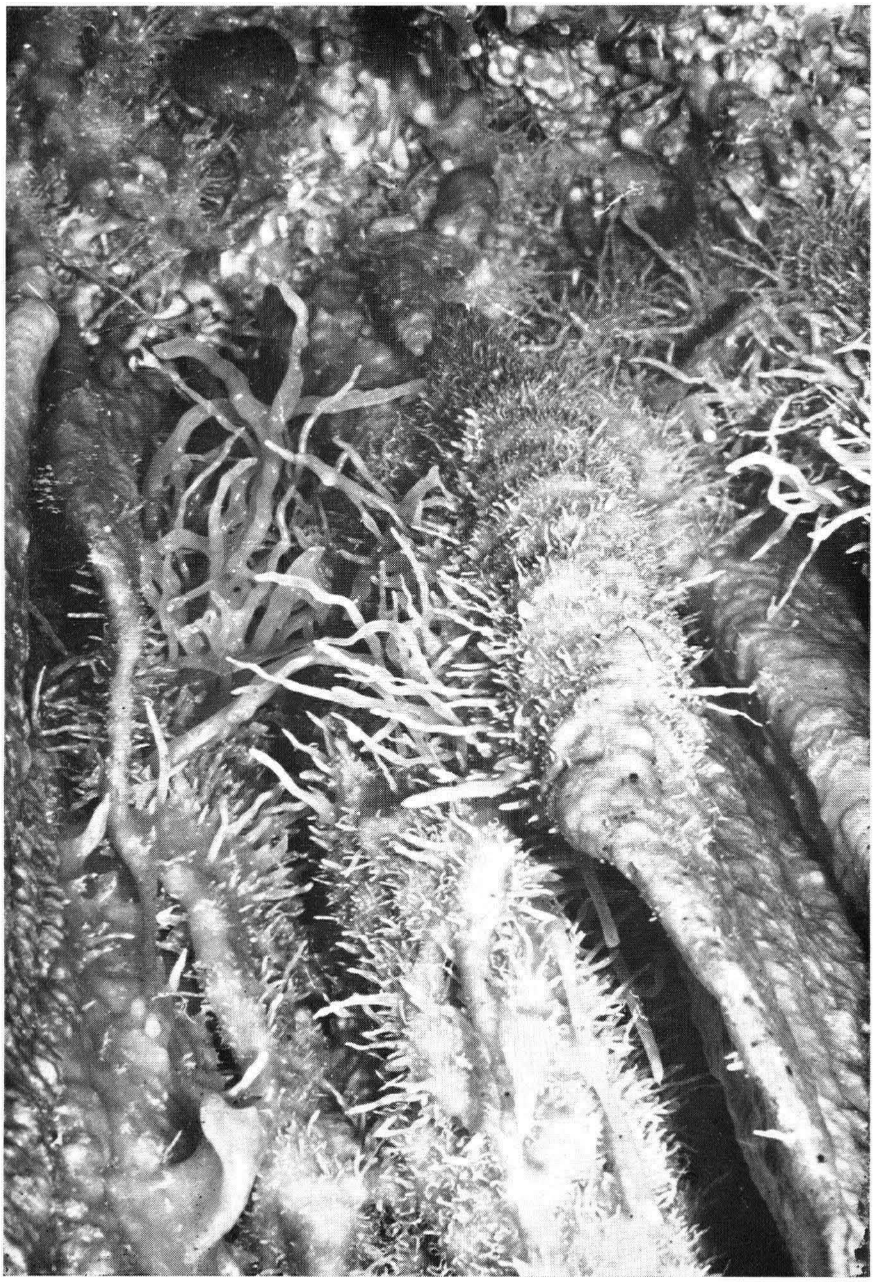
BCRA TRANSACTIONS

BRITISH CAVE RESEARCH ASSOCIATION

Volume 4 Number 4 December 1977



CO_2 in Caves

The Conductance Method

Birds from Gower Caves

Taurus Mountains Caves

Lava Caves in Tenerife

Index to Volumes 3 and 4

Helictites in Odyssey Cave, Bungonia Photo P. Caffyn

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A very short summary of the principal conclusions should accompany every contribution.

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Bloggs, W., 1999. The speleogenesis of Bloggs Hole. Bulletin X Caving Assoc. Vol. 9, pp. 9-99.

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ISSN 0305-859X

TRANSACTIONS OF THE BRITISH CAVE RESEARCH ASSOCIATION

Volume 4 Number 4 December 1977

CONTENTS

Cover photo: **Helictites in Odyssey Cave, Bungonia**
P. Caffyn

Published by and obtainable from
The British Cave Research Association

Bryan Ellis,
30 Main Road,
Westonzoyland,
Bridgwater,
Somerset TA7 0EB.

One copy issued free to members
Extra copies to members £1.50
Non-members price £2.50
Postage extra

Trans. British Cave Research Assoc. Vol. 4, No. 4, pp. 417-429 December 1977

Carbon Dioxide in the Cave Atmosphere

by Julia M. James

Summary

Cave atmospheres at Bungonia are particularly suited to the study of carbon dioxide in caves. The major source of carbon dioxide is provided by the life processes of micro-organisms which live on the organic matter washed in. The rate of carbon dioxide production increases with warm, wet conditions while the quantity produced is dependent on the supply of nutrient materials. The presence of oxygen is not necessary for carbon dioxide production by micro-organisms.

Following total gas analyses the varying ratios of constituent gases have been used to identify three sources of carbon dioxide. The concentration increases with depth but in different rates and in different ratios according to whether the cave is blocked by mud or water. Flood waters at first reduce the carbon dioxide concentration by virtue of increased circulation, but later the concentration builds up because of the fresh supply of nutrients for the micro-organisms.

Carbon dioxide concentrations show a seasonal variation, high in summer, low in winter.

In high carbon dioxide atmospheres speleothem deposition still occurs in places but usually there is solution of speleothems with cavern enlargement. Some changes in carbon dioxide concentration and distribution can be shown to be the result of human activities.

The results of the studies at Bungonia have implications in all caves where excess organic matter can be washed in by floods.

Carbon dioxide (CO_2) is an important component of the chemical equilibria which operate to produce caves, and to decorate them with speleothems. Gaseous CO_2 can dissolve in water to produce a weakly acidic solution — the "aggressive" water — which is essential for dissolving the calcium carbonate in limestone. Whether the water will dissolve limestone or deposit calcite depends upon many factors, including the temperature, the amount of calcium carbonate already in solution and the concentration of CO_2 in the atmosphere above the solution. These same factors also influence the rate at which calcium carbonate is dissolved or precipitated.

High concentrations of CO_2 in the cave atmosphere are known to the caver as "foul air" (James *et al.* 1975). Fortunately the occurrence of foul air is rare and usually restricted to one or two passages in any cave. Four generalisations may be made:

1. In a given caving area there will be only one or two isolated foul air caves.
2. Foul air is most likely to be found in caves in the tropics.
3. Foul air may be encountered in caves in any rock: lava, sandstone, limestone, etc.
4. Caves which are subject to periodic flooding (such as snow-melt) followed by long periods of low rainfall or drought are more likely to contain foul air.

Among exceptions to the first two generalisations are three limestone areas in New South Wales, Australia. These are Wellington, Molong and Bungonia, where foul air is found in caves more often than not. The Wellington and Molong caves contain over 12% CO_2 (all values of CO_2 concentrations in this paper are quoted as volume percent) (Nurse 1955) and study of the atmospheres has been restricted to the fringes of the foul air accumulations. However, Bungonia Caves are amenable for the study of CO_2 in the cave atmosphere because the CO_2 concentration has rarely been recorded above 7%, and it is possible to penetrate the foul air regions to take measurements. The caves are well-explored and mapped (Ellis *et al.* 1972) and extensive dye tracing (James 1973) has identified the underground routes followed by water in the Bungonia area. There is a wide variety of caves of interest to the investigator. These include:

1) single and multi-entrance caves for the study of the variation of CO_2 concentration with air circulation,
2) shallow and deep caves for the study of its variation with depth,
3) mud- and silt-blocked and water-terminated caves for comparison of the mechanisms of absorption and production of CO_2.

The five principal caves at Bungonia consist of groups of vertical vadose shafts connected at various levels by phreatic development, terminating about 150m below the Bungonia plateau surface (Figure 1). Each of these major caves has distinctive CO_2 characteristics. Although there are water connections between them, there are no known free air connections.

Study of CO_2 at Bungonia Caves began in the early 1950s when Burke (1953) collected air samples from Putrid Pit and Drum Cave and tested them with a Haldane gas analysis unit. The studies at Bungonia Caves continued erratically over the years, with numerous cavers taking air samples and analysing them by a variety of methods. The more ambitious (Michie 1967; Crawshaw and Moleman 1970) commenced development of apparatus suitable for field measurements, designed to aid safe exploration as discussed below. In 1972 a detailed study of the cave atmospheres was commenced by the author as part of the study of cold water mineralisation processes in Bungonia Caves (James 1975).

The results of the Bungonia studies are applicable to caves in general, not only to foul air caves. The assumption is often made that cave atmospheres contain the normal atmospheric concentration of CO_2, 0.03%, a figure which shows little variation with altitude or latitude (Bolin and Keeling 1963). This is not so in dry caves (Ek 1968; Ek 1969; Renault 1972) or in well-ventilated stream caves (Bögli 1969; Atkinson 1975; Stenner 1974). Spatial concentrations of CO_2 are found to vary significantly between different parts of caves.

Figure 1.

CARBON DIOXIDE LEVELS AT BUNGONIA CAVES

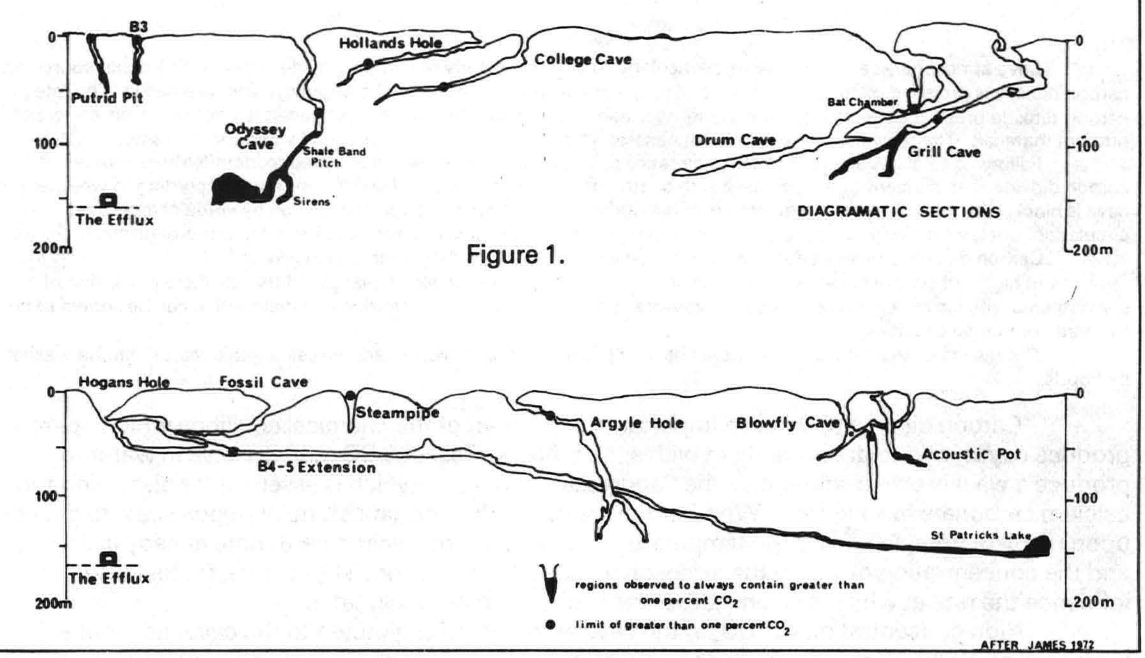


Figure 1.

Sources of the Carbon Dioxide in Caves

1. Diffusion of gaseous CO_2 through the soil and rock into the cave.
2. Evolution of CO_2 from cave waters.
3. Production of CO_2 by micro-organisms.
4. Respiration of plants and animals.
5. Burning of hydrocarbons, such as acetylene and waxes, i.e. candles.
6. Volcanic gases.

It is difficult to assess the contribution of each source to the CO_2 concentration in the cave. In addition the CO_2 may be removed by air movement, solution in cave waters or reaction with moist calcium carbonate. Sources 2, 3 and 4 are believed to be the major CO_2 sources at Bungonia.

The suggestion that CO_2 diffuses downward into caves from the soil (Auld 1960) has been explained as follows: the aerobic micro-organisms in the soil above a cave are constantly consuming oxygen (O_2) and producing CO_2. The O_2 is presumably drawn into the soil from the surface, while the CO_2, being heavier than air of normal composition, diffuses downwards. It then passes through joints and cracks in the rock and into the cave. Gams (1974) has claimed that this mechanism is a major source of CO_2 in Postojna Cave, Yugoslavia, and it may contribute to CO_2 levels in the shallow foul air caves at Bungonia. However, total gas analysis in the major Bungonia caves, and the variation in the results with rainfall and temperature, have indicated that the gas diffusion mechanism is not the major source of CO_2 in these caves.

Cave waters are an important source of CO_2 in the Bungonia Caves. The CO_2 may be produced either as a result of deposition of speleothems (Renault 1972; Moitke 1972) or due to the carbonate equilibria in cave waters (Roques 1969). Deposition of calcite in poorly ventilated sections of a cave may produce a significant rise in the CO_2 concentration, but only low levels ($<$ 0.4%) have been found in the alcoves of Odyssey Cave, Bungonia, where calcite is being deposited. Dissolution rather than deposition of calcite appears to be occurring in most foul air caves, which probably means that the contribution from speleothem deposition is small. The major source of CO_2 in atmospheres above cave waters is thought to be the operation of the $CO_2-H_2O-CaCO_3$ equilibrium. Briefly, water passing through the atmosphere and the soil acquires CO_2 and becomes acidic (Holland *et al.* 1964). The water then percolates through bedding planes and joints in the limestone, where it dissolves calcium carbonate. On reaching the cave atmosphere, CO_2 is released from these mineralised waters, if the equilibrium between the dissolved and atmospheric gases is favourable.

The production of CO_2 from organic matter has slowly gained favour as a major source of CO_2 in caves (Peck 1961; Ek 1968; Ek 1969; Cooke 1971; Gams 1974; Atkinson 1975). In the totally dark sections of the cave, the same processes which produce CO_2 in soils occur in the cave waters, cave muds and organic detritus. Detritus is likely to accumulate in the bottom of joints, shallow overflow pools and sumps: these are also the places where high CO_2 has most often been noted (Ek 1969, Atkinson 1975). Cave muds often have a high CO_2 atmosphere above them, and thus contain higher concentrations of CO_2 than the soil above the cave. Work on the CO_2 concentrations in Bungonia cave muds is one of our future projects, which will utilise a soil probe designed by Miotke (1968).

The CO_2 is produced from the organic matter by micro-organisms which live on the material washed into the cave (plate 1), or on the debris resulting from the occupation of the cave by bats. The respiration of these organisms is a major source of the CO_2 found in the Bungonia Caves. Many species of bacteria have been identified (Dyson and James 1973) from the Bungonia cave muds and waters. Fungi are present: fungal hyphae decorate the mud slopes and walls of the caves. Red and blue-green algae are observed at the cave entrances, and protozoa are found in the cave waters.

Assessment of the quantity of CO_2 produced by micro-organisms is difficult, and requires specially designed experiments to be carried out *in situ*. Our measurements and observations have led to a set of empirical rules, which are similar to those for CO_2 production by micro-organisms in soils (Miotke 1972). Microbially produced CO_2 depends on:

1. *Moisture* The CO_2 concentration in shallow caves at Bungonia decreases in dry conditions due to a decline in the numbers and activity of the bacteria and other micro-organisms as the caves dry out. In the deep caves at Bungonia, the humidity remains between 95 and 100%, and CO_2 production is not reduced in periods of drought.
2. *Temperature* In the lower reaches of deep caves at Bungonia, the air temperature is 18 ± 0.5°C, a favourable temperature for growth of CO_2 producing micro-organisms in the caves. At Wellington and Molong Caves, the seasonal fluctuations in CO_2 levels (Fraser 1958) may be due in part to reduced microbial activity in winter, when the temperature in these shallow caves drops below freezing.
3. *Presence of Organic Matter* The supply of nutrient material appears to be the most significant variable in the Bungonia system. This organic material consists of dissolved and particulate matter in the cave waters and detrital organic material. Throughout the Bungonia caves, organic material may be observed accumulated at the bottoms of shafts, in horizontal passages and in and around the sumps. In some parts its decay is slow: in drier sections of the caves tree trunks show little decomposition. However, leaves, twigs and branches in contact with water are completely decomposed. One tonne of tree detritus will produce one million litres of CO_2 which could, if used completely, dissolve 2 cubic metres of limestone.
4. *Presence of Oxygen* In the early studies at Bungonia, the assumption was made that the supply of CO_2 from micro-organisms would be limited by the availability of oxygen. However, although the highest rates of microbial CO_2 production occur with aerobic respiration, an increase is also observed when O_2 levels are very low, since certain anaerobic micro-organisms also produce CO_2. This means that the presence of oxygen is not necessary for microbial CO_2 production (for example, fermentation — beer or wine).

Plant and animal respiration contributes to the CO_2 levels in Bungonia Caves. During the bat breeding and maternity seasons in Drum Cave there is considerable increase in CO_2 concentration, due both to the respiration of several thousand bats, and to the action of micro-organisms in their waste. Figure 2 clearly shows a peak in the Drum Cave CO_2 concentration during this period (November-February). On occasions it is impossible to take measurements unless the operator wears breathing apparatus. A reduction of the CO_2 levels in the Grill Cave over the years appears to be the result of the bats abandoning this popular and heavily trafficked cave for the Drum Cave.

Respiration of plant and tree roots appears to be an insignificant source of CO_2. However, 1-2% CO_2 has been measured in the Root Chamber of Hollands Hole and 4-5% in The Steampipe, both of which contain tree roots. Tree roots are observed 50m below the surface, in some instances deeply etched into the limestone.

Humans are invaders into the natural system: the CO_2 was present before the caves were descended. The contribution of human respiration to the CO_2 concentration can be obtained from physiological studies. Expired air contains 4% CO_2, and in normal healthy humans at rest the respiration rate is 60 litres per minute. Therefore, in 24 hours, approximately 3500 litres of CO_2 are exhaled. This volume of CO_2 will produce a 0.3% change in the CO_2 content of the atmosphere in a closed chamber 10m × 10m × 10m. Compared to the major CO_2 sources, this is negligible: the measurement accuracy is only ± 0.1%. Nevertheless, measurements of gaseous CO_2 are always performed at the earliest opportunity. If the chamber is small (1m × 1m × 1m) the 3500 litres volume of CO_2 generated in 24 hours is three and a half times the volume of the chamber: extreme care must be taken in measurements in such confined spaces.

Carbon dioxide from burnt hydrocarbons (carbide, candles) is a small fraction of the total CO_2 present in a cave. A cap carbide lamp will produce 20 litres of CO_2 per hour (Stillman and Landecker 1958), which is small compared with the 140 litres or more produced by the carrier of the lamp in the same time. The use of carbide lamps at Bungonia is restricted because they do not burn well in high percentages of CO_2. The use of explosives and engines in the caves considerably contaminates the cave air. Both should be avoided where carbon dioxide studies are being carried out.

Volcanic emission into caves results in the highest values of CO_2 in caves, with values of 36% being recorded in the Hanimec Cave in Czechoslovakia.

5. *Variation of the Composition of the Cave Atmosphere* Total gas analyses allow subtle variations in the cave atmosphere to be detected. They also appear at present to be the most reliable method of indicating the source of the carbon dioxide. Table I illustrates a variety of cave atmosphere compositions for Bungonia caves:-

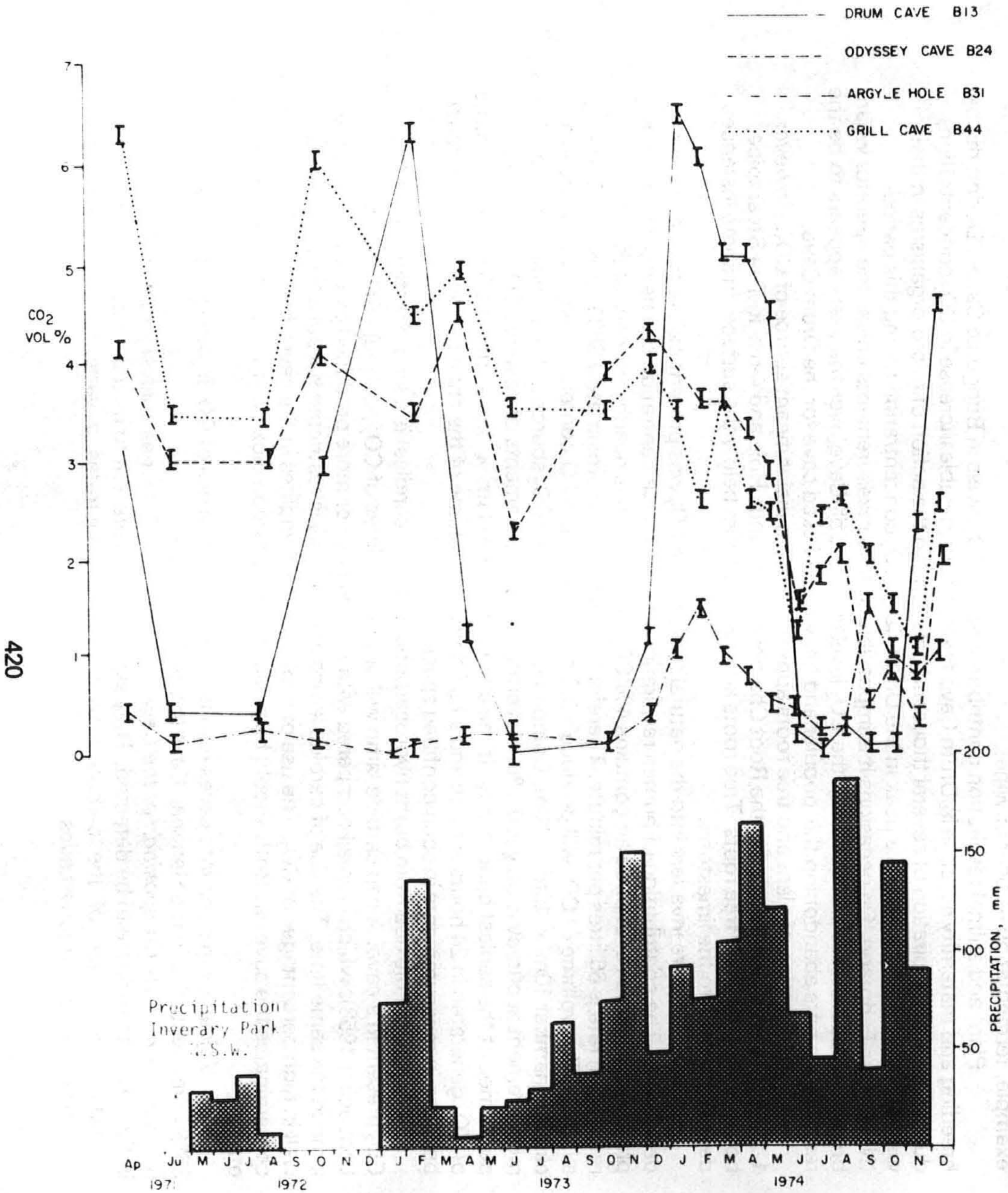


Fig. 2. Variation of carbon dioxide with season and precipitation.

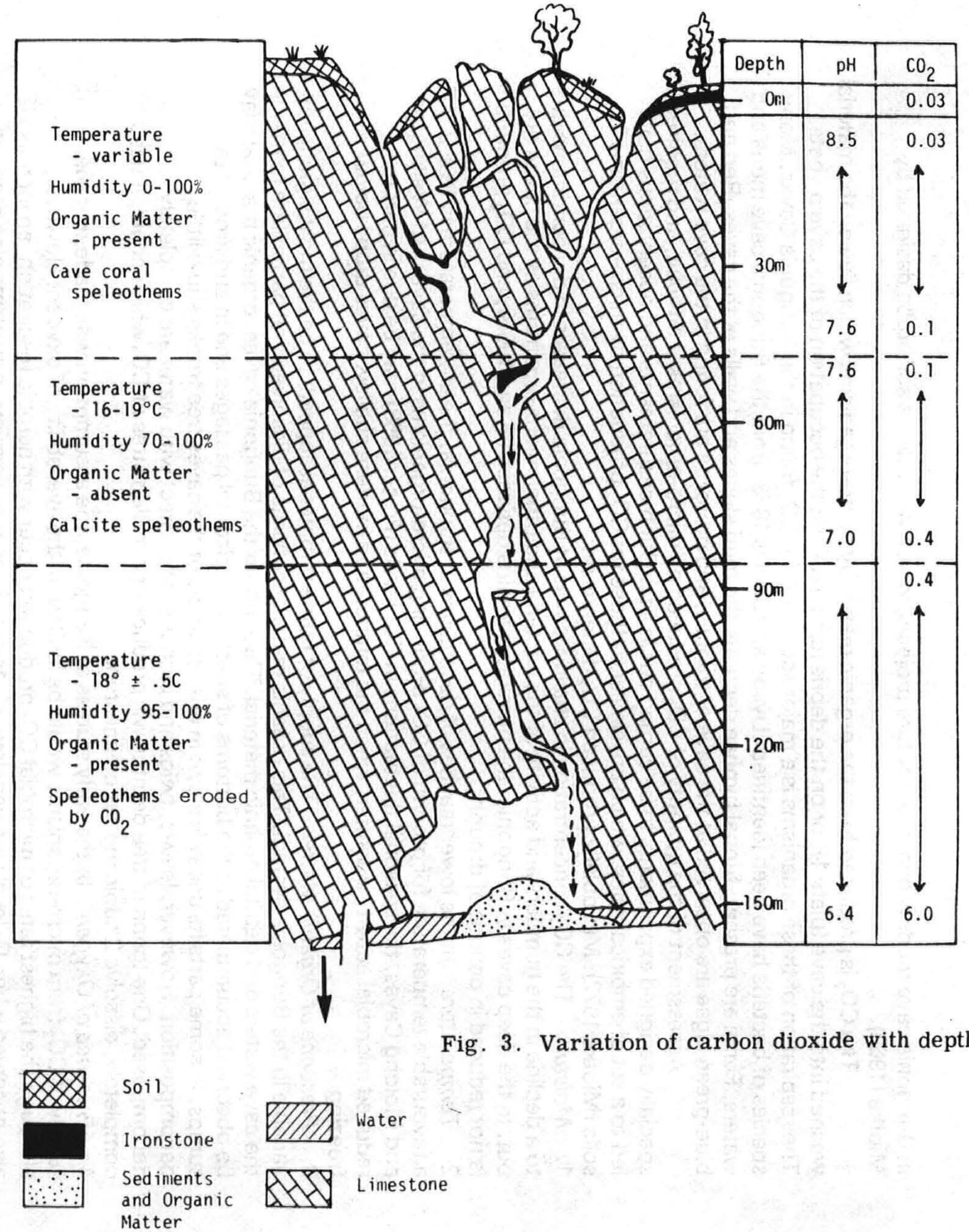


Fig. 3. Variation of carbon dioxide with depth.

Table 1: Major gas analyses for various caves.

Type	CO_2%	O_2%	N_2%*	Source
Atmospheric	0.033	20.95	79.03	(Glueckauf 1951)
Active cave Type I	0.4	20.7	78.9	September 1973 Odyssey Cave
	0.3	20.8	78.9	Ferbruary 1974 Olympus Cave
	0.2	20.8	79.0	September 1974 Chamber
Foul air cave Type II	4.2	15.5	80.3	Putrid Pit (Burke 1953)
	2.8	14.5	80.3	Odyssey Cave, Knockers Cavern, October 1973
	2.8	16.8	80.9	The Grill, The Pool, (Zamberlan 1971)
	3.0	18.0	79.0	The Grill, The Pool, (Moleman & Crawshaw 1971)
	3.5	16.2	80.3	The Grill, The Pool, October 1973
Foul air cave Type III	4.0	12.0	84.0	Pool in Odyssey Cave
	4.5	10.5	85.0	Pool in the Drum Cave
	1.0	10.8	88.2	Pool in the Grill Cave (Zamberlan 1971)
	4.6	11.0	84.4	The Sirens (Odyssey Cave)

*N_2% not measured ∴ (N_2 + Ar + water vapour)

Type I: In regions of the cave where active speleothem deposition is taking place CO_2 is added to the atmosphere (mechanism 2 above). If in addition there is no organic matter present and hence, little microbial growth, then the observed result is an increase in CO_2 and a decrease in O_2 and N_2 (a dilution of the cave atmosphere with CO_2). This effect is expected for all inorganic CO_2 sources: similar behaviour occurs when an inorganic acid is added to calcium carbonate. The diffusion of soil carbon dioxide downwards into the cave (mechanism 1 above) would produce a similar dilution of the cave atmosphere. The results shown in Table 1 are for Olympus Chamber in Odyssey Cave, a region of white calcite flowstone and helictites free of organic matter and soil.

Type II: In the foul air caves at Bungonia, the usual composition of the atmosphere is an increase in CO_2 and N_2 and a decrease in O_2. The increase in Nitrogen can be explained thus:- If carbohydrates are metabolised the CO_2 to O_2 ratio is 1. However, if other materials are present, especially those containing N this ratio is $>$ 1, therefore the percent volume of N_2 will increase (Peck 1961). The results (Table 1) all indicate consumption of oxygen and production of carbon dioxide, demonstrating that micro-organisms are the major source of the carbon dioxide.

In an effort to confirm the above conclusion the carbon dioxide at Bungonia was measured for its stable carbon isotope composition. $^{12}C/^{13}C$ was measured and found to be −23.6‰ (Smith personal communication). Micro-organisms concentrate the light isotope. Measured values for soil in rain forest range from −20 to −23.8‰ (Hendy 1971). However, this exceptionally high result does not prove that the carbon dioxide is produced in the cave, only that it comes from micro-organisms which could be in the soil outside the cave and passes directly from the soil atmosphere to the cave atmosphere.

Type III: When Zamberlan (1971) first reported gas analyses of this type they were received with some doubts. Analyses had been reported several times at Bungonia and similar results are reported from Riverhead Cave, Jamaica (Ashcroft, personal communication). This type of atmosphere is called 'stink damp'. It is typified by high CO_2, an unexpectedly low O_2, and a much higher than usual proportion of N_2, with a possible trace of H_2S, hence the name. The occurrence of stink damp is common in some coal mines. At Bungonia, Type III conditions appear to result from anaerobic bacterial action: under anoxic conditions at the sumps, oxygen is no longer available in cave muds and waters. Aerobic bacteria can no longer persist and anaerobic bacteria become active. Some of these bacteria use nitrate and evolve nitrogen so that the nitrogen concentration in the cave atmosphere may rise considerably. These anoxic conditions are first observed in the small stagnant pools in the cave especially during the period when the bats inhabit the caves. Nitrogen-producing bacteria have been identified from the caves at Bungonia (Dyson and James 1973) and high nitrate values (as high as 750 ppm) occur in the cave waters.

Alternative mechanisms involve removal of oxygen from the cave atmosphere by oxidation of inorganic or organic sediments. For example, the production of sulphuric acid from iron (11) sulphide. In Riverhead Cave, Jamaica, a possible sequence of events producing this condition is:

a) deposition of waste from a sugar mill into the cave stream;
b) fermentation of the sugar waste to form alcohol (C_2H_5OH) (rum) and carbon dioxide;
c) further oxidation of the alcohol to form acetic acid (CH_3COOH) — vinegar.

To define the source of carbon dioxide in caves a complete analysis of the major gases is essential and this, together with observation of the environment in which the gas is produced, will indicate its source.

Accumulation and Distribution of Carbon Dioxide

The concentration of carbon dioxide in the caves studied is far from uniform. The information from observations during the last seven years, together with literature reports from the last seventy years, is summarised in Figure 1. Here the maximum extent of distribution of the carbon dioxide in the cave and the levels below which the Bungonia Caves are never free of carbon dioxide are shown. Note that foul air may be encountered at any stage of the descent of a cave at Bungonia. Measurements and observations on the system have led to the following guidelines for the distribution of carbon dioxide within the Bungonia caves:

(i) Carbon dioxide is denser than air and will sink to the bottom of a closed cave system. On this basis, it is expected that there should be a gradient of carbon dioxide concentration in earth blocked shafts from a high level at the bottom, decreasing up the shaft (see Table 2). Carbon dioxide analyses for such caves at Bungonia (B3 and Putrid Pit) show no significant increase of CO_2 with depth, but the similarly blocked Igue Mathurin (France) (Renault 1972) shows a large carbon dioxide gradient. Local environment differences probably cause this variation. In general at Bungonia, the carbon dioxide concentrations in sealed rift sections of larger caves at Bungonia are relatively homogenous, as seen in The Steampipe, Blowfly Cave and Acoustic Pot.

Table 2. Comparison of carbon dioxide concentrations with depths (taken from existing surveys and recorded to the nearest 5m.).

Putrid Pit		L'Igue Mathurin September 1968		Grill Cave June 1968		Grill Cave March 1971		Drum Cave February 1974		B3 March 1970	
CO_2%	Depth m	CO_2%	Depth m	CO_2%	Depth m	CO_2%	Depth m	CO_2%	Depth m	CO_2%	Depth m
4.2	10	0.1	0	1.0	65	0.2	60	0.5	55	3.5	25
4.3	25	1.0	10	1.0	75	0.8	80	5.0	60	3.7	30
3.9	40	1.5	20	1.5	80	4.0	105	4.5	65	3.6	40
4.8	45	2.0	25	2.9	100	4.1	115	4.0	120		
		3.0	30	3.0	105	5.9	120				
		3.5	40	3.5	115	6.3	130				
		3.75	42.5								
REFERENCES											
Burke (1953)		Renault (1972)		Crawshaw and Moleman (1971)		This work		This work		This work	

At Bungonia the caves with flowing streams which terminate in water traps show a pronounced CO_2 gradient, increasing with depth. Table 2 shows results for the Grill Cave at the end of summer (March) and beginning of winter (June). Similar features have been observed in other stream caves, e.g. Swildon's Hole, Great Britain (Atkinson 1971) and Grotte Moulis, France (Renault 1972). However, the recorded concentrations of carbon dioxide in these are very much smaller.

Drum Cave under normal conditions shows the CO_2 gradient expected for a stream cave. However, during the bat maternity season an inverse gradient has been observed when the Drum Cave Stream is flowing. The carbon dioxide is highest in the chambers inhabited by the bats, which are the source of the CO_2, and decreases down the stream passage towards the sump. Inverse gradients of carbon dioxide in caves have also been noted by Renault (1972). These observations would suggest that this occurs when the carbon dioxide has a local source within the cave.

In various side passages of caves the CO_2 concentration gradients vary, resulting in different CO_2 concentrations at the ends of the passages. In three of the caves there are two sumps at approximately the same depth in separate passages. In the Grill Cave the sumps are 100m apart. It takes water 16 hours to flow from the left-hand branch sump to the right-hand branch sump under normal flow and the CO_2 concentration of atmosphere in the upstream sump is usually in the order of 1% higher than that of the downstream sump. The chemistry of the waters differs only in HCO_3^- concentration and pH, the other ion concentrations remaining essentially constant. In Odyssey Cave there is a similar situation. The sumps are much closer (50m apart) but the atmospheres are dramatically different. The CO_2 concentrations in the Sirens is usually 4% higher than that in Knockers Cavern with a stepped concentration gradient in The Sirens. Again, the chemistry of the waters differs only in pH and bicarbonate ion concentration.

In Argyle Hole the sumps are even closer together (30 m) but are connected by an air and an underwater connection. Only rarely do the atmospheres above the sumps differ noticeably. The difference in atmospheric composition in this case would be expected to be difficult to detect because of the very low concentrations of carbon dioxide normally present in the cave.

(ii) The primary effect of flood runoff should be to freshen the air throughout the cave, by allowing more carbon dioxide to dissolve. Also the strong water currents during floods entrain air along with them near their surface down to the bottoms of caves and this sets up return currents. The resulting air and water turbulence will tend to spread and thin the CO_2.

Steady rain has the same result as a flood: Table 3 shows the changes in carbon dioxide with the variation in rainfall at Bungonia. The secondary effect of flooding is to introduce organic matter, so that after the floods subside the CO_2 increases due to the increased activity of micro-organisms.

Table 3. Response of CO_2 concentrations to rain in Grill Cave.
(from Crawshaw and Moleman 1971)
Rain fell steadily for two weeks prior to 6.7.68 and precipitation during this period was 66mm.

15.6.68		6.7.68	
Depth	**% CO_2**	**Depth**	**% CO_2**
101 m	4.4	98 m	2.9
105 m	5.0	102 m	3.0
114 m	5.2	111 m	3.5

Figure 2 illustrates the variation of carbon dioxide with season and precipitation. The most detailed carbon dioxide measurements were taken of the atmospheres above the sumps in the five deep caves at Bungonia. Figure 2 illustrates the results of measurements in four of the caves; the fifth cave, B4-5 Extension, is extremely arduous and frequently blocked by silt and floods so only occasional measurements could be made in it. These infrequent measurements indicate that the carbon dioxide concentration above St. Patricks Lake is independent of the season and remains at approximately 3%. It would be expected to reach a peak value after a flood but this cannot be measured because the cave remains blocked by floodwaters for several months after the floods subside. The lack of seasonal variation in concentration may be explained by its remote location, although the distribution of the carbon dioxide in the cave varies considerably.

Argyle Hole is not normally considered to be a foul air cave. However, the floods of 1974 did wash organic matter into this cave and caused the CO_2 concentration to rise (Figure 2). Only in unusually high flood conditions such as these would organic matter wash into the cave since it has a small catchment area and rarely has a stream flowing down its entrance. Odyssey Cave and Grill Cave show surprisingly similar variations in CO_2 concentrations with precipitation. They both respond to flood waters with an initial drop in CO_2 concentration and a subsequent increase. Both caves have shown a decrease in CO_2 concentration over a period of years. In the case of the Grill Cave this is thought to be because the bats have abandoned it, whereas in the Odyssey Cave it is probably due to the freer water movement caused by the excavation of the Efflux (Bonwick 1972). Also, the years prior to 1973 at Bungonia were much drier; in 1974 there was three times the average annual rainfall. The increased rainfall may also contribute to the observed decrease of CO_2 levels (Figure 2).

(iii) At Bungonia the cave atmosphere shows seasonal variations. In summer the outside temperature never drops below the average temperature of the caves, about 18°C. Hence the relatively cold dense air remains in the lower levels of the cave without circulating. In winter the caves "breathe": the warmer air inside the cave rises resulting in an expansion of the distribution and a reduction in the CO_2 concentration. The same "breathing" effect was observed on two consecutive winter days in Odyssey Cave. On leaving the cave at 1800 hours it was observed that there was 4.4% CO_2 at the top of the Shale Band Pitch. The next day at 0900 hours it was first encountered 10m above the Shale Band Pitch but the concentration was 4.1%. Many Bungonia caves have been discovered by early morning misting in winter, notably the Steampipe (Holland 1967). This seasonal effect, also noted by Renault (1972) in the Grotte Moulis, France, is clearly illustrated in Figure 2.

At Bungonia the Drum Cave shows the greatest variation in CO_2 concentration, with a maximum in summer and during the bat breeding season. During the winter the cave is completely clear of CO_2. Whether the variation can be interpreted as a true summer-winter effect is questionable. In contrast, Argyle Hole shows little summer-winter variation. Odyssey Cave and Grill Cave show a much smaller but clearly measurable effect and the situation is not complicated by bats. Morphologically these caves (Figure 1) are both relatively small and constricted, while Drum Cave is large.

(iv) Pressure effects will also cause the caves to "breathe" (Wigley 1967). It is expected that at Bungonia these effects are small because the volumes of the caves are small. An exception may be the Drum Cave, where the pressure effect is a possible explanation for the greater variation of CO_2 in the cave relative to the other caves. However, even this cave may have too small a volume to be significant (Wigley — personal communication).

(v) The chemical system $CO_2 - H_2O - CaCO_3$ controls the atmosphere above the cave waters. CO_2 can be dissolved in or be released from the water. Consequently caves containing streams or lakes will have different CO_2 properties to mud- or silt-blocked caves.

The Formation of Speleothems in a Carbon Dioxide Atmosphere

Figure 3 shows a model of a typical active multientrance Bungonia Cave. The diagram shows variation of pH and CO_2% with depth. In the upper levels the humidity and temperature are variable. There is organic matter present, but any CO_2 it produces is dispersed by air circulation. Waters seep through from the surface and lose CO_2 by evaporation. This causes the precipitation of calcium carbonate, usually in the form of cave coral, (plate 2), a speleothem frequently associated with dry caves.

In the middle regions of the cave there are active speleothems. The CO_2 in the cave atmosphere is low (about 0.2%) and the humidity is high, so that saturated waters precipitate calcite upon loss of CO_2 to the cave atmosphere. If the air in the cave remains low in CO_2 throughout, as in Argyle Hole, speleothem deposition can be observed at the sump: the surface of the pool is sometimes covered with calcite rafts which disappear when CO_2 rises above 1%. A similar observation has been made in the Drum Cave, several weeks after a drop in the level of CO_2 from 5% to 1% calcite rafts appear on the water surface.

As would be expected from the information in Figure 3, there is currently no speleothem deposition near the bottom of the caves with high CO_2 concentrations. An exception occurs in The Sirens in Odyssey Cave, where there is an unusual speleothem which consists of thick filaments of organic material with thin calcite or aragonite bubbles at the bottom. these are found in a region usually of 7.3% CO_2 but were discovered when it was entered at the CO_2 value of 4.3%. In some alcoves and high in roofs of passages "young-looking" stalactites may be found and helictites may be abundant (plate 3). Here 3% CO_2, aragonite is being precipitated as fine needles and speleothems (plate 4). Siderite (iron(11) carbonate) crystallises from the Odyssey Cave final pool in times of very high CO_2 and low oxygen in the cave atmosphere.

Dissolution of Speleothems and Cavern Development

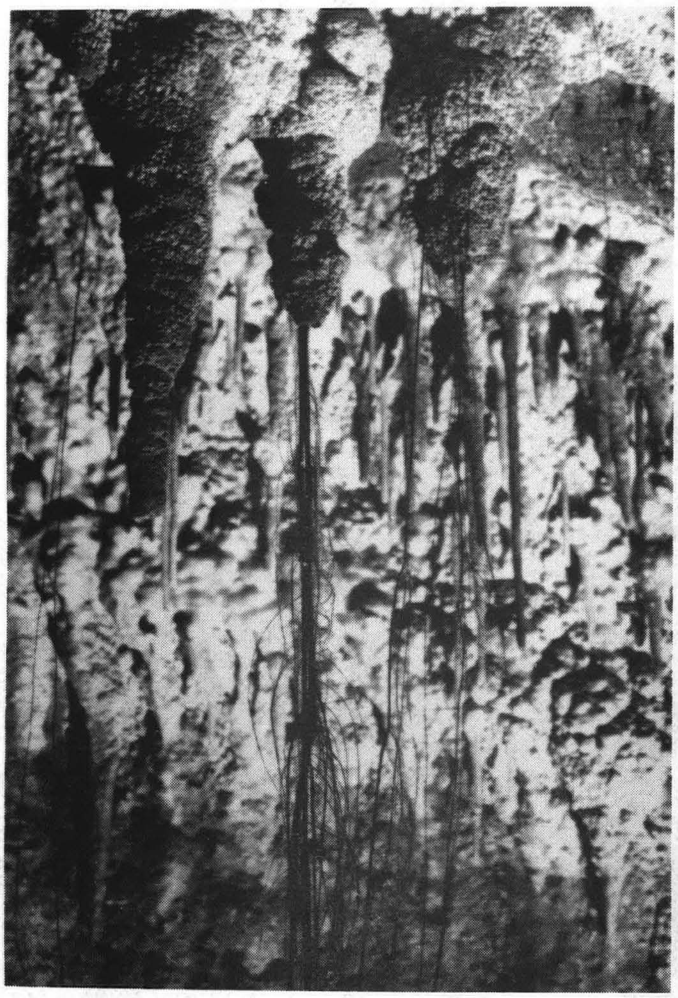
When the rain waters leave the Bungonia soil, they are aggressive and filter through the bedrock joints enlarging them by solution of calcium carbonate. Upon reaching a cave, seepage waters are usually no longer aggressive and calcite is precipitated from them, with release of CO_2. If the waters now move into a region of high CO_2, they become again unsaturated, thus once again aggressive and solution of limestone or dissolution of calcite speleothems may occur. In the lower regions of the Drum Cave and Odyssey Cave, there are many large speleothems which are undergoing such dissolution (plate 5). In these regions of the caves the limestone is friable and spongy showing clear evidence of attack by aggressive waters. The sumps in many of the deep caves are in large chambers, evidence of great chemical corrosion in the past. The approximate volume of the Drum Cave is 120,000m^3 and it contains, during the bat season, 5% CO_2. If this were completely used to dissolve calcium carbonate it would dissolve 12m^3 of calcite or limestone, and this CO_2 may be removed in one flood of several days. It is believed that, in Odyssey Cave, the presence of the CO_2 is recent (approximately 1,000 years (James 1975)) and there is ample evidence within this cave of the removal of calcite and the resulting dissolution of speleothems and wall rock. The large result of this mere thousand years of high CO_2 leads to speculation on how long it would take to form the volume of the Drum Cave: only about 10,000 years if the CO_2 remained at 5% and it was all used in cavern production.

The Caver and Carbon Dioxide at Bungonia

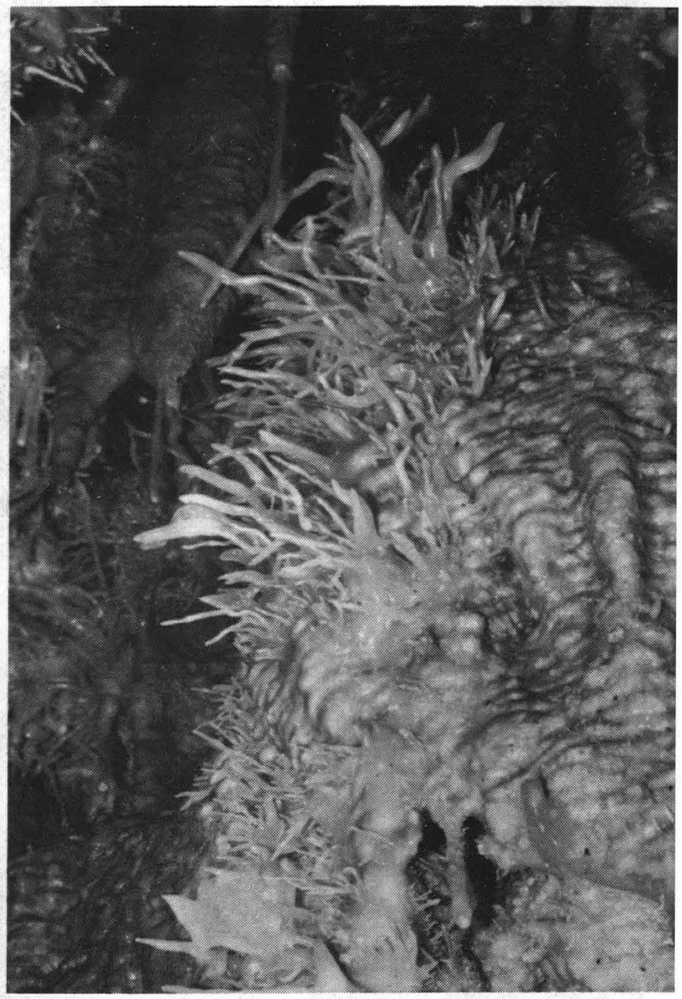
Cavers do not like CO_2 in caves as it prevents exploration and exploitation of the caves. The efforts of Australian cavers to drain Bungonia Caves of CO_2 by digging at The Efflux have all been unsuccessful:

"The original reason for digging The Efflux was to facilitate exploration by draining carbon

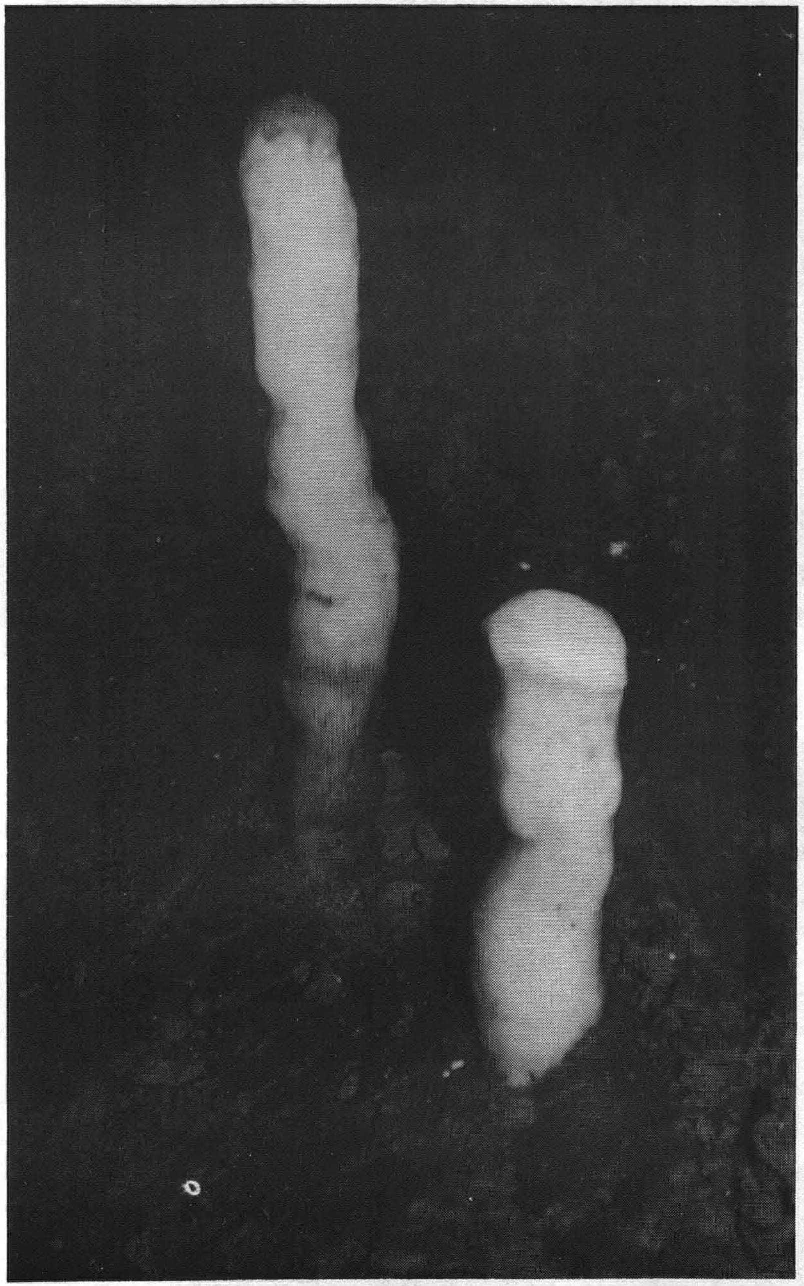
1. Organic debris in the final chamber of Drum Cave.



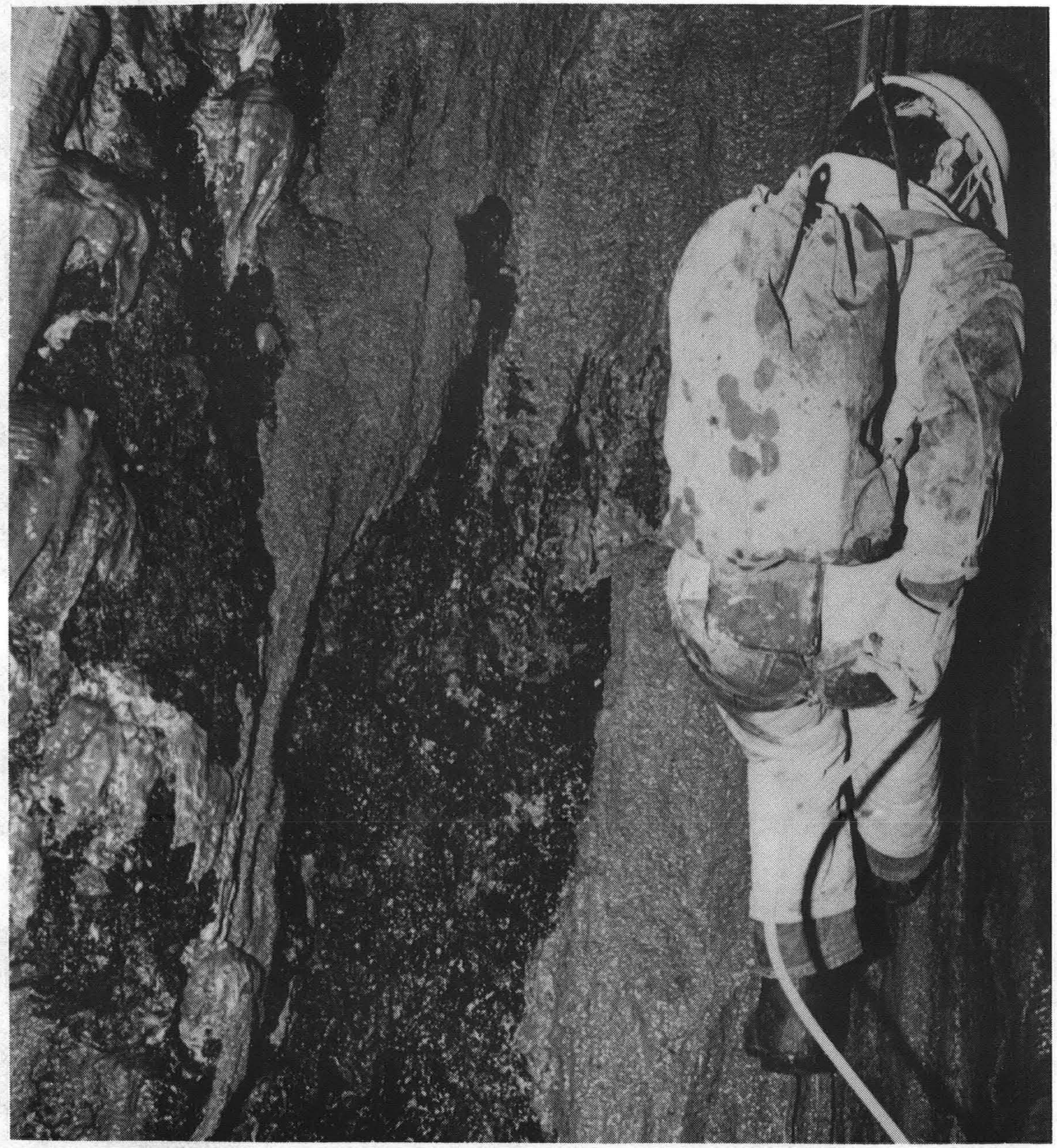
2. Tree roots and'cave coral' in Hollands Hole.



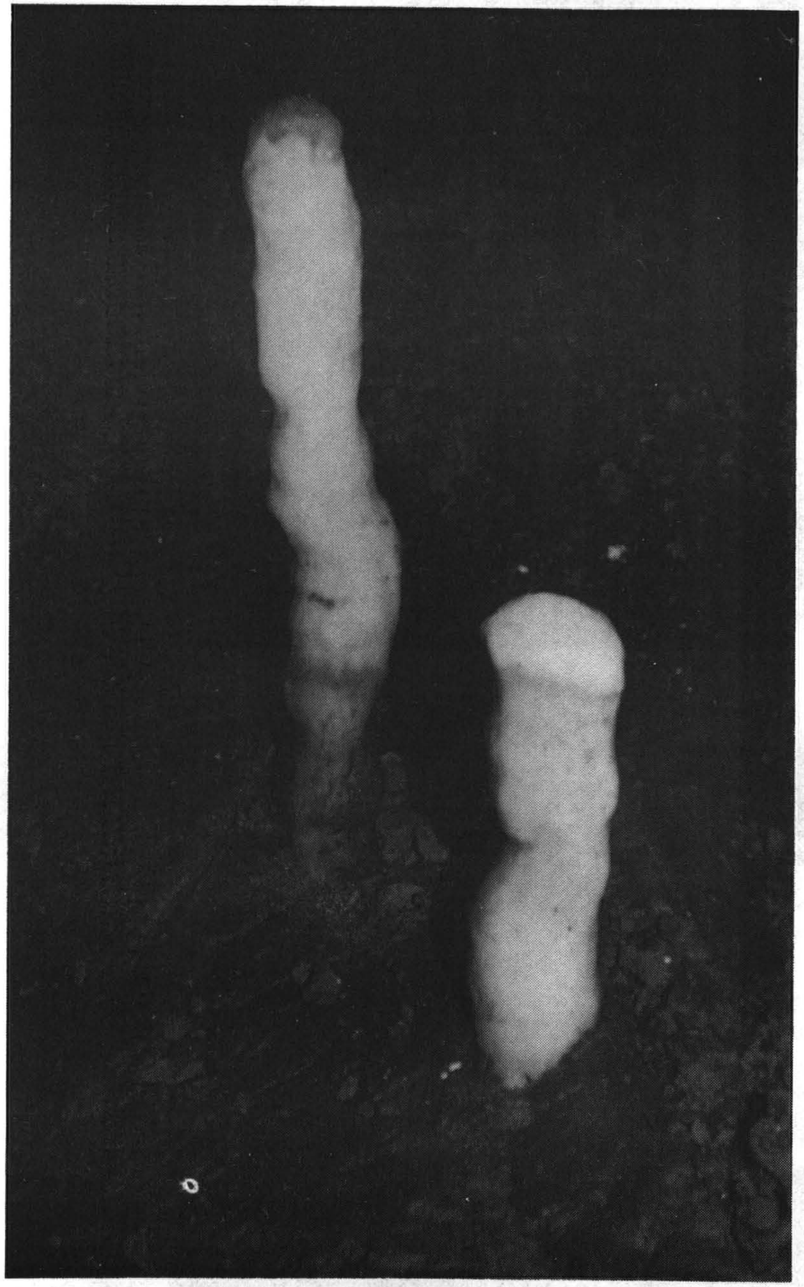
3. Helictite growth in a region of high C
(photo: A. Pavey).



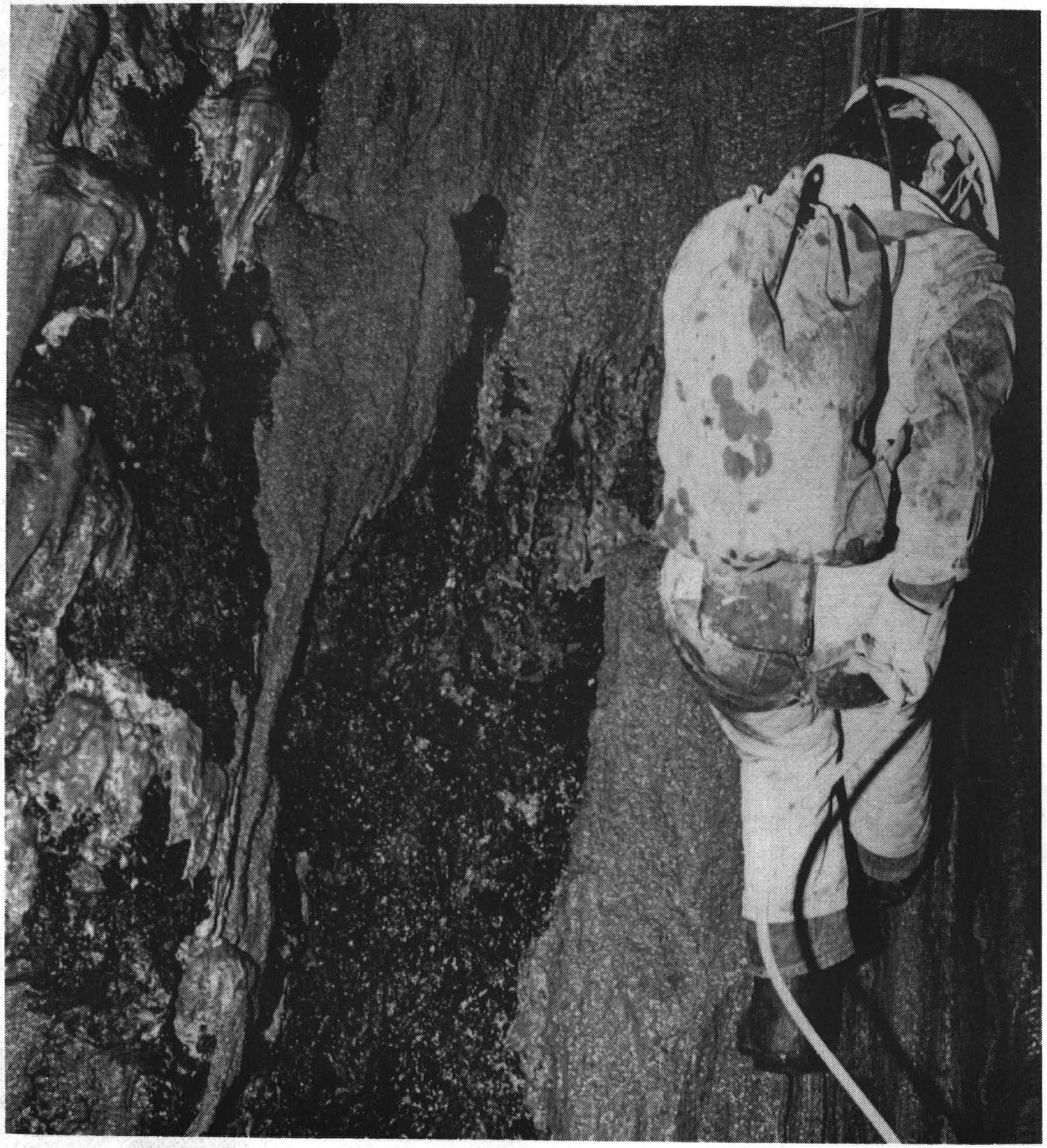
. The Naiads: aragonite speleothems growing in 3% CO_2. (photo: A. Pavey).



5. Solution of calcite flowstone in a region of high CO_2. (photo: A. Pavey).



4. The Naiads: aragonite speleothems growing in 3% CO_2. (photo: A. Pavey).



5. Solution of calcite flowstone in a region of high CO_2. (photo: A. Pavey).

2) sufficient vegetation above the caves to be washed into them during these floods,
3) overall rainfall low enough not to wash the organic matter out of the system.

Bungonia, when compared with many other cave systems both temperate and tropical, must be considered less than ideal for studying CO_2 production: because the vegetation above the cave is sparse, dry sclerophyll forest with medium undergrowth, and the floods washing it into the caves are often years apart. However, the Bungonia cave temperature is ideal for CO_2 production, and this with the geomorphology and hydrology of Bungonia Caves makes them one of the most efficient accumulators and best retainers of CO_2 known in the world.

Acknowledgements

The author wishes to thank the Australian Research Grants Committee, the University of Sydney Research Grant and the Sydney Speleological Society who have helped finance this study. The many members of Australian Speleological Societies who have taken carbon dioxide measurements. D. C. Ford, T. D. Ford, D. I. Smith and Jane Dyson for reading the manuscript critically.

APPENDIX **Methods and Measurements**

Temperature was measured on a calibrated mercury thermometer and read to plus or minus 0.02° centigrade. Humidity was measured by use of wet and dry bulb thermometers. The rainfall results were taken from the Australian Meterological Bureau, Sydney, N.S.W. The majority of carbon dioxide and oxygen measurements in the caves were taken using a Dräger apparatus. The variety of other methods by the other authors was discussed in James *et al.,* 1975. Samples have been collected for analysis in the labaratory by a variety of collection methods (James *et al.,* 1975).

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M.S. Received May 1977.

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Trans. British Cave Research Assoc. Vol. 4, No. 4, pp. 431-439 December 1977

An Appraisal of the Conductance Method for the In Situ Measurement of Total Hardness and Aggressivity

M. Allbutt

Summary

In the most usual conditions the only change in the solute load of cave waters derives from the solution of limestone and the deposition of calcite. By assuming a linear dependence between the amount of dissolved limestone and electrical conductivity a conductance method is proposed for the in situ determination of hardness and aggressivity. Parameters allowing for the temperature correction of conductivity are evaluated. The method has been subjected to experimental appraisal in several limestone areas. Provided waters in a cave system are calibrated for non-hardness solute load their hardness and aggressivity may be estimated to ± 5 p.p.m. $CaCO_3$ and ± 2 p.p.m. $CaCO_3$ respectively.

The Conductance Method

Recent work (Bray, 1975, 1976) has shown the advantages of a conductance method for determining the aggressiveness of cave waters in OFD. A water sample is brought to the laboratory, thermostated to 25°C and its conductance change on equilibrating with solid calcium carbonate is measured. A single empirical constant is then used to multiply the conductance change so converting it to an equivalent in p.p.m. $CaCO_3$. In seeking a means of measuring total hardness and aggressivity at the actual locale and temperature of a sampling point we independently conceived a similar method. This paper presents the results of an overall appraisal as to how closely conductance measurements may meet these objectives but is structured in its presentation so as to highlight more clearly the various assumptions and the limitations inherent in the method. As will be shown awareness of these latter factors imposes a discipline on usage of the method in the field but once this is accepted the manifold advantages of an immediate determination can over-ride doubts as to absolute accuracy.

Experimental

Although the ultimate intention is in situ measurement the appraisal investigation has mainly relied on water samples collected in the field and brought to the laboratory. However sufficient measurements have now been made directly in the field to confirm the validity of the appraisal and in particular to justify the point that temperature is the only significantly different parameter between the two environments.

In general at each sampling point two samples were collected in glass or hard plastic screw-cap bottles. To one was added c. 0.1 gm. Analar calcium carbonate so that equilibration was usually complete by the time the samples were available in the laboratory. Temperature treatment varied. Initially samples were thermostated but, after the determination of the temperature co-efficients of conductivity, samples were deliberately kept cool so as to remain close to their temperature at the collection point. Total hardness was determined on 50 ml. aliquots by EDTA titration as previously described by Wilcock *et al.* (1976).

Conductance was measured using a portable conductivity bridge manufactured by Electronic Instruments Ltd. (model MC1). To improve the sensitivity of this instrument the following procedure was adopted. The mode selection switch was turned to the TEST position and the galvanometer brought to the null position by rotation of the conductance dial. This dial was left in this position for the remainder of the measurement. The selection switch was then turned to the COMPARISON position and a 10,000 ohm non-inductive decade resistance box (a standard laboratory model as manufactured by W. G. Pye Ltd.) was connected across the comparison input socket. The conductance cell containing the water sample was connected across the test input socket. The decade box was adjusted to restore null deflection, the galvanometer being sufficiently sensitive to allow direct resistance readings reproducible to ± 0.2 ohms. Using the appropriate cell constant this resistance was then converted to conductance in units of micro-mhos cms^{-1}. When used in the field occasional erroneous values could be obtained for reasons which were identified as due to leakage currents to earth through the shield of the decade box. Accordingly field measurements were made using the instrument in the conventional manner sensitivity being thereby reduced from 1 part in 10^4 to 1 part in 10^3. At all times the temperature dial was set at 25°C so that no internal temperature compensation took place.

Effect of temperature

For conductance measurements the principal difference between laboratory and field is that of temperature which cannot be pre-selected or controlled in the latter situation. Since conductance is highly temperature dependent we are obliged to convert field measurements to some common temperature datum. It was found that the amount of correction needed was considerably more than the 2% per degree usually adopted for strong electrolytes. Over the range 0° to 30°C graphs of the conductance of cave waters versus temperature showed pronounced curvature which according to a curve fitting computer program POLFIT could only be adequately represented by a quadratic equation in T:

$$K_T = K_0(1 + \alpha T + \beta T^2) \qquad (1)$$

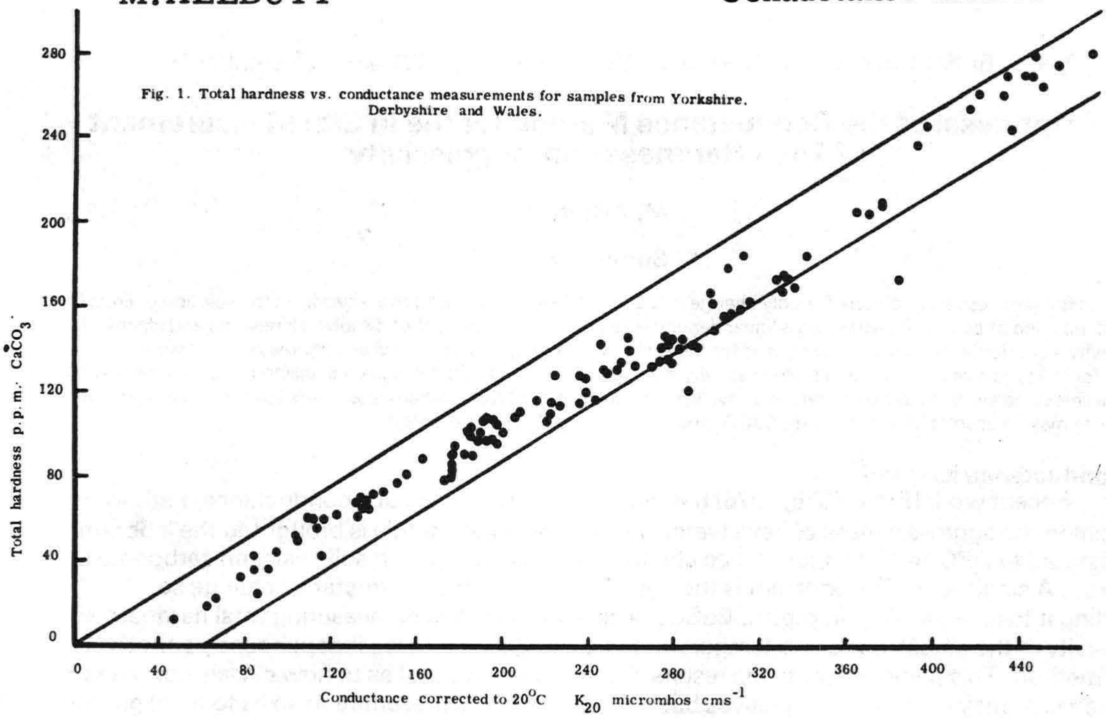

Fig. 1. Total hardness vs. conductance measurements for samples from Yorkshire, Derbyshire and Wales.

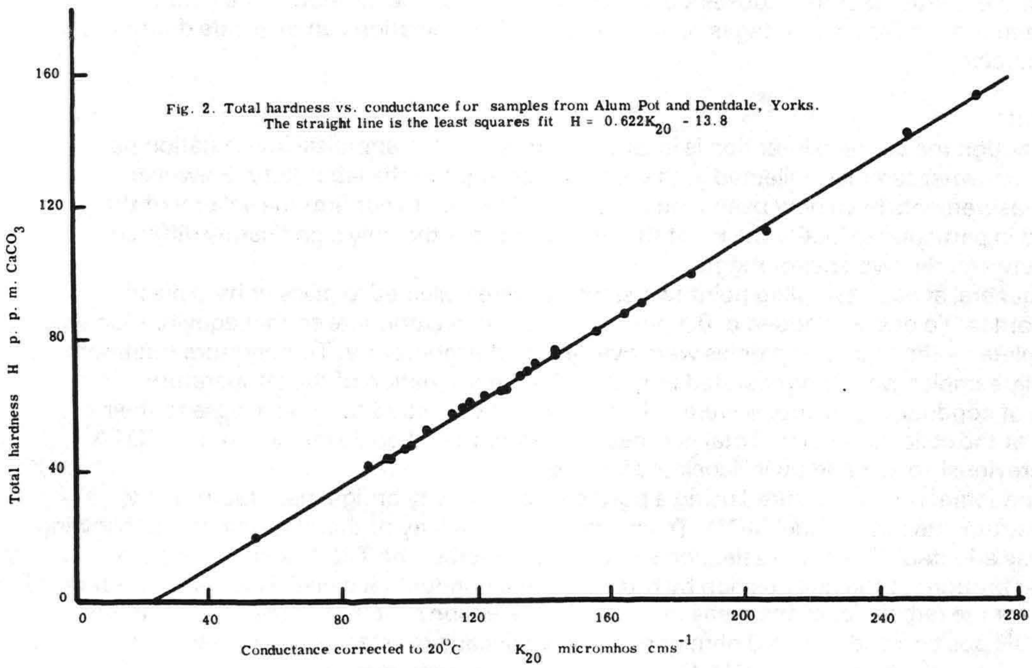

Fig. 2. Total hardness vs. conductance for samples from Alum Pot and Dentdale, Yorks. The straight line is the least squares fit $H = 0.622K_{20} - 13.8$

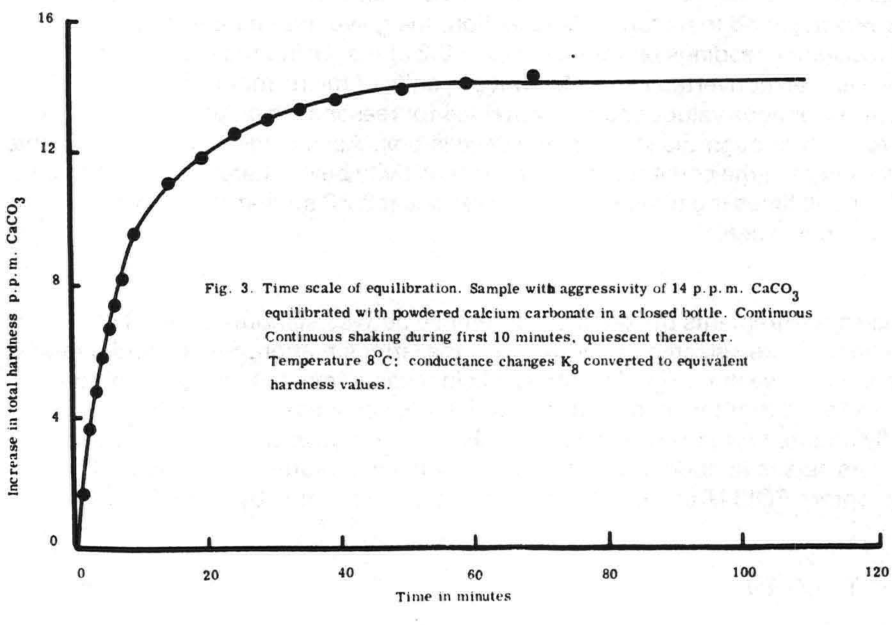

Fig. 3. Time scale of equilibration. Sample with aggressivity of 14 p.p.m. $CaCO_3$ equilibrated with powdered calcium carbonate in a closed bottle. Continuous Continuous shaking during first 10 minutes, quiescent thereafter. Temperature 8°C: conductance changes K_8 converted to equivalent hardness values.

where K_0 is conductance at 0°C,

K_T is conductance at T°C

and α and β are empirical constants whose values varied slightly between different waters. The mean of values for four samples chosen to be as representative of cave waters as possible (see Appendix 1) was

$$\alpha = 3.61 \times 10^{-2}$$

$$\beta = 1.27 \times 10^{-4}$$

and these were used in subsequent conversions to a temperature datum of 20°C.
Specifically conductances measured at T°C were converted to datum by

$$K_{20} = K_T \times (1.7728/(1 + \alpha T + \beta T^2) \qquad (2)$$

where K_{20} is a calculated conductance at 20°C.

We might suspect that the non-linear temperature dependence of (1) is due to changing concentrations of ionic species superimposed on a linear dependence for individual ionic conductance. Some support for this conjecture can be found in figures for the separate ionic concentrations in saturated solutions of calcium bicarbonate kindly provided by Dr. R. Picknett. Four ions only, Ca^{2+}, HCO_3^-, CO_3^{2-} and $CaHCO_3^+$, make significant contributions to conductance, with individual ionic conductances at infinite dilution known for all except $CaHCO_3^+$. Assuming $\lambda_{25} = 40$ for this ion, together with a 2% per degree change for each ion, a first order estimate of expected conductance of calcium bicarbonate solutions at different temperatures can be made (see Appendix 2). For a total hardness of 60 p.p.m. $CaCO_3$ we find:-

Temperature °C	25	20	16	10
K expected	126.67	112.59	101.83	82.48 micromhos cms^{-1}
Ratio R_1	1.12	1.00	0.904	0.733
Ratio R_2	1.12	1.00	0.909	0.775

Two sets of ratios are included above. R_1 is the ratio K expected with respect to the value at 20°C. R_2 is the ratio K_T/K_{20} from equation (2). Agreement at 25° and 16°C is good, justifying the assertion of non-linear behaviour, but not in itself "proving" equation (2) which remains wholly empirical.

Estimation of Total Hardness

Other things being equal conductance will clearly increase as total hardness rises but the important question is whether this dependence is sufficiently regular to permit a conductance measurement to be used solely as an estimate of hardness. Figure 1 may be taken as providing the answer to this question. It shows an indiscriminate plot of around 160 data points for which conductance was measured and total hardness determined by EDTA titration. 120 of the points are from our samples collected in several different areas of Yorkshire, Derbyshire and near Llangollen on different occasions, the remaining points being from Bray (1976) and pertaining to the OFD system. Conductances were measured at temperatures between 9° and 25°C but are converted to a 20°C datum using equation (2).

Our interpretation of figure 1 follows from a model of the cave system as used by Richardson (1974) to describe the Alum Pot area. Prior to entering a cave system catchment waters collect a mixed load of hardness and non-hardness solutes. Within the system the only extra solute derives from limestone solution and this is reflected in an increasing total hardness, the non-hardness solute load remaining constant. If we now assume a linear dependence between hardness and conductance then, in equation form, this can be expressed:-

$$H = \gamma \, . K_{20} - \delta \qquad (3)$$

where H is total hardness in p.p.m. $CaCO_3$

K_{20} is conductance in micromhos cms^{-1}

γ equals the slope of H vs K_{20} line

and δ represents the contribution of non-hardness solutes.

That δ may indeed remain constant for the same cave system or even over the same catchment area is demonstrated by figure 2 which shows 15 data points for samples from the Alum Pot system and the geologically similar Dentdale area all collected within the same 24 hour period. The above description of δ is further supported by a chloride level of 8 p.p.m. Cl found in all samples on this occasion.

Figure 1 is therefore to be described in the following terms. The data points lie on a family of straight lines of constant slope γ but with varying δ. Two lines of slope γ are drawn to define an envelope which contains 95% of all the data points. The excluded points are notable as belonging to samples with anomalously high chloride levels or with appreciable potassium or sulphate contents. The slope of the envelope lines (drawn by hand) gives $\gamma = 0.625$ whilst its vertical width corresponds to 40 p.p.m. $CaCO_3$. This latter figure gives a measure of the uncertainty in a hardness estimation from a conductance measurement or, put more precisely, from figure 1 we infer that there is a 95% chance that hardness calculated by

$$H = 0.625\,K_{20} - 20 \qquad (4)$$

will be accurate to ±20 p.p.m. $CaCO_3$

The possibility of greater accuracy arises if, while studying a common system, a sample is taken for total hardness determination by EDTA titration. We can then "calibrate" the system in terms of δ, that is

$$-\delta = (TH)_{edta} - \gamma . K_{20} \qquad (5)$$

We later assess the worth of calibration but before doing so examine an alternative approach to finding the value of γ. Expecting that samples from the same system will be distributed nearer to a single straight line, as in figure 2, it would be reasonable to calculate γ from the least squares fit to such data points. Some selection of sites is necessary to avoid data which is clustered in too narrow a range of hardness but 8 sets of samples were identified each covering a range of more than 100 p.p.m. $CaCO_3$. A computer program CURFIT was used to calculate individual γ and δ values with results as shown in table 1. Values of γ range between 0.596 and 0.630 with mean of 0.609. However the susceptibility of the least squares fit to inevitable clustering of data points inclines us to reject choosing this mean as a value of γ. We prefer instead to adopt a value based on a set of samples for which the experimental evidence indicates the absence of any anomalies. This is the case with the combined Alum Pot/Dentdale samples shown in figure 2 and accordingly we choose $\gamma = 0.622$ as computed for this line. This is sufficiently close to the value in equation (4) and the median of table 1 to inspire a fair measure of confidence in subsequent calculations.

TABLE 1

LEAST SQUARES FIT TO SETS OF SELECTED DATA POINTS (see text)

Sampling Area	Date	Number of samples	γ	δ
1. Alum Pot	6/12/75	12	0.615	13.3
2. Alum Pot	10/9/76	14	0.596	19.8
3. Dentdale	7/12/75	15	0.631	15.0
4. Dentdale	8/9/76	6	0.576	20.2
5. Dentdale	9/9/76	7	0.609	29.5
6. Derbyshire	11/1/76	16	0.615	21.8
7. Llangollen (World's End)	8/2/76	12	0.599	8.6
8. OFD	—	48	0.630	19.8
Combined 1 and 3		31	0.622	13.8

We are now concerned to test the improvement in accuracy upon using equation (3). The choice of calibration sample is bound to be subjective — should it be from a sinking, rising or streamway? Probably in most instances a streamway will be the preferred choice if only because a streamway will presumably be present even if associated sinkings and resurgences are unidentified.

Tables 2 et seq. are based on a re-working of data points from figure 1 according to the following scheme:

a) conductance K_T as measured at T°C is converted to K_{20} by equation (2)
b) for one particular sample total hardness is determined by EDTA and δ calculated using equation (5)
c) the tables then record

(i) temperature of conductance measurement
(ii) total hardness by EDTA
(iii) estimated hardness calculated by $H = 0.622.K_{20} - \delta$
(iv) difference between (ii) and (iii) as error in estimate
(v) additional data pertaining to aggressivity (see below)

For example table 2 comprises data for samples collected in Dentdale on three separate occasions:
on Dec. 7th 1975 in conditions of moderate flow,
on Sept. 8th 1976 at the climax of the summer drought,
on Sept. 9th 1976 following overnight rain.

A calibration at the Barth Bridge rising is applied for each occasion and the respective δ values of 11.9, 32.1 and 33.1 are perfectly consistent with the expectation of high non-hardness solute loads in low flow conditions. Except for Oliver Gill where contamination by domestic effluent was visually observed, the hardness estimations are within 6 p.p.m. $CaCO_3$ of the titration value but show a clear

TABLE 2 Dentdale Area

Comparison of measured and estimated hardness and aggressivity at 8 sampling points

Calibration at Barth Bridge Rising:- (a) 7/12/75 $\delta = 11.9$
(b) 8/9/76 $\delta = 32.1$
(c) 9/9/76 $\delta = 33.1$

Sampling Point	NGR	T	TH	H	E	ΔH	$\gamma.\Delta K$	Date
Barth Bridge	SD695879	15	141.5	141.5	0	+10.9	+12.5	a
Rising		15	173	173.0	0	0	+2.8	b
		13	174	174.0	0	0	+0.7	c
River Dee above	696878	15	61	63.7	+2.7	+3	+4.0	a
Barth Bridge			river bed dry					b
		12.5	155	159.5	+4.5	—	—	c
Nettle Pot	696875	15	55	59.3	+4.3	+7	+5.5	a
Resurgence		15	135	141.0	+6.0	−2	+2.0	b
		11	116	119.1	+3.1	0	0.0	c
Oliver Gill @	696875	15	59	60.9	+1.9	+40	+40.6	a
Resurgence			resurgence dry					b
		11	168	177.7	+9.7	−2	−3.7	c
Nettle Pot	694874	15	52	52.7	+0.7	+4.5	+4.6	a
Sink		11	106	105.1	−0.9	+3	+1.1	c
Oliver Gill Sink @	694875	12	168	207.7	+39.7	+1	−1.0	c
Mixed Nettle Pot	696876	15	70	71.5	+1.5	+5	+5.0	a
& Oliver Gill Resurgence		14	134	138.7	+4.7	−2	−2.2	c
Popples Rising	729862	14	159	162.5	+3.5	+1	+2.1	c

@ — contamination observed at Oliver Gill Sink

Column Headings

NGR	national grid reference
T	temperature of conductance measurement
TH	total hardness by EDTA titration
H	hardness estimate from conductance
E	error in estimate as (H — TH)
ΔH	aggressivity by EDTA titration
$\gamma.\Delta K$	conductance estimate of aggressivity

TABLE 3 Alum Pot Area

Calibration at Diccan Pot Entrance (a) 6/12/75 $\delta = 13.8$
(b) 10/9/76 $\delta = 24.9$

Sampling Point	T	TH	H	E	ΔH	$\gamma.\Delta K$	Date
Turn Dubs	20	112	113.8	+1.8	+6	+4.8	a
	13	183	188.1	+5.1	—	—	b
Diccan Pot Entrance	20	44	44.0	0	+4	+5.7	a
	13	89	89.0	0	−1	0.0	b
Wilson's Cave Exit	13	115	114.5	−0.5	−2	+3.3	b
Upper Long Churn Entrance	20	43.6	43.1	−0.5	+3.4	+5.9	a
	13	85	85.7	+0.7	0	−0.3	b
Borrin's Moor Entrance	20	43.6	43.6	0.0	+3.4	+4.0	a
	12	90	85.2	−4.8	−4	+0.5	b
Beck in catchment area	20	32	34.2	+2.2	+9	+6.0	a

TABLE 4 Ibbeth Peril Cave in Dentdale SD 741864

Calibration at Top Inlet Passage; $\delta = 31.6$
Sampling date 9/9/76

	T	TH	H	E	ΔH	$\gamma.\Delta K$
Top Inlet Passage	13	140	140.0	0	+5	+6.0
Roof Seepage in Top Inlet passage	13	280	265.7	−14.3	−26	−14.0
Bottom Streamway	12	114	116.4	+2.4	+1	+1.2
Roof Seepage above Bottom Stream-way	12	144	143.0	+1.0	−1	−0.7
Pool in Entrance Passage	13	208	203.6	−4.4	−5	−3.6

TABLE 5 River Lathkill in Lathkilldale, Derbyshire

Calibration at Rising below Ford; $\delta = 5.0$
Sampling date 7/3/76

Sampling Point	NGR	T	TH	H	E	ΔH	$\gamma.\Delta K$
First Risings	SK174656	9	269	272.6	+3.6	+1.4	+0.2
Second Risings	174656	7	275	280.7	+5.7	−1	−1.0
100 m. below footbridge	174655	8	274	279.9	+5.9	−14	−15.1
Opposite Mandale mine	196661	7	254	254.5	+0.5	−18	−15.9
Rising below ford	204662	7	270.4	270.4	0	−0.8	−0.5
Small Rising in north Bank	209660	8	270	266.1	−3.9	−9	−8.6
Over Haddon Bridge	213656	8	262.4	259.8	−2.6	−17.4	−17.3

TABLE 6 Stanley Moor Catchment, Buxton

Calibration at Anthony Hill Swallett; δ = 20.2
Sampling date 11/1/76

Sampling Point	NGR	T	TH	H	E	ΔH	$\gamma.\Delta K$	Cl
Axe Hole Sinking	SK042716	18	35.5	31.2	−4.3	+12	+12.0	9
Plunge Hole Sinking	045713	18	42.5	51.6	+9.1	+9.5	+8.0	16
Jakes Hole Sinking	043709	18	24.5	32.8	+8.3	+16	+11.6	14
Anthony Hill Swallett	046704	18	36	36.0	0	+7.5	+7.2	9
Countess Cliff Resurgence	055710	19	204	206.7	+2.7	−1	+0.7	20
Sherbrook Lodge Resurgence	063723	18	207	214.3	+7.3	−5	−6.6	22
Wye Head Resurgence	050730	19	160.5	169.7	+9.2	−2.5	−5.0	20

Cl — p.p.m. chloride by $AgNO_3$ titration.

bias towards over-estimation. Were Popples Rising or Nettle Pot Resurgence used for calibration this bias would have been eliminated and estimates lie within ±3 p.p.m. $CaCO_3$. A similar level of accuracy is found for samples collected on two separate occasions in the Alum Pot area (table 3). Table 4 presents results taken within an active cave system whereas table 5 provides quite remarkably exact estimates for the River Lathkill in Derbyshire. Here all samples exceed 250 p.p.m. $CaCO_3$, well beyond the range of figure 2, yet, even with conductance measured at around 7°C, estimates are within 6 p.p.m. of titration values.

In contrast table 6 describes data for the worst case examined. The catchment area for Wye Head and Sherbrook Lodge resurgences near Buxton was noted for contamination by road salt and industrial waste. The calibration at Anthony Hill Swallett used relatively clean water as judged by chloride content and in consequence hardnesses elsewhere are consistently over-estimated.

The need to distinguish "clean" and "dirty" systems is an obvious preliminary to application of the method. Fortunately, because of the usual remoteness of catchment areas, clean systems seem relatively common and, given that a calibration sample is carefully chosen and measured, the previous confidence level of ±20 p.p.m. in total hardness is seen to be improved to around ±5 p.p.m. $CaCO_3$.

Determination of Aggressivity

On equilibrating an aggressive water with calcium carbonate both total hardness and conductance are observed to increase with a corresponding decrease for a super-saturated water. Moreover in both cases there appears to be some proportionality between ΔH, the hardness change, and ΔK, the conductance change. Bray (1976) assumes that the value of the ratio $\Delta H/\Delta K$ is the same as that of the slope of the empirical H vs K plot. The justification for this is that since, by definition, only an aggressive water will dissolve limestone then a linearity between H and K must be reflected in the same linearity between ΔH and ΔK. Against this is the proposition that on theoretical grounds there is no case for assuming that because two phenomena identify a parameter with the same dimensions then both parameters must have the same numerical value. Indeed we can isolate three cases where a parameter with the dimension conductance.hardness^{-1} can be evaluated, viz.

1) the slope H vs K_{20} for equilibrium solutions of $CaHCO_3$ — γ_1
2) the slope H vs K_{20} for general cave waters — γ_2
3) the ratio $\Delta H/\Delta K$ obtained by experiment — γ_3

Case 1 can be partially resolved again using data from R. Picknett, this time for different total hardness at the same temperature. From calculated conductances at 20°C we estimate γ_1 = 0.55 as a mean slope. This is likely to be a lower limit since the effects of inter-ionic attraction will diminish actual conductance so increasing the slope. Case 2 has already been discussed. Unfortunately for the evaluation of $_3$, ΔH, when determined by EDTA titration, becomes the difference between two relatively large numbers each in error because of end-point uncertainities by at least ±1 p.p.m. $CaCO_3$. ΔK is inherently less error prone. 21 samples, including both aggressive and super-saturated waters, were identified in which Δ exceeded 4 p.p.m. $CaCO_3$. A weighted mean calculated as
A weighted mean was calculated as

$$\gamma_3 = \frac{\sum \frac{\Delta H}{\Delta K} \times \Delta H}{\Sigma \Delta H}$$

giving γ_3 = 0.696 at 20°C.

This value for γ_3 is significantly different from that for γ_2 supporting the above proposition but to use

$$\text{Aggressivity } (=\Delta H) \quad = \quad \gamma_2 K_{20} \qquad (6)$$

to estimate aggressivity is not likely to give systematic errors exceeding those of the titration method.

To illustrate this additional columns in tables 2 to 6 record aggressivivty determined by EDTA titration (ΔH) and calculated by equation (6) using $\gamma_2 = 0.622$. Given that ΔH can itself be in error by ±2 p.p.m. $CaCO_3$ then the correspondence with $\gamma . \Delta K$ is somewhat better than might have been suspected from the foregoing discussion. Moreover the choice of equation 6, even if of dubious theoretical validity, has the merit that the whole framework of investigation rests on the single assumption embodied in equation (3).

For in situ determinations the conductance method has a certain practical drawback which arises from the time scale for equilibration. By continuous measurement of conductance this time scale can be established. Figure 3 shows a typical result from such experiments showing the conductance changes in an aggressive water dosed with Analar calcium carbonate. Other experiments were carried out in which various shaking/settling regimes were essayed and the general conclusion was that at temperatures below 10°C at least one hour is required for equilibration in a closed bottle and that during this period at least one vigorous shaking should be given. The on-site investigator is therefore obliged to adopt the following discipline.

At the chosen sampling point conductance and temperature are measured to provide a reference datum. A sample is then bottled with calcium carbonate and left in the vicinity — ideally at the same temperature as the datum. This bottle is shaken at least once after the next 30 minutes and its conductance and temperature re-measured after at least a further 30 minutes. Measurements can be made at several sampling points on the same occasion provided a rota of return and agitation can be arranged.

However certain results obtained in this appraisal, notably those from the River Lathkill, cause the author to question the significance of aggressivity values obtained on equilibration in closed containers. It is seen from table 5 that in passing down the River Lathkill hardness progressively decreases whereas supersaturation, as measured in closed containers, generally increases. Clearly the river water is losing CO_2 to the atmosphere faster than the precipitation of calcite. On equilibrating with calcium carbonate in an open container for several days all samples, irrespective of source, declined to a total hardness of 230 p.p.m. $CaCO_3$. The risings are therefore supersaturated with respect to open atmosphere to the extent of 40 p.p.m. $CaCO_3$ whilst being essentially in equilibrium with the cave system atmosphere from whence they came. It is in this area of the dynamic behaviour of the waters of a cave system that the conductance method probably has a major role to play, for it permits the detailed monitoring with time and distance of cave waters within their actual environment. Measurements of conductance along the length of an active streamway or on the mixing of two different water flows can now be confidently translated to actual hardness variations and thereby can help our understanding of cave solution and deposition processes.

Acknowledgements

The Author wishes to thank the Chemistry Department of the North Staffordshire Polytechnic for the loan of equipment, the Whernside Manor Caving Centre for use of laboratory facilities and J. D. Wilcock Esq. for every encouragement and assistance.

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APPENDIX 1

Samples for determination of temperature coefficients of conductivity: Various samples were collected and admixed so as to embrace a wide representation of natural cave waters.

a) Wye Head Resurgence, Buxton (GR SK 050730)
b) Brook Bottom Rising (GR SK 057712) nr. Buxton
c) Sample (a) admixed with local rain-water
d) Mixture of several waters from Dentdale itemised in table 2

Samples were subject to a temperature cycle starting at 15°C cooling to 0°C, warming to 30°C and finally cooling to 15°C again. Conductance was measured at various temperature points around the cycle. Equality of conductance at start and finish confirmed that no change of composition or contamination had occurred. A curve fitting computer program POLFIT was used to find the lowest degree of polynomial in T which would adequately reproduce the experimental data. A quadratic was found satisfactory in that no improvement in the error of estimate was obtained by polynomials of degree 3 or 4. Values of the coefficients K_o, $\propto$, β in equation (1) were respectively

Sample	K_o	$\propto$	β
(a)	172.968	0.034559	0.000130533
(b)	114.224	0.035117	0.000128849
(c)	115.188	0.0374103	0.000129721
(d)	70.6766	0.03749	0.0001192
	Average	0.03614	0.0001271

APPENDIX 2

Individual ionic concentrations in saturated solutions of calcium bicarbonate were obtained by R. Picknett. Individual ionic conductances at infinite dilution were calculated as a function of temperature by

$$\lambda_T = \lambda_{25}(1 + 0.02(T - 25))$$

With values of λ_{25}^{∞} taken from Robinson & Stokes (1955) we find:

Temperature	Ca^{2+}	HCO_3^-	CO_3^{2-}	$CaHCO_3^+$	H^+	OH^-
25	59.5	44.5	69.3	40	349.8	198.6
20	53.6	40.1	62.4	36	314.8	178.7
16	48.8	36.5	56.8	33	286.8	162.9
10	41.7	31.2	48.5	28	244.9	139.0

The contribution of each ionic species to the conductance of the solution is then calculated as $\lambda_T^{\infty} \times z \times c$ where z is ionic charge and c is ionic concentration; e.g. for 60 p.p.m. $CaCO_3$

Temperature	10°C	16°C	20°C	25°C
ions: Ca^{2+}	46.37	56.71	61.96	68.66
HCO_3^-	34.01	41.97	46.11	51.18
CO_3^{2-}	0.99	1.09	1.18	1.28
$CaHCO_3^+$	1.10	2.04	3.32	5.52
H^+	0.001	0.001_5	0.002	0.002
OH^-	0.1	0.02	0.02	0.03
Summation	82.48	101.83	112.59	126.67

Similarly ionic concentrations for solutions of different overall concentration can provide the variation of conductance with total hardness at 20°C

Total Hardness	60	100	300	500 p.p.m. $CaCO_3$
ions: Ca^{2+}	61.96	103.33	300.44	486.07
HCO_3^-	46.11	78.19	231.78	381.35
CO_3^{2-}	1.18	0.78	0.36	0.26
$CaHCO_3^+$	3.32	8.93	67.31	165.21
H^+	0.002	0.05	0.39	1.26
Summation	112.59	191.82	600.28	1034.15

Trans. British Cave Research Assoc. Vol. 4, No. 4, pp. 441-442 December 1977

Non-Passerine Birds of the Ipswichian Interglacial from the Gower Caves

by C. J. O. Harrison

Summary

Four species of non-passerine birds are identified from Ipswichian interglacial material from Minchin Hole and Bacon Hole Caves on the Gower Peninsula, South Wales. The Dunlin *Calidris alpina* occurs among small bones probably originating from owl pellets. A Bean Goose *Anser fabalis* may have been mammalian prey. Only two seabirds were found, the Razorbill *Alca torda* and a shearwater believed to be Cory's Shearwater *Calonectris diomedea*, and it is suspected that these were present as nesting birds. The Razorbill occurs in an early Temperate period, and the Bean Goose in a similar later period. The shearwater and Dunlin occur in a warm period. The former now nests no further north than the Mediterranean, and in identifying material from warmer interglacial periods allowance must be made for the possible presence of similar species from more southerly climatic regions.

Minchin Hole and Bacon Hole are two caves on the Gower Peninsula in South Wales from which fossil bones have been collected recently by members of the staff of the British Museum (Natural History), work at the former cave being organised by Dr. A. J. Sutcliffe and at the latter by Dr. C. B. Stringer (1975). In addition to mammal bones a small number of bird bones and other specimens were collected. The deposits from which these specimens originate date from the Ipswichian Interglacial and at that period the sites would have been present as caves in the face of a sea cliff with an anterior rock platform.

The majority of the specimens are limb-bones of passerine birds, many of them broken. One or two of the species involved are birds which might habitually enter caves in order to nest or roost, but others are birds which would not normally do so. Their presence in the caves is likely to be the work of avian predators. Cliff-haunting diurnal birds of prey such as falcons do not normally enter caves but utilise exposed ledges. Remains of prey species inside caves are likely to be due to owls.

Birds of prey cast up pellets of bones bound together with hair and feathers, and these accumulate beneath a roost site. Insects usually destroy the hair and feathers leaving accumulations of bones which are likely to be a mixture of remains of small mammals and birds. There is a preferred prey size and utilisation of larger prey is limited by the ability to ingest and egest bones. The remains at a roost usually consist of complete and broken bones of a fairly even size, the overall size determined by the size of the predator involved. In the present instance where owls are the likely predators the most probable Recent species, since not all owls use caves, would be the Barn Owl *Tyto alba,* but no owl bones have been found.

The material of this type from the caves is small, much of it up to 10 - 15 mm long. I have at present identified only one non-passerine bird from it, the Dunlin, a thrush-sized wader well within the typical prey-size indicated by other material.

Only a few larger bone fragments are present. One is referable to a goose, and several others indicate the presence of two species of seabirds.

Species and Material

CORY'S SHEARWATER *Calonectris diomedea.* Material — A proximal end of a right tarsometatarsus with shaft, BMNH A5000; an eroded proximal end of a left ulna, BMNH A 5001; a proximal end of a right scapula, BMNH A5002; Bacon Hole, area I, layer 3b. An incomplete distal end and external half of a proximal end of a left tarsometatarsus, BMNH A5003; an internal condylar part of a right tibiotarsus, BMNH A5004; Bacon Hole, area II, layer 3a, upper part of lower cave earth.
BEAN GOOSE, *Anser fabalis.* Material — The proximal end of a right carpometacarpus lacking the process for the first metacarpal, BMNH A4999; Bacon Hole, area IV, layer 2, upper grey clay.
DUNLIN *Calidris alpina.* Material — Distal ends of right and left tarsometatarsi, BMNH A4992-3; a proximal end of a right humerus with shaft, BMNH A4994: Minchin Hole, layer 4a. An incomplete distal end of a right tarsometatarsus, BMNH A4997; a proximal end of a right carpometacarpus, BMNH A4998, Bacon Hole, Area II, level 3a, upper part of lower cave earth. RAZORBILL *Alca torda.* Material — A sacrum, BMNH A 4995, Minchin Hole, area 3, Bone horizon. A distal end of a right ulna, BMNH A4996: Bacon Hole, Area II, layer 4b.

Discussion

The Bean Goose carpometacarpal is a largish bone and the jagged edge of the shaft and missing metacarpal process suggest that it might have been a food relic of a mammalian predator. Dunlins could have been taken when resting on the shore. Both species are more likely on marshy and muddy coasts than on rocky and sandy ones, but might occur in various habitats when on passage, and at present both occur as wintering species over a wide range between the Arctic and North Africa. At Bacon Hole the Bean Goose occurs in the upper, cooler part of the middle period of the Ipswichian (Stringer 1975), and the Dunlin occur in the warmer period.

The two seabird species are of interest in view of the number of species in this category which are not present. If these bones had been brought to the caves by predators which took the larger seabirds one might expect evidence of a range of species including gulls and terns. At the present day the Razorbill shares its general range with three similar-sized species of auk. Of these the Razorbill is the only one likely to nest in a large crevice or cave set in a cliff face, laying its egg on the rocky floor. The fact that the auk remains are only of this species suggests that its presence is probably due to the use of the caves by nesting birds.

The shearwater remains present the same problem of interpretation as do those of the Razorbill. A large shearwater is not normally present within this region and these might be bones of an extinct species or of a similar large species which is still extant elsewhere. Three species of large shearwater occasionally visit British waters at present. They are fast-flying birds, remaining offshore and unlikely to be taken by predators. Their occurrence around Britain is due to long-distance movements outside the breeding season and the breeding sites give a truer picture of their distribution. Cory's Shearwater nests on Atlantic islands off North Africa and through the Mediterranean. The Great Shearwater *Puffinus gravis* seems to be its counterpart in the South Atlantic, nesting on Tristan da Cunha; and the Dusky Shearwater *P. griseus* nests in the southern Pacific.

Zoogeographically it is improbable that either of the southern species would have had a northern population coextant with Cory's Shearwater or would change its breeding season and move north into a zone beyond Cory's Shearwater and retreat again at a later period. It is much more likely that a population of the latter was present. Shearwaters only come to land to breed and, although many species nest in burrows and small holes, Cory's Shearwater will utilise large rock cavities and small caves where a number of pairs may nest on the cave floor. The absence of most other species and the presence of this large shearwater in the Gower caves suggests that, like the Razorbill, it was using these sites for nesting.

Unfortunately the bones themselves do not help in identification. Although the three species differ in some aspects of their osteology, the bones available here are so similar in all three that any identification is deductive rather than certain. In view of the possibility that these birds may have been nesting the proximal end of an ulna is of interest. It is small, approaching that of the Manx Shearwater *P. puffinus* in size. It is damaged and its most noticeable character is the eroded and pitted appearance of the bone, particularly at points of muscle or ligamental attachment where hollows occur on this specimen. It is possible that it originates from a young bird in which the bones are still incompletely ossified.

The presence of both Razorbill and Cory's Shearwater as apparently breeding species might pose a climatic problem since at present the former breeds no further south than Brittany and has a Subarctic to Boreal range, while the shearwater breeds no further north than the Mediterranean and is mainly Warm Temperate in distribution. However, from the mammals and other species associated with these species in the cave strata (Stringer 1975) it is apparent that the Razorbill occurs during an early cool Temperate phase of the interglacial while the shearwater occurs at the warmest period, which tends to confirm the present interpretation.

In view of the presence of a more southerly species during the warm period it is advisable to assume that the other species with similar distributions might also be present. In past work on Pleistocene remains, and particularly in identifying passerine bones, there appears to have been a tendency for only those species now present in northern Europe to be used for comparisons. However, when the climate was warmer there is no reason why species which now have a Mediterranean, North African or Asiatic distribution should not have been involved.

Acknowledgements

I am grateful to Dr. C. B. Stringer and Dr. A. J. Sutcliffe for the opportunity to study the material, and to the above and Mr. A. P. Currant for help and information on the caves and the other fauna present; and also to the National Trust (Wales) which has presented the specimens to the museum.

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M.S. Received 2nd June 1977.

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Trans. British Cave Research Assoc. Vol. 4, No. 4, pp. 443-452 December 1977

Sheffield and Leeds Universities' Expedition to the Taurus Mountains, Turkey 1976

by A. Skuce, A. S. White, S. Worthington and C. Yonge

Following the successful relations established between the Bulgarian and English cavers during the 1974 Sheffield University Speleological Society Bulgarian expedition (Yonge, 1974), the idea of a joint expedition to Turkey was mooted. Accordingly in late July 1976 a long-wheel-base Landrover and Vauxhall Viva van conveyed 13 cavers from Sheffield and Leeds to Sofia to rendezvous with a Bulgarian team of nine, the combined party then to proceed to the Taurus Mountains in southern Turkey. Unfortunately, the Bulgarians were unexpectedly unable to obtain exit visas at the last moment, so the English party had to proceed to Turkey alone. However, arrangements have now been made between Sheffield University and the Bulgarian sports federation (NEK) such that future trips of this kind should be possible.

The Landrover party drove direct to the town of Ayranci on the north flank of the Central Taurus Mountains, while the 'van' team went to Ankara hoping to contact the vice-president of the Turkish Speleological Society, Mesut Cetincelik (who was away on holiday) and to obtain some detailed maps of the areas under scrutiny. Though excellent topographical maps at 1:25,000 and 1:100,000, and geological maps at 1:200,000 are published, all are classified and secret, in common with most Turkish maps: the most detailed map we eventually obtained was 1:800,000, which covered the western half of Turkey.

The two vehicles then met at Ayranci and drove up a track to Berendi, the base for the subsequent reconnaissance. In three days of extensive walking around the Bolkar Daglari much impressive limestone country was seen, varying from oolitic and friable to hard crystalline. Despite the abundance of dolines and the lack of surface drainage, no caves of any size were found.

Following references (Walker, 1967) to a large river cave 500m long at Yer-Köprü this area was visited. The river (Cakit) cave was sumped at both sink and resurgence (Plates 1 & 2), while reconnaissance in the area revealed three small caves in one of the rare limestone bands in a geological succession largely comprised of calcareous mudstone and shales.

The expedition next drove 700km along the coast and then inland to the polje of Tinas Tepe, south of Seydisehir. The polje lies 6km beyond the large bauxite mine at Mortas, the roads built for the mine being invaluable. Thanks to a chance meeting with Nevsat Altan, a mine geophysicist who had studied in Birmingham, we gained valuable local information and were shown several cave entrances. Later Nev and his colleague, Nuri, who was working on the hydrology of the area, both came caving with us. We in turn suffered defeat at their hands in a full-scale football match. In 9 days, several caves in the area were explored and surveyed.

Finally a tourist and photography trip was made in Pinar Gozu, 17km south-west of Yenisarbademli, and all were impressed by the formations, cold, sporting cascades and powerful draught of this cave of great potential.

Regional Geology of the Areas visited:

The Taurus Mountains are located on the southern edge of the Anatolian plateau between the Aegean sea and Iran, and are a Cainozoic tectonic belt. Below, a brief description of the geology is made, with particular reference to the limestones of the region.

(1) Berendi (Ayranci) Area:

The mountains south of Eregli (including the Bolkar Daglari) are composed mainly of a great thickness of Permo-Carboniferous limestones along with limestones of Eocene age. The rocks have all been metamorphosed to the glaucophane facies and consist of marble, crystalline limestone and dolomite. In the north around the Aydos Dagi the limestones are often quite strongly folded in places and there are many small basic intrusions. In the area of the Bolkar Daglari the limestones have generally gentle dips, while karst features are poorly developed in some areas.

(2) Karaisali Area:

The Cakit river cave has formed in a thick sequence of Jurassic and Cretaceous limestones. The rocks at the southern end of the gorge consist of a sequence of limestone shales and limestones (possibly of Permo-Carboniferous age) in which there is some slight cave development. There are several small springs with large quantities of travertine at this end of the gorge and the cave of Yer-Kopru is formed in them.

Large areas of Mesozoic limestones occur in the Agdag Massif to the north with unknown speleogenic properties.

(3) The Seydisehir Area:

The main limestone unit in this area belongs to the autochthonous Mesozoic carbonate series, which consists of a homogenous sequence of generally fine-grained shallow marine limestones about 1500m thick, of Upper Jurassic to Upper Cretaceous age capped by a thin nummulitic limestone horizon of Palaeocene age. These rocks have been overthrust in this area by the Beysehir-Hoyran nappe which consists of a varied sequence of sediments and ophiolites with some generally thin horizons of limestone of various ages.

The Mesozoic carbonate series extends over a large area of the western Taurus and has a well-developed karst morphology. (fig. 2). There are extensive exposures of Cretaceous limestone in the Antalya nappe, which are not shown on the map.

The cave of Pinar Gozu has formed in the lower part of the Mesozoic carbonate series where the limestone appears to be less homogenous and more shaly and sandy.

The cave found north of Seydisehir (Guvercin Magara) has probably formed in the Cal Tepe formation, a lower Cambrian sequence of limestone and dolomites, 100m thick, which only outcrops locally.

For references to the geology see: Campbell (1971), Walker (1967) and Geological maps of Turkey (C.1960).

Caves of the Seydisehir Area:

(1) The Caves of Tinas Tepe

The caves of Tinas Tepe have been described by Chabert (1967); Bakalowicz (1968); Agnoletti (1969) and others. We used the description of Chelsea (Marsh, 1969) and although it was a little inaccurate, it had at least brought us to this area.

The main entrance, (Tinas Tepe Dudeni), a magnificently large sink at the lower end of a 2-3km long polje, was sited below an impressive broken wall some 500m in height. Beyond this lay Lake Sugla and the emergence of the caves water some 9km away and 400m lower than the polje level. In the wall could be found a number of caves remnants of an earlier phase of development (See plate 3 and fig. 4). The smaller of the upper caves contained lone bats and large empty snail shells. The longest of the upper caves (Tinas Tepe Magara) was well decorated in flowstone and dry gour pools of considerable size (plate 4). The main passage here had a kind of Plimsoll line along much of its length dividing the passage such that the lower part was adorned with white crystals which grow during the winter months when the pools are full. In the summer period the pools progressively dry out, leaving, at the time we were there, two or three deep pools above the pitch. Clearly, many people had visited this pleasant and roomy cave (probably for many years) and some of the formations had suffered.

At 500m from the entrance the passage closed to a high and narrow rift before plummeting 27m (88ft) down a flowstone pitch, entering one side of a huge chamber split by two deep static lakes. Litter left by Polish cavers was in evidence here as elsewhere.

Tinas Tepe Dudeni, the main active sink, dropped down a series of cascades in open air to a boulder-strewn floor 40m lower. This level could be reached by a heady circuitous path which picked its way down the gigantic entrance hole and it was only when passing into the first chamber that a 13m pitch was encountered. The chamber could be followed around a corner where the water ran into a somewhat incongruous, high narrow rift. This change of character was exemplified by wet caving in canal sections or trouser-splitting traversing; wet pitches of 10m (33ft) (free-climbable) and two 18m (60ft) were then all that was required to reach the main canal and eventually the bottom at —170m. Above the 10m pitch a large dry inlet passage could be followed for some distance, somewhat reminiscent of the upper cave.

Following the water involved considerable traversing (long wooden stemples had been left by another party) or swimming with the company of vast numbers of small frogs. Occasional log-jams provided pleasant respites from the cold water and subsequently the cave seemed to terminate in a large chamber. However, an inconspicuous low duck was passed by Tony in which he had unknowingly (until his return to Britain) explored some 350m of huge passage much in character with the entrance chamber (Armchair Extension). Here the French, in spite of the natural abundance of fresh food, had stopped in 1969. Indeed, had the water been 10cm higher (and it had been much wetter that year) then it would have appeared as a sizeable terminal sump.

Perhaps further drought would indicate that we too were stopped by merely another duck and not the sump shown finally on the survey.

(2) Reconnaissance of the areas adjacent to Tinas Tepe

From the base camp beside Tinas Tepe caves six set set off in the Landrover in search of a deep pothole mentioned in Chelsea Speleological Society reports, which was cited as being 5km away in adjacent polje. By following the partially constructed new road to the south a narrow south-westerly extension of the main polje was found, though the level of the polje floor here was 110m above Tinas Tepe caves. Two caves were found at the edge of the polje floor; Karakisla Magara and Karabayir Dudeni and these were subsequently fully explored (see next section). The party then followed rough tracks over a col into a neighbouring polje which extended for about 15km and contained several discrete drainage systems.

Three small sinks near the track were investigated, the caves lying between 1 and 2km NW of the village of Taskesikli (see fig. 3). 2km south of the village two streams converged to sink in a pothole, Catayagi Dere Dudeni, previously visited by the Italians (Agnoletti, 1969). The 39m (125ft) entrance pitch is followed by a very wet 7m (23ft) drop to a deep sump pool with many frogs.

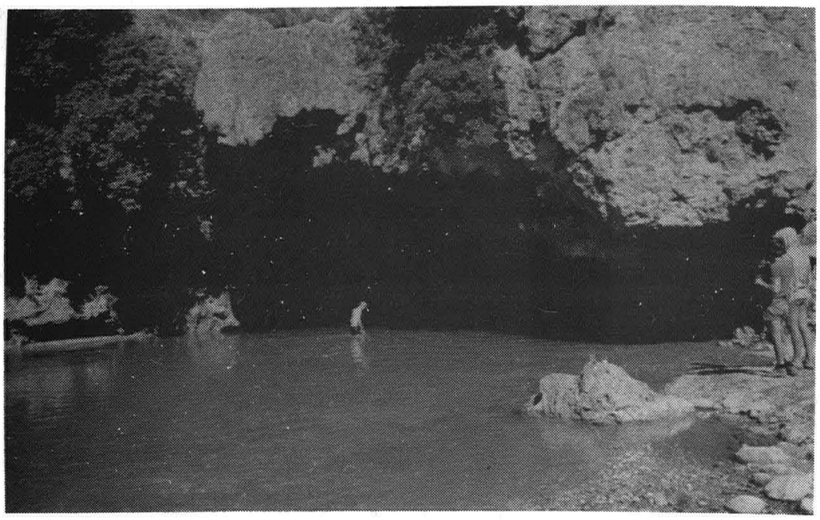
Beyond Catayagi Dere Dudeni the polje broadened out, and in a day's reconnaissance only one feature of interest was found; a 10m (33ft) shaft with a sump at the bottom (Küçüksülek Dudeni).

The pothole mentioned by the Chelsea report was finally found 4km SE of Tinas Tepe, as an active sink in a 2km long polje. This cave, Golcuk Dudeni is described later.

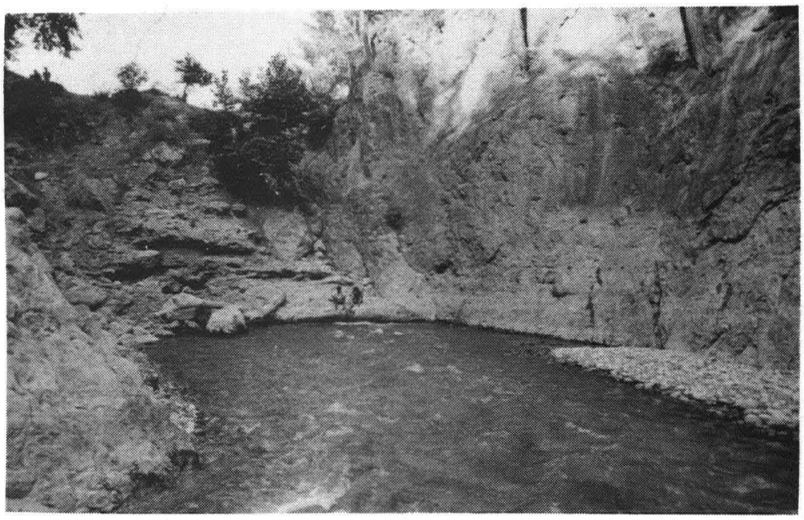
Reconnaissance in the hills of Kocayusuf Dagi and Serif Dagi revealed a staggering

CAVES OF THE
TAURUS MOUNTAINS
TURKEY

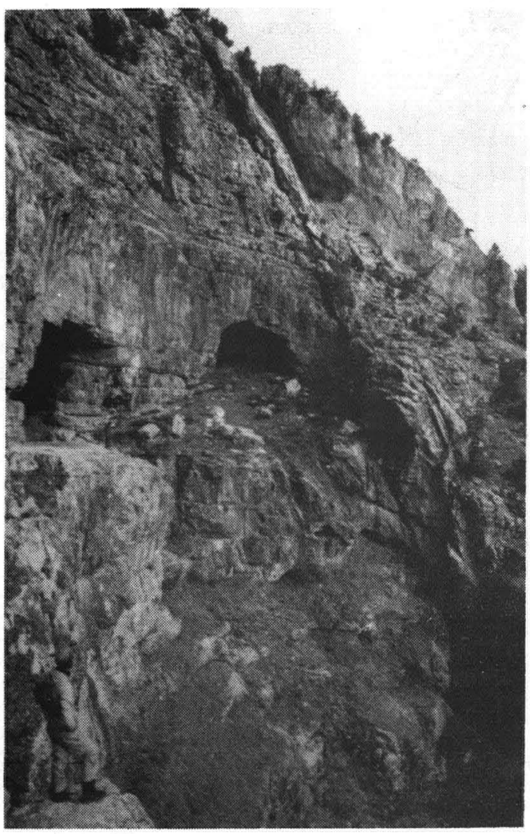
A.S.White



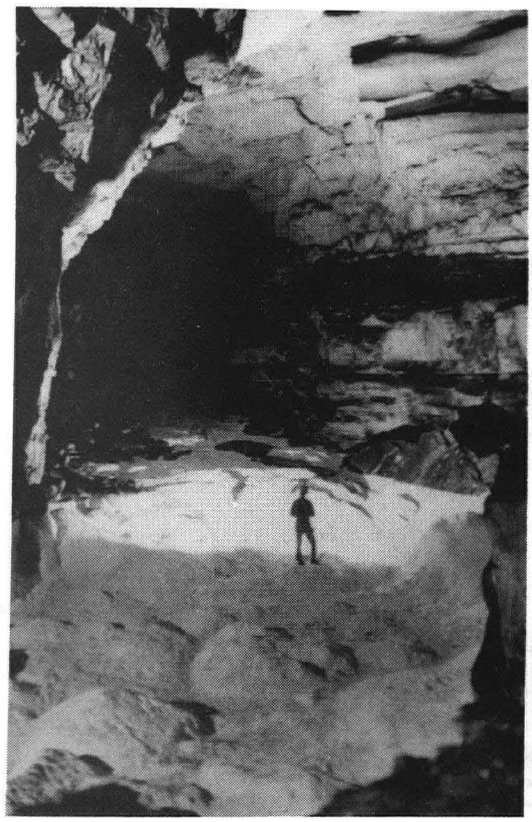
1. Resurgence of the Cakit River at Yer-Kopru from beneath a tufa deposit.



2. Sink of the Cakit River at Yer-Kopru beneath a wall of tufa 15 m thick.



3. One wall of the impressive polje of Tinas Tepe showing two of the upper level entrances.



4. A dried-out gour pool in Tinas Tepe Magara (Photo C. Pugsley).

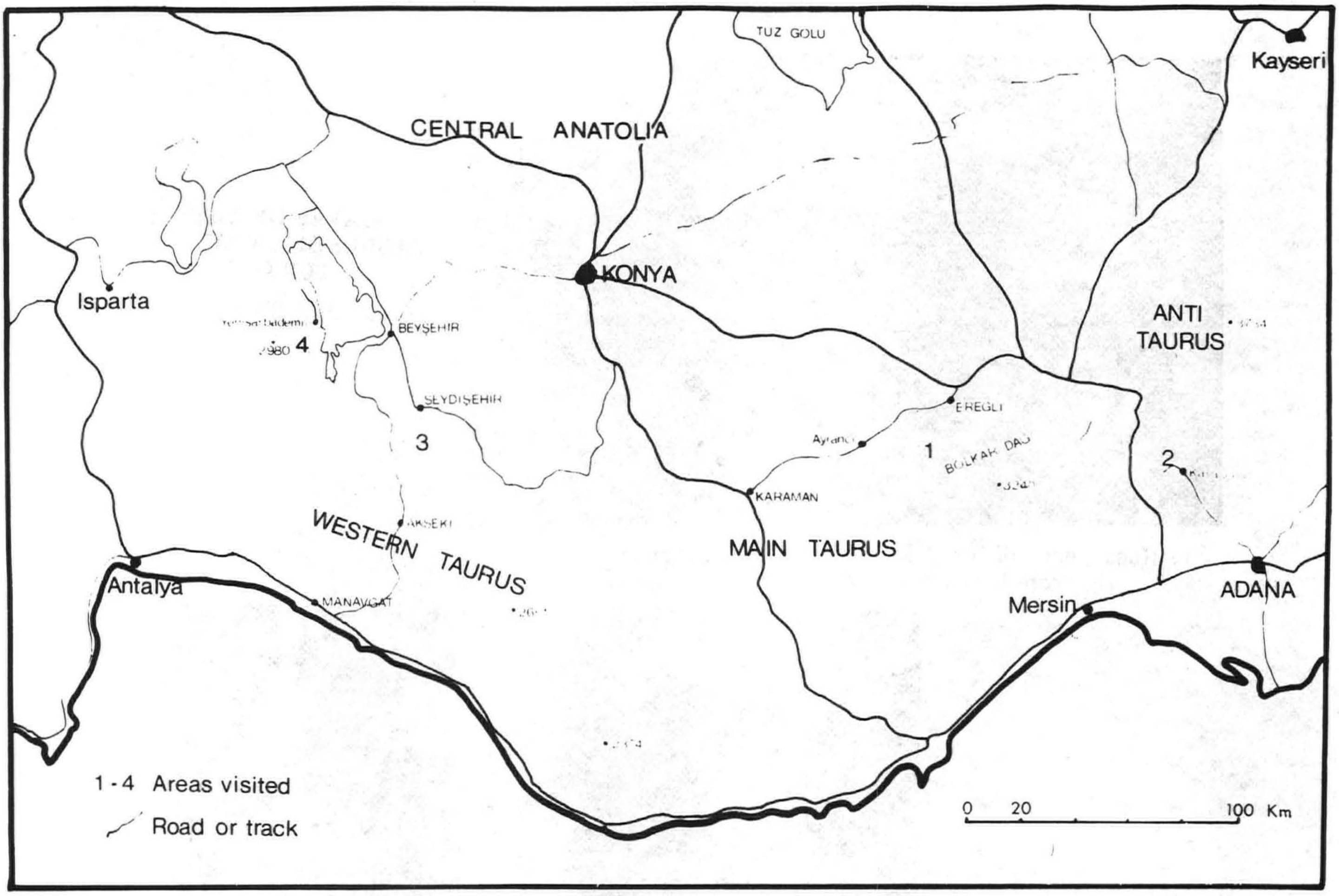


Fig. 1.

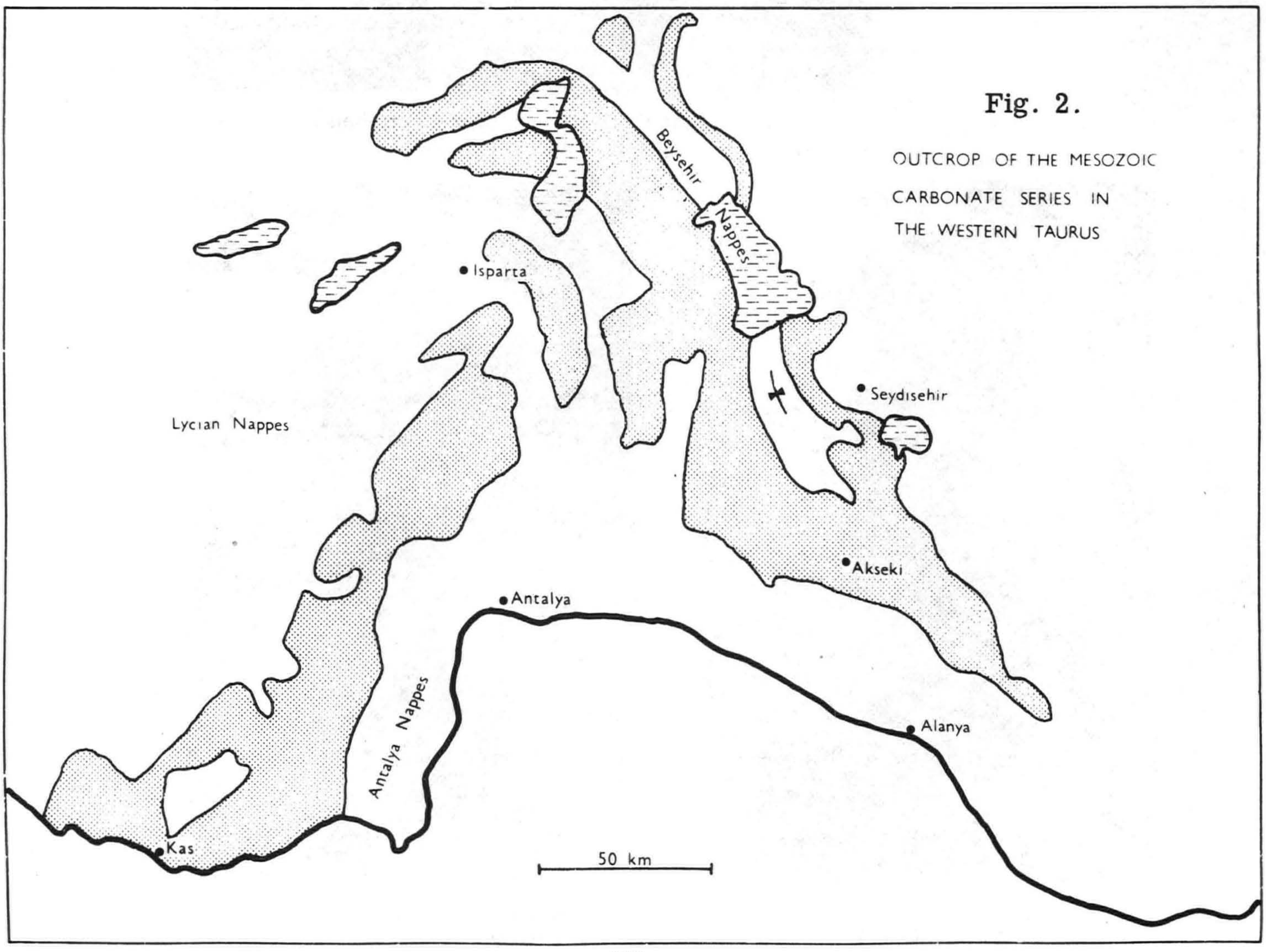


Fig. 2.

OUTCROP OF THE MESOZOIC CARBONATE SERIES IN THE WESTERN TAURUS

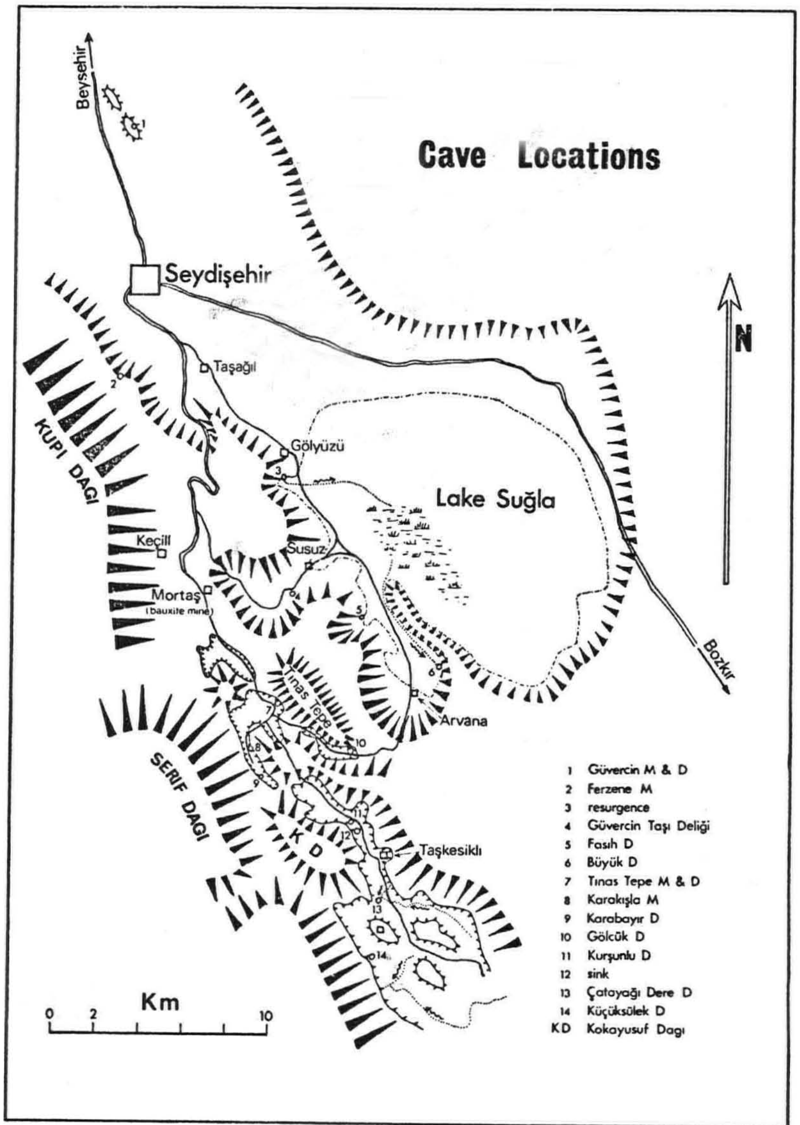

Cave Locations
Beysehir
Seydişehir
N
Taşağıl
Gölyüzü
Lake Suğla
KUPI DAGI
Keçili
Susuz
Mortaş
(bauxite mine)
Bozkır
Tınas Tepe
Arvana
SERIF DAGI
K D
Taşkesikli
Km
0 2 10
1 Güvercin M & D
2 Ferzene M
3 resurgence
4 Güvercin Taşı Deliği
5 Fasıh D
6 Büyük D
7 Tınas Tepe M & D
8 Karakışla M
9 Karabayır D
10 Gölcük D
11 Kurşunlu D
12 sink
13 Çatayağı Dere D
14 Küçüksölek D
KD Kokayusuf Dagı

Fig. 3

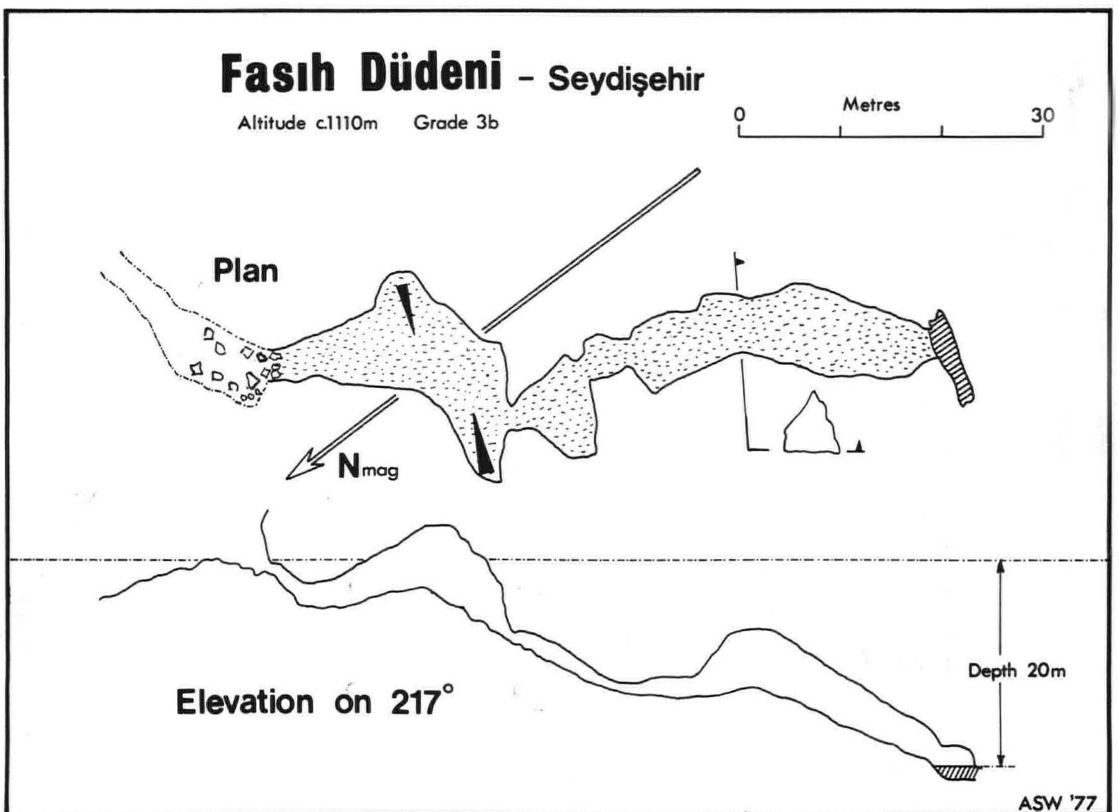

Fasıh Düdeni - Seydişehir
Altitude c.1110m Grade 3b
0 Metres 30
Plan
Nmag
Elevation on 217°
Depth 20m
ASW '77

Fig. 7

Fig. 4. CAVES OF TAURUS MOUNTAINS

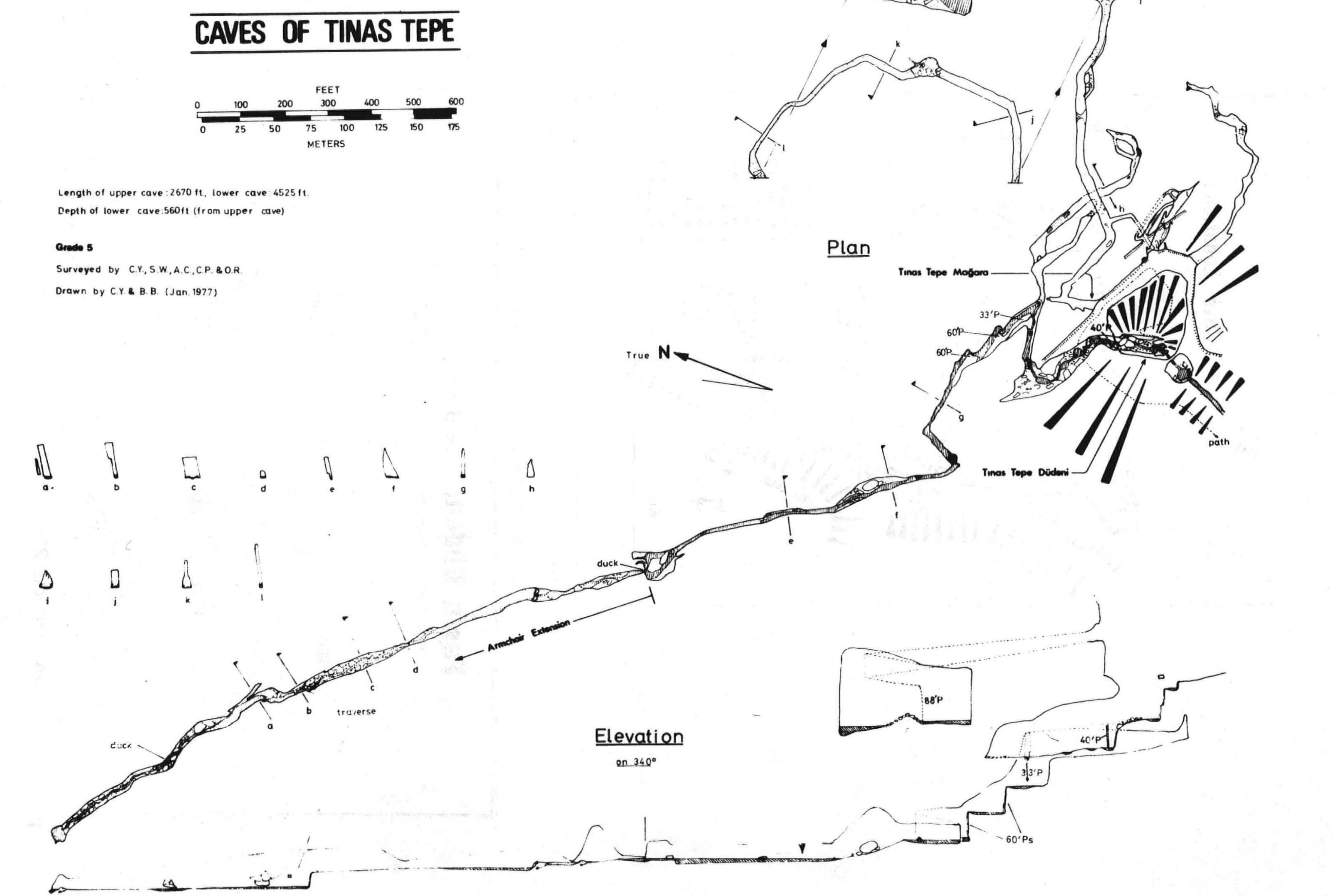


Fig. 5.

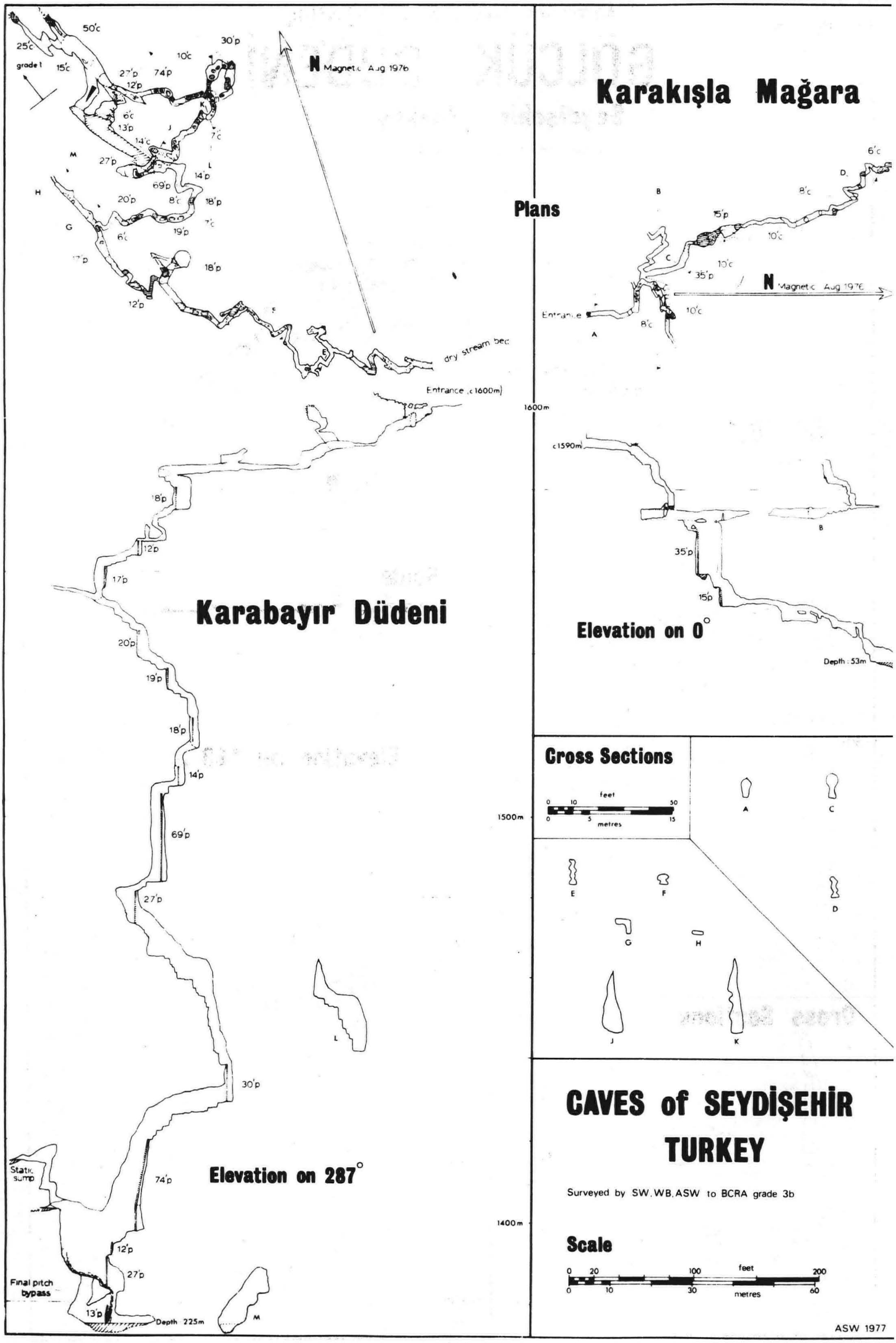

Karakışla Mağara
Plans
N Magnetic Aug 1976
Entrance
Elevation on 0°
c1590m
Depth: 53m
Karabayır Düdeni
dry stream bed
Entrance (c1600m)
1600m
1500m
1400m
Elevation on 287°
Static sump
Final pitch bypass
Depth 225m
Cross Sections
feet
metres
CAVES of SEYDİŞEHİR
TURKEY
Surveyed by SW.WB.ASW to BCRA grade 3b
Scale
feet
metres
ASW 1977

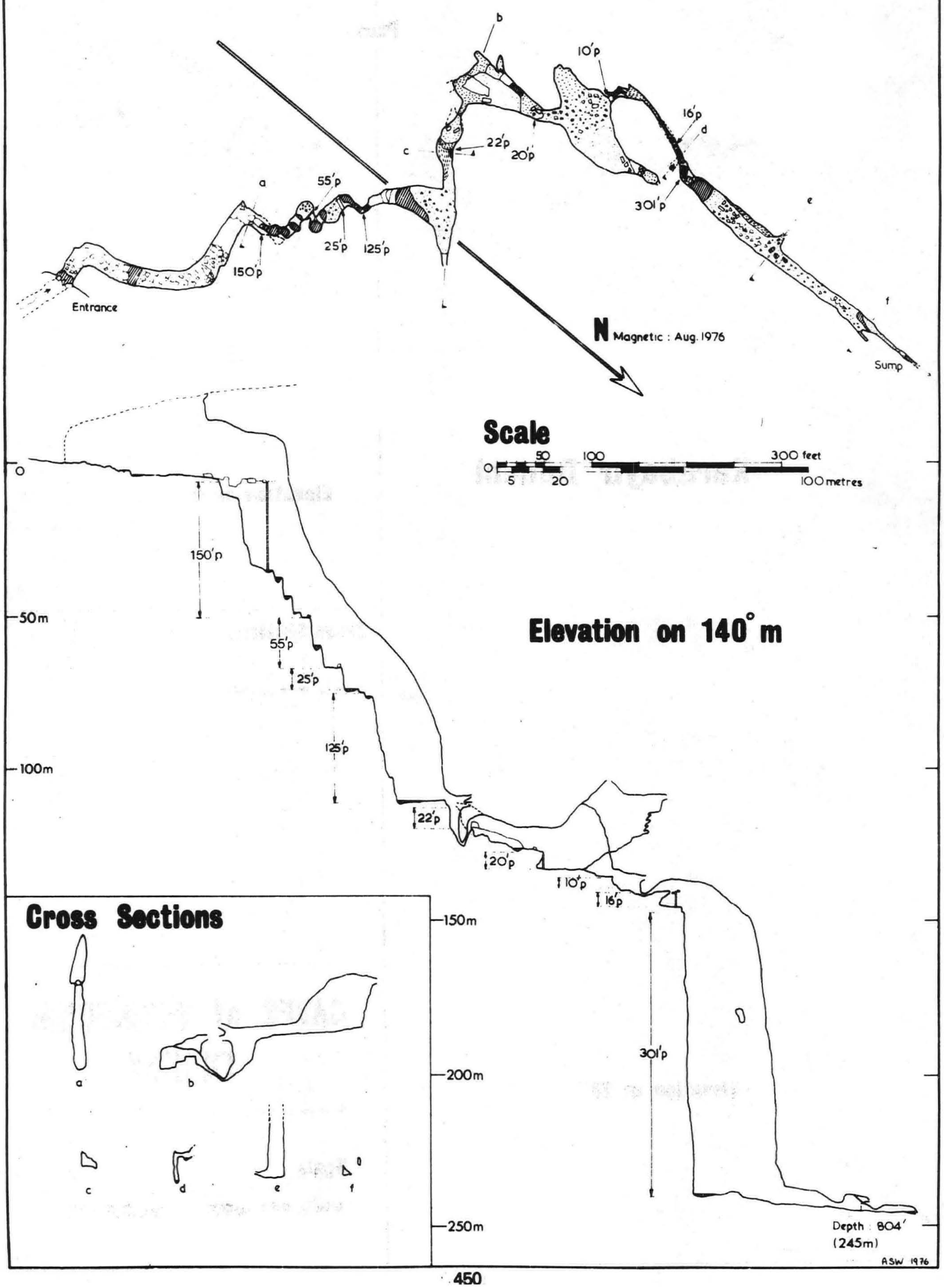
Fig. 6.

CAVES OF TAURUS MOUNTAINS

GÖLCÜK DÜDENİ

Seydişehir, Turkey

Altitude : 1565m — BCRA Grade 5c



profusion of shakeholes up to 60m across with abundant cypress trees away from the hill tops. Most were less than 20m deep, though a few were deeper and some contained snow plugs. Due to the lack of surface drainage the chances of making significant discoveries seem to be low.

(3) Karakisla Magara and Karabayir Dudeni

Karakisla Magara was visited by Tony and Chas Leonard. A solid walking size passage led to a shattered area, caused by nearby blasting, where daylight entered from the roof. Two short climbs followed by a series of gour pools, some dry, led to a junction. The left passage lowered to a mud choke, while in the other the gours continued to an 11m pitch (35ft). A traverse over the pitch went past a large stalagmite boss and into a boulder choked crawl. The pitch landed in a huge, deep gour pool with a 3m dam. A 5m (15ft) pitch into a chamber terminated the pleasant part of this cave, the rest being covered with mud. In a few places the passage became blocked with mud but in every case a route over the top was found.

The cave finally sumped at —53m. No signs of previous exploration were found, nor have any references to it been located. The pot was similar to others in the area in that winter flooding inundates at least the lower part of the cave if not the entire system. For the survey see fig. 5.

Karabayir Dudeni: The entrance lies at the edge of the polje floor, in summer there being a dry stream bed leading to it. During the reconnaissance a brief match-lit inspection by Steve revealed 22m of vadose passage leading to a twig-filled sump.

Tony and Chas Leonard returned later to survey the find and found the 'sump' to have 30cm airspace. They continued along the narrow vadose streamway, down one short pitch, through a squeeze and along a hands-and-knees crawling canal to another short pitch, only to be stopped by a third pitch. Returning with more tackle, Steve descended the 5m (17ft) pitch. After a small inlet passage, the streamway became a deep canyon and started to descend rapidly by a series of short pitches and climbs, with one of 21m (69ft). Lack of tackle at the tenth pitch again halted exploration, but an eager party of Tony, Bill and Steve returned the following day. Below this pitch water could be heard ahead, and the eleventh drop was quickly tackled. A further two short pitches dropped into a 3m wide streamway. Hopes were dashed though when, only 10m downstream, below a short pitch the stream entered a deep and final looking sump. A similar distance upstream from the inlet series a 20m (66ft) waterfall was encountered. The following day Andy Skuce and Chas Yonge climbed the wall left of the waterfall, only to find the stream sumping after a short distance, while a further climb upwards led to a static sump (fig. 5).

(4) Golcuk Dudeni

This is situated at the southern end of the Tinas Tepe ridge. Two streams unite and flow to the polje edge where they meet the limestone in a vertical sided gorge.

The pot had previously been visited by the French (Bakalowicz, 1968), the British (Marsh, 1969; Gilbert, 1969) and the Italians (Agnoletti, 1969) who had retreated due to the lack of tackle or time. The French returned and reached a sump at —138m (Chabert and Raimond, 1972).

It was visited by Bill and the two Andys who expected a series of very wet pitches. However, apart from a small amount of spray on some, they were surprisingly dry. 75m down, two bolts at the head of a 38m (125ft) pitch were the last signs of previous exploration and below the next short pitch a slope of coarse mud and decomposing vegetation slid steeply down into a crawl which immediately ascended just as steeply, but was too tight. A small amount of digging cleared the way sufficiently for them to emerge into a chamber. Although it continued and they suspected that it must be new ground, time was pressing so they returned to camp. In fact, their dig, normally under 5m of water, was the French sump which had dried out.

The following evening Bill returned with Chris and Tony and continuing, climbed into a trench on the left of the bedding chamber following it to a short pitch into a large cavern. To the right a slope of delicate drip formations led up to a boulder choke; and above this a series of calcite toadstool formations was climbed but at the top a further climb looked unpromising. The outlet from the cavern was a short drop requiring a handline. Spurred on by the rumble of a distant stream they went into a constricted rift and down a pitch to its true floor. Soon the rift opened out at the edge of a black hole. It was obviously very deep (a stone bounced after two seconds and fell for a further five before coming to rest) but it had peculiar acoustics for the stream sounded much nearer.

In camp, much surmising was indulged in and a day later Tony, Chas Yonge and Bill placed two bolts at the head of the pitch and descended. It was measured to be 301 feet deep (92m) and was called Mahogany 301 due to the eroded flowstone with a wood-grained pattern which covered the upper part. Surprisingly there was no stream at the bottom, although further along a small trickle did emerge from under some boulders. This was augmented from a choked inlet on the left but immediately afterwards the massive canyon lowered and narrowed and confined one to crawl over numerous debilitated frogs to a miserable sump in a narrow rift, a most unfitting conclusion to a fine pot.

It is probable that future visitors will find the pot sumped below the 7m (22ft) pitch. The sump certainly drains very slowly and after the winter floods (tree trunks and debris strewn about the cave indicate its severity) an extended dry period would be essential. On the other hand there are roof levels on either side of the siphon which could provide a bypass. Apart from these, the only other passage seen but not entered was further along the rift beyond the penultimate pitch.

A comparison of our survey (fig. 6) with the French reveals an accumulative depth discrepancy starting with 1m at the first pitch and reaching 18m at the extent of their survey. Unfortunately their survey is ungraded, so if a clinometer was not used, a proportion of that could be accounted for by neglecting the slope error on the pitches.

(5) Lake Sugla and adjacent areas

Fasih Dudeni is situated in a small limb of Sugla Golu between Tasagil and Arvana; the entrance is located below a small cliff in the hillside above the polje and at the head of a dry streambed. The latter feature signifies that it is effluent at times.

A steeply descending boulder slope leads directly to a large, dark-walled chamber. An undulating but generally downward-trending passage continues through a low section into a second chamber with a steep mudslope leading to a static sump (fig. 7).

Buyuk Dudeni was found as the major polje sink near Arvana. This was looked at provisionally and found to consist of at least 200m of passage formed on two parallel hading rifts. It sumped at a depth of about 25m. The wide obvious entrance nearby gave a very short cave choked with soil, but this also acts as a sink in normal conditions.

Guvercin Tasi Deligi is situated in a large doline within sight of Sugla Golu, two entrances were available; the original, a large shaft 47m deep, and the more recent Kesdeligi Magarasi in a nearby shakehole. A muddy boulder choke followed by a long broad mud slope led more or less to the base of the shaft, both intersecting a sizeable streamway (felt to be an extension of Tinas Tepe Dudeni streamway). Downstream was short, sumping in a foul pool laced with putrefying fish. In contrast, upstream went for well over 1000m in beautiful and large passage; breakdown alternating with lakes and very similar to the extension passage in Tinas Tepe Dudeni. The French had appropriately inscribed "69" above the sump at the top end (Raimond and Chabert, 1972).

Ferzene Magarasi: 4km south of Seydisehir is a 500m scarp with limestone outcropping in a cliff face at an altitude of 1,400m. A circular entrance 6m in diameter situated at the base of the cliff led into the cave approximately 350m long. The passage was generally large with a few short constricted sections and several minor drops and climbs. This cave is very well decorated but badly damaged by vandals (Raimond, 1972).

Guvercin Magara and Dudeni: Tony, Chas Leonard, Linda, Chas Yonge, Odile and Fran were taken by Nuri to near the top of one of two isolated hills 7km north of Seydisehir. Two small caves were encountered; the first was investigated for 10m until stopped by a deep throated growl presumed to be a wolf or bear; the second begun with a 15m shaft (ladder) landing on a considerable heap of swift guano in a steeply inclined chamber (20m across). A number of ways off soon terminated and no water was evident. Breakdown, massively developed stalagmite and well established swift colonies in a sickly-sweet stifling atmosphere testified to the inactivity and lack of potential of the cave.

Hydrology:

Estimates were made in a few places of stream flow rates. During the visit 1.5 ls^{-1} (measured) was sinking at Tinas Tepe and flowed to the downstream sump without picking up any appreciable inlets. The system is heading towards Guvercin Tasi Deligi and vice versa, there being 3.5 km left to explore with a vertical separation of about 150m (certainly a good prospect for divers). At the upstream sump in Guvercin Tasi Deligi the flow had increased to 3 ls^{-1}. From there the stream sank in a pool under the left wall 700m downstream to re-appear shortly before the downstream sump. Although we do not have accurate figures, this sump appears to be at the same level as the only active rising at 1090m which was also the static sump level of the vauclusian rising (Fasih Dudeni).

The stream encountered at the bottom of Karabayir Dudeni is probably derived from Serif Dagi and at about 10 ls^{-1} was the largest underground stream in the area. Its destination could be presumed to be the same rising, which with an outflow of 50 ls^{-1} can certainly account for all the known underground drainage. However, there must be considerably more drainage off such a large area and a large proportion of this must flow away without reaching the surface, to join the water which sinks at the Sugla polje. It is thought that the ultimate destination of this water is at the powerful risings in the Manavgat river gorge 60 km distant or even directly into the sea. But, this aside, a good deal of local water-tracing needs to be carried out. However, due to the size of the underground reservoirs coupled with low flow rates, very large flow-through times would be involved, and the task would be impracticable for parties on short stays during the summer.

Other members of the expedition were:
W. Boley, A. Crawley, F. Heggerty, C. Leonard, L. Miller, C. Pugsley, O. Renault, C. Tringham, D. Tringham.

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A. S. White,
University of Leeds.

Trans. British Cave Research Assoc. Vol. 4, No. 4, pp. 453-469 December 1977

Geology of the Lava Tube Caves around Icod de los Vinos, Tenerife

(Report of the expeditions to Tenerife from the Shepton Mallet Caving Club in 1973 and 1974)

C. Wood and M. T. Mills

Abstract

Three caves, the Cueva del Viento, Cueva de Felipe Reventon and Cueva de San Marcos, appear to form part of a vast lava tube cave network underlying the area around the small town of Icod de los Vinos, Tenerife. This paper describes the exploration and research carried out in two of these caves during 1973 and 1974. The Cueva del Viento was surveyed then to a length of 10km. Its morphology is extremely complex, being made up of two cave labyrinths, one lying above the other, but features of the main genetic stages are recognisable and its genetic history deducible. The associated Cueva de San Marcos, over 2km long, is of special scientific interest because the whole lava flow has been truncated by the cliff-face at Puerto de San Marcos, offering an unparalleled opportunity of relating cave morphology to flow structure. It is shown how the cave represents only a small part of the total distributory network of lava tubes.

The Canary Islands archipelago, regarded as two detached provinces of Spain, is situated in the Atlantic Ocean, 95km off the West African coast. It comprises seven principal islands: Fuerteventura, Gomera, Gran Canaria, Hierro, Lanzarote, La Palma and Tenerife. Mills (1974) has shown that all of these islands hold an interest for the speleologist, though systematic cave study to date has been restricted to Lanzarote and Tenerife. Tenerife lies at the centre of the island group and is not only the largest island, with an area of 2060 km^2, but it is also the highest, with Pico Teide attaining an altitude of 3718m. Like most of the other islands, Tenerife was subjected to volcanic activity in the historic period, with the last eruption on the island being that of Chinyero in 1909.

The lava tube caves covered in this report lie near the northern coast of Tenerife, around the small town of Icod de los Vinos (Fig. 1), 47 km west of the capital, Santa Cruz de Tenerife. Three principal caves lie within the study area:

(1) the Cueva del Viento is the longest cave complex, with 10 km of mapped passages, and its upper entrance is located 2km WSW of Icod de los Vinos at latitude 28°20′ 32″N and longitude 13°00′ 50″W;

(2) the Cueva de San Marcos, with neighbouring shorter caves, possesses over 2km of mapped passage and is located 1 ½ km north of Icod de los Vinos in the basalt sea-cliff overlooking the beach at the little village of Puerto de San Marcos;

(3) the Cueva de Felipe Reventon, not yet located and explored by the authors, has a reputed length of over 2km and is thought to lie beneath part of Icod de los Vinos.

There are reputed to be shorter caves lying parallel with the Cueva del Viento and, no doubt, the other two caves, but difficult terrain, vineyards and banana plantations makes location difficult. In total, these caves form one of the longest and most complicated lava tube cave networks in the world: the whole area around Icod de los Vinos being underlain by an enormous, shallow, segmented cave complex. Because the geological investigation of such a large and complicated system of caves is of necessity a long term project, and because neither of the authors forsee a return to the area in the near future, this paper aims at recording the survey- and geological work so far carried out in August, 1973, and April, 1974, in order to clear the way for future research.

Previous Exploration and Research

The first recorded exploration of the *Cueva del Viento* took place in 1969-70 and was carried out by the Sección de Esploraciones Vulcanoespeleologicas de la Guancha (SEVG) del Grupo Montañero de Tenerife and Sección de Esploraciones Subterráneas de la Agrupación Excursionista de Etnografiá y Folklore de Barcelona, under the direction of Carlos Teigell. As a result of this work the cave was claimed as the longest lava tube cave in the world (Teigell, 1970), for its length of 6.18 km exceeded the length of the Cueva de los Verdes on Lanzarote which, according to the Spanish, had formerly held this title. In his description of the cave, Teigell commented upon its archaeology, meteorology and biology and confirmed that it possessed two entrances, the upper (Cueva de las Breveritas) lying at an altitude of 640m and the lower (Cueva de los Piquetes) at 580m. Other articles on the cave appeared the same year (Trogoblio, 1970; Anon., 1970 and 1970a) and described regional caving camps which included the Cueva del Viento in their itineraries. The following year Grupo de Esploraciones Subterráneas del Club Montañes Barcelones visited the cave and quoted a length of 6.200 km and a vertical range of 580m (Montoriol-Pous, 1971). The full report of this expedition subsequently appeared (Montoriol-Pous and de Mier, 1974) which repeated these figures and reported on the cave's morphogenesis and secondary mineralization. In November, 1971, the U.S. caver W. R. Halliday, apparently concerned with claim-jumping going on in Europe, which had ousted Ape Cave on Mount St. Helens, Washington (variously quoted as 3.400 or 3.418km) from what the North Americans regarded as the premier position as the world's longest lava tube cave, made a point of visiting both the Cueva de los Verdes and the Cueva del Viento. His reports (Halliday, 1972 and 1972b) described the Cueva del Viento as an extensive labyrinth cave which, according to SEVG survey (a plan at a scale of 1:1000) possessed a total length of 6.211km (though he noted that at least two passages remained unexplored). As near as he could calculate from the survey, a 9m 'collapse sink' (an American term which we would like to discourage, because 'sink' is not applicable to lava tube caves) broke the cave into two main parts of 1.578 km and 4.623 km respectively. Later, Montoriol-Pous (1972) repeated the figure of 6.211 km for the total length of the cave, but stated that the figure of 580m for the vertical range was a preliminary figure only and was subject to verification/checking (Spanish: 'a comprobar'). This important qualification appears to have been omitted from all other references and, as a result of the much lower figure for the vertical range of the cave obtained from our own survey, was the reason for us being involved in a certain amount of argument, particularly with P. Courbon. He had previously quoted the 580m vertical range (Courbon, 1972 and 1974) and, in one article, did say that the survey was complete. Possibly this vertical range was never checked and as the SEVG survey is a plan only it did nothing to assist the researcher. In fact, the dimensions of the cave are still misquoted: for example, Aellan and Strinati (1975) quoted the length of the Cueva del Viento as 6.180 km and a vertical range of 580m.

The *Cueva de San Marcos,* formerly known as the Cueva de Guanches (we assume this to be the same cave from its description), was a celebrated burial cave of the Guanches, who were the pre-conquest inhabitants of Tenerife. Stone (1880) stated that the cave was 11,000 feet (3.353 km) long and extended to the Ice Cavern in the Peak. Even in the 1930s (Brown, 1932) this cave (known at the time as the Guanche Burial Cave) was a recommended excursion from Icod de los Vinos, when one could enter the cave via an upper entrance and walk through a passage for 400 yards (365m) to a hole overlooking the sea. Halliday (1972a, 1972b and 1972c) visited this cave in November, 1971, and reported that it contained 2.200km of surveyed passage, still going in the direction of the Cueva del Viento. He noted two entrances: one in a banana plantation and one in the sea-cliff at Puerto de San Marcos. It was suggested that the cave was in the same flow as the Cueva del Viento, which appeared late pre-historic.

There is very little literature on the *Cueva de Felipe Reventon* other than brief mentions and vague locations. For example, Montoriol-Pous and de Mier (1969) gave its length in a footnote in one paper, but had more to say about this cave in the report of their 1971 expedition to the Cueva del Viento (Montoriol-Pous and de Mier, 1974), when they stated that caves of minor importance were also examined by them, the biggest being the Cueva de Felipe Reventon, estimated to be about 2km long and situated, like the Cueva del Viento, in the district of Icod de los Vinos. The location, exploration and survey of this cave remain prime objectives of any future expedition.

Brief narrative of the expeditions

30 days were spent in the field during August, 1973, and April, 1974, as the expeditions were organised around package tours each of two weeks duration. The first expedition used Puerto de la Cruz as a base, which entailed travelling daily the 20km or so to the caves. During the first week, much of the Cueva de las Breveritas was surveyed, though at the time we thought that this cave constituted the whole of the Cueva del Viento and we were not to learn of our mistake until many months later. On the 6th day in the cave the total surveyed length exceeded 5.500 km and one insignificant draughting passage was reluctantly left to be surveyed the next day. To our great surprise (and dismay!) this passage eventually led to a 4m deep hole and lava-fall and into an extensive lower cave which, after an exhausting 8th day of surveying, was found to possess a length of 2.340 km. The total length of the cave at the end of that day amounted to 7.922 km, which exceeded the variously quoted 6.181 km for the whole of the Cueva del Viento, and this fact, together with the lack of evidence of previous visits by other people to the lower cave, led us to believe that the lower cave was a new discovery. Due to the time-consuming surveying programme on this expedition (the 5 expedition members worked continuously in two groups for eight days), little time was available for making geological observations in the cave or of the surrounding district, other than to catalogue characteristic cave forms and to examine the surface morphology of the flow around Icod de los Vinos and Puerto de San Marcos.

On return to England subsequent examination of a newspaper article by Teigell (1970), which we had only managed to retrieve on Tenerife, revealed that we had only surveyed the upflow part of the Cueva del Viento, known as the Cueva de las Breveritas. A second visit was made to Tenerife, therefore, in April, 1974, with the objectives of locating and surveying the downflow part of the Cueva del Viento (known as the Cueva de los Piquetes), surveying the Cueva de San Marcos and investigating the geology of the sea-cliff at Puerto de San Marcos, where interesting exposures of the lava flows were noticed in 1973. The Cueva de los Piquetes was surveyed in three days and was found to possess a length of 2.080 km which, when added to the length of the Cueva de las Breveritas, gave a total length for the Cueva del Viento of 10 km — a far cry from the variously quoted 6.181 km! The Cueva de las Breveritas and the Cueva de los Piquetes were found to be separated by what was initially thought to be an impenetrable choke, but we were later informed (pers. comm. P. Courbon) it was the foundations of a wine-vat sunk into the cave! The vertical range of the Cueva de los Piquetes was found to be 217m which, when added to the vertical range of the Cueva de las Breveritas of 261m, gave a total of 478m. The survey of the Cueva de San Marcos and neighbour in the cliff at Puerto de San Marcos was successfully accomplished also in April, 1974, and was found to possess a length of 2.130 km and a vertical range of 69m. Passage forms were recorded both in the Cueva de los Piquetes and the Cueva de San Marcos and, also in the latter, flow direction through the cave was ascertained. Some time was spent examining the structural characteristics of the lava flows comprising the cliff at Puerto de San Marcos and much of the study area was walked over in order to collect data for a map of the surface morphology of the flow and to find other caves.

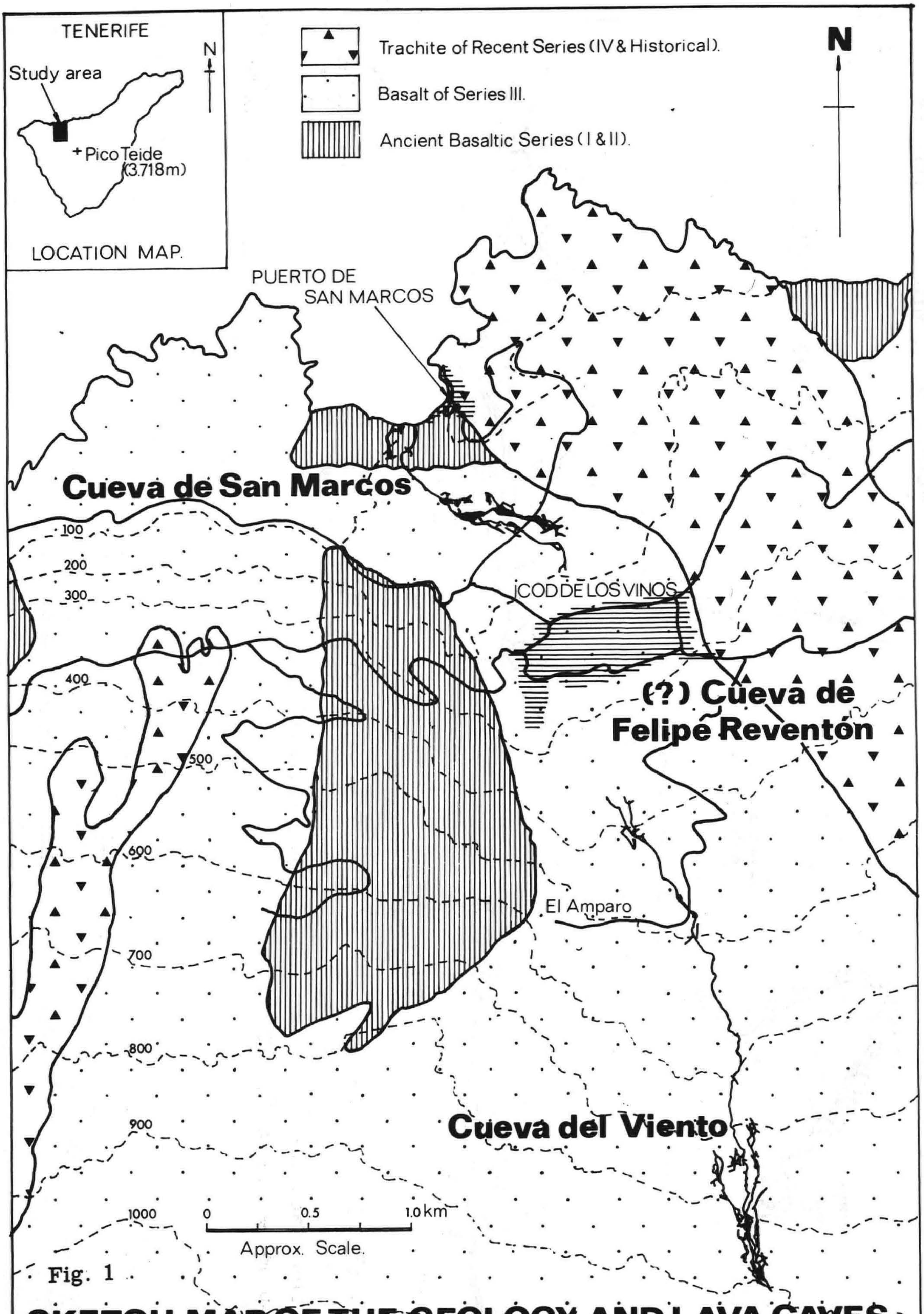
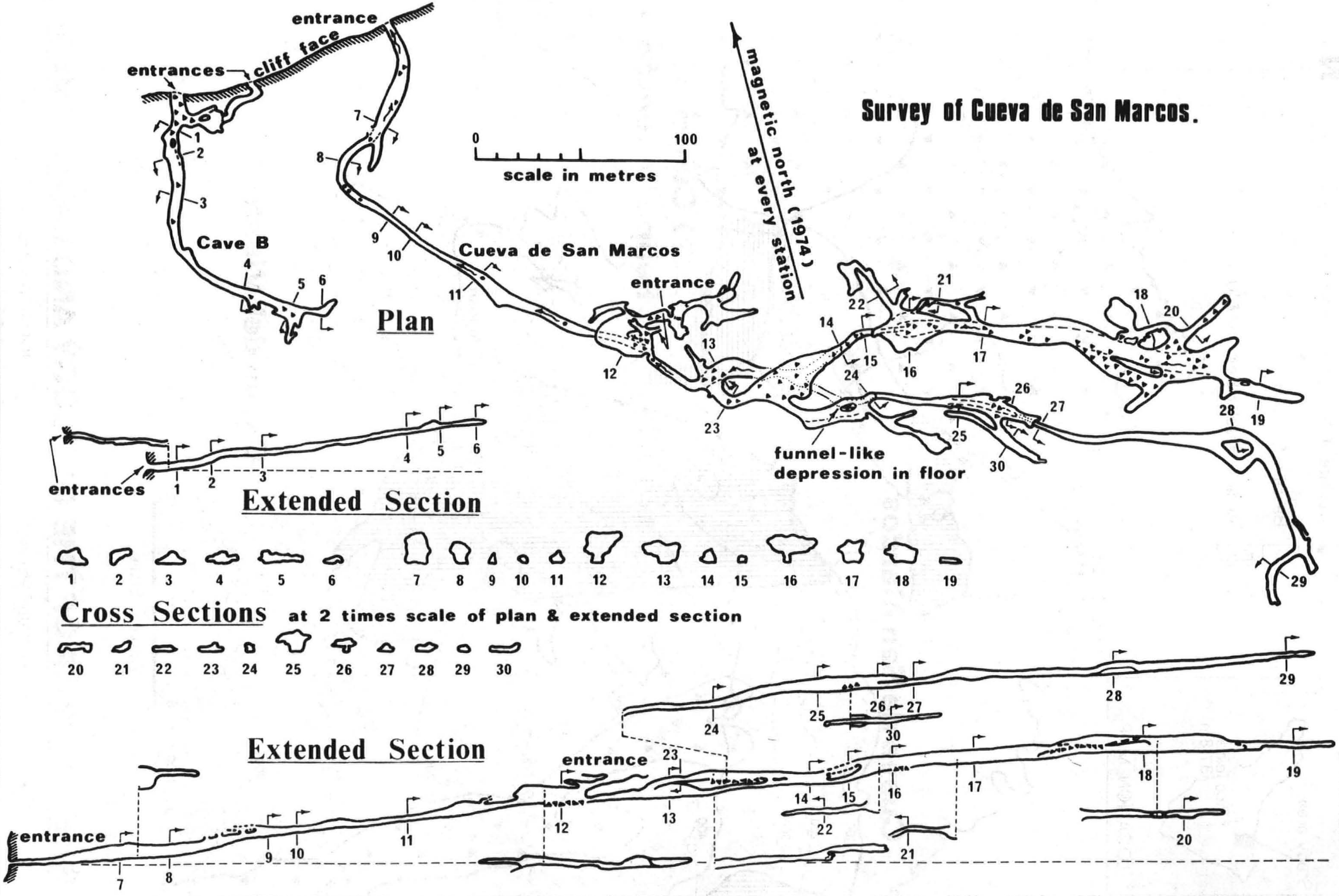


Fig. 1

SKETCH MAP OF THE GEOLOGY AND LAVA CAVES.

(Based on Mapa Geologica de España & Institituto Geografica topographical map, No.1103)

Fig. 3. C. WOOD & M. T. MILLS Tenerife



The Cave Surveys

For the sake of consistency the same survey techniques were carried out on both of the expeditions. We were well aware from our own previous work in Iceland of the errors that could arise from the use of magnetic survey techniques in lava tube caves due to the variable attraction of the wall rock, but we chose to make a magnetic survey of the Cueva del Viento for the following reasons: (i) we were aware of the reputed length of the cave, and therefore the considerable time needed to survey it, before we arrived on Tenerife; (ii) the lightest surveying instruments had to be chosen because of the limited weight allowance on the aircraft; (iii) a survey by means of a cave theodolite utilizing the included angle at every station meant both backward and forward readings at every station and would have made the surveying time required three times longer than if we used a leap-frogging technique; (iv) a non-magnetic survey similar to that made in Iceland required the use of tripods which, as we later found out, would have been impossible in many of the small passages of the Cueva del Viento; (v) it was felt that the attraction of the wall rock in the Cueva del Viento would be less than that of Icelandic caves because it was suspected (correctly) that it did not carry a glass lining (Bowler, 1971).

Magnetic survey techniques were therefore used, for it was believed that any loss in accuracy would be compensated by an ensurance of the completion of the survey. The instruments used were 30m Fibron tapes read to the nearest 0.05m, Suunto compasses (type KB-14/360) and clinometers (type PM-5/360 PC) read to the nearest 0.5°, which were hand-held, although care was taken to minimize errors due to station movement. Survey stations in the main passages and often at junctions off the main route were marked with numbered white adhesive tape for reference during the period of the survey and removed from the cave before departure. Wall distances and roof heights were measured at every station and at significant points between them (though where the roof was too high it was estimated). The 'leap-frogging' technique was used throughout the survey.

Upon return to England the survey figures were reduced to rectangular co-ordinates using four figure logarithmic tables and surveys at the scale of 1:2000 (Cueva del Viento) and 1:1000 (Cueva de San Marcos) were plotted from these after checking against a line survey for any mathematical errors. Because of the complexity of the Cueva de las Breveritas some passages were not drawn on the plan in order to preserve clarity: for example, high level recesses and chambers in the vicinity of cross-sections 27 and 28. Also in order to preserve clarity, only the principal side passages were drawn on the extended section of the Cueva del Viento. Twenty one closed traverses were made in the Cueva de las Breveritas and their closure errors were distributed proportionally to the slope distance between stations. The traverses varied in length from 37.65m to 211.90m and had closure errors of 0.49% to 7.80%. There were only two very small closed traverses in the Cueva de los Piquetes and four in the Cueva de San Marcos of 29.35m, 52.70m, 61.24m and 79.11m, with the largest closure error being 8.21%. A closed traverse across the surface between the two entrances and through the cave from respective entrances to either side of the separating choke in the Cueva del Viento failed to close by only 0.2m vertically and 10.5m horizontally: the thickness of the choke can only be guessed, but lies in the region of 10m.

The survey of the Cueva del Viento was drawn on three sheets at a scale of 1:2000. The survey of the Cueva de las Breveritas forms Sheet No. 1 and consists of plan, extended sections and cross-sections, with the outline of the upper cave superimposed upon the lower. Sheet No. 2 consists of a plan, extended section and cross-sections of the Cueva de los Piquetes. Sheet No. 3 consists of a full plan only (Breveritas and Piquetes) with the upper and lower caves of the Cueva de las Breveritas separated for clarity and an inset of the more complicated parts of the Cueva de las Breveritas enlarged at twice the scale of the main plan. The survey of the Cueva de San Marcos was drawn at a scale of 1:1000 and consists of a plan, extended section and cross-sections. The surveys drawn for this paper (Figs. 2 and 3) are reductions of the original surveys. Note that the lower cave in the Cueva de las Breveritas, discovered by us in 1973, is shaded in Fig. 2 for clarity. A comparison between the plan of the Cueva del Viento prepared by the SEVG and our own plan reveals a similar form (excluding the lower cave which, at the time of our survey, had not been explored by the Spanish), though the former is elongated and comparison of the lengths of the cave between its north and south extremities gives a variation of at most 5% between the two surveys.

An altitude of 580m a.s.l. at the entrance of the Cueva de las Breveritas was determined by averaging two descents to sea-level using a Thommen pocket barometric altimeter (Swiss manufacture) reading direct to 10m and by estimation to 5m.

Space does not allow a full verbal description of the caves and this, together with a description of the routes through them and their exact locations, is to be published in the Shepton Mallet Caving Club Journal, Autumn, 1977.

The Geology of the Study Area

The geology of the area around the lava tube caves is shown in Fig. 1, using data abstracted from Mapa Geologico de España, Sheet 1103 (Inst. Geologico y Minero de España), 1968. The place of the local geology in the volcanic succession of the island as a whole is shown below:

Recent Series Basalts and Trachybasalts (IV & Historical)	Recent Series Salic (= Acidic) Rocks
Series III Basalts	Trachyte and Trachybasalt Series
	Upper Canadas Series Rocks
Lower Canadas Series Basalts	Lower Canadas Series Solic Rocks
Ancient Basalt Series	

The geological evolution of the island is summarized after Hausen (1956), Fuster, *et. al.* (1968 — unfortunately, a second-hand reference, for according to the British Library this paper is out of print and not available in Britain) and Borley (1975) as follows. Overlying a basement complex which is not seen are rocks of the Ancient Basalt Series. These are mainly found in two parts of the island: the oldest rocks forming the Anaga peninsula in the north-east, while younger lavas form the Teno peninsula in the north-west. Rocks of the Ancient Basalt Series are considered to have been erupted from fissures, forming lava shields, and comprise alkalic basalt and ankaramitic lavas and pyroclastics. Abdel-Monem, Watkins and Gast (1968) gave an age of 15.2Ma-7.2Ma for these early lavas. Volcanic activity then became more centralized with the production of the Lower Canadas and Upper Canadas Series and the Trachyte and Trachybasalt Series. A number of volcanoes produced large amounts of pyroclastic material and lavas, ranging from alkali basalt through trachybasalt to phonolite, and ultimately formed a volcanic complex believed by some to have risen almost 5000m a.s.l. At a later stage (late Pleistocene) emptying of a high level magma chamber and faulting caused the summit region to collapse and slip northward, forming the depression of Las Canadas: the stratified pyroclastic deposits of Bandas del Sur represent the final phase of activity of this period. Contemporaneously, and a little later, volcanicity produced the Series III basalts and pyroclastics which overflowed the walls of the depression in many places. Vulcanicity of the Recent Period was mainly restricted to the Las Canadas depression, within which the two central volcanoes Pico Teide and Pico Viejo emerged, composed of lavas ranging from trachybasalt to phonolite. A final phase of activity was represented by the growth of clustered adventive cones over the island which erupted lavas of alkali basalt or trachybasalt and phonolite. This phase of vulcanicity passed into the historic period with the last eruption on Tenerife of Chinyero in 1909.

The most authoritative geological map of Tenerife, Mapa Geologico de España, Sheet 1103 in the 1:100,000 series shows the lavas upon which Icod de los Vinos stands as Series III Basalt, while the area of the cliffs at Puerto de San Marcos are shown as basalts of the Ancient Basalt Series (Fig. 1). Without access to the memoir describing this map (Fuster *et. al.,* 1968) the authors are reluctant to accept this view as it contradicts their belief that the lava tube caves constitute parts of a single complex that formed either in one large lava flow, or in two lava flows, much closer in age than the duration of time between the Ancient Basalt Series and Series III. Confirmation of this idea will come from an analysis of the form and situation of the Cueva de Felipe Reventon, which may be the missing link between the Cueva del Viento and the Cueva de San Marcos (Fig. 1).

The lavas regarded as basalts of the Ancient Series exhibited in the sea-cliff at Puerto de San Marcos, which hold the Cueva de San Marcos and a variety of smaller caves, were cursorily examined in April, 1974. Fig. 4 shows the general succession of the lava flows exposed in the cliff-face. As the authors were not equipped for exposed climbing only the flows lying behind the Amarca Apartments were examined in any detail, though the general succession of the lava flows was easily worked out from the western headland of the San Marcos bay. Beneath the majority of the lava flows lies either a recognisable soil horizon or an extremely conspicuous brick-red tuff, which in many places has been eroded, leaving large rock shelters beneath the base of the lava flow. Structurally the lava flows are divisible into two contrasting groups:

(1) lava flows numbered 1, 2, 3, 6, 7 & 9 are recognisable for their strong columnar jointing or massive appearance;

(2) lava flows numbered 4, 5 & 8 are recognisable for their (apparent) horizontal jointing.

Hand specimens were not obtained for laboratory study and any relationship between rock type and structure is not known and must be left for the future. Suffice it to say, lava tube caves were observed only in the flows exhibiting the apparent horizontal jointing.

Closer examination of flows 5 and 8 revealed them to be composed of small flow units or 'toes', whose jointing pattern explained the overall apparent horizontal jointing. A detail of flow 5, illustrating its structural characteristics, is shown on Plate 1. In general, flows 5 and 8 ranged in thickness from 6-18m, being made up of as many as 10 elliptical units vertically. The units were thin and wide and were difficult to recognise, though detailed inspection revealed typical characteristics: a distinguishable external ropy surface, frequently oxidized to a chocolate-brown colour; an external narrow zone of high vesicle density; jointing parallel with the exothermal surfaces; an internal core region of little jointed lava of light vesicle density or, alternatively, a small lava tube. Plates 2 and 3 show examples of small tubes carried in elliptical units of the flow and these tubes bear all the characteristics internally of the larger lava tube cave passages. Tubes varied in size from 15cm high to 5.5m high, though by crawling into some of the smaller tubes it was possible to observe them connecting with others, and occasionally they were seen to be branches of larger tubes: for example, at Cave B on the Cueva de San Marcos survey (Fig. 3) the smaller entrance occurs high in the cliff face and lies at the centre of a small flow unit.

In their study of the Cueva del Viento, Montoriol-Pous and de Mier (1974) accepted that this cave had formed in basalt of Series III age and stated it to be an olivine-augine basalt of porphyritic texture. The lava flow fills the broad descending valley in which Icod de los Vinos stands and houses the main cave complexes of the Cueva del Viento and the Cueva de Felipe Reventon. The source of the lava is not known, though this could probably be determined during future fieldwork. Nor is the area, thickness or volume of the lava flow known, for much of it is buried beneath later lava flows and nowhere is the base of the flow seen. Structurally, this lava flow resembles flows 5 and 8 at the cliff at Puerto de San Marcos. Where exposures are observed, as beside the road above Icod de los Vinos, small tubes occur in flow units. Surface tubes abound and bare rock surfaces exhibit excellent ropy structures indicative of great magma mobility, though it is felt that this mobility was more a consequence of a high effusion rate and very steep gradient (averaging 14-15°), rather than high magma fluidity.

Geology of the Cueva del Viento

The Cueva del Viento is of especial note to the speleologist, for not only does it possess a complexity of form that, to the authors' knowledge, is not repeated in anything like the same degree in any other cave of this type, but also, with a length of 10km, it ranks only after Leviathan Cave, Kenya, and possibly Kazumura Cave, Hawaii, in the list of the world's longest lava tube caves.

Morphology

The survey (Fig. 2) shows the form of the Cueva del Viento in plan, long profile and cross profile. The cave comprises two main parts: (i) an upper cave totalling 7.66km, dominated by the long, meandering main tube of the Cueva de las Breveritas and the Cueva de los Piquetes, linking a number of (today) unconnected passage complexes; (ii) a lower cave that partly trends beneath the line of the upper cave in the Cueva de las Breveritas, comprising 2.34km of passages in two main branches. The lower cave is connected to the higher cave in only one place, via a small 4m high pot and lavafall.

Features of the cave's morphology which deserve further description are: (1) the unusually complex planimetric form; (2) the sinuosity of the main passage; (3) the steep, multi-level long profile; (4) the great variety of constituent passage forms.

(1) **Cave complexity.** The Cueva del Viento exhibits an unusually high degree of passage complexity for a lava tube cave. Montoriol-Pous and de Mier (1974) thought that there might be some relationship between the form of the cave and the very steep gradient upon which cave genesis had occurred. In order to compare the planimetric form of caves they had investigated in Iceland and the Canary Islands, they devised an 'indices planimetrico' — $Ip = \frac{Lp}{Pe}$ — where Ip was the indices planimetrico, Lp was the total length of the cave, and Pe was the distance between the two furthest points in the cave. The figure representing the form of each cave was then plotted against their respective gradients. As a result of this study, Montoriol-Pous and de Mier concluded that (a) a high degree of passage complexity in lava tube caves correlated with a high slope angle, as is the case at the Cueva del Viento and, (b) within the Cueva del Viento itself, areas of greater complexity correlated with areas of higher gradient.

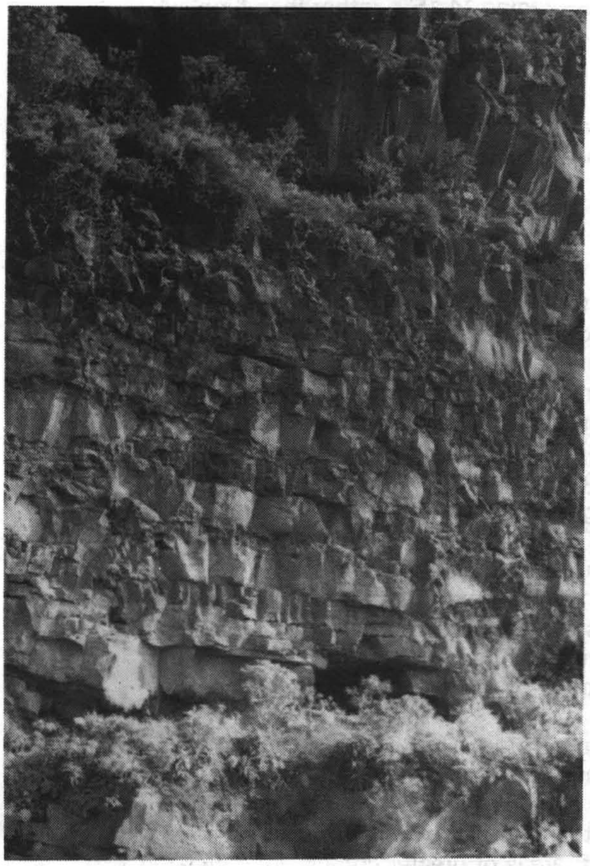
Although the idea of comparative quantitative analysis seems to the present authors to be a most useful means of assessing the relative contributions of the controlling factors on the morphogenesis of caves, at this stage they are reluctant to agree with the conclusions reached by Montoriol-Pous and de Mier for the following reasons:

(a) firm conclusions cannot be based upon a limited sample of five caves;
(b) the genesis of a lava tube cave is a function of unique and complex relationships between a number of highly variable factors of which gradient is but one example and the contribution of gradient to cave genesis (albeit in this case a very important contribution) must be viewed in the light of its influence, along with other factors, in the maintenance of the mobility of the lava — gradient alone cannot be responsible for cave complexity;
(c) Visual interpretation of our own survey and analysis of our survey notes do **not** support the contention that the most complex parts of the Cueva del Viento correlate with areas of steeper gradient.

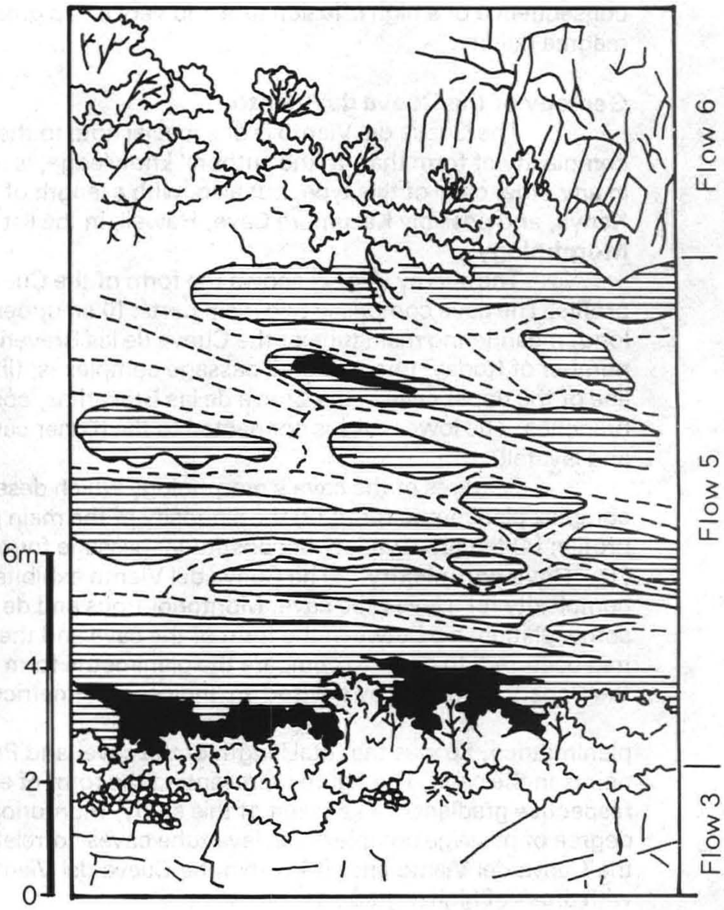
At the moment the present authors offer no reason for the complexity of the Cueva del Viento, other than to suggest that it may be the result of a special combination of the controlling factors, possibly a very high and constant effusion rate, emplacement over a broad surface with a very steep gradient, with consequent extreme magma mobility. Comparative quantitative analysis will eventually provide the answer, but this must wait until sufficient data is available. Meanwhile, we remain with the cave survey as a qualitative statement of the cave's complexity.

(2) **Sinuosity of the main passage.** In plan, the main passage of the Cueva del Viento, particularly between the two entrances, exhibits pronounced sinuosity. Sinuous bends have been recognised in many other lava tube caves and some authors have attempted a quantification based upon the methods employed in the measurement of river meanders. Such studies, though, have been carried out in order to compare the forms of lava tubes and lunar sinuous rilles, which are believed to be analogous features (Hatheway and Herring, 1970), rather than to attempt an explanation of sinuosity in lava tubes. Greeley and Hyde (1971) noticed that some sections of the lava tubes in the Cave Basalt of Mount St. Helens occupied, and were probably controlled by, the bed of an ancient stream, and other lava tube caves may similarly be topographically guided. This does not explain the regularity of meander bends in caves like the Cueva del Viento, however, and observations of active lava flows in Hawaii by Cruikshank and Wood (1971) have shown that fluvial-like processes of bed 'erosion' and bank-cutting (lateral melting and plucking of softened wall rock, particularly on the outer walls of bends) may be operative in open- and closed lava channels. If this is the case, then sinuous bends in lava tube caves may be, like river meanders, an equilibrium condition resulting from adjustments among the controlling variables of the flow.

(3) **Long profile and gradient.** Lava tube caves may possess great lateral extent, but they lack the vertical development of limestone caves. When multi-level lava tube caves are found, it is usual that the lower part of the cave has captured the flow of an upper cave through the roof of the lower



1. Detail of Flow 5.



2. Detailed structure of lava toes in Flow 5.

3. Small tube in a toe in Flow 5 .

4. Small tube in Flow 8.

and the two caves are linked via one or more lava-falls. This is the case in the Cueva del Viento where, in the Cueva de las Breveritas, the lower cave is linked with the upper cave via a single 4m lava-fall.

The total vertical range of the Cueva de Viento is 478m by our survey, giving a mean gradient of 11°. This gradient is fairly constant, apart from the occasional small steps where the gradient may rise locally to 30°. The average gradient of the Cueva del Viento must be one of the highest known and it must have been a very important factor in cave genesis, for example, in the maintenance of magma mobility. In their study of the Bandera lava tube caves of New Mexico, Hatheway and Herring (1970) found mean gradients of 0°35'-0°48' for the Bandera- and Twin Craters Tubes and suggested a lower limit of tube formation of about 0.5°. Perhaps the gradient of the Cueva del Viento of 11° lies near to the upper limit of tube formation?

(4) **Passage profiles.** The survey shows the 81 passage cross-profiles surveyed in the Cueva del Viento during 1973 and 1974. Most of the profiles were measured in order to provide regular documentation of passage forms, though some were specially selected because they illustrated a characteristic or unusual shape.

As in the study of limestone caves, an analysis of passage profiles in lava tube caves allows an interpretation of the genetic history of the cave. Even the casual observer in the Cueva del Viento cannot fail to notice that certain forms are very common, though there is a gradual gradation between one form and another. Thus, it was possible to group the surveyed profiles into eight general types and two representatives of each type are illustrated in Fig. 6.

Morphogenesis

The morphogenesis of a lava tube cave is complex and its interpretation is difficult. Wood (1975 and 1977) has shown that a lava tube cave is the cumulative result of developments occurring in successive genetic stages which he identified as: (1) conduit (lava tube) construction; (2) conduit drainage; (3) breakdown and collapse. Each cave is shown to be unique, because it evolved in a direction through the genetic stages dictated by the particular environmental situation in which cave genesis was induced. Unfortunately, we do not know what particular set of factors controlled the genesis of the Cueva del Viento, or how these factors differed from the factors which controlled the genesis of other caves, but the modifications caused by each of the genetic stages are easily recognised and are used here as the basis for morphogenetic interpretation.

Stage 3 The cave has not been significantly altered by collapse. The two entrances were formed through roof collapes and there are a few areas of collapse in the Cueva de las Brevitas. As a result of so few exposures of the lava flow, no generalizations are possible on the relationship between the passage forms and the flow structure.

Stage 2 Modifications of the lava tube caused by its drainage, with subsequent adherence of cooled lava to the walls and floor of the original conduit, are extensive in the Cueva del Viento. Such modifications are seen in the passage profiles identified in Fig. 6. It was found possible to explain the variety of passage forms in the Cueva del Viento by constructing a theoretical model in which a cylinder, filled with fluid lava, was spasmodically drained, with individual still-stands of the fluid level in the conduit being marked by the growth of lateral benches and surface crusting, while diminution of the flow led to a gradual reduction in conduit dimensions. This is shown in Fig. 6. One particular feature of the cave's morphology worthy of special mention is the occurrence of tiered passages that result from the convergence of lateral benches. Recurrence of this feature throughout the cave results in many flat-out crawls through tiny triangular-shaped passages.

Stage 1 Evidence of the developments that occurred in Stage 1 must be looked for in the planimetric form of the cave, for this suffered least modification during the later stages.

(a) It appears that the lower cave (i.e., the cave lying beneath the Cueva de las Breveritas) formed before the lava flow, or flow unit, containing the upper cave was emplaced, and the lower cave 'pirated' some of the active flow from the upper cave via the 4m pot. This point of view is supported by the following:

(i) the lower cave trends across the line of the upper cave;
(ii) the lower cave possesses a character and size not reflected by the upper cave;
(iii) flow features in the passages surrounding the 4m pot, which is a lavafall, indicate a flow direction into the lower cave.

It is suggested that the lower cave formed within a lava flow that was later buried by the Series III basalt, or it formed in an early unit of the Series III lava, there having been a break in effusive activity before a later unit containing the upper cave was emplaced. In either case, collapse of the roof of the lower cave in the region of the 4m pot today, before the emplacement of the upper lava flow, or flow unit, was necessary for the capture of some of the drainage of the upper tube. It appears, however, that the main flow in the upper cave was never captured by the lower and the lower cave possibly only received additions of fluid lava during periods of high surges when the main route overflowed.

(b) Some of the passage forms of the complexes of the higher part of the Cueva de las Breveritas are anomalous and cannot be explained in the terms of Fig. 5. These passage complexes appear to have formed from a pattern of sub-parallel, or braided, open channels, which periodically flooded, causing the development of spillways or escape routes for the excess lava.

Enlargements of the two main passage complexes in the higher part of the Cueva de las Breveritas are shown in Fig. 6. A traverse of the main route through each of these complexes involves alternate crawling through triangular-shaped passages and walking through narrow, trenched sections, where high lateral benches cause the passage to assume a 'T' shape. These alternating passage profiles would be adequately explained by Fig. 6, but for the fact that as many as six subsidiary passages may radiate off from any one point **above** the lateral benches. Similar features are found in the large passages lying parallel with the main route, to which the main route is connected via the higher level subsidiary network.

Obviously, if the main route and the parallel routes formed as enclosed conduits, connections would not be possible, and so it is suggested that the higher level connecting tubes formed before this part of the Cueva de las Breveritas was completely roofed. The connecting tubes probably originated in flow units caused through either lava overflowing the banks of sub-parallel, or braided, open channels during successive high surges, or overflow through 'skylights' (areas where the roof of an active lava tube has collapsed) from a similar sub-parallel, or braided, lava tube network. Thus, once formed, these subsidiary tubes may have only been used periodically, facilitating the transportation of excess liquid lava during periods of flooding in the main tube.

It is interesting to note also that as a result of such flooding, a tongue of lava spread across the area underlain by the lower cave and was captured by it at the roof collapse where the 4m pot is situated today, forming yet another outlet for overflow.

(c) Some smaller passage complexes, and parts of the larger complexes, formed as a result of the superimposition, convergence and divergence of tubes carried in individual small flow units; for example, the complex around Galeria Barroso. Such flow units are easily identified at surface exposures of the lava flow above the cave and mini lava tube networks are found by crawling into units with hollow cores. There is clear evidence in the cave also of small scale tube networks, convergence of the flow in some passages having caused the removal of the separating wall to leave distinctive 'M' shaped passages.

(d) Superimposed flow routes appear to have converged in the central section of the Cueva de los Piquetes. The upper route meanders across the line of lower route and is today segmented as a result of partial drainage into the lower route. The lower route is today represented by the main passage. Superimposition of the upper route may have been the result of overflows before the lower was roofed, or alternatively, the lower tube was subsequently buried by a higher, later flow unit and tube network, only parts of which have drained.

Summary of the genetic history of the Cueva del Viento

(1) Either emplacement of a lava flow older than Series III, or the first effusive phase of the Series III basalt flow, forming a large flow unit, in which the lower cave, Cueva de las Breveritas, was formed, originating first as a large open channel which eventually became roofed.

(2) A period of little- or non-activity in the region, drainage of the lower cave, cooling of the lava flow and collapse of a small roof section of the cave in the region of (today) the 4m pot.

(3) Renewal of voluminous and continuous effusive activity with a new flow, or flow unit, causing the formation of a system of long, braided or sub-parallel channels down the steep slope above Icod de los Vinos and across the line of the older tube.

(4) Selection of the most favourable flow routes: 'erosion' of the tube by hot, flowing lava, causing modification of passage forms and patterns (e.g., enlargement of the conduit, meandering, etc.). Fluctuations in the lava level caused the channel to overflow periodically, particularly higher up the slope, and lava spread away from the main routes. Continued periodic flooding resulted in the formation and maintenance of 'escape' or 'overspill' tubes, connecting the main feeder routes and occupying surface units, slowly advancing away from the main feeder. Roofing of the main tubes progressed, with the 'skylights' through which the lava escaped during high surges roofing last. Overflow, or a new flow unit, crossing the line of the lower cave was captured at the roof collapse and formed the 4m pot and lavafall.

(5) Continued advance of the lava flow, with periodic surges being accommodated now underground through the spillways. Surface flows strengthened the roof and later tubes formed across the line of the main tube and were captured by it (e.g., Cueva de los Piquetes).

(6) Cessation of effusive activity at the vent and gradual, sluggish drainage of very viscous lava from the tube, causing its subsequent modification and diversity of passage forms.

(7) Cooling of the flow and collapse of the roof in two, or possibly three places. Some collapse of the walls and ceiling of the cave.

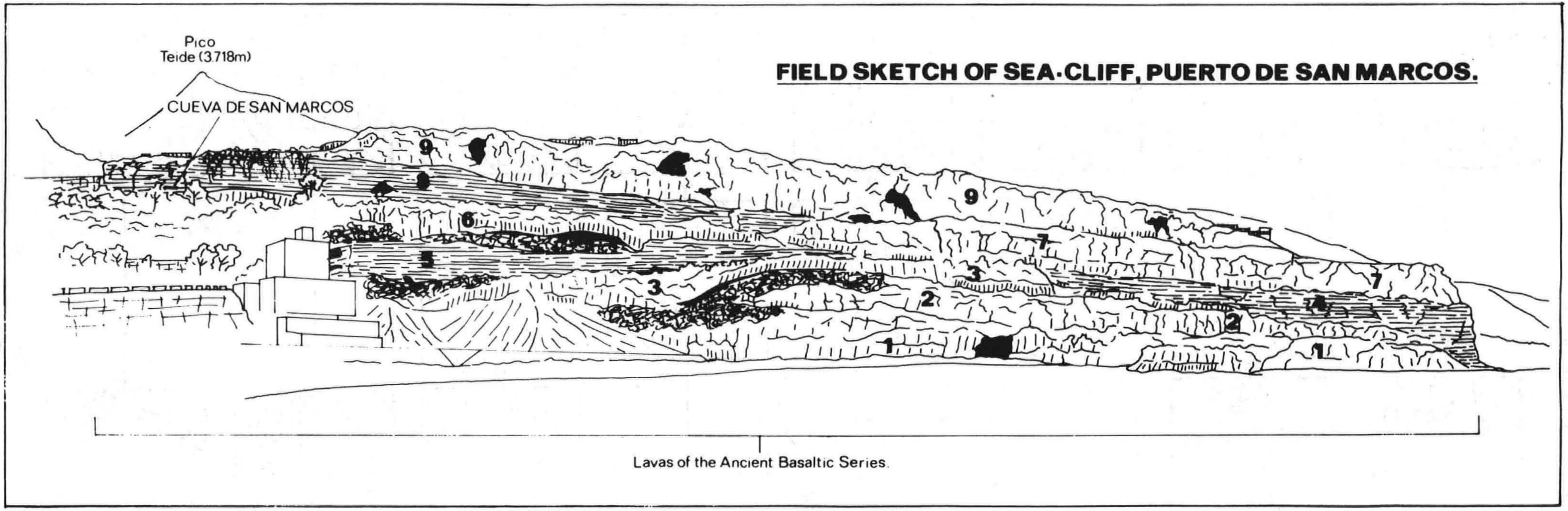
Geology of the Cueva de San Marcos

An investigation of the geology of the Cueva de San Marcos was carried out in April, 1974. The cave is of outstanding scientific interest because it has been truncated at the cliff-face at Puerto de San Marcos, offering a unique opportunity of relating the cave form to the flow structure so well exposed in the cliff.

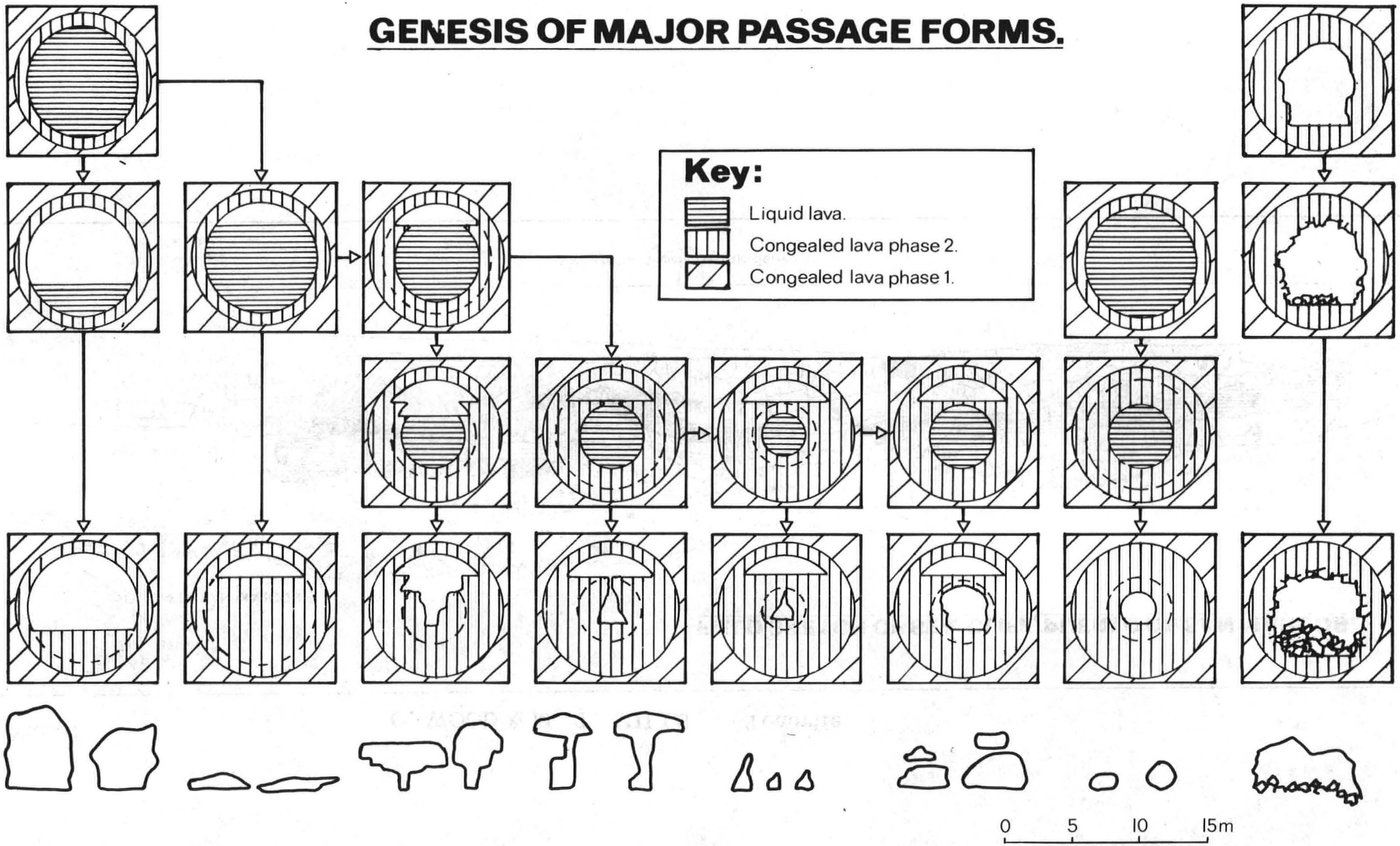
Morphology

The form of the cave in plan, long profile and cross-profile is shown by the cave survey (Fig. 3). There are two entrances; one lying in the cliff-face overlooking the beach at Puerto de San Marcos and the other, higher entrance, resulting from roof collapse, lying behind the cliff in a banana

Fig. 4. C. WOOD & M. T. MILLS Tenerife



GENESIS OF MAJOR PASSAGE FORMS.



Cross-sections abstracted from surveys of Cueva del Viento and Cueva de San Marcos.

Fig. 6. C. WOOD & M. T. MILLS Tenerife

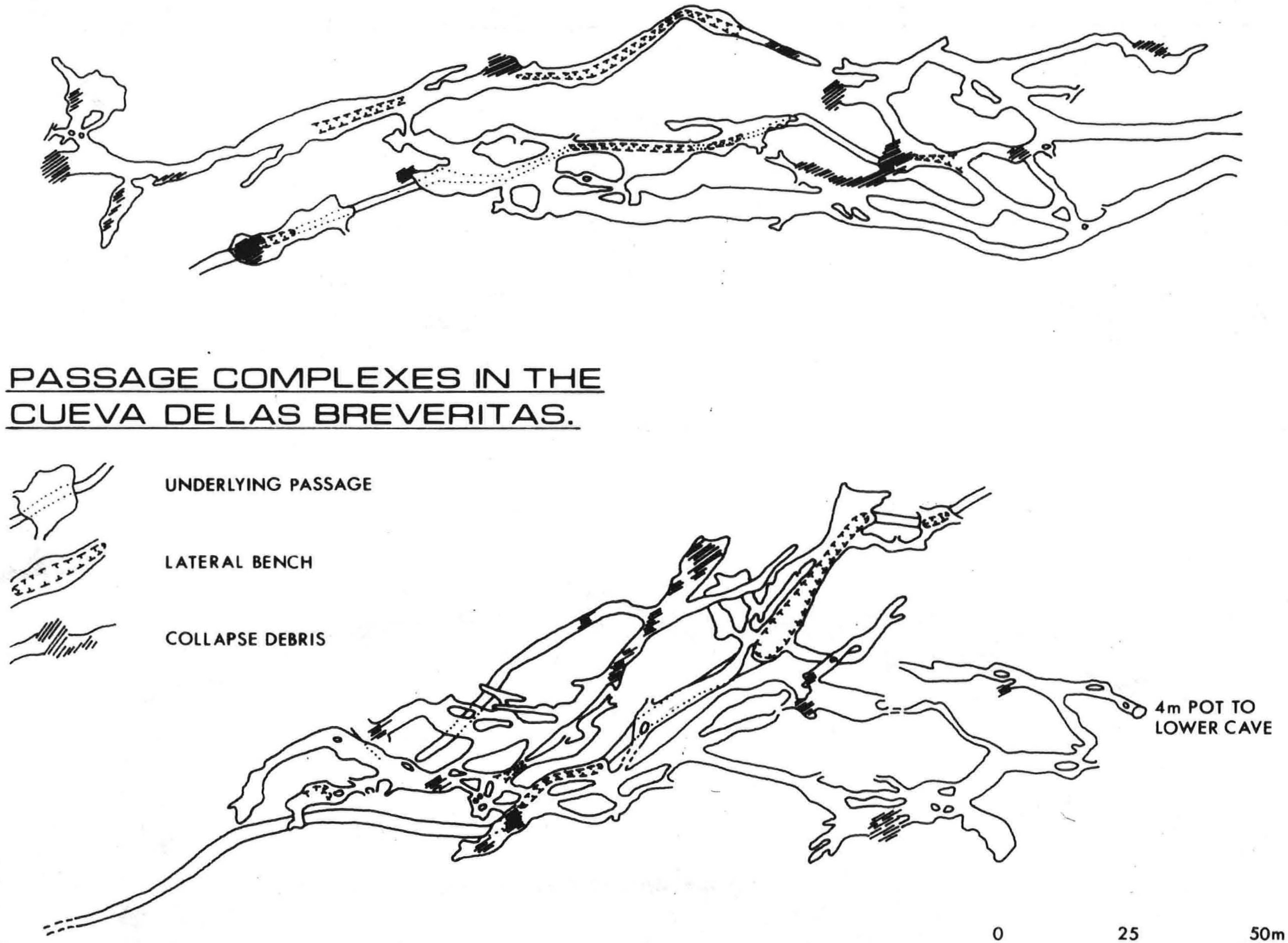
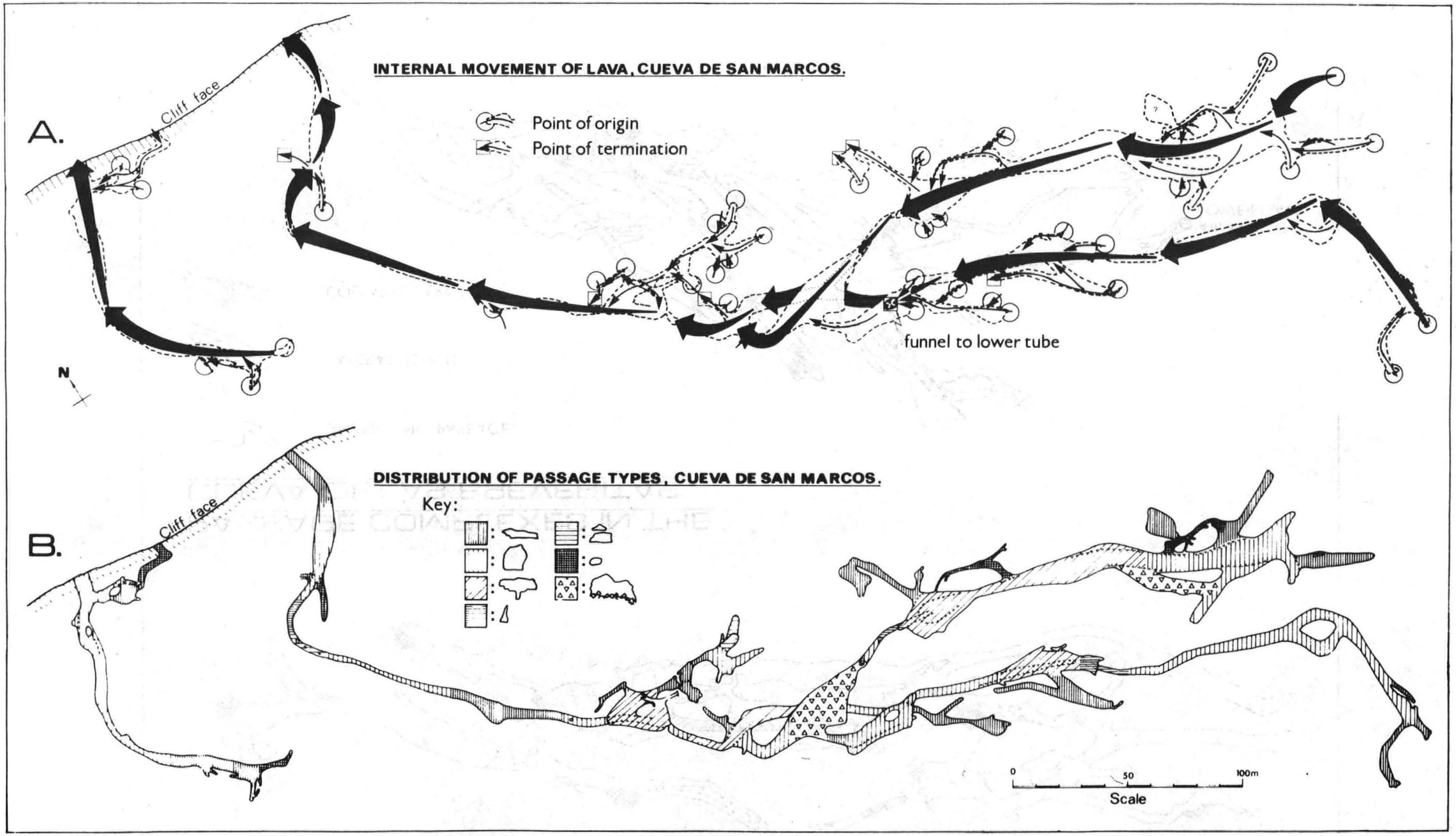
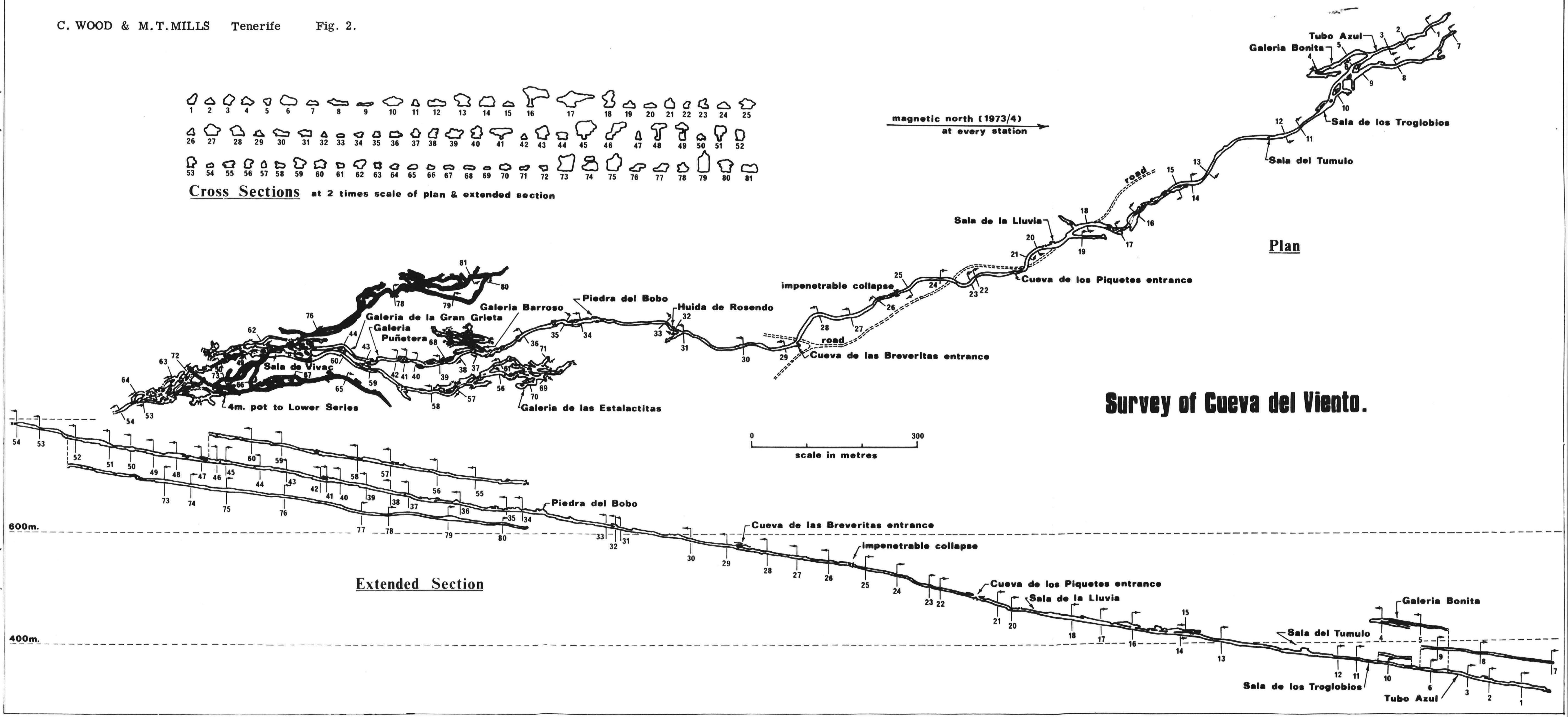


Fig. 7. C. WOOD & M. T. MILLS Tenerife



C. WOOD & M.T. MILLS Tenerife Fig. 2.



plantation. In plan the cave possesses two main passages which converge downflow about halfway through the cave. The northerly branch passage possesses large dimensions, a sandy floor and connects with higher level passages overlying the point of confluence of the two main passages. The southerly passage is more restricted in its dimensions, but is a classic asymmetrical tube with an "aa" (clinkery or spinose) floor. In addition, some 200m of passage lies behind (i.e., to the north of-) the higher entrance. The average gradient of the cave is 6°.

Passage forms in the Cueva de San Marcos group into the same types that occur in the Cueva del Viento, though some passages in the Cueva de San Marcos are very spacious and breakdown is of much greater importance.

Tiered tubes of the type discussed in the previous section, caused by the convergence of lateral benches, are ubiquitous in the Cueva de San Marcos. Other unusual features are impressive lateral benches near the higher entrance, which are the result of converging lava flows; a series of stepped benches and a deep trench in the region of Section No. 16, which are the remains of an underground lava lake; and the funnel-like feature in the floor of the upper level passage.

The internal drainage pattern

Fig. 7A is a diagram showing the pattern of drainage of fluid lava during the active life of the lava tube. The diagram was constructed from data plotted in the cave. The direction of the flow of the lava was partly determined by the overall (i.e., roof **and** floor) direction of passage gradient, and partly by analysis of fossil flow features. Points of origin of the flow in the cave were easily recognised at 'lava springs' and are shown on the diagram as open circles. Points where the liquid lava sumped the passage, eventually congealing and blocking it, were recognised as 'lava seals' and are shown on the diagram as open squares. The diagram illustrates the complexity of the flow through the lava tube and is a very useful aid for morphogenetic interpretation.

Morphogenesis

Following the example of the previous section, evidence of the genetic stages will be described in the reverse sequence, because later stage modifications hide, or frequently obliterate, evidence of the earlier stages.

Stage 3 Breakdown of the roof and walls is common in the Cueva de San Marcos, but only in three places does it significantly control the form of the cave:

(1) the form of the passage from which Section No. 20 was taken is predominantly joint-controlled and its floor is composed of collapsed roof blocks;

(2) across on the opposite side of the main northerly passage, a big loop has suffered extensive collapse and piled boulders form a raised platform along the side of the main tube;

(3) a large chamber, extensively modified by collapse, lies above the confluence of the two main passages.

There are other areas of collapse in the cave, particularly in the main northerly passage, and roof collapse has formed the higher entrance. The reason for collapse and breakdown is uncertain, though lava tubes are particularly susceptible to collapse because of the abundance of joints, partings and flow units contacts in the surrounding lava flow. All collapses in the Cueva de San Marcos occurred after the floor had solidified and may have resulted soon after this due to cooling and contraction of the surrounding flow. Some water does enter the cave in places through the roof, probably from irrigation ponds on the surface, and this may have encouraged some collapse. Similarly, earth tremors from volcanic activity on the island, and the vibrations caused by heavy traffic on the road over the far end of the cave, may have loosened the already fractured roof.

Exposures of the lava flow are not well displayed inside the cave, but do show a structure similar to that seen at the cliff-face.

Stage 2 As in the Cueva del Viento, passage forms in the Cueva de San Marcos are the result of modifications resulting from the drainage of the lava tube and are explained in Fig. 6. In addition, in the Cueva de San Marcos, it was found possible to construct a generalized 'morphogenetic map' by plotting the position of dominant passage types through the cave (Fig. 7B).

Stage 1 Figs. 7A and 7B clarify many of the problems of the formation of the Cueva de San Marcos.

(a) It is evident from Fig. 7A and from the structure of the flow exposed in the cliff-face and in the cave, that the main passages of the Cueva de San Marcos were the feeder tubes for a vast system of smaller distributary tubes in Flow 8, and the form and extent of the cave is the result of only partial drainage of this tube complex about the main feeders. The main flow routes through the tube complex would have been the most sensitive to adjustments in the discharge of new lava from the vent, while flow through the distributary routes was controlled by developments taking place in the feeder routes. At cessation of vent activity, the main routes would have been the most likely of the lava tubes in the complex to drain of residual lava because (a) they were directly connected with the vent, (b) they carried a greater volume of lava, which must have remained mobile for a longer period than the lava in the smaller distributary passages, and (c) drainage of the distributaries could not proceed without a sufficient head of liquid to force continued forward flow, which obviously they could not have had if the level of the main conduit had dropped below the level of the entrances to the distributaries (it will be noticed that entrances to the majority of side passages occur high in the walls of the main tube), and reverse drainage could not have taken place unless there was space to receive the residual lava from the side routes as a result of the lava level in the main route having lowered. Thus, one can speculate that if the residual lava in the lava tube complex had remained mobile for a much longer period (i.e., the lava was less viscous, or there was a steeper gradient), then the extent of the cave network would have been much greater than it is today, for more of the tube system from which the cave originated would have drained.

(b) The complexity of the Cueva de San Marcos is a reflection of a large number of ingressive and eggresive side passages and there are few closed loops as in the Cueva del Viento. These minor passages fall into three general types.

(i) Some pass across the line of the main route; for example, near the points from which Sections No. 7 and 13 were taken. Both cross the main route just under the roof and, in the Section No. 7 example at least, access can only be made via an exposed climb up the wall of the cave. The difference in the direction of the flow of the main route and the transverse route is shown in Fig. 7A. It is suggested that these transverse passages are later formations, having originated when lava was emplaced across the roof of an earlier formed tube which, during subsequent enlargement of the lower, caused the higher flow to be captured by the lower.

(ii) Other side passages are more difficult to account for, though there are two possible explanations; (a) it may be found that enlargement of the main feeder tubes caused the capture of previously formed tubes and gave them permanence through continued flow (i.e. incision of the main tube across the line of divergent older routes); (b) perhaps more likely, these side passages originated as overflows of the original channel (i.e., before roofing). The passages off the main route in the region of Section No. 16 tend to support the latter view, for it appears that ponding of the flow took place here, with the passage from which Section No. 22 was taken acting as an overflow route from this pond.

(iii) Some loops, for example, at Section No. 28, appear to have originated simply as part of the main channel.

(c) The upper level passage overlying the confluence of the two main routes appears to have formed partly as a result of the ponding at Section No. 16, when overflow flooded across the roof of the earlier formed tube. An early outlet for this lava was the tube which lies today behind the upper entrance, though this flow was eventually captured again by the main route just downflow of the confluence (at Section No. 13). Other surface flows converged with the main higher level flow from the south east. At some stage lava broke through the roof-, and was captured by, the lower level in the region of Section No. 24, as shown by the great funnel-like depression in the floor of the upper cave and the corresponding lava spring in the lower cave.

(d) The branch passage emanating from the region behind the upper entrance is a very low passage involving flat-out crawling in many places. Figure 7A shows the flow direction of this passage to be toward the main route and it may have been an important tributary, but is now filled with undrained lava. The reason for it remaining undrained is easy to explain: (i) the outlet was into the main tube where larger flow caused the lava in the tributary to be held back, or ponded; (ii) meanwhile, lava was invading the tributary from behind via the passage near Section No. 13.

Summary of the genetic history of the Cueva de San Marcos

(1) Advance of the flow front across the line of the cliff-face today by the 'toe-budding' process, causing the construction of a lava flow composed of small, piled elliptical units. Gradual lengthening of the channel network from which the small units emanated. This network in the region of the cliff-face initially consisted of two small channels which converged.

(2) Stabilization of the channel, its gradual enlargement through bed 'erosion' and leveé construction. Overflows during high surges causing lateral lobes to advance across the surface away from the channel, thickening the flow. Some new flow units emanating from the channel developed their own tubes and were maintained by continued flow from the main route. Gradual roofing of the channel network, though for a period the channel was incompletely roofed.

(3) In one place in the channel an obstruction caused the flow to pond and lava eventually escaped across the roofed part of the channel immediately downslope, causing the formation of a higher level tube. This lava eventually found its way back into the main channel lower down the flow after crossing the line of the main tube.

(4) The channel was eventually fully roofed and the roof was strengthened by overflows and by the addition of new flow units, some of which held their own tube networks.

(5) Enlargement of the main tube caused the capture of lava carried in overlying tubes.

(6) Vent activity ceased and the tube drained. As the level in the main tubes lowered, the tributary passages gradually drained, though their drainage was not extensive as their gradient was away from the main tube. Drainage of the lava lake near Section No. 16 left pronounced 'shorelines' or lateral benches. The nature of the drainage in the different parts of the tube network controlled the eventual shape of the resulting cave passage, there being great variety throughout the cave.

(7) The lava flow cooled and contraction led to jointing and collapse of the walls and roof occurred. The sea eroded the coastline to produce the high cliff at Puerto de San Marcos and abruptly truncated the cave. Water dripping into the cave and the vibrations caused by heavy road traffic overhead continue to weaken the roof.

Acknowledgements

The authors wish to express their thanks for help with the fieldwork carried out by the following SMCC members: A. J. Butcher, G. A. Dodding, M. Illingworth, D. W. Wilkinson and J. Trenchard of the University of Leicester, Dept. of Geology.

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Index to Volumes 3 and 4

1976-1977

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