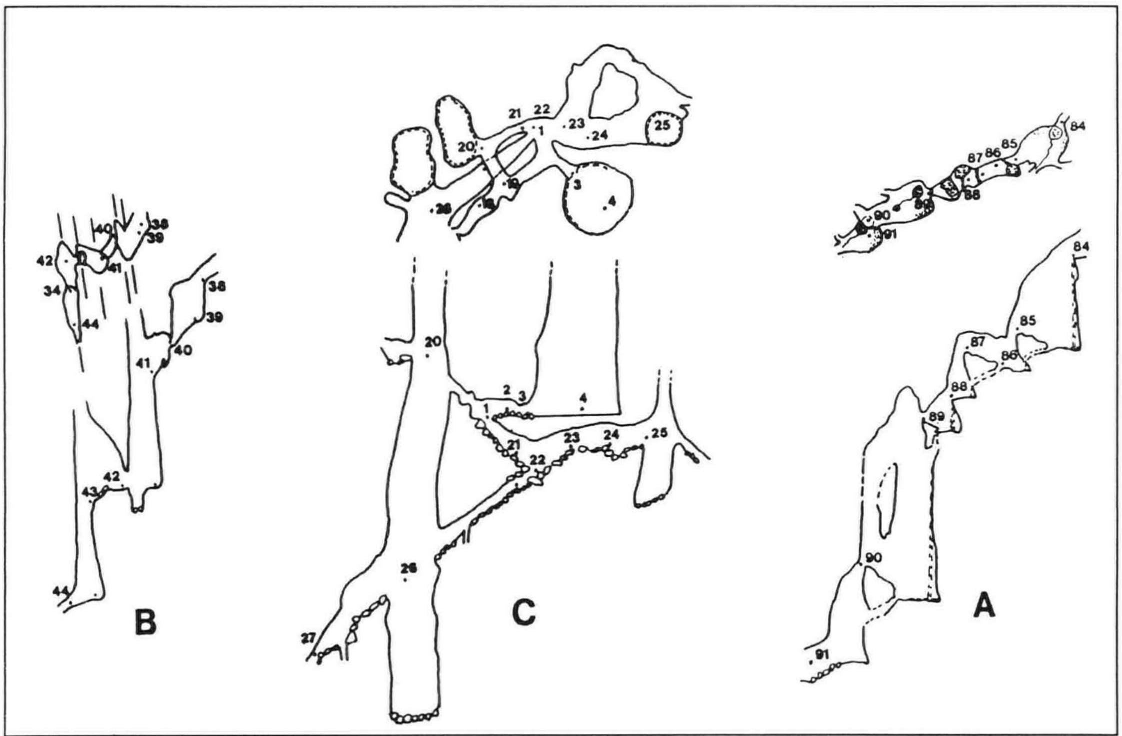
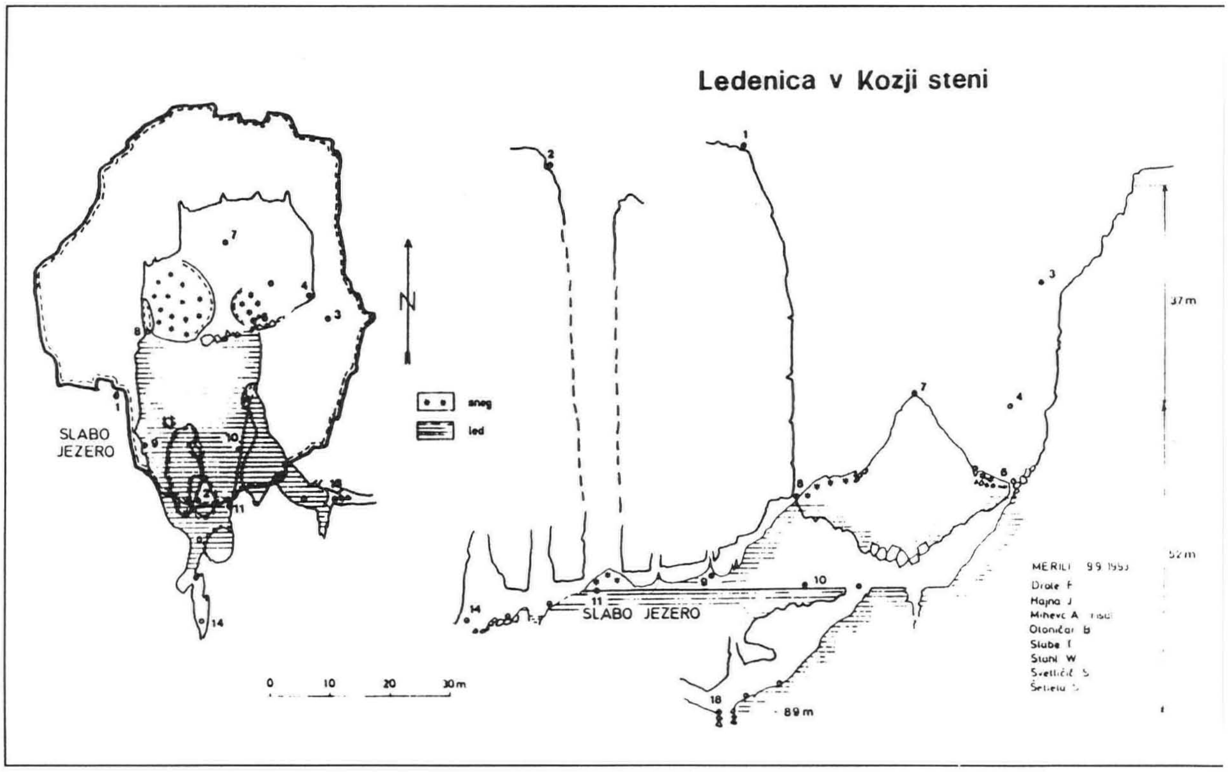


Figure 2. Shaft types in Velika ledena jama, Paradana.
A - Stepped shafts, B - Independent shafts, C - Fissure zone shafts.

Figure 3. Ledenica in Kozja stena. The entrance shaft into the cave resembles smaller collapse dolines in the area and shows obvious connection to a N-S fissure zone.



the first and second type of shafts are rather stable and do not change considerably although exposed to sharp climate. Fissure zone shafts often have huge entrance pitches and marked disintegration of the rock along the fissures may be observed. Due to their huge entrance openings these shafts are more liable to be filled up by breakdown rocks or ice. The biggest such entrance shaft is that of Ledenica in Kozja stena which is similar in shape to a collapse doline (Fig. 3). The entrance, at 1200 m a.s.l., is a 60 m deep vertical drop having the dimensions of 50 x 60 m at the top. At a depth of about 50 m the shaft narrows to 30 x 25 m and its total volume is 86.000 m^3. The bottom of the entrance pitch has a double depression leading downwards into common chamber where there is a large ice lake closing the cave continuation. The entrance pitch has developed in a strong N-S fissure zone by the linking of parallel shafts.

CONCLUSION

Dolines are a characteristic relief feature on high karst plateau of Trnovski gozd. In some of them one may observe bigger or smaller vertical sections or else, the dolines resemble the collapse dolines. The origin of collapse dolines is attributed by most authors to collapse or subsidence of large horizontal passages above underground flows. However, on the Trnovski gozd plateau there are no known channels which could be the remains of underground passages. Instead, the caves on the plateau are simple or stepped potholes, the latter being composed of vertical shafts with short joint passages. They were formed by percolating rainwater in the vadose zone but their morphology indicates various degrees of geological influence.

Shafts within the fissure zones form a marked morphological type. These shafts are arranged in a series along the same fissure or along parallel fissures. Hence the shafts are either parallel or lie one above the other. When these shafts are linked due to breakdown of the in-between walls big chambers (horizontal linkage) or deep shafts (vertical linkage) may occur. In Velika ledena jama in Paradana the shafts within such a series originated in a 30 x 70 x 300 m vertical section with a volume of 36,000 m^3.

Shafts of the same type which are now open to the surface due to corrosional sheet weathering may be distinguished by their larger dimensions. For example, the entrance shaft of Ledenica in Kozja stena has a volume of 86,000 m^3. A funnel-shaped doline, 40 m deep and with a radius of 45 m would have the same volume.

REFERENCES

Habic P., 1968, Kraski svet med Idrijco in Vipavo. *SAZU, Dela 21*, Institut za geografijo 11, 1-243.

Habic P., 1978, Razpored kraskih globeli po dinarskem Krasu. *Geografski vestnik* 50, 17-31.

Maire, R., 1990, "La haute montagne calcaire", *Karstologia Mémoires*, no. 3, 731 pp. Thèse d'Etat à Nice. Fédération française de spéléologie, Paris and Association française de karstologie, Grenoble.

Maucci, W., 1975, L'ipotesi "dell'erosione inversa" come contributo allo studio della speleogenesi.- Le Grotte d'Italia. *Atti del Seminario di Speleogenesi, Varenna*, 5-8 ottobre 1972, 236-285.

Mihevc, A. and Gams, I., 1979, Nova odkritja v Veliki ledenici v Paradani (kat.st.742). *Nase jame*, 20, 7-20.

Mihevc, A. and Zupan, N.,1988, Izvor in Mineraloska analiza sedimentov v Veliki ledenici v Paradani. *Speleobih*, 1-2, 17-25.

Placer L. and Car, J., 1974, Problem podzemeljske razvodnice Trnovskega Gozda Krize gore in Crnovrske planote. *Acta Carsologica*, 6, 81-93.

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 or research establishments. Information and applications for Research Awards should be made on a form available from Simon Bottrell, Dept. of Earth Sciences, University of Leeds.

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An award, or awards, with a minimum of around £1000 available annually, to overseas caving expeditions originating from within the United Kingdom. Grants are normally given to those expeditions with an emphasis on a scientific approach and/or exploration in remote or little known areas. Application forms are available from the GPF Secretary, David Judson, Hurst Farm Barn, Cutler's Lane, Castlemorton Common, Malvern, Worcs., WR13 6LF. Closing date 1st February.

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Grants are given annually to all types of caving expeditions going overseas from the UK (including cave diving), for the purpose of furthering cave exploration, survey, photography and training. NCA delegates administration of the awards to the Ghar Parau Foundation, to prevent duplication of cost and effort, and to provide a desirable degree of independence from NCA. Application arrangements are as for Ghar Parau Foundation Expedition Awards, see above.

Expedition organisers living in Wales, Scotland or Northern Ireland, or from caving clubs based in those regions should contact their own regional Sports Council directly in the first instance. It is possible that the inauguration of the National Lottery may result in different arrangements for grant aid.

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An annual award, currently £50, 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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