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Limestone stack off Koh Tapoo. Phangnga Bay.

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This Journal was (and is) intended to be wide ranging in scope from the scientific study of caves and their contents, to the history of caves and cave areas and the technical aspects of cave study and exploration. The territory covered is Australasia in the truest sense – Australia, New Zealand, the near Pacific Islands, New Guinea and surrounding areas, Indonesia and Borneo.

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AN INVESTIGATION OF THE MECHANISMS OF CALCIUM CARBONATE PRECIPITATION ON STRAW SPELEOTHEMS IN SELECTED KARST CAVES - BUCHAN, VICTORIA

E. Canning

Abstract

The relative significance of straw speleothem growth resulting from evaporation and from CO_2 degassing was determined in Lilli-Pilli and Moons Caves (Buchan, Victoria) from a seven-month study of cave climate and water chemistry. The relative importance of these two mechanisms was inferred from the calculation of straw growth rates according to a degassing model and an evaporation model. The modelled straw growth rates from the carbon dioxide degassing model were on hundred to one thousand times those attributable to evaporation.

A third model was used to calculate straw growth rates from the overall supersaturation of the water. Growth rates were found to be within the range of 0.01 to 0.07 mm per annum.

INTRODUCTION

This paper reports on a study of the processes which lead to the growth of straw speleothems in limestone caves. The aims of the study were:

(a) to determine, from the possible mechanisms which could result in precipitation of calcium carbonate on straw speleothems, which are the dominant ones in two cave systems chosen;
(b) to determine the effect of seasonal changes in the soil and cave environments on the rates of speleothem growth.

For comparative purposes two cave sites were investigated. Because air movement is an important factor in determining the meteorological conditions within a cave system, and that subsequently these conditions are major factors in determining the mechanisms of calcite precipitation, two cave systems of differing ventilation patterns were studied. Thus this investigation involved a cave in which ventilation was restricted, and which was expected to have a constant environment with respect to the various cave atmospheric parameters. In contrast, the second system chosen possessed a constant air flow which was expected to result in a dynamic environment reflecting changes in the outside atmospheric conditions.

In each of the cave systems chosen, data were collected which would enable the cave meteorology and water chemistry to be determined. These data were then applied to physico-chemical models describing straw growth rates due to evaporation, CO_2 degassing and the overall supersaturation of the straw droplet. Thus the relative importance of each of the processes of precipitation was quantitatively determined.

FIELD STUDY AREA

The study area chosen was the Buchan karst district in eastern Victoria [see Figure 1].

The basic stratigraphy of the Buchan area consists of a carbonate sequence, the Buchan Group, overlying a thick sequence of quartz rich volcanics called the Snowy River .pa

Volcanics. The Buchan Group consists of the Buchan Caves Limestone which is overlain by the Pyramids Mudstone, the Taravale Mudstone and the Murrindal Limestone comprised of the Rocky Camp and McLarty Members. Figure 2 presents a diagram showing the relationships between the stratigraphic units and Figure 3 is a geological map of the Buchan Valley area.

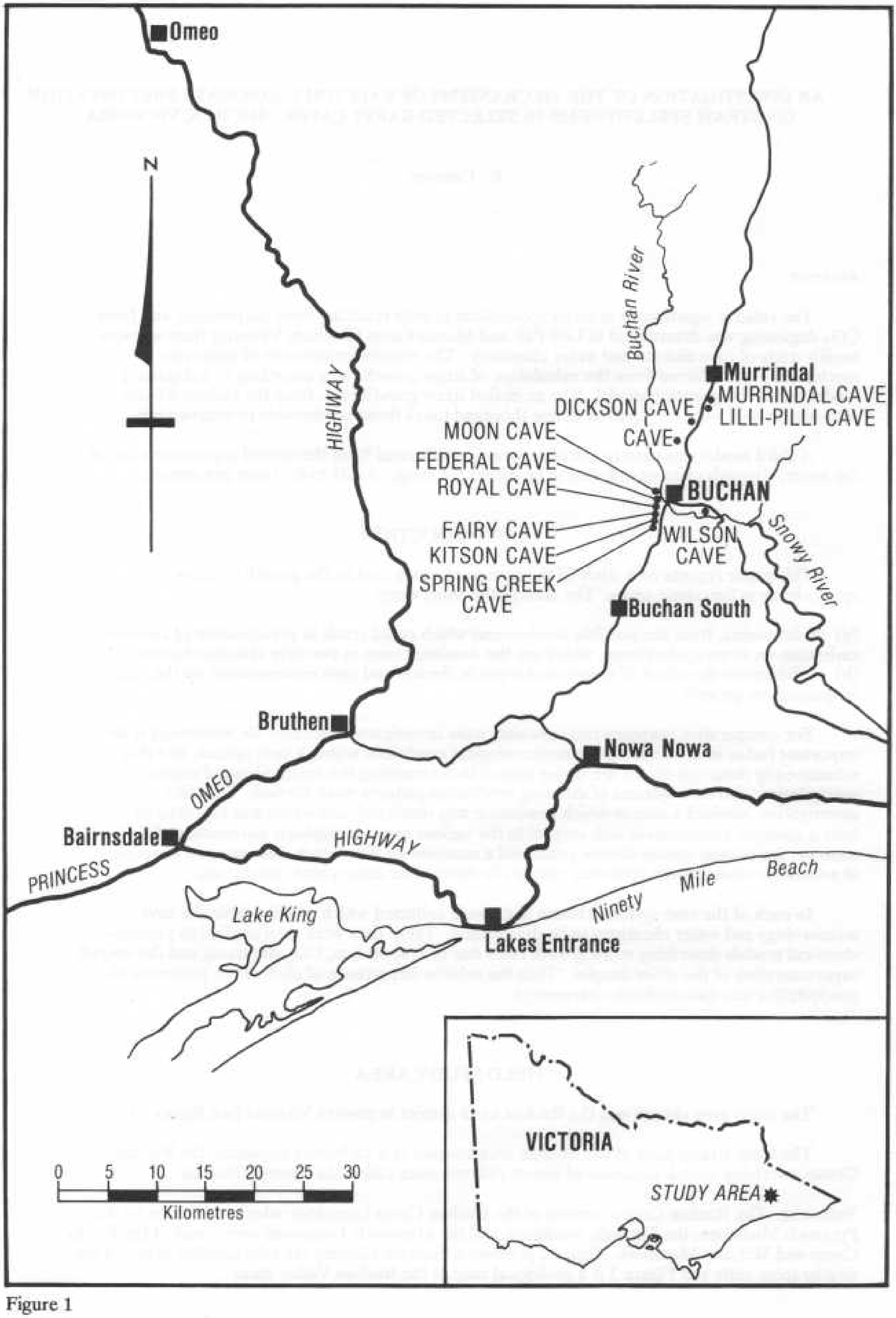
Omeo
N
HIGHWAY
Buchan River
Murrindal
MURRINDAL CAVE
LILLI-PILLI CAVE
DICKSON CAVE
MOON CAVE
CAVE
FEDERAL CAVE
ROYAL CAVE
BUCHAN
FAIRY CAVE
KITSON CAVE
WILSON CAVE
Snowy River
SPRING CREEK CAVE
Buchan South
Bruthen
Nowa Nowa
OMEO
Bairnsdale
HIGHWAY
PRINCESS
Beach
Mile
Ninety
Lake King
Lakes Entrance
VICTORIA
STUDY AREA
0 5 10 15 20 25 30
Kilometres

Figure 1

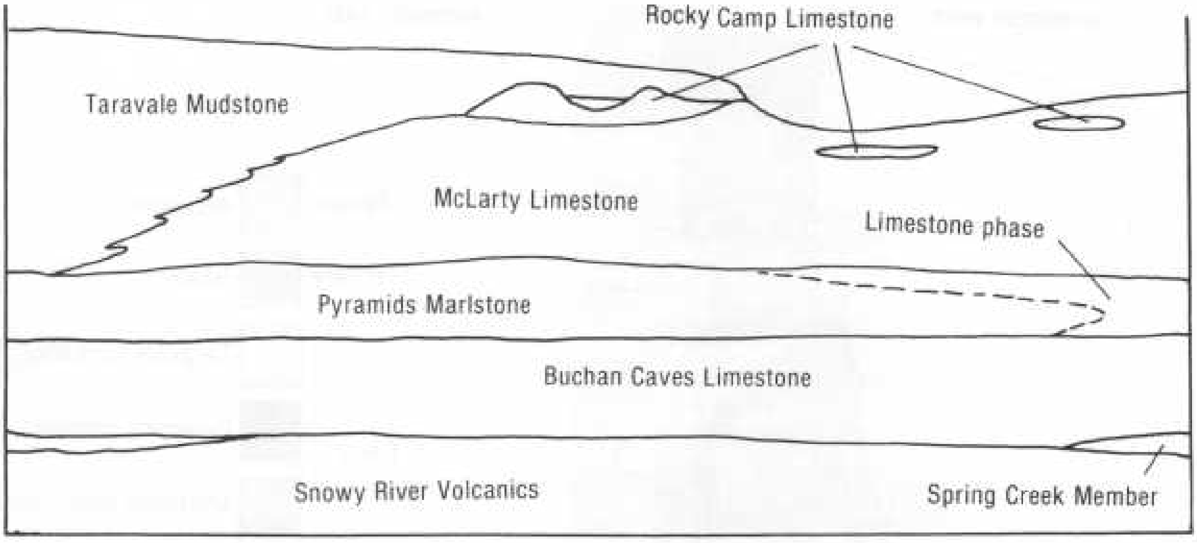

Figure 2.

Study Sites

The caves studied were selected primarily because they possessed active formations from which 150 ml drip samples could be collected within a reasonably short period of time, i.e. normally less than ten hours. Ease of access for instruments was also a consideration.

Lilli-Pilli Cave, M-8, is located within the Buchan Caves Limestone sequence [see Figure 3]. It is a dry stream passage cave. Many large areas of excellent formation are present in this cave, including Buchans best example of rimstone barriers. A solid gate present at the entrance to this cave restricts air movement between the cave and the outside environment. Compositional analysis of the limestone comprising Lilli-Pilli Cave gives a ratio of $CaCO_3$ to $MgCO_3$ of 2.2 : 1 (Teichert et al. 1958).

The second cave chosen for this study, Moons Cave B-2, is also located within the Buchan Caves Limestone sequence. Moons Cave is a stream passage cave which contains a permanent stream draining into Spring Creek. The cave is quite well ventilated owing to the presence of two entrances at different elevations; air velocity measurements over 24 hours at the fairly constricted entrance produced figures between 0.2 and 1.7 m/sec. Speleothem development is mainly in the form of stalactites and straws with small amounts of flowstone. Compositional analysis of the limestone comprising Moons Cave shows a $CaCO_3$ to $MgCO_3$ ratio of 2.7:1.

MATERIALS AND METHODS

In each cave a series of recording stations was chosen at which cave atmospheric and water chemistry data were collected approximately once a month over a period of eight months. Cave atmospheric parameters studied were humidity, temperature, air velocity and the partial pressure of carbon dioxide. Humidity and temperature were determined using a Lambrecht thermohygrograph and a Brannan whirling psychrometer. Carbon dioxide levels in the cave air were determined using a FOXBORO 'Miran' 101 specific vapour analyzer and a Drager portable gas detector. Air velocity measurements were made using a TSI model 1650 hot wire anemometer.

Drip samples were collected in rinsed 250 ml polyethylene bottles and the temperature of the samples was determined before removal from the cave. Immediately after removal from the cave the pH and conductance of the samples were determined using a Metrohm model E588 pH-meter and a Metrohm model E587 conductometer. Alkalinity was also measured immediately by titrating to 4.5 pH with 0.03 molar HCl (determined by standardising against sodium carbonate). Within twenty-four hours the samples were titrated with EDTA using standard methods in order to determine calcium and magnesium concentrations [Douglas 1968].

Ionic species abundances, partial pressures of carbon dioxide and saturation indices of calcite and dolomite were computed using the WATSPEC aqueous solution model [Wigley 1977].

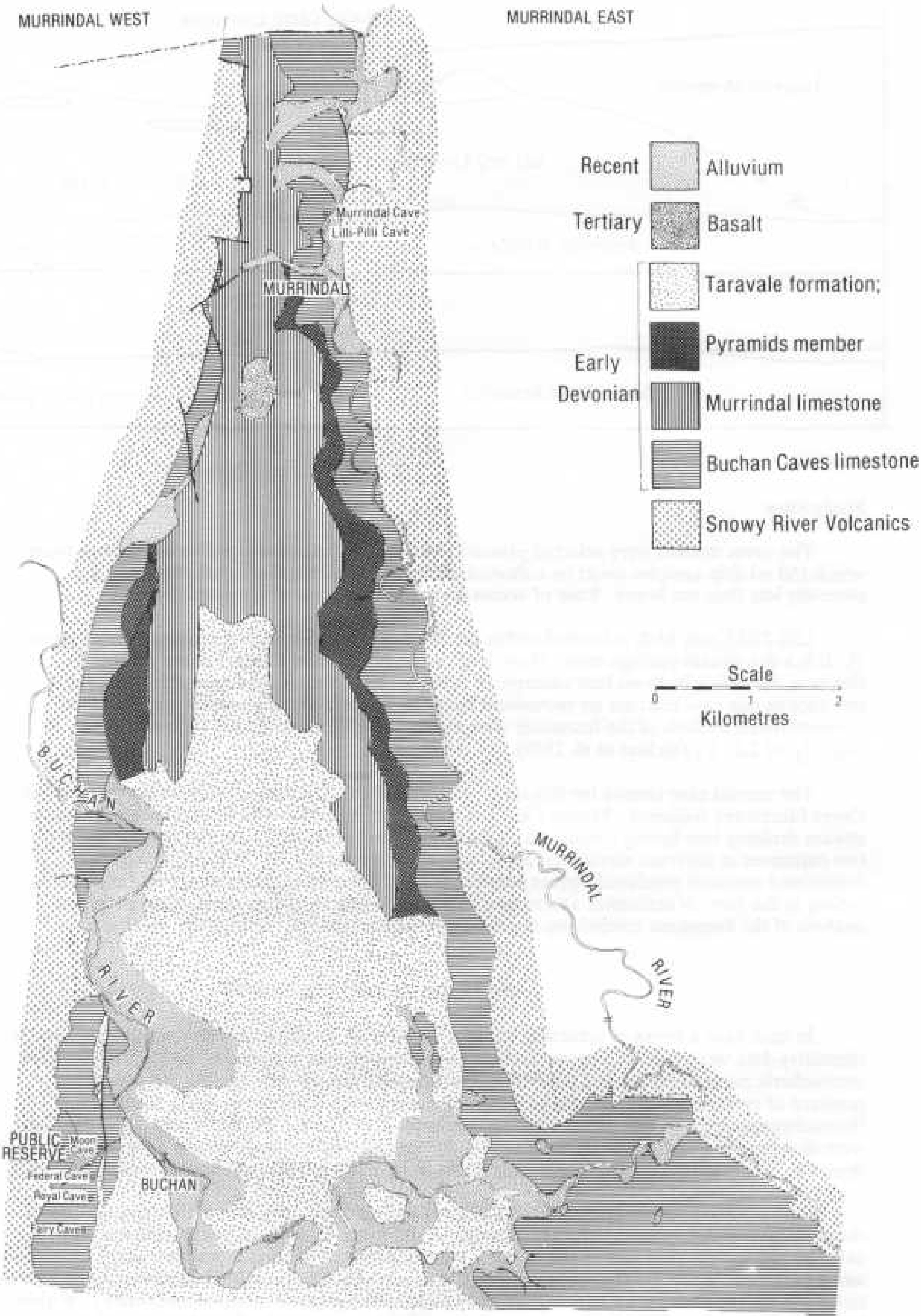

Figure 3. Geology of the area

The data thus gathered were used to solve the following three equations in order to determine amounts of precipitation due to CO_2 degassing, evaporation of H_2O and total supersaturation.

MODEL CALCULATIONS

Degassing equation

The following equation was adapted from the work of Groothius and Kramers [1955] who derived a calculation to determine the amount of SO_4 absorbed by individual drops of water at the tip of a capillary tube. This calculation can successfully be applied to the degassing of CO_2 from droplets. Working at the liquid/gas interface, this equation describes the rate of movement of CO_2 to the interface and its loss through the interface as determined by the differences between the PCO_2 [partial pressure of CO_2] in the air and the PCO_2 of the liquid.

Thus

$$\frac{M(t)}{t} = \frac{4}{3\sqrt{\pi}} \quad \frac{(Pg - Ps).\sqrt{\frac{D}{t}}}{Hre} V$$

where:

m (t) = mass decrease mmol. $CO_2\ s^{-1}$

t = time of drop formation in seconds

Pg = partial pressure of CO_2 in the air

Ps = partial pressure of CO_2 in the droplet

D = coefficient of diffusion of CO_2 in water

$1.4 \times 10^{-5}\ cm^2\ s^{-1}$ (at 20°C)

re = average drop radius

0.061cm

V = average drop volume

$40 \times 10^{-2}\ cm^3$

H = Henry's constant; used to convert partial pressures to concentrations.

21.7 atmospheres $mmol^{-1}\ cm^3$

re and V, as described in Groothius and Kramers [1955] are empirically derived values which describe the volume and radius for a growing droplet on capillary diameters of 2 to 8 mm.

In order to determine rates of calcite precipitation it is necessary to convert from mmol s^{-1} to $m^3\ s^{-1}$:

$$\underset{[\text{rate } CO_2 \text{ loss Kg } s^{-1}]}{KG} = \frac{m(t)}{t} \times 0.1$$

$$\underset{[\text{rate calcite loss } m^3 s^{-1}]}{KM} = \underset{[\text{density of calcite}]}{KG / 2.65 \times 10^3}$$

A major assumption made here is that the flux loss of CO_2 in mmol. equals the flux loss from solution of $CaCO_3$ in mmol. This assumption is supported by Dreybrodt [1980] as necessary simplification of a complex set of reactions.

Thus, in order to obtain straw growth rates due to CO_2 degassing:

$$\frac{\text{rate of loss of calcite } m^3 s^{-1}}{\text{annulus area of straw } m^2} \times \text{no. S per a} \times 1.000 = \text{straw growth rate mm } a^{-1}$$

Evaporation Equation

The evaporation model states that a certain amount of calcite will be deposited due to a given amount of evaporation of H_2O from the surface of a water droplet. The following equations, which were basically derived from Atkinson [1983] aim to determine (1) the evaporation rate from a spherical droplet, (2) the amount of calcite deposited due to this evaporation and (3) the rate of growth of a straw with a known annulus area.

(1) Evaporation rate

$$\frac{dm}{dt} = K \times r \times E \times V \times Da$$

where $\frac{dm}{dt}$ = evaporation rate in $kg.s^{-1}$

$K = 1.14 \times 10^{-6} m^2 s^{-1}$ at 15°C

a rate constant depending upon temperature; derived from Wigley [1975:82]

$r = 2 \times 10^{-3}$ m
drop radius

E = deficit ratio;
$\frac{\text{air humidity - saturated value}}{\text{saturated value}}$

V = ventilation factor; derived from Squires [1951:61]

Da = $1.0 \text{ kg } m^{-3}$; density of air

(2) Calcite deposition

$$\frac{dV\ CaCO_3}{dt} = \frac{1}{DW} \times \frac{1}{DC} \times \frac{dm}{dt} \times \frac{mCa}{10}$$

where

$$\frac{dV\ CaCO_3}{dt} = \text{Calcite deposition in } m^3s^{-1}$$

$Dw = 1 \times 10^3\ kg\ m^{-3}$; density of water

$Dc = 2.65 \times 10^3\ kg\ m^{-3}$; density of calcite

$$\frac{dm}{dt} = \text{evaporation rate } kg\ s^{-1}$$

m Ca = calcium concentration mmol. L^{-1}

(3) $$\frac{\text{Calcite deposition } m^3\ s^{-1}}{\text{annulus area of straw } m^2} \times \text{no S per a} \div 1{,}000 = \text{straw growth rate mm } a^{-1}$$

Supersaturation Equation

The supersaturation equation considers the rate of calcite deposition resulting from a certain degree of supersaturation of the solution. The following equation from Picknett et al. [1976] gives the rate of calcite deposition in kg m due to the liquid/solid surface reaction rate.

$$R = -S\,(k_1 - k_2\,[Ca^{2+}]\,[CO_3^{\ 2-}])$$

where S = surface area

$k_1 = 6.48 \times 10^{12}$ mole. s^{-1} cm^{-2} ; $k_2 = 870$ mole. s^{-1} cm^{-4}

$[Ca^{2+}]$ = calcium concentration mole. cm^{-3}

$[CO_3^{\ 2-}]$ = carbonate concentration mole. cm^{-3}

The rate of deposition is proportional to the surface area and the calcium and carbonate concentrations. Thus, the rate of deposition in moles per cm^2 is:

$$R = -(k_1 - k_2[Ca^{2+}]\,[CO_3^{\ 2-}])$$

In order to convert from moles of $CaCO_3$ $cm^{-2}\,s^{-1}$ to $kg\ m^2m^{-1}$:

$$RK = KM \times R \times 1 \times 10^4$$

$$GRm.\ s^{-1} = Rk/DC\ m.s^{-1}$$

where RK = rate of deposition in $kg\ m^2\ s^{-1}$

KM = number of kg per mole $CaCO_3$; 0.1 kg $mole^{-1}$

GR = growth rate

DC = density of calcite; $2.65 \times 10^3\ kg\ m^{-3}$

To convert from $m.s^{-1}$ to mm. a^{-1} :
$GR = m.a^{-1} = GR\ m.a^{-1} \times 1{,}000$

ASSUMPTIONS OF THE MODELS

CO_2 Degassing and Evaporation Equations

The resulting straw growth rates calculated using these two equations may be compared. Although it is evident from the results obtained that both models are over-estimating rates of precipitation, it is not possible to determine exactly the amount of over-estimation which is occurring. Relative importance of the two mechanisms may nevertheless be inferred from the model results.

The major limitation of both models is that only those processes occurring at the liquid/gas interface are considered. Thus, both modes disregard solution reactions, bulk solution diffusion and the reactions at the liquid/solid interface as being rate controlling. It is therefore assumed that flux loss of CO_2 and H_2O from a droplet equals flux loss of calcite. A second assumption made by both models is that the droplet is in a state of saturation when it emerges into the cave atmosphere; it is thus immediately able to deposit calcite due to the loss of CO_2 and H_2O.

The Supersaturation Equation

Despite the assumptions made by this model it may be considered to give a reasonably close approximation of straw growth rates. This model works at the solid/liquid interface and is thus not comparable to the model describing H_2O loss and that describing CO_2 loss which work at the liquid/gas interface.

The major assumption made by this model is that the droplet possesses a constant supersaturation for the entire time in which it is suspended from the straw. Thus this equation does not allow for the time lag between the droplet forming on the end of the straw at equilibrium and attainment of supersaturation by degassing of CO_2 or evaporation. In order to account for this factor the equation results are divided by two giving an average supersaturation value for the droplet. This assumes that supersaturation occurs at a steady rate.

RESULTS

The results of the application of the supersaturation, CO_2 degassing and evaporation equations to the data collected are given in Tables 1 to 6.

For each cave the mean straw growth rates and the standard deviation for each of the physico/chemical models used are given in Table 7. The mean growth rates for each straw speleothem over a year were determined by using a sine curve fitted by eye to calculate mean free Ca and CO_2. This method was used because an arithmetic mean would have resulted in a heavy bias towards the February to May figures. The results of the application of the CO_2 degassing and the evaporation models, however, were arithmetically averaged for each drip site. The arithmetic mean, rather than the sine curve mean, is adequate for these models as the results are being used for comparison rather than as accurate predictions of growth rates.

DISCUSSION

The results of the physico/chemical models used are here discussed in the light of cave atmospheric and water chemistry parameters.

CO_2 Degassing Model

The CO_2 degassing model estimates loss of CO_2 at a rate determined by the partial pressure difference between a water droplet and the air. Thus seasonal variations in PCO_2 will affect the rates of calcite deposition caused by this mechanism over time.

As shown by the CO_2 degassing model results (Tables 1 to 6) there is a general trend in both caves towards increasing growth rates over the time period of sampling. This trend may firstly be related to characteristics of the model itself. When a straw is dripping rapidly, the PCO_2 difference between the drop and the air is kept at a maximum as there is less time for degassing than when a straw is dripping more slowly. Thus, as the PCO_2 difference between the drop and the air declines over the time that a drop is suspended from the straw, rates of CO_2 loss decline. In the straws sampled there is a general trend towards increasing drip rates between February and August which is directly related to increased amounts of precipitation. The increasing drip rate, whilst increasing the rate of loss of CO_2, also decreases the time available for the effects of CO_2 degassing to result in calcite precipitation. If diffusion through the bulk of the solution or the reactions within the solution or at the liquid/solid interface are rate controlling the projected increase in growth rate with increasing drip rates may not be as extreme as the figures given suggest.

TABLE 1: Straw growth rates determined using the evaporation equation - Moons Cave (mm. a^{-1})

DATE	SITE NUMBER 1	2	3	4
28. 2.85	0.024	X	0.028	X
6. 3.85	0.024	0.023	0.025	0.024
12. 3.85	0.024	E	0.025	0.023
3. 4.85	0.024	0.024	0.026	0.024
10. 4.85	0.019	0.020	0.024	0.024
12. 5.85	E	0.024	0.027	E
28. 5.85	0.024	0.024	0.027	0.025
19. 8.85	E	E	0.027	0.026

E = eroding straw i.e. undersaturated
X = inactive straw

TABLE 2: Straw growth rates determined using the evaporation equation - Lilli-Pilli Cave (mm. a^{-1} X 10^{-3})

DATE	SITE NUMBER 1	2	3	4	5	6	7	8
27. 2.85	X	X	8.5	3.6	6.4	3.7	4.9	3.6
1. 3.85	X	X	7.6	7.6	6.4	3.7	4.8	4.4
5. 3.85	X	X	7.6	X	6.4	4.8	4.8	X
12. 3.85	X	X	6.2	X	7.3	4.0	4.7	4.4
4. 4.85	5.5	5.6	5.4	5.4	7.2	5.7	E	6.7
9. 4.85	4.5	4.5	5.2	7.5	E	5.9	6.8	X
14. 4.85	X	X	7.8	X	5.3	5.0	5.9	5.5
17. 8.85	X	X	E	X	E	E	E	5.9

E = eroding straw i.e. undersaturated
X = inactive straw

TABLE 3: Straw growth rate determined using the CO_2 degassing equation - Moons Cave (mm. a^{-1})

DATE	SITE NUMBER 1	2	3	4
28. 2.85	5.37	X	4.36	X
6. 3.85	8.66	5.89	5.96	2.0
12. 3.85	13.09	E	7.68	3.34
3. 4.85	7.08	8.52	10.66	4.23
10. 4.85	8.15	5.81	6.59	5.36
12. 5.85	E	15.36	17.18	E
28. 5.85	15.93	19.46	162.70	9.03
19. 8.85	E	E	74.85	49.77

E = eroding straw i.e. undersaturated
X = inactive straw

TABLE 4: Straw growth rate determined using the CO_2 degassing equation - Lilli-Pilli Cave (mm. a^{-1})

DATE	SITE NUMBER 1	2	3	4	5	6	7	8
27. 2.85	X	X	1.98	1.39	3.11	0.62	3.31	0.99
1. 3.85	X	X	3.03	2.83	7.74	3.17	6.58	1.55
5. 3.85	X	X	3.52	X	4.7	1.47	7.71	X
12. 3.85	X	X	3.01	X	4.7	2.22	12.82	1.69
4. 4.85	7.33	4.98	6.13	1.52	13.01	3.92	E	X
9. 4.85	4.84	4.98	5.83	X	E	3.53	16.47	X
14. 5.85	X	X	5.85	X	9.42	3.41	30.28	5.9
17. 8.85	X	X	E	X	E	E	E	12.53

E = eroding straw i.e. undersaturated
X = inactive straw

TABLE 5: Straw growth determined by supersaturation equation - Moons Cave (mm. a^{-1})

DATE	SITE NUMBER 1	2	3	4
28. 2.85	0.056	X	-0.019	X
6. 3.85	0.0075	0.045	0.082	0.238
12. 3.85	0.01	0.0025	0.116	0.229
3. 4.85	0.048	0.045	0.095	0.21
10. 4.85	0.018	0.061	0.155	0.154
13. 4.85	-0.0065	0.022	0.0475	-0.024
28. 5.85	0.0125	0.016	0.044	0.108
19. 8.85	0.0046	-0.03	0.013	0.028

X = inactive straw

TABLE 6: Straw growth determined by supersaturation equation - Lilli-Pilli Cave (mm. a^{-1})

DATE	SITE NUMBER 1	2	3	4	5	6	7	8
27. 2.85	X	X	0.074	0.109	0.09	0.065	0.09	0.13
1. 3.85	X	X	0.043	0.046	0.023	0.03	0.042	0.073
5. 3.85	X	X	0.045	X	0.058	0.034	0.033	X
12. 3.85	X	X	0.06	X	0.038	0.048	0.02	0.083
4. 4.85	0.009	0.052	0.054	0.108	0.035	0.035	0.0003	X
9. 4.85	-0.001	0.005	0.046	X	-0.0001	0.054	0.009	X
14. 5.85	X	X	0.047	X	0.041	0.049	0.00117	0.02
17. 8.85	X	X	-0.006	X	-0.0065	0.014	-0.0049	0.022

X = inactive straw

TABLE 7: Mean straw growth rates calculated using three physico-chemical models (mm.a^{-1})

		Moons Cave	Lilli-Pilli Cave
Supersaturation equation	- Mean	0.017	0.05
	S.D.	0.007	0.01
CO_2 degassing equation	- Mean	17.3	5.4
	S.D.	12.6	3.2
Evaporation equation	- Mean	0.024	5.2×10^{-3}
	S.D.	0.0008	0.98

Seasonal variations in the PCO_2 of the solution may also affect the estimated rate of straw growth due to degassing. There is a trend towards increased amounts of CO_2 dissolved in the ground-water during the winter months as compared to the summer/autumn months. Carbon dioxide enrichment of the groundwater usually occurs in the soil zone. As reported by Atkinson [1977], the PCO_2 present in the soil zone varies seasonally, usually peaking in spring. However, there are certain factors which may cause the PCO_2 of cave drip waters to show a reversal of this trend. Of greatest importance is the effect of soil water temperatures. According to solution kinetics, the warmer the water the less CO_2 it is able to hold in solution. Thus, the cooler soil water of the winter months is capable of dissolving more CO_2 than the soil water of the summer months.

Measurements of the soil zone PCO_2 in winter resulted in readings of 0.2% by volume. Drip samples collected in Lilli-Pilli Cave, which was beneath the measurement site, have a PCO_2 one or two orders of magnitude higher than this value. This may be accounted for by a number of factors. Firstly, it is possible that there may be CO_2 enrichment of the gas phase in the bedrock unsaturated zone. As described by Atkinson [1977], high winter precipitation rates may wash organic matter into bedrock joints and cracks where it decays, producing CO_2. As the descending water dissolves carbonates it is thus able to take up further CO_2. A second factor which may account for the difference between the soil PCO_2 and the drip sample PCO_2 is that the catchment area for the cave waters may be situated in a more densely vegetated an area the higher the soil PCO_2 is likely to be, due to the release of CO_2 by plant root systems.

The effect of collection techniques will also play a part in the trend towards higher winter PCO_2 values. As the drip rate is most rapid in winter there is less time available then for degassing from the droplet. Thus the drip water will reach the collection bottles with a higher proportion of its original PCO_2 remaining, as compared to water from a straw which is dripping more slowly.

The mean PCO_2 of Moons Cave drip water is almost four times that of Lilli-pilli Cave drip waters. The mean air PCO_2 of Moons Cave is, however, less than the mean air PCO_2 of Lilli-Pilli Cave by a ration of 0.7 : 1. Thus the difference between the mean air PCO_2 and the mean water PCO_2 is greater in Moons Cave than in Lilli-Pilli Cave; this should cause more rapid degassing and thus greater straw growth rates in Moons Caves. The results support this with a mean straw growth rate 3.2 times greater in Moons Cave than Lilli-Pilli Cave.

Evaporation Model

The results of the application of the evaporation model to the data collected may be used to determine the relative importance of this mechanism at different points throughout a cave system and to enable comparisons between cave systems to be drawn.

Straw growth rates due to the evaporation of H O from the water droplets are one order of magnitude greater in Moons Cave than in Lilli-Pilli Cave. This difference may be attributed mainly to the effect of air movement, which increases evaporation rates by replacing the saturated air around the water droplet with unsaturated air. In Moons Cave a winter mean daily air movement of 26 cm per second at the sample sites was determined. Including this figure in the model significantly increases the calculated evaporation rates. In contrast, air movement in Lilli-Pilli Cave is insignificant and would have little influence on evaporation rates.

Spatial variability of relative humidity within a cave system is one factor which will influence variability of growth rates due to evaporation. In Moons Cave the standard deviation about the mean growth rate is very low (0.008) because the sampled straws are in close proximity and thus experience similar relative humidities. In Lilli-Pilli Cave the sample straws are at wider intervals and thus the effect of spatial variability of relative humidities on straw growth rates (S.D. 0.98) is evident.

In addition to the rate of evaporation, the amounts of calcite deposited also depend upon the concentrations of free Ca within solution. In making a comparison between the two caves studies it is evident that Moons Cave has significantly greater amounts of free Ca in solution than Lilli-Pilli Cave. Evaporation of H O concentrates the amount of free Ca in solution, thus the difference between Moons and Lilli-Pilli Cave free Ca concentrations may be due to the greater amount of evaporation in Moons Cave. It is also possible that Moons Cave drip water had an initially greater free Ca concentration which was further increased by evaporation.

From a review of the literature, it appears that evaporation as a mechanism for precipitation on straw speleothems is only important in arid climates. For example, Hill [1978], using a model similar to the one applied here, determined that evaporation was an important process in Carlsbad Caverns, New Mexico. Conversely, Atkinson [1983], working in the alpine environment of Castleguard Cave, Canada, determined after the application of the evaporation model used here, that evaporation contributes no more than a few percent of total calcite deposition. Evaporation as a mechanism for precipitation on straw speleothems is generally considered to be of minor importance [White 1976].

Supersaturation Model

The Supersaturation Model combines all the processes which may be causing supersaturation of the solution and calculates a reasonably realistic estimate of the resultant growth rate.

The application of the supersaturation equation to the drip samples of the two caves studied revealed that there is considerable variability of growth rates within each of the caves. The mean growth rate for the Moons Cave samples is 0.017 mm a^{-1} with a standard deviation of 0.007, and for Lilli-Pilli Cave the mean growth rate is 0.05 mm a^{-1} with a standard deviation of 0.01.

The application of the WATSPEC programme to the drip sample data collected revealed a decline in the calcite saturation index from summer to winter. This apparent decline may be a result of the increasing drip rates which allow less CO_2 degassing to occur and thus reduce the possible supersaturation. The decline evident in PH is related to this as there is an inverse relationship between solution PCO_2 and pH. In addition, relatively high precipitation rates during winter may create a hydrostatic pressure which forces the groundwater through the soil and bedrock zones before it has attained equilibrium. Thus the groundwater may be in a state of undersaturation when it reaches the end of the straw.

CONCLUSION

The following conclusions may be drawn from the data in the light of the initial aims:

(1) CO_2 degassing as a result of the partial pressure difference between the groundwater and the cave air is the major mechanism causing growth of straw speleothems in the two cave systems studied. A small amount of precipitation is also occurring owing to the effects of evaporation; supersaturation caused by evaporation is between one hundred and one thousand times less than the supersaturation caused by the CO_2 partial pressure difference.

(2) Seasonal fluctuations in drip intervals and certain parameters of the sample chemistry and cave atmosphere influence rates of straw growth. The effects are relatively minor, however, and CO_2 degassing as a mechanism for precipitation continues to dominate to roughly the same degree over the period of sampling.

(3) A comparison between the two caves studied reveals similar growth rates owing to CO_2 degassing. The evaporation model, however, calculates a growth rate for Moons Cave which is one order of magnitude greater than the growth rate for Lilli-Pilli Cave. This difference is due mainly to the effect of air movement in Moons Cave increasing the rate of evaporation.

(4) By applying the supersaturation equation to the water chemistry results it was possible to determine reasonably realistic growth rates. Seasonal fluctuations in growth rates were evident, with the majority of late autumn and winter readings being only slightly supersaturated or undersaturated, and thus with the potential for erosion. The two caves studied exhibited similar straw growth rates.

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MANGROVES, MOUNTAINS AND MUNCHING MOLLUSCS: THE EVOLUTION OF A TROPICAL COASTLINE

Kevin Kiernan

Abstract

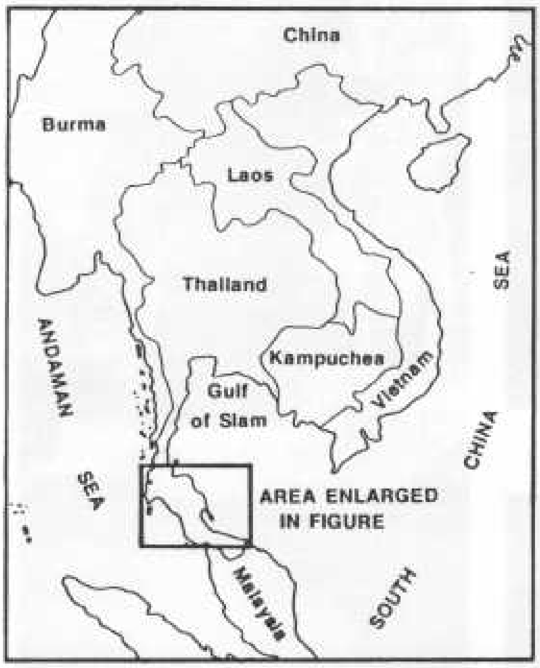
The highly scenic Andaman coast of peninsular Thailand is locally dominated by steep limestone hills and karst towers that rise from broad alluvial plains, from mangrove swamps or from the sea. The karst terrain stretches north and west across the Malay Peninsula to the Gulf of Siam. Some of the variations in the style of this karst have resulted from lithological and structural factors. However, steepening of the slopes by marine erosion at times of formerly higher sea levels has probably been important to the development of the most spectacular parts of this landscape. Notches and caves cut in limestone towers up to10-15m above present sea level may represent the maximum transgression of the Last Interglacial. Morphological evidence hints that former shorelines may now lie hundreds of metres above present sea level due to diastrophic movements during the late Cainozoic. However, this evidence is equivocal and it has been argued that similar landforms in neighbouring parts of Malaysia may be the result of terrestrial planation processes that operated independent of sea level during the Pleistocene glacial stages.

INTRODUCTION

Rugged mountains and broad alluviated plains characterise much of the Andaman coast of peninsular Thailand. Lower lying areas extend across the peninsula from the Strait of Malacca to the Gulf of Siam. Much of this terrane lies at less than 50m asl., but it is locally dominated by limestone hills and mountains that rise to an elevation of up to several hundred metres (Garson et al 1975; Odell and Odell, 1984; Kiernan, 1986; De Harveng and Le Clerc, 1986). Many of these eminences have vertical or even overhanging sides, particularly towards the west of the peninsula. The result is what must be one of the most precipitous landscapes on earth. In the area between the towns of Phangnga and Krabi the towers extend into the sea to form a series of improbable islands (Plates 1&2), popularised in the James Bond movie Man with the Golden Gun. Much of this landscape is suggestive of a tropical paradise, with these rugged mountains rising above lush rainforests or palm-fringed beaches. This paper provides a reconnaissance-level description of the coastal landscape on the westernmost part of the peninsula, and reviews some of the geological and palaeoenvironmental influences that may have given rise to it.

Three principal types of terrain can be distinguished within the region. Coastal lowlands generally lie within c.50-100m of present sea level and extend inland along valley systems. Steep limestone hills and mountains rise from these lowlands to in excess of 600 m. Further inland are higher but less steep ridges formed of Palaeozoic sediments and Mesozoic granite. These trend broadly N-S and reach 1360 m altitude. The area experiences a moist tropical climate that is highly favourable to chemical weathering. The yearly mean diurnal temperature is 26^{o}-30^{o}C, dropping to just under 20^{o}C during the cool season. Rainfall averages 2388 mm on the island of Phuket on the western edge of the area, and 2150 mm on the Langkawi Islands immediately south of the Malaysian border. Rainfall extremes reach 6606 mm pa and 1300 mm pa at Takua Pa a short distance north of Phuket (Brown et al, 1951). The rain arrives in short tropical downpours from May to June when the Southwest Monsoon blows from the Indian Ocean, and again in September to October prior to the arrival of the cooler and drier Northeast Monsoon that blows from China.

The principal settlements are on Phuket Island to the west of the limestone belt; the towns of Phangnga, Krabi and Trang close to the northern shoreline of the Strait of Malacca; and Phattalung, which lies 170 km southwest of Phangnga and drains into the Gulf of Siam. The towerkarst extends discontinuously to the Gulf of Siam, c.80km NE of Phangna. It also



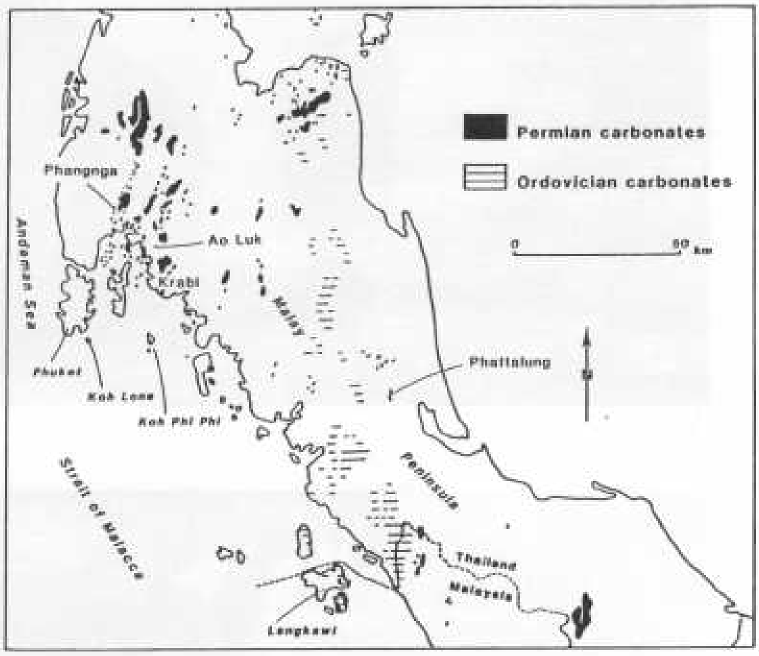
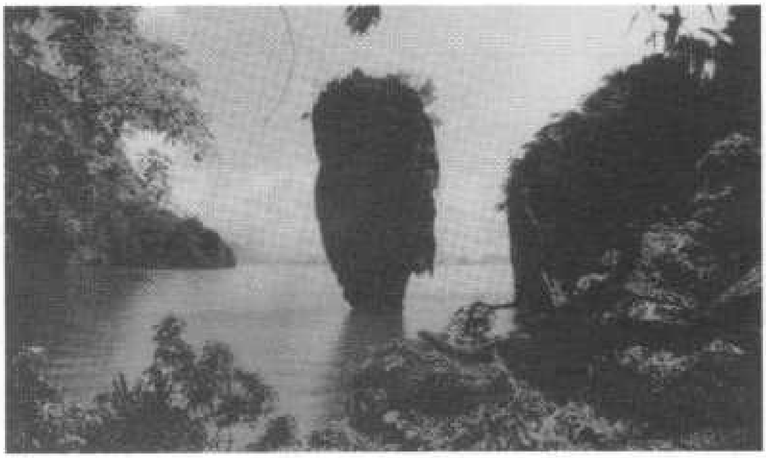


Figure 1. Location of the study area. Figure 2. Distribution of Permian and Ordovician limestone in peninsular Thailand.

continues southwards into northernmost Malaysia where it is best known from the states of Perlis, Kedah and the rugged Langkawi Islands, c.120 km SSE of Phattalung (Figure 2). Picturesque fishing villages, sometimes built on stilts over the warm Andaman Sea, attest to the importance of fishing to the local economy. Large rubber tree and coconut plantations; extensive paddyfields; tin mines; and forests reflect other economic mainstays. Tourism is of considerable importance at Phuket. The area is ethnically diverse with Malay, Indonesian and Chinese influences mingling with the Thai. Moslem communities are widespread, as on Koh Phi Phi Don, an idyllic island of palm-fringed beaches overlooked by high karst towers and which is shared between a moslem and a sea-gypsy community.

Two principal limestone formations are present (Figure 2). Karst development is most impressive in the Ratburi Limestone (Brown et al, 1951) which is equivalent to the Moulmein Limestone of southern Burma (Garson et al, 1975). The Ratburi Limestone has a stratigraphic thickness in this area of c.800 m; south of the Malaysian border where it is known as the Chuping Limestone it appears to be c.1000 m thick (Jones, 1978). It conformably overlies rocks of the Phuket Group. Further limestone of Ordovician age forms part of the Phuket Group and is most widespread in the south of the area. It also extends into Malaysia where it is known as the Setul Limestone and has a stratigraphic thickness of 1100 m (Wyatt, 1983; Wongwanich et al, 1983). Although considerable karst development has taken place in this limestone its surface expression is generally much less precipitous than is the case with the Permian rocks.

The limestones occur in broad synclinal structures that have axes which trend N-S or NE-SW, some of which are displaced by or terminate against faults. The limestone forms parallel strike ridges along the limbs of these folds (Garson et al, 1975). This general pattern continues southward into Malaysia where the structure remains dominated by N-S trending fold axes and coulisses. The lower Palaeozoic sediments were uplifted and folded during the lower-late Devonian by N-S compressional forces, and were faulted during and after the Triassic in response to sustained E-W compressional stresses (Jones, 1978). Orogenic activity is generally believed to have slowed drastically at the end of the Mesozoic or early in the Cainozoic, since the rare Miocene-Pliocene sediments of the northern Malaysia are subhorizontally disposed and the Quaternary sediments lie horizontal (Tjia et al ,1977). Kuenan (1950) assumed there had been little significant vertical movement since the development of a system of graded valleys that today occur beneath the shallow coastal seas, placing this erosion at c.300 ka BP. Normal faults with throws of a few metres affect some of the Pleistocene sediments (Roe, 1953; Burton,



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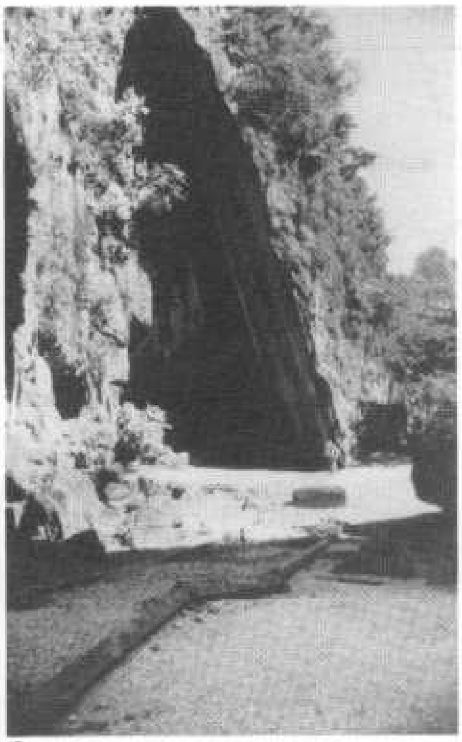

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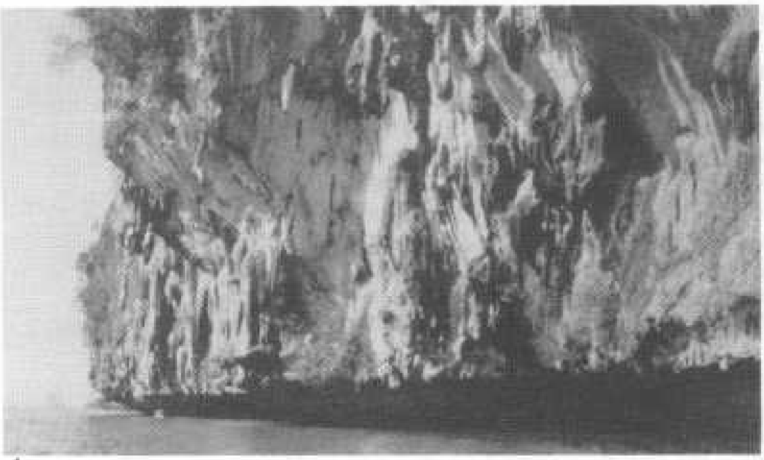

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Plates 1 - 5. 1. Limestone stack off Koh Tapoo. Phangnga Bay. The prominent overhang close to the base is at c.4-6m asl. 2. Grotto roofed by a large slab of limestone that has slipped from the flank of a limestone tower on Koh Tapoo following undercutting by the sea. 3. Elevated notch at 4-6m, widespread on karst islands in Phangnga Bay, and notch developing at present sea level. 4. Notch at 4-6m and higher level overhangs on an island in Phangnga Bay. Note boat for scale beneath the overhang, extreme left hand side. 5. Freshwater mollusc shells sealed beneath flowstone in a notch at the foot of a limestone tower near Ao Luk village, c.40m asl. Further remnants of the shell bed are visible on the notch wall to either side of the column on the left, at about two-thirds height.

1963)but these may be the result only of basement collapse or gravity sliding. Garson et al (1975) sugest that the area forms part of a stable block between the orogenic belts of the Andaman-Nicobar islands to the west and the Philippines to the east. However, Bunopas (1981) has suggested that considerable uplift may have affected much of Thailand during the Quaternary and Tjia et al (1977) have invoked a few hundred metres of diastrophic uplift to explain putative raised shorelines in the Langkawi Islands.

SURFACE KARST

The karst in the areas of Permian limestone is characterised by strike ridges or isolated towers of limestone up to 600 m high that have very steep to vertical sides. Over most of the area they rise from alluvial plains; elsewhere they loom above broad mangrove swamps along the lower reaches of the principal streams such as the Khlong Phangnga, Mae Nam Marui and Mae Nam Ao Luk; and they project out of the sea in Phangnga Bay and near Ao Luk. Further offshore limestone towers are present forming all or part of islands such as Koh Phi Phi Don and its smaller companion Koh Phi Phi Leh, c.45 km SSW of Krabi. The towns of Phangnga and Ao Luk are dominated by the massive ridges and towers among which they are set, the former particularly so by the long 500m high ridge of Khao Chang which virtually parallels the main street, and the latter by an array of towers up to 400 m high. The towers that occur in the Ao Luk-Krabi area have a more tabular form than do those in the Phangnga area. The eminences formed of Ordovician limestone tend to rise less vertically than those formed of Permian limestone, and elongate ridges rather than isolated towers are the norm.

Tower steepening has been aided by lateral solutional undercutting at their foot. Such undercutting is commonly regarded as fundamental to towerkarst development, and has variously been attributed to solution by swampwaters; to corrosion and corrasion by allogenic rivers (McDonald, 1976); and to subsoil solution processes (Jennings, 1976). Jennings (1976) has shown that cliff-foot caves occupy 10% of the tower margins at Bukit Batu in Malaysia, and a very qualitative assessment suggests that the figure may be comparable in peninsular Thailand. For reasons outlined later my own contention is that marine processes may have been very important to tower evolution in this area, as has previously been hinted at by Odell and Odell (1984) who commented that "the lower parts of the land became covered by the sea and developed into towerkarst" but did not expand upon this proposition. The towerkarst topography further south in northern Malaysia has at various times been explained as the product of block faulting, subaerial erosion, folding, plastic flow, marine erosion, aeolian erosion or combinations of these (Fitch, 1952; Paton, 1964).

Probably the largest of the many enclosed depressions is a polje that measures around 12km N-S and 2km E-W that lies c.80 km NNE of Phangnga and c.25km west of Amphoe Khiri Rat Nikhorn. Nearby are other enclosed depressions up to 200m deep and 1km^2 in extent. Shallow and irregularly shaped depressions are developed on the alluvial plains between Krabi and Ao Luk. The largest of these is narrow and sinuous in form and over 3 km long, but others are broader. Limestone is not always exposed below the closed contour due to the thickness of the alluvial mantle but the depressions do suggest that the alluvial sediments are underlain by limestone. Other enclosed depressions occur on the tops of the limestone eminences. Odell and Odell (1984) report polygonal karst to be common above 1000m. further inland. Garson et al (1975) report that aerial photographs show well developed karst with large sinkholes and internal drainage atop some of the innaccessible towers and some of these are sufficiently large to be discernible on the 1:50 000 map sheets. This is very evident on a small scale at the caves Tham Russi and Tham Luk Sue in Phangnga. Both are developed in small hillocks, the cores of which have collapsed.

A variety of karren forms have developed on the towers with rillenkarren particularly prominent on some of the steep limestone islands, and kluftkarren and spitzkarren on summits. Hardy xerophytic plants that have colonised dry rock ledges sometimes overhang the sea incongruously side by side with lush tropical rainforest that has developed in areas where sediment has accumulated.

CAVES

The longest caves have been developed where allogenic streams that run across the alluvial plains have tunnelled through limestone ridges. Such a situation is commonly attributed to streams retaining aggressivity through being perched upon clastic sediments well above the level of the limestone bedrock and this is likely to be the case here. However this general assumption may not always be valid. At Tham Than Bokkoroni near Ao Luk a sizeable stream has deposited an impressive sequence of travertine pools and cascades despite having been underground for only 200 m. This hints that the water was already largely saturated with respect to calcium carbonate and that its precipitation after emerging from the cave merely reflects greater aeration of the water in an area of steeper gradient downstream of the cave.

The three longest caves of which I am aware in this part of Thailand are all active stream caves. Tham Tapan and Tham Phung Chang are virtually in Pangnga town. Tham Tapan is an attractively decorated cave with just under 1 km of passages developed on two branches. Generally fairly low roofed, the ceiling of its highest chamber lies no more than 20 m above stream level. Tham Phung Chang (Elephants Stomach Cave) passes right through Khao Chang (Elephant Mountain), mostly in the form of a narrow rift that is generally c.15 m high. De Harveng and Le Clerc (1986) have recorded a further cave just under 1 km in length, Tham Thong, which lies c.30km NE of Phangnga. Other caves have been developed by small streams that pass through hillocks at Phangnga, the best known of which are the very attractive little Tham Russi and adjacent caves such as Tham Khao Ngum and Tham Luk Sue. Several successive stream levels are recognisable from niches on the walls of Tham Luk Sue.

Some of the caves serve as Buddhist temples, as exemplified by Tham Suwan Ku Ha, a spacious cave with c.300 m of passages developed on two principal levels. Other caves occur high in karst towers in many localities and are termed "hanging caves" by Odell and Odell (1984). The origin of some short through caves that pass beneath limestone islands in Phangnga Bay is uncertain, but marine erosion has certainly played a prominent if not dominant role in sculpting their present form. On the other hand the so-called Swallownest Cave or Viking Cave on Koh Phi Phi Leh is only partly of marine origin, since high and narrow rifts indicate that infiltration from the tower itself has been very significant. The development of notches at the base of towers can lead to the mechanical failure of the unsupported limestone wall. One grotto 4-6m wide and 15-20m high on the island of Koh Tapoo in Phangnga Bay is roofed by a massive limestone slab that has slipped from a tower and now stands leaning against its flank (Plate 2).

QUATERNARY DEPOSITS

The Quaternary sediments of the area include eluvial (residual), colluvial, alluvial and beach deposits that occur both on the surface and in caves. Weathering of the limestone has produced thick terra rossa soils, with the less pure Ordovician limestones generally giving rise to the thickest of these. The colluvial sediments include screes that occur at the foot of some of the limestone hills; some matrix-supported diamictons; hillwash sediments that are dominated by terra rossa ; surface travertine deposits and speleothems. The travertine reaches 3 m thick on the flanks of some towers and is generally soft and porous. Jones (1978) reports that in northern Malaysia similar travertine is generally massive finely grained crystalline aragonite. Secondary carbonates have been precipitated as large stalagmites in caves such as Tham Tapan; as flowstone terraces up to 10 m high in the Swallownest Cave of Koh Phi Phi Leh (illustrated in Jackson, 1985); and as oolites in Tham Tapan and in many of the caves in northern Malaysia (Jones, 1978).

The alluvial deposits include estuarine muds and silts which Garson et al (1975) report to overlie gravels near Phuket. Further upstream the alluvial deposits range from silts and muds to cobbles, with even boulders present in some cases where non carbonate rocks occur in the catchment (Jones, 1978). Alluvial sediments are present in many of the caves, such as some of the sands in Tham Suwan Ku Ha. The presence in the alluvial sediments of placer minerals, particularly tin, has led to the development of many mines and in northern Malaysia some rich mines are located in caves. The alluvial sediments in the caves of the Setul Boundary Range consist of semi-consolidated clays, sands and gravels; compacted muds; and cemented calcareous grits and conglomerates in which fluvial structures are preserved (Jones, 1978). Authigenic cave earths formed from the insoluble residue of limestone breakdown often in combination with guano are also of economic significance as fertiliser in some areas. Travertine has been deposited along some streams as in the public park downstream of Tham Than Bokkoroni.

The beach deposits are also widespread and consist of gravel, sand with shell and coral fragments and occasional beachrock, all but the last-named also being found in some of the caves. In many cases alluvial sediments have accumulated behind the beach ridges. Longshore drift operates from north to south on exposed parts of the coast. Some of the beach deposits occur above present sea level, as near Takua Pa where Garson et al (1975) report that beach gravels and sands rest upon marine-eroded mudstones 10-15 m above present sea level.

EVOLUTION OF THE LANDSCAPE

Towerkarst is commonly asserted to be the progeny of a humid tropical climate. Its geographical focus in the humid tropics supports this contention. Warm temperatures, abundant rainfall and luxuriant vegetation certainly augur well for rapid limestone dissolution, and rates of cave passage entrenchment in the tropics may be orders of magnitude greater than in some temperate karsts (Gascoyne, 1981). But if climate is the principal determinant of form, the topography that has developed on the Ordovician and Permian limestones ought to be similar which, as Jennings (1971) points out, is not the case in northern Malaysia. Nor is it the case in peninsular Thailand.

While towers that today rise from the sea and from mangrove swamps have developed on the Ordovician Setul Limestone in the Langkawi Islands, elongate ridges such as the Setul Boundary Range are more the norm for this rock. On the other hand, it is also noteworthy that some of the most impressive of the towerkarst lies close to the present coast, with rather more rounded limestone hills often occurring further inland (Odell and Odell, 1984). This suggests that differences between the limestones and also in stage or environmental history may partly underlie the evident differences in karst style. The remainder of this paper briefly explores some of the evidence for these propositions.

The influence of lithology and structure

The differences between the landforms that have developed on the Ordovician and Permian limestones are major ones. The assemblage of karst forms that has developed on the Permian rocks exhibit slopes that are generally much steeper. This would seem to lend some support to the contention that lithological and structural factors may be the critical determinant of karst styles. Brook (1981) has argued this on the basis of apparently tropical karst landforms that are well developed at Nahanni in subarctic northwestern Canada. Occasional karst towers can also be found outside the tropics (Jennings, 1981). For instance, there are small dolomite towers in the Maxwell River Valley in temperate Tasmania that have summits formed of highly siliceous beds which have inhibited erosion. In neither case could a history of warmer Cainozoic climates be invoked to explain these landforms, which points towards controls other than climate.

Differences in the styles of karst that have developed in the tropics have been attributed to lithological factors by a number of workers (eg. Sweeting, 1958; Verstappen, 1964; Panos and Stecl, 1968). Wilford and Wall (1965) found that in Borneo, for instance, the eminences often tend to be formed of pure, massive, recrystallised coral-algal biolutite, with the intervening lowlands being underlain by less pure calcarenite and calcirudite. Monroe (1954) has argued that in Puerto Rico also, different lithologies have given rise to specific groups of solution phenomena. Day (1982) surveyed the lithological characteristics in a number of tropical karst areas and found that the steepest topography occurred on the purest limestones. He also demonstrated that the purest limestones were harder than the less pure rocks that he tested. Crowther (1984a) has shown that further south in peninsular Malaysia the smoothest meso and micro topography, and the deepest soils, occur on impure limestone with moderate slopes.

Although no detailed comparative studies of the relationships between different limestone facies and landforms within either of the two limestone formations of peninsular Thailand have been undertaken, there are major differences between the lithology of the Permian limestones and the lithology of the Ordovician limestones that have probably conditioned the style of the karst that has developed (Jones, 1978). Cherty, clastic (calcarenite and fine grained calcirudite) and massive facies have been identified in the Permian Ratburi Limestone (Garson et al, 1975). Further south in Perlis and North Kedah the Permian Chuping Limestone is micritic or calcilutitic with indistinct crystals, or locally has dismicrite or crystalling sparite (often biomicrite or biosparite). On the Langkawi Islands this limestone is generally crystalline, with some coarse marble or saccharoidal dolomite on Palau Dayang Bunting. Here sparite with crystalline dolomite intergrown with finer calcite in a decissate fabric is common, and the karst is sometimes more subdued. Overall, the Permian limestones are generally of high purity (CaO c.30-35%; CO2 c.43-47%; MgO c.0.22-22%)(Garson et al., 1975). In contrast, the Ordovician Setul limestone is less massive and generally less pure. Cave development in this rock has been strongly guided by sedimentary structures (Crowther, 1976). While some of this rock is of high purity and there are some areas of dolomite, for the most part it contains considerable detrital and carbonaceous material. It may therefore have a higher level of primary permeability. The impurities give rise to thick residual soils that also may inhibit karst development to a degree (Jones, 1978). On the other hand Crowther (1984b, 1986a) has shown that in areas underlain by the Kinta Limestone Formation (Silurian-Permian) in NW Malaysia chemical denudation is appreciably more rapid beneath the soils of the plains than on the towers.

The structure of both limestones is variable. The Ratburi Limestone is generally massive, and faults provide many vertical planes of weakness. The limestone mountains in the Phangnga area generally trend N-S or NE-SW parallel to the principal faults (Garson et al, 1975) and to the overall structural grain. Elongate ridges are more common than isolated towers. Many of the enclosed depresssions are elongate along the strike of the limestone, including the polje west of Amphoe Khiri Nikhorn. An important series of NW-SE trending faults lies transverse to this grain and has undoubtedly facilitated isolation of the towers, the faces of some of which are faultline scarps. Fault scarps are unlikely given the probable age of the faulting and the rapid rate of chemical weathering. Jones (1978) has argued that in northernmost Malaysia karst tower isolation has been aided by the superimposition of a late Mesozoic E-W drainage system across the axis of a narrow, synclinally folded outcrop, with these streams having later been captured by others that came to flow southwards across less resistant rock units. The style of this karst is consistent with the proposition (Brook, 1981) that such a structure must favour the development of a strong vertical component in the landscape. The two longest caves in the area, Tham Tapan and Tham Phung Chang, both trend NW-SE parallel to the fault-guided secondary grain of the surface landscape. Tham Thong trends approximately N-S (De Harveng and Le Clerc, 1986) and, hence, also may be fault-guided.

In the Phangnga area the bedding of the Permian rock varies from virtually horizontal to steeply or vertically dipping (Garson et al ,1975). Most of the towers seem to be developed on steeply dipping rock. In contrast to most of the Permian limestone the Ordovician limestone is generally well bedded and forms elongate ridges of considerable length, such as the Setul Boundary Range. Although the karst is less spectacular on the Setul Limestone many classical karst landforms are apparently developed in it in northern Malaysia, including extensive caves and huge depressed areas locally known as "wangs" (Jones, 1978). Jennings (1972) has reported what he termed "an exaggerated Yugoslavian holokarst" developed on a massive plateau area at 300 - 600 m where the enclosed depressions are much steeper sided than those of the classical Yugoslavian karst. Both this type of karst and towers are apparently present on the Langkawi Islands where the Setul Limestone is pure and mechanically strong (Jennings, 1972). While this suggests that litho-structural factors do permit the development of steep slopes on at least some of this limestone, its well bedded nature is likely to promote horizontal elements in the landscape where the dip of the rock is gentle. In addition, an extensive area of rugged karst is developed on the homoclinal dip of the Chuping Limestone in the southwest of the Langkawi Islands (Jones, 1978).

These considerations seem broadly consistent with the views of Tjia (1969) and Brook (1981) who have asserted that the spacing of vertical joints and faults and of horizontal bedding planes governs slope development on tropical karst by controlling the rates of solution in these directions, with slopes being more gentle where there are definite horizontal planes of weakness.

Sea level change and landform evolution

Odell and Odell (1984) have suggested that much of the low lying terrain from which the karst towers of peninsular Thailand rise has previously lain inundated beneath the sea. A history of changes in the relative levels of land and sea has undoubtedly played a major role in the elaboration of this coastal landscape. There is considerable evidence to suggest that all the island towers previously stood upon a coastal plain that has been partly swamped by postglacial transgression. There is also some evidence to suggest that in still earlier times the sea stood higher than today, thereby affecting the morphological development of the karst by direct marine action and by raising the base level of fluvial and lacustrine processes.

(i) Eustatic sea level change

The bathymetric chart of the present coast clearly shows a network of drowned valley systems and reveals that over the entire embayed area between Phangnga and the Langkawi Islands the sea is very shallow. The maximum depth of the water off the shore of the outlying Koh Phi Phi Leh is c.26 m with the water slightly shallower (c.23 m) offshore from both sides of the Koh Phi Phi Don isthmus. The bottom lies at a broadly similar depth between these islands and Koh Lone off Phuket, and also eastwards towards the shore of the peninsula. Since sea level during some of the glacial stages of the Pleistocene was ~150 m below that of the present day (Chappell and Thom, 1977) this entire area would have formed a plain over 100 m above sea level at that time. It has probably been above sea level at least six times since the Last Interglacial and been so more often than not during most of the Quaternary.

The question therefore arises as to whether all the caves that occur at present sea level in the island towers are truly sea caves as suggested by Odell and Odell (1984). The high rifts in the Swallownest Cave of Koh Phi Phi Leh indicate that infiltration from the tower was probably the dominant factor in its development. Some of the caves that pass through the base of the limestone islands in Phangnga Bay may have had their origin during these times of lower sea level when low energy streams might have been able to more effectively deepen their channel by solutional attack upon flanking limestone outcrops than by mechanical incision of their own bed deposits. The presence of large freshwater lakes in sinkholes further south on Pulau Dayang Bunting in the Langkawi Islands also attests to karst development during these times of low sea level (Jennings, 1971). In this latter area the cliffs extend well below sea level and there are present day intertidal notches but no low tide platforms (Hodgkin, 1970). Similar towerkarst is also present in the Vung Ha Long archipelago of Vietnam, where Silar (1965) once again records the steep descent of towers to a shelf at -20 m, and there are seawater lakes accessible from the coast through caves. Drowned towerkarst on a smaller scale occurs in the Gulf of Thailand on Koh Mae Ku in Ang Thong National Park, Changwat Surat Thani. Steep limestone islands are also present in the Mergui Archipeligo, Burma where they rise from the shallow sea floor at about -12m. Steep sided enclosed depressions are accessible at low tide through caves that pass through the coastal cliffs. As in southern Thailand some of the caves in these towers are celebrated sources of swiflets nests that are gathered for birds nest soup (Carpenter, 1868).

I have taken the opportunity to directly inspect the shallow submarine topography at the foot of the towers in the southeastern bay of Koh Phi Phi Don, using scuba. Here there is a very marked shelf mantled by sand at -12 m and then a steep riser to a shelf of living coral at -2.5 m, but the thickness of coral accretion over any drowned upper shoreline at the tower foot was indeterminable in the area inspected and has masked any drowned notching. The bathymetric chart reveals a shelf at -10 to -8 m close inshore off Koh Phi Phi Leh, Koh Lone and elsewhere, with a steep descent beyond this. In Phangnga Bay the water depth seldom exceeds 5 m which facilitates the construction of stilt villages such as that at Koh Panyi, and also facilitates the dredging of the sea floor for tin.

Jones (1978) has claimed that caves in the Setul Boundary Range extend to 46m below sea level. Further south along the Malay Peninsula submerged shorelines have been documented by Tjia et al (1977) at -90 to -82 m; -67 to -60 m; -51 to -50 m; -45 m; -36 m; -33 to -30 m; -22 to -20 m; -18 m; -13 m; -10 m and -8 m. Tjia et al have interpreted these as true eustatic shorelines, unlike Silar (1965) who invoked tectonic downwarping to explain the drowned towerkarst of the Vung Ha Long archipelago in Vietnam. Geyh, Kudrass and Strief (1979) suggest, on the basis of numerous radiocarbon assays from the Strait of Malacca, that sea level was lowered eustatically to -40 to -60 m from ~ 36-10 ka BP; rose from -13 to +5 m from c.8-4 ka BP and then approached its present level. Data from Biswas (1973) suggests that the sea was at -70m about 11.8 ka BP. Given this history the gross topography of limestone eminences rising above subdued plains seems most likely a subaerial one. However, the facts that the steepest of the towers that are formed on the Ratburi Limestone appear to be those nearest the coast (Odell and Odell, 1984) and that the towerkarst topography is developed on the Ordovician limestone virtually only where the eminences rise from the sea and from mangrove swamps in the Langkawi Islands both hint that the sea has provided a further control.

There is evidence to suggest earlier sea levels that were also well above those of the present day, and this has important implications for detailed tower morphology. A notch that varies from c.1 m to a couple of metres deep has been observed close below the level of the barnacles that cling to the limestone towers in Phangnga Bay. Hodgkin (1970) reports that in the Langkawi Islands the upper limit of barnacle encrustation approximates the mean high water neap. There the daily tidal range is 2.6-2.9 m, with a spring range of 2.25 m and a neap of 0.65 m.

Barnacles on limestone coasts may armour the rock to a degree. However, sea level notches are able to develop on carbonate coasts due to a number of processes: the ingestion of carbonate rock and secretion of acids by the bivalve mollusc Lithophaga ; boring sponges; respiration by other organisms in contact with the rock; boring algae; and solution by seawater that is not saturated with respect to all forms of carbonate and which may be more aggressive at night due to a slowdown in photosynthetic activity (Hodgkin, 1970; Schneider, 1976; Trudgill, 1985). Oysters are prolific in the adjacent Langkawi Islands only below low tide level and only very rare small individuals are found above high tide level (Tjia et al, 1977). On Aldabra Atoll, Trudgill (1976; 1985) found that grazing accounted for 36% of the mean annual rate of surface removal in notches where abrasive sand was also present, and 64% where it was absent. Such notches should therefore not be termed "wave cut" (Verstappen, 1960).

The possibility that apparently "terrestrial" notches that occur at the base of inland towers might be of marine origin in such an environment of fluctuating relationships between the levels of the sea and of the land must therefore be considered. Trudgill (1976) has documented a rate of marine notch deepening of 1mm.pa. from Aldabra Atoll, and given that erosional undercutting in this fashion occurs almost universally around the base of drowned towers the implications for slope development are likely to be profound. Paton (1964) has suggested that marine notches should be higher from floor to roof than notches formed by stream or swampwater, with the floor and roof of marine notches sloping inwards with increasing steepness and the notch approaching an arc in section. Notches that face open sea are higher from floor to roof than those found on more protected coasts (Tjia et al, 1977). Paton suggests that in the case of stream and swamp notches, rapid lowering of the base level of erosion should produce multiple grooves that are low, deep and smooth with a relatively flat floor and roof. Notches of this latter kind are to be found on the bases of some of the towers near the town of Phangnga and in caves such as Tham Luk Sue.

High arcuate notches above present sea level are widespread in Phangnga Bay. The most prominent of these is generally 4-6 m above the barnacle line and 4-6 m deep (Plate 3). It is sometimes compound. Hodgkin (1970) has reported notches 4 m deep in the Langkawi Islands that approximate the spring tide level where the sea is calm but increase in elevation with wave action. Tjia et al (1977) contend that the deepest cut of the notch is usually at mean sea level.

The presence of stalactites and other travertine deposits within the notch 4-6m asl. at Phangnga Bay indicates that it is not presently being eroded to any significant extent. The upper limit of the notch sometimes broadly approximates the ceiling of caves that pass beneath some island towers. Speleothems often also hang from these ceilings.

Similar notches, overhangs and remnants of overhangs that may represent former open notches occur at a variety of higher levels on many island towers. The height estimates that follow are poorly scaled and indicative only, but should serve to convey the general impression. At the two Phi Phi islands there is a hint of a possible further notch at c.8 m that seems to roughly approximate the floor level of the Swallownest Cave, the entrance to which reaches c.12 m and roughly accords to the top of a widespread overhang. Closer inshore and further to the north a notch at Tham Lod also lies at an estimated 8-10 m with an adjacent overhang and upper level cave entrance lying c.10 m higher.

Further south in Malaysia, Tjia et al (1977) have recorded evidence of probable shorelines around the southern margin of the South China Sea at 0.5-0.7m; 1.5m; 2-3m; 5m and 10m. Radiocarbon dating indicates that a number of shorelines from -67 to +3 m have formed during the past 11 000 years, with others still more elevated being of greater age.

(ii) caves, notches and erosion surfaces above approximately 15m asl.

Several lines of evidence point towards the possibility of additional former shorelines above c.15m asl. These include the presence and character of notches on towers; high level caves in towers; tower summits and breaks of slope that are accordant over wide areas and which may represent marine abrasion surfaces; overhangs high on tower walls that appear to be broadly accordant with one another and with breaks of slope on other parts of the towers; possible beach deposits; and alluvial deposits that may reflect a previously higher base level that was imposed by the sea.

The roof of the upper level cave at Tham Lod lies at c.25 m. Nearer Koh Panyi the base of a large and widespread overhang also lies at c.20-30 m, its crest at c.40 m (Plate 4). Nearby are further overhangs with their bases at estimated heights of c.70 m and c.120 m, and both roughly coincide with breaks of slope on gentler walls of the towers. Given the generally low relief of the coastal plains that flank much of the peninsula, if these features on the island towers truly reflect past higher sea levels then marine processes must once have been active well inland and can be anticipated to have left their legacy on the inland towers.

Several kilometres from the coast near Ao Luk village deep notches are widespread at or close to the base of many of the towers. Here a 1m thick bed of intact freshwater gastropod and bivalve shells is sealed beneath flowstone and stalagmites in one such notch, apparently in growth position (Plate 5). Available topographic maps do not permit the precise altitude of this notch to be determined, but it seems to lie at least 40 m above present sea level. Small caves that open off the back of the notch descend into the tower to a point slightly below the level of the surrounding plain where they are choked by silt. The growth of the shell bed in the basal notch must have been due to a higher base level than is the case at present, which in turn may or may not have been the result of a higher sea level. Higher in this particular tower are further caves, the uppermost of which lies c. 50 m above the plain and commands a panoramic view of the landscape. Loose shells, primarily of freshwater mussels and small gastropods, have also been located amid a bed of sand here. However, since these are not in growth position the possibility exists that they may have been carried here by prehistoric inhabitants or visitors. Cave entrances at a similar or even higher level are evident in many other localities, including the tower immediately beside the Phangnga port and Khao Ok Thalu at Phattalung.

Above this level the evidence becomes far more difficult to recognise and interpret. Accordance of breaks of slope and tower summits seems fairly widespread, and this hints at possible erosion surfaces at 110-150 m; c.190 m; c.200-230 m; 250 m; 270-300 m; 350-370 m; c.400 m; 450-490 m; and possibly 530-570 m. However, considerably more work is required to confirm these tentative impressions.

Notches, caves, raised beach sediments and breaks of slope that may represent erosion surfaces have again been recognised in a number of areas further south in Malaysia (Nossin, 1964; Tjia, 1970;). Tjia et al (1977) have argued that there is morphological evidence of former shorelines around the southern margin of the South China Sea in Malaysia at 12-13m; 18m; 25m; 30-32m; 34-36m and 50m. Paton (1964) suggests that an elevated marine notch may be present c.7.6m above the base of Gunong Tasek, north of Ipoh, but that the only inland notch similar to those that he found around the Langkawi Islands is on the western side of Bukit Koplu near Kodiang. He concedes that this latter could have been formed by swamp erosion but argues that the Kinta Valley, Kedah and Perlis have almost certainly been drowned by previously higher sea levels and, hence, are likely to have been affected by marine erosion despite the fact that the broad form of the hills is of subaerial origin. Jones (1978) reports a high level cave known as Gua Badak that lies 50 m above the foot of a tower on the southern side of Bukit Chuping. In this latter area are numerous breaks of slope at 75-76 m that coincide with the upper limit of the Older Alluvium, which consists of boulder beds and horizontally bedded clays, sands and gravels. Tjia et al (1977) report at least ten possible erosion surfaces between 15m and 400 m in the Langkawi Islands. Not all need be strictly marine in origin, but any formed by fluvial erosion may have reflected a base level dictated by the sea during the early or mid Pleistocene (Stauffer, 1973).

However, the question of former high sea levels in Malaysia is a contentious one. Walker (1956) considered the Older Alluvium to be of marine origin and that it had been deposited during a period of eustatically raised sea level, with incision having occurred during times of lower glacial sea level. However, several more recent writers have argued that these deposits are of fluvial origin (Siram, 1968, 1969; Newell, 1971; Haile, 1971; Jones, 1978). Verstappen (1975) has suggested that the deposits and asociated benches that have been cut in bedrock could be attributed to subaerial processes during the Pleistocene glacials when he envisaged that double planation (Budel, 1957a,b) was likely to have taken place under conditions that were drier and more conducive to non-concentrated surface wash than is presently the case. He argued that the benches were pediments and the Older Alluvium was the result of hillwash. Alternatively, accordant summits in karst areas may result from a process whereby lateral corossion occurs once sinkholes become filled by an insulating plug of soil and sediment (Aubert, 1969; Crowther, 1984). Haile (1971) has argued that there is no evidence in Malaysia for sea levels more than 15m above that at present, basing this on the inconclusive nature of the evidence above 15m asl., including the absence of marine fossils.

Total melting of the earth's ice masses could theoretically cause the sea to rise above its present level by c.100 m, although after allowing for isostatic compensation a more probable figure lies at c. 65 m (Stearns, 1961; Walcott, 1972).Following the suggestion of Flint (1971) that the sea reached a level 30-50m above its present position during Pleistocene interglacials, Tjia et al have argued that the putative shorelines up to c.50m are explicable in terms of eustatic sea level change. However, it is now apparent that during the Last Interglacial the sea reached a point no more than 10m above its present position and that it was probably never any higher than this at any time during the Quaternary (Shackleton and Opdyke, 1973; Bloom et al 1974; Bowen, 1978). While local variations in the relative levels of land and sea are likely, due to such factors as variations in coastal geometry and hydroisostasy, it seems unlikely that the evidence for sea levels much above 10m can be explicable solely in terms of eustatic changes. Allowing for hydrisostatic affects the evidence Haile (1971) recognised at up to c.15m may represent the Last Interglacial shoreline.

Paton (1964) makes the point that some of the Malaysian towers that stand 70m or more above present sea level could only have been subject to marine erosion so long ago as to allow ample time for any marine landforms to have been erased. He also argues that if the form of the towers is of marine origin then cliffs, caves, grooves and platforms should be found upon other rocks besides limestone that have been subject to erosion by the sea in recent times. Yet the age of any drowning of inland tower bases is entirely dependant upon the rate of uplift which must be regarded as still being uncertain, and as Paton concludes the topography that develops by predominantly mechanical erosion of non-carbonate rocks bears little resemblance to that which results from solution of limestone.

CONCLUSIONS

This coastal landscape with its rugged towerkarst is not simply the product of a humid tropical climate but rather it has resulted from a complex interplay between, climato-geomorphic, lithological, structural, marine and fluvial influences and processes. The gross morphology of eminences and plains is likely to be of subaerial origin and to have been greatly influenced by the lithology and structure of the limestones. Important components of the landscape may be the result of planation processes that were active when the climate was drier during glacial times. The balance of probabilities suggests that the present architecture of at least the most coastal of the towers and the genesis of many of the caves is the result of erosion by the sea when its level was higher relative to the level of the land than is the case today, or of fluvial erosion when the base level determined by the sea was relatively higher . Known eustatic sea level change would be sufficient to explain the former shorelines that now lie below present sea level, and some of the landforms and caves up to c.10m or perhaps 15m above present sea level. Hence, this putative progeny of a humid tropical climate has been critically influenced by lithology and structure; has been suckled by distant polar ice sheets; and may owe almost as much to the voracious appetites of oysters as to monsoonal downpours.

Past eustatic change in the sense of widely recognisable levels of the "ocean" are dependant upon changes in volume of ocean basins, changes in the volume of ocean water or change in the ocean surface or geoid (Morner, 1976; Tjia et al 1977). If the suggestion that the area has been tectonically quiescent during at least the latter part of the Pleistocene is true then these karst towers could not have been affected by marine erosion more than c.10-15m above present sea level without profound hydroisostatic or geoidal changes. The same situation as applies at Phangnga may be true of the coastal towers with caves and terraces that occur 14-19m above sea level in the Vung Ha Long archipelago of Vietnam, regarded by Silar (1965) as having undergone tectonic uplift but for which Jennings (1971) suggested a possible eustatic explanation. Verstappen (1975) argued that some postglacial rise of the Malay Peninsula may have occurred since no drowned shorelines had been recorded below -70m (Biswas, 1973), which is rather shallower than the maximum glacial sea level lowering known to have occurred during the Pleistocene glacial stages. More recently, Tjia et al (1977) have provided evidence of a further drowned shoreline beneath the South China Sea at -82 to -90m. While this does not eliminate the discrepancy it does highlight the weakness in this line of argument, namely that not all the drowned shorelines in this area have neccessarily been detected as yet.

Although the region is at present largely free of earthquakes and several lines of evidence suggest that it may have been stable for perhaps the last 300ka., an alternative explanation for what may be old shorelines that now lie high above present sea level in peninsular Thailand is Quaternary diastrophism. However, the origin of the accordant breaks of slope and summits adjacent to peninsular Thailand in northernmost Malaysia remains contentious and it must be acknowledged that terrestrial planation processes (Verstappen, 1975) or sediment stultified karst development offer plausible alternative explanations for at least some of the evidence. If they are of marine origin, the erosion surfaces that occur at up to 400m in the Langkawi Islands demand at least a few hundred metres of uplift during the Quaternary. Bunopas and Vella (1983) have recorded significant Quaternary deposits in the mountains of Thailand that have been uplifted to great elevations, while Bunopas (1981) has suggested that unstudied marine terraces and raised shorelines adjacent to the Gulf of Thailand, and alluvial terraces around the Central Plain, are probably also the result of rapid uplift during the Quaternary.

Improved mapping and dating of the deposits associated with some of the surfaces and caves might help resolve some of the many unresolved questions concerning the origin of the erosion surfaces and related features. Verstappen (1975) has argued that the Older Alluvium was formed during the Wurm (and earlier?) glacials, citing radiocarbon assays that have been obtained from near the base of the Older Alluvium near Kuala Lumpur, where the sediments that rest on limestone and granite below present sea level have been dated at c.36-42kaBP. However, some doubt must attach to these assays since they lie close to the effective limit of radiocarbon dating and the possibility of contamination by younger carbon must be taken into account. In addition, the Older Alluvium is reportedly lateritised (Burton, 1964)). In northern and central Thailand heavy lateritisation seems confined to sediments that are at least middle Pleistocene in age (Thiramongkol, 1983). This suggestion is supported by palaeomagnetic and fission track dates of 690-950ka BP on basalts that overlie laterite-capped terraces at Ban Don Man (Barr et al, 1976) and the presence of tektites of middle Pleistocene age overlying the laterites in northeastern Thailand (Gentner et al,1969; R. Ford and C. Burret, pers. comm.). There is some magnetostratigraphic evidence that the basal part of the Older Alluvium may predate 730 kaBP (Haile and Watkins, 1972).

The most elevated of the erosion surfaces in peninsular Thailand are unlikely to be younger than Pliocene or Miocene in age. Detailed study would no doubt reveal the pattern of morphological and depositional evidence relevant to this question to be far more complex than that revealed by this initial cursory examination. The high probability of preservation of depositional evidence in caves high on the limestone towers (Gale, 1986), coupled with the low gradient of the plains and sea floor, make the coastal karst landscapes of peninsular Thailand an ideal locality in which to pursue these questions of eustatic and isostatic change. Continuing research in this area should include detailed geomorphic mapping and uranium series assays of secondary carbonates that should enable light to be shed on the dating of geomorphic events beyond the reliable range of the radiocarbon techniques used to date the more recent shorelines. Among the questions waiting to be resolved are the history of sea level change, the age of the alluvial sediments, the history of tectonic uplift, the chronology of relief evolution, and the processes that have helped shape this visually stunning landscape.

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MEASUREMENT OF SMALL CHANGES IN PRESSURE OF CAVE AIR USING AN AIR BAROMETER

Erik Halbert

Abstract

This paper describes an extremely simple form of barometer which is capable of measuring changes in air pressure of less than five pascals. The principle of operation, construction and use are described and examples are given of its use both inside and outside the cave environment.

INTRODUCTION

During work in the Grill Cave at Bungonia it was necessary to measure the difference in barometric pressure between the surface and a series of points throughout the depth of the cave. A number of requirements had to be met by the instrument. Firstly it had to have a sensitivity to differences in barometric pressure of about five pascals, equivalent to t a vertical difference in height of some 0.4 m in an air column at sea level. Secondly it had to be compact and tough enough to withstand carrying to the bottom of the Grill Cave. Thirdly it had to be easy to read in poor light and muddy conditions. Lastly it had to be very cheap.

In practice the first requirement conflicted strongly with the other three and no readily available instrument could be located. Fortin type barometers, using mercury have sufficient accuracy but are bulky, fragile and relatively non-portable. Aneroid barometers can be small, light and portable but are also delicate when designed to be highly sensitive. Neither type is cheap.

To overcome the problem a simple form of air barometer using a sensitive manometer was constructed and the success of this device suggested that it may form a valuable addition to the instruments available to the average caver. With this barometer a reference pressure is established and then by adjustment, a column of liquid of known density is balanced against the new air pressure. The length of the balanced column is directly proportional to the change in ambient pressure.

THE AIR BAROMETER

Barometers based upon working fluids other than mercury have been developed in the past. Middleton (1964) in his exhaustive history of the barometer describes types using water, sulphuric acid and glycerine as well as air. While air barometers were developed early they were generally unsuccessful until the invention of the vacuum flask around 1890 and thereby the ability to maintain an air volume at constant temperature. Middleton documents several air barometers based on a vacuum flask design and using the gas laws relating pressure and volume to measure pressure.

The instruments tend to suffer from a variety of problems such as 'sticking' of the indicating fluids and a general inability to run for any length of time unattended without the index going off scale. They are therefore not used where long term recording of pressure change is important. However, for special purposes involving spot measurement of pressure change these limitations are not relevant and the simplicity of construction (Trowbridge, 1973) and high sensitivity become quite attractive.

Principle of Operation

The present instrument establishes a reference pressure (the ambient pressure at location A) in the closed leg of the manometer and maintains this pressure by level adjustment when the instrument is moved to location B. It may be readily shown (Hughes and Brighton, 1967; Giles,

1978) that the change in ambient pressure in going from A to B is balanced by the change in level of the fluid in the open column. Since the fluid has a specific gravity of 1.0, then 13.6 mm fluid (760 x 13.6) equivalent to the standard atmospheric pressure of 101 325 Pa. Thus one millimetre of fluid is equivalent to a pressure change of 9.80 Pa.

The relationship between air pressure and altitude is well established (Neiburger, Edinger and Bonner, 1982) and is shown in Table 1. Since air is a compressible fluid the rate of pressure change with altitude is not constant. However, in any individual caving area in Australia the vertical range will probably be limited to several hundred metres and in any particular cave the range will probably be less than one hundred metres. The errors introduced by assuming a constant rate in these situations will therefore be small and a value of 11.5 Pa/m has been taken for the most general case. Thus one millimetre of fluid is equivalent to 9.80/11.5 = 0.85 m altitude change. Similar calculations readily yield the factors shown in Table 2 for fluids of different specific gravity.

Outside Australia, there are many caves with depths exceeding 500 m (eg Nettlebed Cave in New Zealand at 838 m). In such cases it is still possible to use the general figures derived above. However, more accurate figures may be determined if there is pre-existing altitude data available from local information or topographic maps. Obviously, the more accurate the altitude information, the more the altitude factors may be refined. In some cases moreover, it may also be possible to determine local altitude factors directly if the vertical separation between two points is accurately known.

CONSTRUCTION

The apparatus consists of a small glass bottle kept in a vacuum flash filled with a slurry of crushed ice and water. The flask is attached via flexible tubing (internal diameter 1 - 2 mm) to a sensitive U-tube manometer. The tubing passes through a hole drilled in the screwcap of the flask and has a joint which is opened to equalise pressure in the manometer legs at the start of a series of measurements.

Vacuum Flask and Bottle

The vacuum flask is critical to successful operation since the air within the bottle must be kept at constant temperature. The slurry of ice is kept well mixed by inversion to avoid thermal stratification effects. This mixing is carried out prior to each pressure measurement and is more readily carried out when a 125 ml bottle is used than when a 250 ml bottle is used, since the smaller bottle diameter allows free flow of the ice slurry. The flask will keep the bottle at 0 C for about three days on one fill of ice and a plastic lined flask (or metal flask) will minimise the risk of flask breakage.

Manometer

Two types of vertical reading manometer were used. The first was a twin channel glass manometer (Warburg type) with etched millimetre graduations over 30 cm. The second was 80 cm of flexible tubing (internal diameter 1 - 2 mm) containing 50 cm (0.9 ml) of manometer fluid, adjusted and read against a 30 c, ruler attached to a white board. The board in turn was flexibly attached to the vacuum flask with elastic tape. The latter type of manometer is much more convenient in caves and both may be read to 0.5 mm. An inclined manometer or electronic manometer would further increase sensitivity if this was important for a particular project.

Indicating Fluid

Manometer fluids are described by Umbreit, Burris and Stauffer (1964). However, any commercial manometer fluid with a specific gravity of 1.0 and which is compatible with the tubing may be used. A very convenient fluid may be prepared by adding about two percent detergent to Parker permanent blue ink. Another one which was not used but should be particularly appropriate in caves would be a fluorescein solution with added detergent. Non-aqueous fluids having specific gravities in the range 0.8 to 1.0 were also tried and these give greater sensitivity than aqueous fluids as shown in Table 2.

Table 1 U.S. Standard Atmosphere

Height m	Temperature C	*Pressure Pa	**Pressure Change Pa/m
0	15.0	101 300	
500	11.7	95 500	-11.7
1000	8.5	89 900	-11.2
1500	5.2	84 500	-10.6
2000	2.0	79 500	-10.1

* data obtained from Berry, Bollay and Beers, 1945 and Riehl, 1978 and rounded.
** pressure change for one metre change in height upwards.

Table 2 Pressure and Altitude Factors for Manometer Fluids of Different Specific Gravity

Specific Gravity	Pressure Factor Pa/mm	Altitude Factor m/mm
1.0	9.8	0.85
0.9	8.8	0.77
0.8	7.8	0.68

OPERATION

1. At location A, the joint in the closed leg of the manometer is opened and the fluid levels are adjusted to an appropriate point on the scale. In the case of a cave survey where all locations might be expected to be below the entrance then the set point might be around the 250 mm mark to maximise the depth which may be measured. Where subsequent locations are above the initial location then a setting around 50 mm might be appropriate. The manometer is then closed and the levels are noted. This sequence sets the reference conditions.

2. The manometer is taken to a new location and the fluid in the closed leg is adjusted back to the level it had at location A.

3. The level in the open leg is again noted.

4. Steps 2 and 3 are repeated for each location.

5. The change in level of the open leg between location A and each of the other locations is calculated and converted to either pressure change or altitude change using the formulae:

Pressure change (PA) = Level change (mm) x 9.8

Altitude change (m) = Level change (mm) x 0.85

Although not essential to operation of the air barometer, it is found very useful to have a 'T' junction and valve between the manometer and the vacuum flask. This enables pressures to be equalised without opening the joint as described in step one above. However, it has the disadvantage of being susceptible to accidental knocking with resultant error in measured pressure change.

Sensitivity to Ambient Temperature Changes

A traditional source of inaccuracy in air barometers was the high sensitivity that these instruments had towards change in pressure caused by change in ambient temperature. In an uncontrolled instrument a temperature change of one degree centigrade would cause a pressure change of about one part in three hundred. This occurs since the pressure of a given mass of gas, at constant volume, is directly proportional to the absolute temperature of the gas. At ambient temperatures of around 25 C, the absolute temperature is around 300°K (273.2 + 25). Thus a one degree centigrade change in temperature is a change of one part in three hundred. With the instrument initially at ambient pressure ($P \simeq 100\ 00$ Pa), this would be equivalent to a change of 333 Pa or 34 mm change in level of manometer fluid. The temperature coefficient would be 34 mm/°C, resulting in highly erratic operation.

With an insulated instrument the volume affected by ambient temperature change is reduced by a factor , the ratio of the volume of the manometer tubing outside the vacuum flask to the volume of the glass bottle. In the present instance, using tubing with an internal diameter of 1.5 mm, $\gamma = 1/250$. This decreases to about 1/1000 when the larger bottle and smaller diameter tubing are used. When $\gamma = 1/250$ the temperature coefficient is reduced to about 0.15 mm/°C and at $\gamma = 1/1000$ it is 0.04 mm/°C. In practice it is unusual for ambient temperature swings in excess of ten degrees to occur during the period of pressure measurement and correction for this effect is therefore not normally needed. For high accuracy, temperature correction may be readily applied and or the reference conditions may be updated.

DISCUSSION

Uses for the Barometer

There are several ways in which this instrument can be used in caving activities. These particularly include cave climate studies where detailed measurement of pressure is important and barometric surveys:

1. The monitoring of pressure change at constant altitude.

This use is valuable when barometric surveys are being carried out above or below ground since it allows the surveys to be controlled and adjusted for non-altitude related changes in air pressure.

2. The measurement and monitoring of pressure change with depth in a cave.

Figure 1 shows the relationship between depth and pressure change in the Grill Cave on 7th April 1984. The pressure was measured at a series of ten stations throughout the depth of the cave, both on the trip down to the sump at the bottom of the cave and then again on the way back to the surface. In this case a non-aqueous fluid of specific gravity 0.9 was used in the manometer and the data were corrected for non-altitude related pressure changes. To do this the manometer was read at constant height on the surface for several hours before and after the cave survey and these data in conjunction with the survey data were used to calculate non-altitude related changes. The depths of the stations were known from a CRG Grade 6 survey map held by Sydney Speleological Society. In this paper no attempt is made to analyse the shape of this curve. Such a study would include things such as survey accuracy, and the role of carbon dioxide on air density, etc on the slope of the graph and is being considered elsewhere.

3. The rapid estimation of cave depths.

This is valuable when caves are long and complex and can be carried out far more rapidly than conventional cave surveying.

4. The rapid estimation of relative heights of entrances etc.

FIGURE 1. Grill Cave, 7/4/84

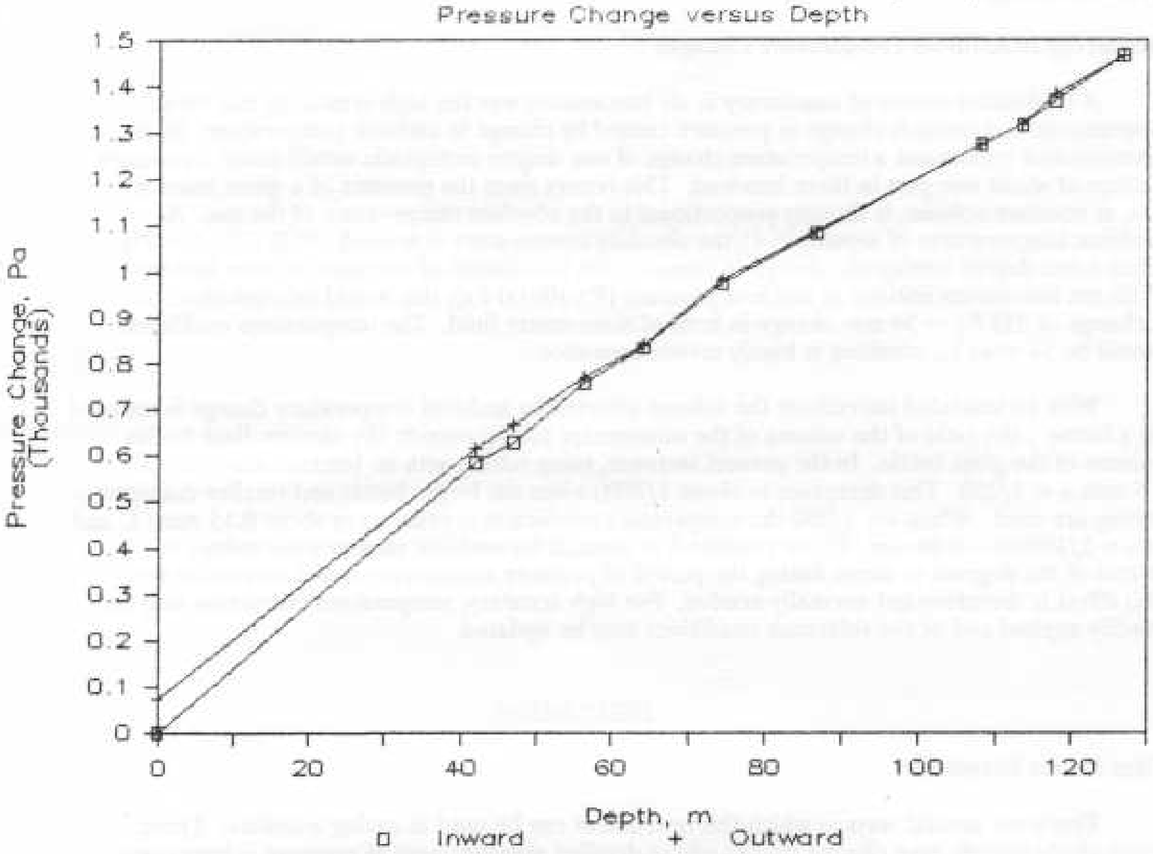
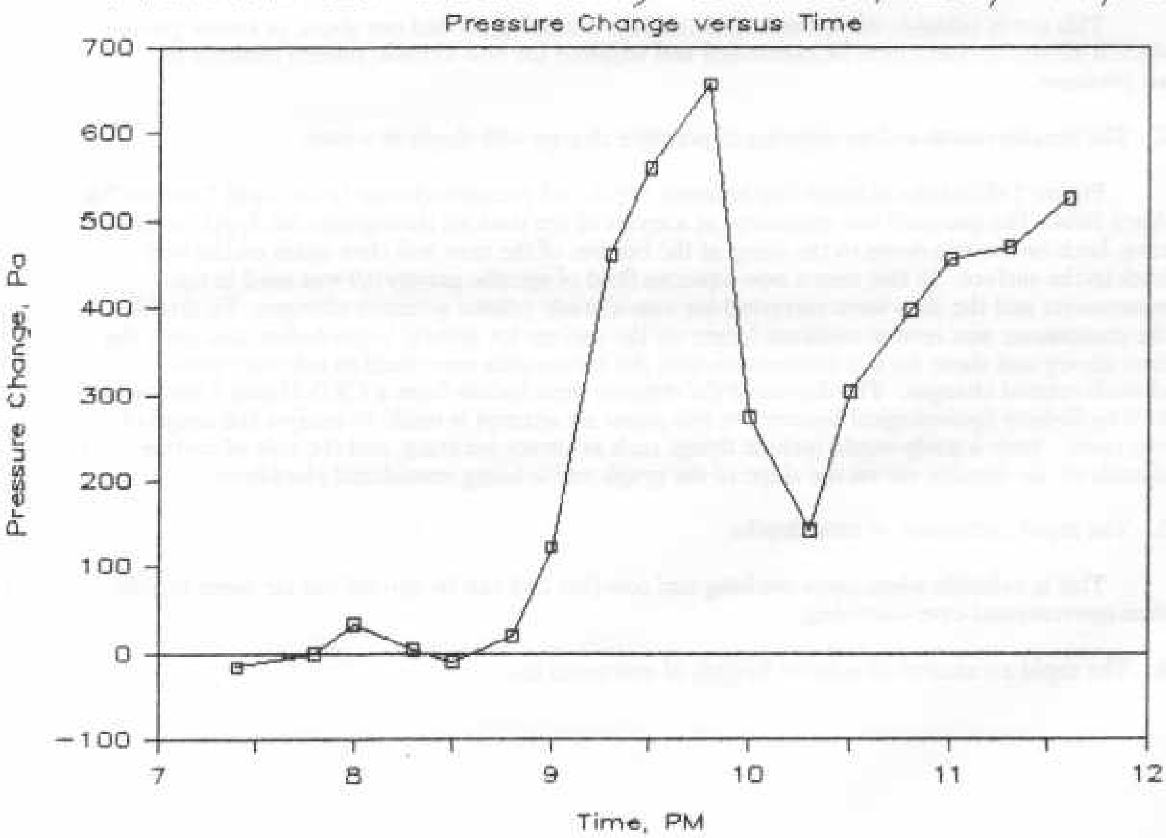


FIGURE 2. Southerly Buster, 26/11/86



The barometer may also be used to monitor daily weather changes and a typical trace is shown in Figure 2, which records detail of the pressure changes occurring when a strong Southerly Buster passed over Sydney on the evening of 26th November, 1986.

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APPENDIX

Variation in the Force of Gravity

The derivation of the manometer fluid level change to differential air pressure ratio uses standard atmospheric conditions (ie 0°C and standard gravity of 9.8 m/s^2). This ratio will change with varying manometer fluid density and local gravity. To generalise:

$$\Delta P / \Delta h = \rho_m g_l \times 10^{-3}$$

where P is air pressure differential (Pa), Δh_m is manometer level change (mm), is the ρ_m density of the manometer fluid (kg/m^3) evaluated at the manometer fluid temperature and g_l is local gravitational acceleration
(m/s).

The International Gravity Formula is

$$g_l = 9.780\,49(1 + 0.005\,288\,4 \sin^2_\gamma - 0.000\,005\,9 \sin^2 2_\gamma)$$

where γ is latitude and g_l is at sea level (Meriam, 1975). Further correction may be made for altitude for extreme accuracy. For a barometric survey carried out near sea level, near the equator (g_l =9.78) and at an ambient temperature of 30°C (ρ_m =995.3 kg/m^3).

$$\Delta P/\Delta h_m = 995.3 \times 9.78 \times 10^{-3} = 9.73 \text{ Pa/mm}$$

which gives a relative error of 0.7% against the figure of 9.8 used in the general case.

$$((9.8-9.73)/9.73) \times 100 = 0.72$$

Alternate Calculation of Altitude Factor

In the general case

$$P = \rho_a g_1 h_a$$

where P is air pressure (Pa), ρ_a is air density (kg/m^3), and h_a is the head of air (m). If ρ_a and g_1 are constant then

$$dP/dh_a = \rho_a g \text{ and } \rho_a = PM/RT$$

where P is the absolute pressure (bar), M is the molecular weight, R is the universal gas constant, and T is the absolute temperature (°K). Thus

$$dP/dh_a = Pg_1 \times 28.97/0.083\,15\,T = 348.41Pg_1/T$$

Using the data from Table 1 for say 1500 m and standard gravity

$$dP/dh_a = 348.845 \times 9.806\,55/(273.15+5.2) = 10.37$$

this compares with 10.6 obtained using the linear approximation between 1000 and 1500 m.

THE SOURCE OF THE JENOLAN RIVER

Kevin Kiernan

Abstract

Geomorphological and hydrological investigation of un-mapped limestone outcrops and enclosed depressions that occur between North Wiburds Bluff and the headwaters of Bindo Creek has confirmed the presence of significant karst well to the north of the boundary of the Jenolan Caves Reserve and that karst drainage could conceivably breach the Great Dividing Range. The limestone becomes progressively less well dissected northwards with the karst being very subdued at the northern end of the belt. Fluorescein testing has shown that a streamsink at the southern end of this area drains directly to Central River in Mammoth Cave, and thence to imperial Cave and Blue Lake. This indicates that at least some of the limestone in this area is continuous beneath the surficial covers with the main Northern Limestone rather than being a discrete lens. The situation has important management implications in view of expanding forestry operations in the area since these have the potential to seriously increase the sediment load of waters that pass through wild caves and the Jenolan tourist caves complex.

INTRODUCTION

The Jenolan River rises from the crest of the Great Dividing Range at 1260m and is separated from streams flowing N to join Bindo Creek by a saddle at c.110m. It then flows SSE down McKeowns Valley following the strike of non-carbonate Upper Silurian rocks. About 5 km from its source there is a major kink in its course where it turns sharply westwards for a few hundred metres and then sharply SSE again before following an intermittent surface course down the strike of the Jenolan Caves Limestone to Blue Lake at c.760m asl. adjacent to the Jenolan tourist cave complex.

Despite the considerable attention that Jenolan has received over many years, the geology, geomorphology and hydrology in the headwaters of the Jenolan River is very poorly known, and no current geological maps indicate limestone upstream of North Wiburds Bluff. Chalker (1971) recognised the presence of limestone here but did not map the area and dismissed the outcrops as discontinuous lenticular masses. Descriptions of a number of the limestone outcrops were provided by Dunkley (1972). Shannon (1976a,b) suggested that the limestone in this area was continuous with that further south although the map that accompanies the latter report does not extend upstream of North Wiburds Bluff. However, Lishmund et al. (1985) in their compilation on the limestone deposits of NSW reiterated the suggestion that only isolated lenses were present. It has since been suggested that enclosed depressions in this area represent hollows left in the landscape after isolated pods of limestone dissolved out of the surrounding non-carbonate rocks (S.R. Lishmund pers.comm. to A.P. Spate). Unfortunately, the excellent geological map by Allan (1986) does not extend this far upstream and, hence, the situation has remained unresolved.

KARST IN THE HEADWATERS OF THE JENOLAN RIVER.

The area under discussion lies north of that part of the Jenolan karst commonly known as the Northern Limestone, the upstream boundary of which has generally been depicted as lying in the vicinity of Watersend Cave and North Wiburds Bluff. Karst further north towards the head of McKeowns Valley appears to have been first described by Dunkley (1972). Most recently, a set of detailed but as yet unpublished notes and sketches have been compiled by the Chief Guide at Jenolan Caves, Mr. Ernst Holland. The possible significance of the area was assessed in very general terms without any water tracing data being presented in the review of the geology, geomorphology and hydrology of the Northern Limestone by Shannon (1976).

The karst landforms that occur in this area include sinkholes that reach up to 50m in diameter and 15m deep and which may be the largest at Jenolan, together with some fluted limestone outcrops. There are at least four streamsinks, all perched on the western side of the valley up to 80m above the level of the surface course of the river. Only one tributary from the west is known to maintain a surface course all the way to the river. The linear trend of this set of karst landforms is at a broadly similar orientation to that of the main Jenolan karst belt further to the south, although the surface expression of the karst is less pronounced. Surface exploration has hitherto failed to reveal any resurgences that could account for the water that goes underground at these northern streamsinks. These facts hint that the area could be a continuation of the main cave bearing strata at Jenolan and raise the possibility that the subterranean drainage of the area could be integrally related to that of the Northern Limestone.

In addition to the area between North Wiburds Bluff and the head of the valley, a series of shallow depressions is present in Quaternary surficial covers to the north of the Jenolan-Bindo divide. That some of these are enclosed is evident from the fact that they hold water under wet conditions (E. Holland, pers. comm.). They appear to be sinkholes formed by solution of limestone beneath the Quaternary mantle. The surface expression of the karst here is still less pronounced than that in the upper part of McKeowns Valley. The linear trend of the dimpled terrain continues at much the same orientation as the area further south. This raises the possibility that the Jenolan Caves limestone may continue through the crest of the Great Dividing Range from McKeowns Valley into the Bindo Creek catchment. This raises in turn the further possibility that some of the drainage to Jenolan Caves could originate north of the apparent divide.

THE QUESTION OF CONTINUITY.

In order to assess the likelihood of continuity between the limestone areas upstream and downstream of North Wiburds Bluff, an attempt was made in October 1987 to locate a streamsink in the more upstream area from which it might be possible to trace the drainage. Unfortunately conditions were too dry at the time to permit testing from the northernmost karst. Instead, at 9:45am 9 October 1987, 1.5kg of fluorescein was placed in a strongly flowing stream that disappears underground at c.990m about 1.6 km upstream from North Wiburds Bluff. It was hoped that by placing activated charcoal bags along the course of the Jenolan River as well as in selected caves further to the south it would be possible to ascertain, in particular, whether the stream regained the surface or remained underground. The former would be permissive of a discontinuous lenticular mass of limestone as argued by Chalker (1971) and reiterated by Lishmund et al (1985). On the other hand, a continuous underground course would almost certainly demand a continuous limestone body as proposed by Shannon (1976 a,b).

One charcoal bag was placed c.100m downstream of the major kink in the course of the Jenolan River, and a second bag was positioned several hundred metres further downstream close to the point where the river was sinking into its bed. Other bags were placed in Central River and Lower River in Mammoth Cave, in the main river passage of Imperial Cave and also in sump 6 in Imperial Cave.

The dye was observed to appear in the old weir at the upstream end of Blue Lake between 6 pm and 11 pm 12 October 1987, giving a total travel time of c.81-86 hours to cover the linear distance of c.5.5km. The stream in the Imperial Cave river passage was observed to still be a strong green colour at 8.30 am 13 October 1987. The dye had reached the small weir by the hydro station by 9.30 am 13 October 1987, by which time Blue Lake had assumed a vivid green colour which it retained for over one week.

An activated charcoal bag recovered from Lower River at noon on 12 October 1987 proved strongly positive. This replacement bag was removed at 11:00 am on 17 October 1987, and also proved strongly positive. Another strongly positive result was obtained from the activated charcoal bag in the Imperial Cave stream. No result was obtained from sump 6 in Imperial Cave due to its having ceased to flow. However, the geographical position of sump 6 and the similarity of the sands further upstream in sump 7 (S. McCartney, pers. comm.) to those in the normally dry bed of the Jenolan River near Spider Cave suggest that this is part of a minor tributary rather than an anabranch of the main underground river.

An initially ambiguous result was obtained from the most upstream of the charcoal bags in the Jenolan River. The alcoholic KOH solution produced from this was green in colour and it fluoresced when irradiated with ultra violet. However other aspects of its appearance were in some ways dissimilar to fluorescein, the fluid having a texture rather similar to finely curdled milk. A negative result from the surface bag further downstream aroused further suspicion, for although the sinking point had retreated upstream of the placement by further suspicion, for although the sinking point had retreated upstream of the placement by the time this latter bag was collected it seemed not improbable that this retreat occurred after the dye would have already reach Mammoth Cave c.2.2 km. further downstream.

A fluid similar in character to that from the uppermost Jenolan River bag was also obtained from Central River in Mammoth Cave. Subsequent spectrophotometer analysis of the upper Jenolan River sample and the Central River sample indicated that no fluorescein was present in either. These results underline the need for caution in the use of activated charcoal bags to detect the passage of fluorescein. The green colour obtained is probably a natural fluorescence derived from the surrounding vegetation. Problems with leachates from native vegetation have previously been suggested in the Yarrangobilly area (A.P. Spate, pers. comm.) and the writer has experienced similar difficulties in the Cracroft area of south-western Tasmania. In this latter area tannin derived from the vegetation is retained in activated charcoal to the extent that the solution produced has such a strong brown colour that visual detection of fluorescein can be prevented even when the dye is present.

CONCLUSIONS

The experiment reported here indicates that water sinking into at least the southern part of the "northern Northern Limestone" maintains a continuously underground course to Mammoth Cave and the Jenolan tourist cave complex. This calls very mush into question the suggestion that the limestone masses upstream of Wiburds are discrete lenses or pods (Lishmund et al, 1985). Subsequent to the conduct of this test advice was received from J.R. Dunkley concerning the outcome of two water tracing experiments uncompleted at the time of his 1972 paper and unreported since. These results lend confidence to the interpretations presented here. In one test, 454g of fluorescein was placed in the first westerly tributary upstream of Wiburds Lake Cave and charcoal bags recovered from the main surface stream proved negative. In the other test 454g of fluorescein was injected into a stream that sinks in the valley south of that reported on in the present paper. This dye was not detected again, nor seen in the main surface stream (J. Dunkley, pers. comm.).

These results beg the question as to just how far northwards the limestone may extend continuously and also the extent of the underground catchment. Perhaps it is noteworthy in this regard that it has been suggested by Welch (1976) that the best prospect north of Wiburds of gaining entry to the fabled Woolly Rhinoceros, a section of cave long theorised to exist, is the streamsink now shown to connect to Lower River!

Another consideration relates to a longstanding question in the hydrology of Jenolan, namely whether Central River joins Lower River upstream or downstream of the appearance of the latter in the southern section of Mammoth Cave (King and Welch, 1976). In the test reported in this paper fluorescein failed to reach Central River despite the fact that the charcoal bags from Lower River were strongly positive. This suggests that the presumed confluence of those two streams must lie further to the south. It tends to confirm the suggestion by Handel and James (1977), based on differences in water chemistry, that Central River cannot be an anabranch of Lower River. Central River is very much more susceptible to weather changes than Lower River. Shannon has suggested that the tributary Hennings Creek may be the source of Central River from a pool that it forms in the bed of the Jenolan River, from advances that it stimulates in the Jenolan River itself, and from gravel storage in the neighbouring flat (Shannon, 1976b; Handel, 1976). This possibility seems worthy of further investigation. Fluorescein placed at a sinking point of the Jenolan River outside Serpentine Cave in 1972 is known to have reached Central River (Shannon, 1976b).

The information now available concerning the limestone areas in the northernmost part of McKeowns Valley has important management implications. No regard was initially paid to the possibility of local karst or to the potential impact on the Jenolan Caves when logging of the native forests north of the Caves Reserve boundary was undertaken 2-3 years ago. Although these operations were eventually halted some of the ground disturbed at that time together with some of the fire trails in the area continues to be a source of sediment during heavy rain. In addition, extensive plantings of exotic pine are present at the head of the valley and these will be cut at some time in the future, while new pine planting has recently been undertaken northwards from the apparent surface drainage divide at the head of the valley in an area of karst that could conceivably also form part of the catchment of the Jenolan River. Thus there is considerable present and planned forestry activity in an area at least part of which has been shown to have a direct and rapid underground connection with some of the most celebrated of the Jenolan caves. In the light of the significant threat to the caves which production forestry in this area may pose in terms of increased sediment loads, pollution from spillages or spraying, changes to flow regimes and other affects, further investigation of the geology, geomorphology and hydrology of the northernmost limestone should be given a high priority to provide a sound basis for management and the rationalisation of land tenure.

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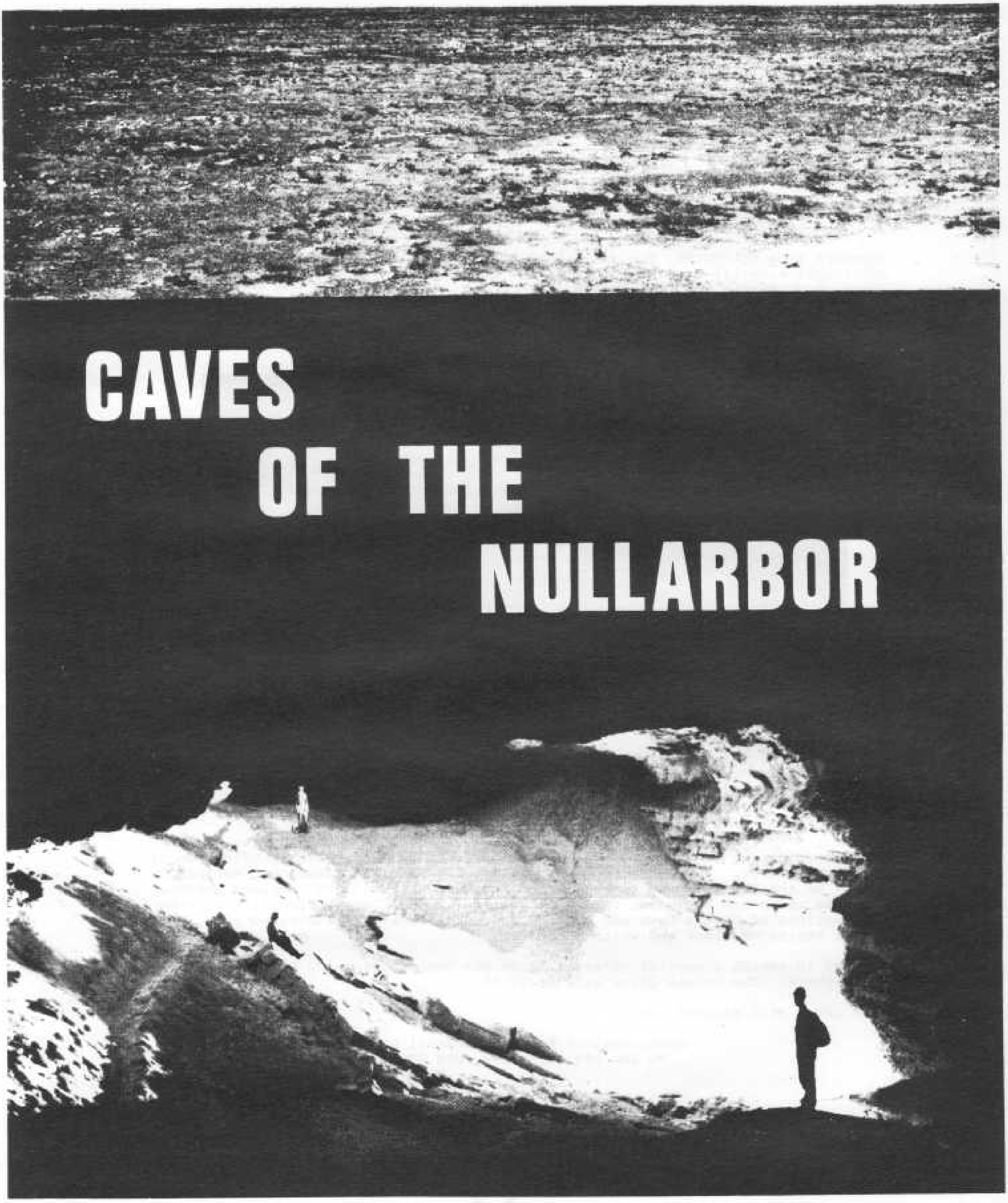

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