WESSEX CAVE CLUB

OCCASIONAL PUBLICATION

MENDIP KARST HYDROLOGY RESEARCH PROJECT

PHASES ONE AND TWO

T ATKINSON, D.P. DREW with C.HIGH

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PHASES ONE AND TWO

by

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Chapter ONE

INTRODUCTION

In order to provide a sound framework of basic knowledge of present day hydrological conditions within the Mendip Hills, a five year research project is being undertaken by the University of Bristol Geography Department, with the financial assistance and co-operation of the Avon River Authority, Somerset River Authority, and Bristol Waterworks Company. The main object of this project is the tracing of all the major swallet streams of Mendip, and thus the delimitation of catchment areas for particular risings. In addition, studies of limestone solution rates, water budgets, percolation water, and water quality, will be made. The information obtained from this work may be of value both in practical terms (e.g. assessment of water reserves, pollution problems) and for further research work. For example, no full study of speleogenesis within an area can be made without detailed knowledge of the contemporary drainage system.

This first report gives the results of Phases One and Two of the project, together with an account of the techniques used. Phase One was concerned with the drainage of the north flank of the Beacon Hill pericline, in essence the catchments of Ashwick Grove Risings and St. Dunstan's Well Rising. Apart from the swallets draining off the southern flank to the Asham Wood and Holwell springs, work is now complete in this area.

Phase Two was concerned with tracing some of the feeders to Cheddar and Wookey Hole Risings in Central Mendip. As these are the two largest resurgences in the Mendip Hills, much of the future work will be concerned with the establishment of the catchment areas of these two springs, and in particular the "watershed" between them. To some extent each individual phase of the project will form an independant unit, and the results obtained will be published in the same form as the present report, at irregular intervals.

Chapter TWO

WATER TRACING TECHNIQUES

One of the major problems in geomorphological research in karst areas is that drainage is largely subterranean and therefore many of the techniques employed for investigation are indirect. The main exception to this is direct cave exploration, but in general only a small percentage of active and disused drainage channels are accessible by this means.

The tracing of the subterranean courses of streams which sink on limestone forms an integral part of any study of limestone hydrology. Many different techniques have been evolved to trace cave waters. They may be divided into,

1). Dyestuffs - e.g. fluorescein. The reappearance of the dye may be detected visually, or the dye may be recovered from the stream by absorbing it on a suitable material. Examples are the use of activated charcoal for fluorescein, or cotton strip nets for Rhodamine B.

2). Chemical Methods - This involves the addition of a chemical to the swallet stream which may be detected at the rising by chemical analysis of water samples or by electrical conductivity measurements. Examples are common salt and Ammonium Sulphate.

3). Mechanical Methods - The tracer in this case consists of some type of particles which are added to the swallet streams and carried as bed or suspended load. They are detected at the rising by collection on nets or by direct observation. Examples are the addition of chaff, polypropylene floats, or lycopodium spores.

4). Bacterial Methods - Cultures are made of specific, harmless, bacteria, and added to the swallet stream. The rising is detected by producing further cultures from water samples taken from a number of risings. An example of a suitable harmless bacterium is Serratia indica.

5). Radioactive Tracers - A fast decaying radio-isotope is added to the swallet stream, and the rising is detected using a geiger counter. Suitable isotopes are Iodine 131, Tritium.

To be fully viable, a water tracing technique should conform to as many as possible of the following criteria.

1). It should be harmless in the concentrations used, both to men and animals.

2). The tracer should not be offensive to water users, e.g. dyes should not be present in visible concentrations in water supplies.

3). Its effectiveness should not be impaired by acid or alkaline waters.

4). It should not affect cave fauna or flora.

5). It should be possible to trace several swallets simultaneously.

6). The time taken for the tracer to reappear should be as true as possible a reflection of the actual time taken by the water.

7). The amounts of tracer used, and the method of detection, should be sufficiently sensitive and reliable for negative results to have the same value as positive ones.

8). The method of tracing should ideally be such as to provide additional data concerning the nature of the drainage system.

9). Detection at the risings should be by automatic or semi-automatic means.

10). The materials should be inexpensive.

11). The method should not be time consuming.

12). The tracer should not be a substance which occurs naturally in the area in which it is to be used.

No water tracing technique yet evolved fulfills all these criteria. For the experiments on Mendip it was considered that criteria 1)., 2)., 5)., and 8)., must be fulfilled. This ruled out the use of visual dye testing, radioactive, and bacterial methods. After experimenting, it was decided to use the technique of tracing by lycopodium spores developed by Zötl (1959) for the main work. In addition, fluorescent dyes will be used when necessary, to supplement or corroborate the results obtained using lycopodium.

Lycopodium Spore Water Tracing

Method

Lycopodium clavatum is the spore of a club moss. It is a facetted, almost spherical, cellulose, structure, approximately 30 microns in diameter. The small size of the spores means that very large numbers of them can easily be introduced at a sink, and as in theory only one spore need be caught at a rising to prove a connection, a very high percentage loss of spores en route may be tolerated. The spores appear to be virtually indestructible under cave conditions, especially if coated with a resistant carbamide resin. In addition, it is possible to dye batches of spores different colours, thereby allowing several different swallets to be tested simultaneously. This makes possible valid comparisons of flow rates for different swallets. The spores are trapped in conical plankton nets placed in the risings. The nets act as filters, allowing water to pass through them, but trapping the lycopodium spores. Samples of the material trapped in the net are then examined under the microscope, and the spores present, if any, counted. Direct comparison of the lycopodium method with other tracing techniques suggests that flow times from swallet to rising obtained using lycopodium are considerably more accurate than those obtained by other methods.

Preparation of the Spores

The small size of the spores makes it essential that they be thoroughly wetted before introduction at the stream sink, otherwise they could float on the surface and be trapped at underground siphons. The procedure for dyeing lycopodium spores adopted was as follows. The spores are added slowly to water in the presence of a wetting agent (Teepol 610 is suitable), until they form a thin paste. The mixture is then boiled with continuous stirring for one hour, after which it is removed from the heat and dyestuff is added. About 15 gm. of dye dissolved in 200 cc. of methylated spirits per kilogram of spores should be used. The mixture is then kept at 90° C for a further hour, with continuous stirring. The spores are then allowed to cool, and if required a carbamide resin is added. This involves the addition of 80 cc. of 20 % Potassium Hydroxide solution, 60 gm. urea dissolved in water, and 200 cc. Formalin solution, per kilogram of spores. Whether a carbamide resin is used or not, 200 cc. of Formalin solution per kilogram of spores should be added to prevent mould forming if the spores are to be stored for any length of time.

The spores may be washed and cleaned using a filter pump to suck water through them, and dried in an oven at 70 °C if required. This technique was adopted for the East Mendip tests, but for the larger quantities used on Central Mendip the mixture was evaporated until it formed a thick paste, and stored in large plastic bins in this condition. Introduction of the spores at the sink is greatly facilitated if they are in the form of a paste.

Considerable experimenting with a wide variety of dyestuffs has revealed only five dyes which are suitable for dyeing lycopodium spores. These are, Malachite Green, Saffronine, Magenta, Methyl Violet and Bismarck Brown. If undyed spores are used in addition it is therefore possible to test six swallets simultaneously.

Collection of Spores and Analysis of Samples

The construction of the nets used on all the tests so far is shown in Fig. 1. The front, canvas portion of the net simply funnels water, and the spores are trapped in the fine mesh silk or nylon section. Nylon netting of 25 micron mesh has been found to be the best material for the filter. To take a sample the net is lifted up vertically, open end uppermost, and allowed to drain. The spores are washed down and concentrated in the rubber tube at the apex of the funnel, and the clip can be removed and a sample taken in a suitable test tube. 20 cc. to 50 cc. of sample are usually collected. When the net is put back in the stream the clip is not replaced for a few moments, to allow the spores still remaining in the rubber tube to be washed away. In the tests conducted to date, two diameters of net have been used, 8 ins. and 18 ins. respectively, depending on the sampling site. Both sizes were mounted on supporting frames of wood or Dexion (see Plates 3,4,6), with a filter of chicken wire over the front of the net to prevent damage by floating debris.

The samples obtained from the net are if necessary treated with concentrated Hydrochloric acid or boiled with Potassium Hydroxide to remove excessive calcite or organic material. They are then centrifuged at 3000 r.p.m. for 1 - 1½ hours to concentrate the spores. The liquid is poured off and the residue examined under the microscope at a magnification of x100. The number of spores of each colour from each sample may be counted if data to produce concentration diagrams is required.

Field Technique

The amount of spores required for any individual test is difficult to estimate unless reliable information concerning the nature of the drainage system is available, (including prevalence of silt, flooded zones, etc.).

Amounts used should be based on the discharge of the largest resurgence to be sampled rather than on that of individual swallet streams. This will represent the maximum degree to which the spores can be diluted. A rough indicator of the amount to be used where little is known about the underground hydrology is to allow one kilogram of spores per mile of underground travel, per 10 cubic feet per second discharge at the largest possible outlet. This assumes that approximately 10 % of the discharge of the rising is "capped". If the proportion of the rising capped is more or less than this the amount of spores used can be varied accordingly.

One of the main problems to be overcome in lycopodium tracing is that of contamination. To minimise this nets and spores should be stored well apart, in different rooms; dyeing and post-collection analysis should be carried out in different laboratories; and the personnel involved in putting the spores into the swallets should not be concerned with sampling or with analysis of samples.

Interpretation of Results

The number of spores obtained in each sample may be plotted graphically against time, or, better, in block diagram form, to produce concentration diagrams. From this diagram the first appearance of the spores at the rising (the minimum travel time) and the peak concentration may be read off. The form of the concentration diagrams obtained varies considerably but generally shows either a normal distribution or a right-skew (see Fig.2). The degree of skewness and the temporal spread of the concentration diagram are almost certainly functions of transit time and the nature of the system traversed (e.g. zones of low flow rate, such as sumps, are likely to disperse and prolong the spore wave). As yet, little research has been carried on concerning the analysis of concentration diagrams in relation to these parameters, and consequently no attempt has been made to interpret in detail the diagrams obtained in Phases One and Two of this project, in this respect.

Fluorescent Dyestuffs

Of the currently used fluorescent dye tracers, (Rhodamine B, Fluorescein, Eosin, Durazol Orange), only fluorescein was considered suitable for use in the Mendip water tracing experiments. The technique adopted is that of Dunn (1957), involving the absorption of the dye at the rising on activated charcoal. The dye is later elutriated from the charcoal using a 10 % solution of Potassium Hydroxide in ethanol. This technique permits the use of very small quantities of dyestuffs which cause no visible discolouration of the resurgence waters. For future work the use of the fluorescent dye Pyranine Conc. in conjunction with a fluorimeter is visualized.

Chapter THREE

HYDROLOGY AND LIMESTONE SOLUTION

Introduction

The chief parameters to be measured in a study of karst hydrology are, water input at the swallet stream sinks, output at the risings, precipitation, and evapotranspiration.

Discharge measurements will be made by installing 90 degree V - notch weirs or rectangular sharp-crested weirs (with or without continuous recorders) or by the establishment of rating curves for each site using current meters and stage gauges. Discharge and precipitation records for the last several decades are already available to some extent in this area.

The solution studies are essentially a continuation of work already initiated on Mendip (notably by Smith and Mead, 1962), and will consist of analysis of water samples from the swallets and risings with respect to Calcium and Magnesium Carbonate contents. Readings of pH will also be made. The data obtained from this work, in conjunction with the water tracing results will permit a general picture of the hydrology of the area to be built up.

Finally, the relatively new technique of pulse wave analysis will be employed where suitable, and this is outlined below.

Pulse Wave Analysis

Pulse wave analysis of karst springs is a new and powerful tool in karst research. Almost all the previous work in this field has been conducted by Ashton (1966), who was responsible for developing the technique to its present standard. The methods adopted by the present authors were those recommended by Ashton.

At times of precipitation, cave streams draining a karst area will undergo a relatively rapid rise in discharge, followed by a fall to a more normal level when precipitation ceases. This rise and fall in discharge constitutes a flood wave, or pulse, which will travel down the passages of a cave and ultimately emerge at a rising. Because of the greater bulk of the flood water, and in some cases of its greater velocity, it will dissolve less limestone than would the normal stream. The arrival of the actual flood water at the rising may be detected by a sharp fall in Calcium Carbonate and pH values. The analysis of a system by means of such a flood pulse is based upon a comparison of the times of arrival at the rising of the discharge pulse and the actual flood water. The flood water may affect the other characteristics of the system, and if temperature and turbidity are recorded as well as hardness, pH, and discharge, it is possible to extract a maximum amount of information from the data.

To illustrate the principles involved, consider a system of which the discharge and hardness curves are shown in Fig. 3. The arrival of the discharge pulse at A is accompanied by a rise in hardness as slow-moving, hard, water is driven out of the phreas by the flood pulse. The latter is transmitted instantaneously through the phreas. At C the actual flood water arrives and hardness drops markedly. The distance along the time axis between B and D, therefore, gives the time taken by the water to traverse the phreas. Moreover, the area beneath the discharge curve between A and C gives the volume of the phreas. Such information is useful not only in the academic study of karst landscape, but also in the field of water supply.

The reader wishing for a full account of the theory of pulse wave analysis should refer to Ashton's paper (1966).

Field Techniques and Logging of Data

The five parameters to be measured are turbidity, pH (and saturated pH), temperature, hardness, and stream discharge. Ideally, an apparatus should be used which will log all these parameters onto a continuous recorder. Such an apparatus is not available at the present time. The methods in use by the authors are described below. In future reports it may be assumed that these methods were employed, unless otherwise stated.

1). Measurement of Discharge

A continuous stage/discharge recorder, set on a one ft. range, is used to record discharge.

2). Measurement of Hardness

250 cc samples of water are taken in polythene bottles. These are returned to the laboratory and titrated within ten days, using standardized EDTA solution, and screened or unscreened murexide (Ammonium Purpurate) as an indicator. Screened murexide is preferred, as it gives a clearer end point.

3). Measurement of pH and saturated pH

pH is measured in the stream, using a portable, battery powered, pH meter, reading to 0.1 units of pH. The meter is standardized in the field, using pH 7.0 buffer solution. The electrode of the meter is equipped with a cavity which can be filled with Calcium Carbonate powder, for the measurement of saturated pH. Care should be taken to ensure that readings of pH and saturated pH are both taken at the same temperature.

4). Measurement of Temperature

An ordinary thermometer, graduated in 1 °C or 0.5 °C, is not sensitive enough for use in most Mendip resurgences. A mercury thermometer graduated in 0.1 °C is used.

5). Measurement of turbidity

This is the most difficult parameter to measure, as it is frequently too low to record, even in high stage conditions. The simplest method is to pour water into a measuring cylinder until a mark made on its base can no longer be seen. The volume of water in the cylinder in then recorded. This gives a relative indication of turbidity, which is all that is required. As large a measuring cylinder as possible should be used, unless the turbidity is very high, in which case a smaller one may be calibrated against the larger.

Chapter FOUR

PHASE ONE: WATER TRACING ON EAST MENDIP

Introduction

The area examined was the northern flank of the Beacon Hill Pericline, between Little London in the west and Leigh-on-Mendip in the east. During a series of eight seperate water tracing runs between June 1965 and November 1966 the fifteen major stream sinks in this area were traced, the chief object being the delimitation of the catchment areas of the risings at St. Dunstan's Well and Ashwick Grove. Two distinct risings occur at St. Dunstans - east and west - at the same altitude and some five feet apart. Two groups of risings may be distinguished at Ashwick Grove - Higher and Lower - 1000 ft. apart horizontally and 30 ft. vertically. During the tests, risings at Gurney Slade were also netted, but gave consistently negative results.

The tracer used was lycopodium spores, and in addition results were checked in several cases using fluorescein / activated charcoal, and / or Rhodamine B or Malachite Green. Consistent results were obtained irrespective of the technique used.

The normal weather flow at each of the main risings is approximately 2 cubic feet per second, whilst that at the swallets varies from 0.04 cubic ft. per second (Midway) to 0.9 cubic ft. per second (Stoke Lane Slocker).

The swallets tested were, from east to west, Pitten Street Slocker, East End Sink, Stoke Lane Slocker, Brickdales Inn Slocker, Withybrook Slocker, Midway Slocker, Larkshall Swallet, Blakes Farm Swallet, Springfield Slocker, Oakhill Swallet, Stout Slocker, P1, P2, P3, (three innominate sinks into which water percolates through the soil) and Little London Swallet.

Silk nets of seven inches diameter were used to cap the risings throughout these tests.

Results

The results obtained are shown in Fig. 4. Times of reappearance, flow rates, and amounts of spores used are shown in Table 1. The sinks shown in Fig. 4. are:-

1. Pitten Street
2. East End
3. Stoke Lane
4. Brickdales Inn
5. Withybrook
6. Midway
7. Larkshall
8. Blakes Farm
9. Springfield
10. Oakhill
11. Stout
12. P1
13. P2
14. P3
15. Little London

The risings marked are :-

R1 Whitehole
R2 St. Dunstan's East
R3 St. Dunstan's West
R4 Ashwick Lower
R5 Ashwick Higher

It seems most unlikely that the catchments for Ashwick Grove and St. Dunstans risings extend beyond the swallets tested. To the east, Pitten Street Slocker has been shown to resurge at Whitehole Spring, and to the east of this the Carboniferous Limestone is overlaid by Liassic rocks. The boundary of the catchment may therefore be placed between the East End and Pitten Street valleys. To the west, the Little London group of swallets appears to mark the west extremity of the catchment, water sinking further west presumably running to Gurney Slade.

The Swallets

1). Pitten Street Slocker

The only swallet tested to the small Whitehole Rising. The nature of this rising suggests that its chief source may be percolation water.

2). East End Sink

Although nearer to Whitehole than to its resurgence at St. Dunstan's Well, its course to the latter may well be a result of the stream adopting part of the old drainage system that leads towards St. Dunstan's that exists in this area. Surprisingly, the water does not join the Stoke stream but crosses it without mixing to resurge at the more westerly of the St. Dunstan's risings.

3). Stoke Lane Slocker

This is the only stream in the area that can be penetrated for any distance. Fig. 4. does not show the route of the known cave. Stoke Lane Slocker is not a typical swallet in that the stream sinks almost half-way across the limestone outcrop, and seems to be following an ancient cave system, in part at least. The low rate of flow (see Table 1) may be accounted for by the very low gradient to the rising and the known presence of considerable zones of canal in the cave.

4). Brickdales Inn Slocker

A very small wet weather sink with a very steep gradient to its rising at St. Dunstan's East.

5). Withybrook Slocker

This is the only stream flowing to both sides of St. Dunstan's Well. The two hour time lag between the resurgence of the water at the east and west sides of the rising suggests that the stream splits some distance before the rising.

6). Midway Slocker

Water sinking at this swallet reappears at both St. Dunstan's Well East and at the Lower Ashwick Risings, suggesting that it is on or near to the subterranean "watershed". All swallets further west flow to Ashwick. The extremely rapid flow time (2.5 hours) and rate (1600 ft. per hour) to St. Dunstan's suggests that the stream may flow eastwards to join the St. Dunstan's-Withybrook Fault, and fall at a steady gradient to the rising. It may be that the three swallets near the fault which flow to St. Dunstan's (Withybrook, Midway, Brickdales Inn) all join this flow line, as in each case rate of flow is high.

7-10). Larkshall, Blakes Farm, Springfield, Oakhill

These swallets comprise the remainder of the drainage for the Lower Risings at Ashwick Grove. They all have similar flow rates. Springfield Slocker, with a higher gradient to the Higher than to the Lower Ashwick Risings, is the only unusual feature in this catchment.

11-15). Stout Slocker, P1, P2, P3, Little London Swallet

These are the feeders for the Higher Ashwick Risings, and appear to form a unit on their own, with relatively high rates of flow. With the exception of Stout Slocker the streams disappear at indeterminate points on marshy ground, and surface features indicate that they have gone underground comparatively recently.

The Risings

1). St. Dunstan's East

This is the largest individual rising in the area. Spore concentration curves (not illustrated) for the Withybrook, Midway, and Brickdales streams are markedly similar, with a sharp rise and rapid falloff, whereas the concentration diagram for the Stoke Lane Slocker stream shows a slow build-up and a prolonged fall-off spread over several days. This supports the view that the Withybrook, Midway, and Brickdales streams join early in their paths, but do not join the Stoke Lane water until close to the rising. The known part of Stoke Lane Slocker has long sections of flooded passage and canal, and this may explain the flattening of the concentration curve.

2). St. Dunstan's West

Only two of the swallets tested contribute to this rising - East End Sink, and part of the Withybrook flow. Significantly more spores from Withybrook appeared at this rising than at St. Dunstan's East. This may be a reflection either of the different percentages of the Withybrook water flowing to each spring, or on different conditions within the two sets of passages. In order to reach this rising, East End water must cross the Stoke Lane, Brickdales, and Midway flow lines (see Fig. 4).

3). Ashwick Lower

That the three risings comprising this source (Wishing Well and two capped risings) are interconnected, is shown by the fact that spores from all the swallets draining there appeared at all three.

4) Ashwick Higher

Of the feeders to this rising Stout Slocker and Little London gave spore counts five to seven times higher than the other three swallets. In the case of Stout Slocker this may be due to its greater discharge, and in the case of Little London to the presence of rather less silt in the system.

Conclusions

The flow lines established show considerable complexity - streams bifurcate to more than one rising, and cross one anothers' paths without mixing. This is similar to the results obtained by Zötl (1959) in the Dachstein Alps, Austria. The presence of discrete risings only a few feet apart at St. Dunstan's Well and 1000 ft. apart at Ashwick Grove, together with the nature of the stream traces, suggests that the conventional concept of water table is invalid in this area, the streams appearing to flow in discrete channels from sink to rising. When nets have been left at the risings for several weeks between test runs, no spores have been trapped, and this also would seem to point to the absence of a large body of standing water behind the risings.

It is now possible to define with reasonable accuracy the boundaries of the catchments for the St. Dunstan's Well and Ashwick Grove Risings. Eastwards the boundary must lie between the Bector Wood Valley and Pitten Street. The latter swallet drains to Whitehole and to the east the limestone is overlaid by Lias within a short distance. To the west, Little London marks the end of the line of swallets draining off the flank of Beacon Hill, and thus the subterranean watershed must lie directly to the west of this swallet. The boundaries between the catchments for individual risings within this area are less easy to define. No differentiation of catchment can be made for the two risings at St. Dunstan's Well, but the divide between that and Ashwick would seem to follow roughly the line of Fairy Lane. All drainage to Lower Ashwick lies between the Withybrook Fault in the east and the Oakhill Fault in the west, whilst the Upper Ashwick catchment lies west of the Oakhill Fault, with the exception of Stout Slocker.

Treating the catchments as individual units (no division between St. Dunstan's East and West can be made) a noticeable increase in mean flow rate of swallet water, across the area east to west is apparent. This is shown below :-

Swallets draining to Whitehole	600 ft. per hour
" " " St. Dunstan's Well	660 ft. per hour
" " " Ashwick Lower	780 ft. per hour
" " " Ashwick Higher	890 ft. per hour

Correlation of increasing flow rate for individual swallets with increasing sink to rising gradient (hydraulic gradient) gives a coefficient of +0.309, indicating no correlation. Similarly, no correlation exists between increasing rate of flow and decreasing swallet to rising distance (+0.111). The increased flow rate westwards must therefore presumably be related to better graded flow channels.

The main factors delimiting the catchment area for any one rising are likely to be, the local geology, the hydraulic gradient, and the sink to rising distances. Although geological factors may provide minor controls on flow paths, they do not appear to influence drainage patterns on East Mendip generally. Similarly, swallet to rising distance does not appear to be a very significant factor, but steepest hydraulic gradient does - eleven out of the sixteen flow lines established being along minimum hydraulic gradient lines. Only when the difference between hydraulic gradients to two or more risings is less than 0.6 degrees for a particular swallet, do other factors appear to become dominant in deciding the flow path. It is hoped that a more detailed and rigorous discussion of this area will be published at a future date.

Chapter FIVE

PHASE TWO : CENTRAL MENDIP WATER TRACING

Central Mendip comprises the area of the Mendip Hills between the Winscombe Valley in the west and Slabhouse in the east. Geologically, it consists of three periclines, elongated east-west, and arranged en echelon from WNW to ESE. Outcropping in the cores of the periclines are quartzites of Old Red Sandstone (Devonian) age, and these are flanked by a Carboniferous Limestone succession 3200 ft. thick, with a basal Limestone Shale member (the Lower Limestone Shale). The main folding of the rocks occurred in late Carboniferous times, and the lowest Triassic rocks are scree deposits and sharpstone breccias banked against the Carboniferous Limestone. These deposits are known locally as Dolomitic Conglomerate.

In the south, the hills rise steeply from the peat moors of the Somerset Levels, which are close to sea level, to a plateau surface cut on the limestones at 750-850 ft. O.D. The south side of the hills presents a continuous steep face from Axbridge in the west to Shepton Mallet in the east. The Old Red Sandstone rocks in the cores of the periclines form whaleback eminences whose tops are 100-200 ft. above the level of the plateau.

The drainage of the hills is almost entirely subterranean, but the surface of the limestone plateau is dissected by dry valleys which debouch into one of the several gorges cut into the steep south face of the hills. Cheddar Gorge is the largest of these, and Ebbor Gorge, Biddlecombe and Batscombe are also important. Rainwater collects on the sandstone outcrops, which are covered by thick peat deposits, and flows in streams onto the limestone, where it is engulfed in swallet caves. Most of these are located in the floors of the valleys. The water reappears in springs at the foot of the hills. On the south flank, the largest springs are at Cheddar, Wookey Hole, St. Andrews Well, Rodney Stoke, and Axbridge, but there are a large number of smaller springs and risings also. The six swallets tested in January 1967 are all located to the south of the sandstone outcrops, and only this part of the area has been described. On the north side the topography is similar, though in the east the edge of the hills is less steep and descends to the Radstock Plateau.

The Swallets

The six swallets tested in January, 1967, are, from west to east, Longwood Swallet, Manor Farm Swallet, Swildons Hole, Eastwater Swallet, St. Cuthberts Swallet, and Ramspit. Brief descriptions of each are given below.

1). Longwood Swallet

The swallet stream has a mean discharge of about 0.4 cubic feet per second (Atkinson, in prep.). The entrance to the cave is 250 yards from the Lower Limestone Shale contact, in one of several excavated depressions in the valley floor. In their untouched state, these depressions are filled with stream debris and boulders. Two such depressions are actively engulfing water today, and there are several points upstream of these at which part of the stream sinks in its own bed. Morphological study of the cave (Atkinson, op.cit.) suggests that it has always discharged to the same rising. It is 465 ft. deep and is entered at 700 ft.O.D.

2). Manor Farm Swallet

The stream is about one quarter to one third the size of that at Longwood. It sinks in a single depression in the floor of a valley, about 250 yards from the shale contact. Excavation has revealed a 50 ft. high buried cliff, against which are banked boulders, yellow clays, and stream deposits. A small cave, 60 ft. long has been discovered beneath these, but it is blocked by boulders at the far end. The floor of the depression is at 744 ft.O.D.

3). Swildons Hole

This cave is also entered in a valley floor. The entrance is at the end of a small blind valley excavated in the floor of a much larger valley, which debouches into Cheddar Gorge. The stream is about as large as that at Longwood. Morphological studies (Stanton, 1957, Ford, 1963) suggest that the 4 miles of known cave developed as a phreatic network largely controlled by dip and strike. Ford (op.cit.) has detected four successive levels of development, each lower than the level preceding it. The discharge from these was to the south east throughout the cave's history. The entrance is at 778 ft.O.D. and the deepest point reached is 540 ft. below the entrance.

4). Eastwater Swallet

A small stream, similar in size to that at Manor Farm, sinks at the foot of a 30 ft. cliff at the end of a blind valley. The entrance to the cave is collapsed, forming a pile of limestone blocks, but beyond lies a three dimensional network of passages. There have been no detailed studies, but a brief inspection suggests that discharge may have been from more than one point in the known network. The entrance is at 779 ft. O.D. and the deepest point reached 390 ft. below it.

5). St. Cuthberts Swallet

This cave is located beneath a large uvala, whose appearance has been much altered by mining. The stream is similar to those at Eastwater and Manor Farm, and sinks at a number of points on the west of the uvala. The study of the cave made by Ford (op. cit.), while incomplete, suggests that its final discharge has always been in the same direction, south east, controlled by a large fault running north west - south east. The entrance is again at 779 ft. O.D. and the cave is 400 ft. deep.

6). Ramspit

A steep-sided depression taking a stream of widely varying discharge. Usually the stream is about one third the size of that at Swildons Hole. This swallet is remarkable in that it is located on Dolomitic Conglomerate.

Locations of the Swallets

The locations of the swallets are given in Fig. 5. Note that Longwood and Manor Farm are both situated to the north of Cheddar Gorge and are entered in the floor of valleys tributary to the gorge. The other three large caves (Swildons, Eastwater, St. Cuthberts) are all well to the south east of the Gorge, but are located in a valley which is also tributary to it. Ramspit is close to the top of Ebbor Gorge, which has no branching system of valleys at its head.

The Risings

Seventeen risings between Axbridge and Wells were capped. From west to east, they are, Axbridge, Cheddar, Laubram Batch, Barnet's Well, Honeyhurst, Rodney Stoke, Springhead, Westbury Main Rising, Westbury (Railway Inn), Hollybrook, Easton, Wookey Hole, Glencot, St. Andrews Main, St. Andrews (Scotland Spring). The locations of all these are shown in Fig. 5.

1). Axbridge

The spring is located in a pond behind Axbridge Church.

2-4). Cheddar

The stream issuing from Cheddar Gorge is fed by a number of springs of which the two largest are located at 89 ft. O.D., beneath the cliff on the south side of the gorge, 50 yards down-gorge of Gough's Cave. The upstream spring (First Feeder) is the larger, while the Second Feeder, about 30 yards down stream, discharges about one fifth as much in normal weather. First Feeder is a low, wide, arch in the cliff, filled to the roof with boulders, so that the stream now wells upwards between the boulders and the arch. In the Second Feeder, water rises vertically up a narrow rift 6 ft. in from the cliff and blocked with boulders.

Between these two springs is the cave of Sayes Hole, in which divers have explored 200 ft. of submerged passage with a strong current, at a depth of about 30 ft. below the water level in the springs.

On the north side of the gorge, on the other side of the road at this point, is an artificial lake, in whose floor are five small springs. Two of these are discoloured if the mud in Sayes Hole is stirred up.

The total mean discharge of the Cheddar Springs is 36 million gallons per day (BWW records).

5). Laubram Batch

A small stream rises from muddy ground in the floor of a small blind valley or depression, about half a mile north of Laubram Corner, near Cheddar.

6). Barnet's Well

This rising is in the village of Draycott. On the south side of the village, at a road junction just north of the railway station, is a stone walled spring. The small stream drains into a ditch whence it is piped into a nearby drainage rhyne.

7). Honeyhurst

The site of the BWW borehole south of Draycott. A concrete overflow pipe carries the overflow from the borehole into a drainage rhyne. The borehole is 70 ft. deep, in Keuper Marl (Upper Triassic) rocks. The overflow is normally a small trickle.

8). Rodney Stoke

The actual spring is covered by a BWW pumping house. Above the spring is a small cave. Discharge is considerable, about the same as that at Axbridge. The spring is located in the blind valley running north of Rodney Stoke Village.

9). Springhead

Scattered small risings on the east side of the Rodney Stoke Valley give rise to a small stream which joins that from Rodney Stoke.

10). Westbury Main Rising

A stream rises from Dolomitic Conglomerate above the village of Westbury. Discharge is about one third that of Rodney Stoke.

11). Westbury (Railway Inn)

An ill defined spring in muddy ground gives rise to a small stream which runs through the grounds of the Railway Inn, in the centre of the village.

12). Hollybrook

The spring is about half a mile north of the road from Westbury to Easton. The stream crosses beneath the road at the hamlet of Hollybrook. It can be seen to the north of the roadside, where it issues from a culvert.

13). Easton

The overflow from a borehole, and from a small spring, may be seen flowing in a ditch on the road from Easton to Wookey Hole.

14). Wookey Hole

This rising, the source of the River Axe, is within the Wookey Hole Cavern, which is located at 208 ft. O.D., at the head of a wooded gorge just north of the village of Wookey itself. The ordinary tourist may go as far as the third cavern within the cave, beyond which the roof is submerged. Divers have penetrated beyond this point for a further 850 ft. The maximum depth reached is 90 ft. in the Fifteenth Chamber, and beyond this point the passage ascends. At the present limit of exploration there is a small airspace, but the way forward is not clear.

The mean discharge of the spring is about 20 million gallons per day (BWW Records).

15). Glencot

This is a small rising, now covered by an ornamental fountain, in the grounds of Glencot School, half a mile south of Wookey Hole village. The water from it joins the River Axe.

16). St. Andrews Well (Main Rising)

In the grounds of Wells Cathedral, at the east end of the Cathedral itself, is the complex of springs known as St. Andrews Well. The two largest springs are St. Andrews Main Rising and Scotland Rising, described below.

At St. Andrews Main Rising a large stream appears from beneath the turf. The underlying rocks are Triassic (Keuper) marls. The stream flows into an artificial lake which conceals other risings. Discharge is not known but is similar to that at Rodney Stoke.

17). St. Andrews Scotland Rising

This rising is situated a few yards south west of the Main Rising. The water wells up from the floor of a small pond and the water is channeled westwards in a ditch.

The Water Tracing Tests

The six swallets described above were traced between January 1st. and January 7th. 1967. Stage was high at the start of the tests, but fell off to average winter levels at Cheddar and Wookey by the end of the experiment (see below). The tracers used were differently dyed lycopodium spores, according to the methods described in Chapter Two. Lycopodium was not used at Ramspit where 50 gm. of fluorescein, dissolved in alcohol, was poured into the stream. The amounts and colours of the tracers used for each swallet are shown in Table 3.

The risings described above were all capped with 25 micron mesh nylon plankton nets. Two sizes of net were used, the larger with an aperture of 18 ins. diameter, the smaller with one of 8 ins. In addition, activated charcoal fluorescein detectors were placed in Rodney Stoke, Springhead, Hollybrook, Easton, and both Westbury Risings. The approximate percentage of the flow capped at each rising was estimated by eye, and is shown in Table 4.

The tracers were placed in the swallet streams between 1200 and 1235 on January 1st. Sampling began at 2000 that night and continued at 4 hour intervals until 2400 on January 4th. Thereafter, samples were taken daily up to and including January 7th. Fluorescein detectors were changed every 4 hours until 2400 on January 3rd., after which they were left in place until January 7th.

The combined discharge of Wookey Hole and Glencot Risings was recorded on the BWW continuous stage recorder at Henley, near Wookey. At its peak, at 1500 on December 29, discharge was 88 million gallons per day. A second peak occurred at 1200 on December 31, of 61 million gallons per day. By 1600 on January 3rd, discharge had fallen to 22 million gallons per day.

The discharge at Cheddar was of the same order, but was measured using an uncalibrated recorder, so no absolute figures can be given.

Results

The results of the water tracing are of two types. Firstly, it was established that Swildons Hole, Eastwater Swallet, and St. Cuthberts Swallet, drain to Wookey Hole, and that Longwood and Manor Farm Swallets drain to both the main feeders, and possibly also the Lake Springs, at Cheddar. Of the other sites sampled, only Glencot produced any spores, but these were very few in number, and of such uneven distribution in time, that they can be attributed to contamination of the net. The fluorescein placed in Ramspit was not detected. These results are summarized in Fig. 5.

The second type of results may be summarized in a block diagram of numbers of spores of a particular colour in standard samples taken every four hours, against time. Such diagrams are given for both Cheddar and Wookey Hole in Figs. 7,8,9,10,11,12,13. Two points are of interest. Firstly, the times of arrival of the first spores may be read off. These are as follows,

Longwood to Cheddar	20 hours.
Manor Farm to Cheddar	20 hours.
Swildons to Wookey	25 hours.
Eastwater to Wookey	16 hours.
St. Cuthberts to Wookey	11 hours.

Secondly, the graphs show a high variation, with many peaks and troughs. This is totally different to the situation on East Mendip, where the graphs are smooth. At Cheddar First Feeder the graphs for Longwood and Manor Farm both show an exact coincidence of peaks and troughs, which recur in an 8 hour cycle. This cycle is extremely difficult to explain in terms of any known natural mechanism. During the time covered by the samples which show this fluctuation (0830 on January 2nd to 2000 on January 3rd) the hydrograph at Cheddar was falling at a more or less uniform rate, and no coincidence of variation in discharge, or any other parameter, with the variations in numbers of spores can be obtained (see Fig. 14). If a natural mechanism does exist to produce this variation, it must be located in the First Feeder alone, as the graphs for Second Feeder do not show a similar variation. However, the presence of similar numbers of spores in both First and Second Feeders, and the almost exact coincidence of hardness values of samples taken from each during the summer of 1965 and during January 1967, suggest that they have the same source. Furthermore, the bifurcation of the two from a single passage seems unlikely to be very far upstream of the springs. If this is the case, then it is difficult to fit the complex mechanism required to produce eight hour cycles of fluctuation into the short passage between the First Feeder spring and the bifurcation.

If natural mechanisms are involved at Cheddar they must also exist at Wookey Hole, where the graphs show even more variation. However, the variations in numbers of spores from Swildons, Eastwater, and St. Cuthberts are not fully coincident. This fact, combined with the difficulty of explaining the variation in natural terms, suggests that it is due to randomness in the processing or sampling procedures. Unfortunately, this cannot be established without further data.

As stated in Chapter Two, the interpretation of concentration diagrams is in its infancy, and no detailed interpretation can as yet be attempted. The high variation of the Wookey and Cheddar curves precludes this in any case. However, it is possible to make a few suggestions as to the nature of the swallets traced by considering minimum time of arrival of the spores, numbers of spores recovered, and the gradients from the ends of the known caves to the risings. The swallets will be considered in two sections, those flowing to Wookey and those to Cheddar.

1). Swildons Hole

This stream takes 25 hours to reach Wookey Hole, longer than either St. Cuthberts or Eastwater, suggesting that the unknown sections of cave are water filled or nearly so. The gradient from the end of the known cave to the rising is 7.6 ft. per thousand feet, and the lower parts of the known streamway have long water-filled sections, supporting this conclusion. The high numbers of spores recovered, suggests that the passages are fairly free from obstruction.

2). St. Cuthberts Swallet

The short travel time of 11 hours and the high numbers of spores recovered (60,000 in one sample at the highest point of the concentration diagram), suggests an open, dominantly vadose, passage. The initial gradient of the known cave is steep, but becomes flatter in the lower sections. The gradient from the known terminus to Wookey is 13.3 ft. per thousand feet, and the fast travel time makes it likely that the actual gradient of the unknown cave will be fairly even.

3). Eastwater Swallet

The travel time for this swallet is 16 hours, but the spore count is low, only one tenth of that at St. Cuthberts. The gradient from the end of the known cave to the rising is 13 ft. per thousand feet, which is the same as that at St. Cuthberts. The differences in travel time and spore count may be explained by supposing the unknown sections to be obstructed , probably by mud, which would filter the spores.

4). Longwood Swallet

The spore count is high compared with that of Manor Farm, suggesting relatively open passage. The gradient from the end of the cave to the rising is 12.7 ft. per thousand feet.

5). Manor Farm Swallet

The time taken for the spores to reach Cheddar is 20 hours, the same as that at Longwood, suggesting these two caves join early in their journey to the rising. The low spore count suggests obstructions, which must therefore be located between the swallet and the point where the two streams join. As no large cave is known at Manor Farm, the gradient to Cheddar, (655 ft. in 13,200 ft.) is rather meaningless. It is likely, however, that this cave descends steeply at first, in order to join the Longwood stream at or below 235 ft O.D. (the altitude of the bottom of Longwood Swallet) early in its passage to Cheddar. This, if true, would reflect a general trend in the Mendip Swallet caves to descend steeply at first and more gently further along their courses.

Table 6 compares the flow rate of the spores, calculated from the minimum travel time and the straight line distance from swallet to rising, with the hydraulic gradient from each swallet to its rising. The correspondence between these two quantities is 80 %. The sample of five caves is so small, however, that this may not be typical for the area.

Table 7 compares the proven stream connections from swallet to rising with the hydraulic gradient from each swallet to the St. Andrews, Wookey, Glencot, Rodney Stoke, Cheddar, and Axbridge Risings. If the most likely risings on theoretical grounds are taken as those to which there is the steepest hydraulic gradient, a 100 % correspondence between theory and experiment is obtained. It therefore seems likely, again allowing for the small sample of five caves, that hydraulic gradient plays a considerable part in determining the paths of underground streams in this area.

Chapter SIX

A PULSE WAVE EXPERIMENT AT CHEDDAR AND THE RESULTS OF WATER SAMPLING DURING PHASE TWO, JANUARY 1967

Apart from water tracing, two other aspects of hydrological research were undertaken in January 1967. These were a pulse wave experiment at Cheddar, and the systematic sampling of the water from the important risings on the south flank of the hills. The results of both of these pieces of work are inconclusive, but both remain interesting in view of the basic information they provide, and the problems which they reveal.

The method of pulse wave hydrology has already been described in Chapter Three. A limited pulse wave experiment was set up at Cheddar First Feeder, and was run from 2000 on January 1st. to 2400 on January 4th. Discharge was measured using a Munro horizontal stage recorder, which was specially installed for the duration of the tests. Because the recorder was installed only for a short period, it was not calibrated, but peak discharge on December 31, before the start of the tests, was estimated at about 100 cubic feet per second.

Water samples were taken from First Feeder at half hour intervals, and pH, saturated pH, and temperature, were measured at the same time, using a small portable pH meter and a mercury thermometer calibrated in 0.1 °C. The values of Calcium Carbonate in ppm. and relative stage are shown in graph form in Fig. 15.

During the week preceding the tests there was heavy precipitation. The two biggest storms were on December 28th and December 30th. Unfortunately, no rain gauge records for this week are available to the authors at the present time, so the times and amounts of precipitation cannot be established with any more accuracy. Cheddar Rising was not observed after these storms until the morning of December 31st. Discharge was observed to reach a peak during that afternoon, and the hydrograph record beginning at 2100 on December 31st shows a plateau until 1040 on January 1st followed by a steady fall to 2400 on January 4th, when the record ends. There was no further rain in the area throughout the week January 1st to 7th. It therefore appears that the initial effects of the discharge pulses due to the rain the previous week were not recorded, and from this point of view the experiment was a failure. The intensive sampling involved, however, has produced some interesting data which is discussed below.

Firstly,pH, saturated pH, and temperature at First Feeder show no variation which cannot be ascribed to observational error, apart from a diurnal variation in temperature. Therefore, only the Calcium Carbonate values obtained from the water samples are discussed further. All the samples were titrated for Ca^{++} ion within a few days of being taken. The compleximetric method using EDTA (Schwarzenbach 1959) was used, and the titration error is estimated to be ± 3 ppm. Results are given as parts per million (ppm) of Calcium Carbonate in solution.

All the values of Calcium Carbonate fall within the range 205-50 ppm. The graph of Calcium Carbonate against time (see Fig. 15) shows three characteristics of note.

1). A gradual rise in the average value from the start of sampling on January 1st to about 2400 on January 3rd. This may be reasonably attributed to the falling hydrograph over the same period.

2). A gradual overall decline in the average value from about 2400 on January 3rd to 2400 on January 4th, when intensive sampling ended. This is comparable with the decline on the other important risings sampled (see below). It does not coincide with any rise in the hydrograph, and is therefore unlikely to represent the arrival of actual floodwater from either of the big storms the week before. Any further explanations must necessarily be extremely tentative, but one possible explanation is that this rising has a large and complex phreas. The rise in the Calcium Carbonate curve might be explained by the mixing of still water with a high Calcium Carbonate content with the flood water, and the subsequent fall by the exhaustion of this reservoir of still water and its complete replacement by the flood water remaining in the phreas, which has a lower Calcium Carbonate value. A small piece of positive evidence in favour of this hypothesis is that spores from Longwood and Manor Farm continued to arrive in small numbers until January 5th. It should be appreciated, however, that this hypothesis is offered only as an explanation, and remains extremely tentative until such time as further tests can be conducted.

3). A very marked almost rhythmic variation in Calcium Carbonate values every one to two hours, over a range of 5-20 ppm. This variation is outside the probable range of titration error, and has been observed at Ashwick Grove Risings also. No satisfactory explanation for it can be offered.

During the course of the water tracing, water samples were also collected from the risings at Axbridge, Rodney Stoke, Wookey Hole, and both St. Andrews Well risings. These samples were taken every four hours, at the same time as the nets were sampled. On one occasion (on the evening of January 4th) all the risings were sampled. The samples were analysed for Ca^{++} ion in the same way as those from Cheddar.

The values of Calcium Carbonate in ppm for the important risings are shown as points on graphs in Figs. 16, 17. The values of all risings on the evening of January 4th are shown in Table 5. The maximum range over the period January 1st to 5th was in the range 215 - 280 ppm. However, this range was shown by one rising only, St. Andrews Scotland Spring. The other risings show a smaller range, generally 220 - 270 ppm. Cheddar was generally lower than the other risings at 220 - 245 ppm. There is a general accordance of rising values within these ranges, but the pattern of these values is by no means consistent. At certain times the values of some risings rose while those of the others fell (e.g. at 1200 on January 3rd, Wookey and Axbridge were rising while the other three stayed level or fell sharply). All the curves show a high variation in peaks and troughs, and it may be suspected that this is an expression of the same type of background variation as was observed at Cheddar. The sampling interval is eight times as long, however, so no certain conclusions can be drawn about this.

There is only one overall trend apart from the general rise from January 1st to 4th, and that is a tendency for values to decline from January 4th to 5th. This, like the decline over the same period at Cheddar (see above), is not easy to explain as the hydrograph at Wookey, as well as at Cheddar, continued its steady fall throughout this period. The general lack of pattern, combined with this contrary reaction to a declining hydrograph, makes any useful interpretation difficult. At Wookey, where lycopodium spores continued to arrive from Swildons Hole until January 6th, it might be possible to invoke a similar explanation to that tentatively advanced for Cheddar. Certainly, at Wookey diving has revealed a large phreas. It is possible to conclude, that there must be factors other than discharge and aggressiveness controlling the Calcium Carbonate content of risings, even over a limited period of time.

The results of sampling all the risings show that there are some local differences, but these, like the more intensive sampling of the larger risings, are difficult to fit into any overall explanation. The unusually high Calcium Carbonate content for Honeyhurst and both Westbury springs could be attributed to the passage of these streams through presumably restricted channels in Dolomitic Conglomerate and (at Honeyhurst) Keuper Marl rocks. Both these rocks are calcareous, and it is unlikely that a small stream will give rise to large passages in either of them.

At St. Andrews Well, there are noticeable differences between the Calcium Carbonate values of the Main Rising and Scotland Rising, even though these two are only 20 yards apart. This is interesting in the light of other multiple risings which have been investigated at St. Dunstan's Well, East Mendip, and Killeany Rising, Co. Clare, Eire, (Drew 1966, Smith and Nicholson, 1962). The phenomenon of multiple but seperate risings is worth closer investigation.

As well as the samples taken at the risings, and dealt with above, single samples were also taken from each of the major swallets tested, at about 1400 on January 3rd. The values for Calcium and Magnesium Carbonates are as follows.

St. Cuthberts	$CaCO_3$	79ppm	$MgCO_3$	10ppm
Eastwater		41ppm		9ppm
Swildons		175ppm		16ppm
Manor Farm		167ppm		19ppm
Longwood		203ppm		15ppm

The swallets feeding Wookey Hole are generally lower, and the Wookey water is higher in Calcium Carbonate. This would seem to indicate that more solution goes on in the Wookey catchment than in that of Cheddar. It must be remembered, however, that the swallets sampled represent only a small fraction of the total catchment.

These results in general indicate that the pattern of solution in this area, especially over short periods of time, is far from being properly described. The type of background variation observed at Cheddar is especially puzzling, and it will be interesting to discover whether it also occurs at low stage conditions in this and other risings. The multiple rising at St. Andrews Well will also doubtless repay further investigation. It is clear that a great deal more frequent, and more intensive, sampling is required in this area.

Chapter SEVEN

DISCUSSION

This chapter will be divided into two parts. In the first, the implications of the results given above in relation to theoretical concepts of limestone erosion in the Mendips will be considered. In the second, the practical implications of the work conducted so far will be discussed.

1). Theoretical

Ford (1963, 1966) has proposed a model for the development of caverns in the Mendips in which he attempts to relate a detailed geomorphological study of five caves - Swildons Hole, G.B. Cave, St. Cuthberts Swallet, Wookey Hole Caves, and Cheddar Caves - to the general geomorphology of the area and the stages of Pleistocene time. In each of the five caves studied, predominant levels were detected, and these are thought to be related to different levels of a water table at the time of formation. The relative chronology of each cave is worked out in detail, and a correlation between successive "water tables" at Cheddar and Wookey, and Pleistocene marine benches on the south flank of the hills is obtained. Correlations between the events in the swallet caves and those in the risings are attempted, and quite good results are obtained. The method by which this chronology is tied to Pleistocene time is as follows.

Firstly, dates are obtained for the various events at the risings at Cheddar. This is done by comparing the altitudes of bore passages to Pleistocene marine benches. The latter, while they may be detected at several points on the south flank of the Mendips, are not always present at the cave entrances. However, a good correlation is obtained. The stratigraphy of the deposits in the main bore of Gough's Cave is then considered. The basal layer here is a deposit of water laid sand, which is thought to mark the period when streams were abandoning the main bore, in favour of the present risings. This is an adjustment from discharge at a base level at 120-30 ft. O.D. (Hoxnian, or Penultimate Interglacial), to one at 70 ft. (Ipswichian, Last Interglacial). The sand deposits are stratigraphically close to a Cresswellian ("Younger Dryas" of Ford) habitation layer (Donovan, 1955). This gives the date of adjustment to the modern springs as being sometime in the Last Glaciation (Weichselian).

The next, and for the purposes of this discussion, most critical part of this account of Ford's model, will be described in terms of the dating of Swildons Hole and G.B. Cave. A similar process is adopted for St. Cuthberts and Wookey Hole, but is not explained in detail here. The intervals in altitude of past "water tables" in Swildons Hole correlate with those between bore passages at Cheddar. The conclusion is drawn that Swildons Hole discharged to Cheddar during the Pleistocene. When the sequence of erosion in G.B. Cave is compared with that in Swildons Hole, and the volumes of erosion in the two caves compared with time available, it appears that G.B. Cave originated in the Last Interglacial. There are remains of two rhythms of erosion and aggradation in G.B. The older of the erosion phases is assigned to the Last Interglacial, the younger to the Chelford Interstadial. The older fill is assigned to the early cold period of the Last Glacial, and the second fill to the main cold period. In Swildons Hole, a similar process of working back in time from the dated transition from a 120-30 ft. "water table" to a 70 ft. one at Cheddar is adopted.

Two important points serve to invalidate this model, in the authors' opinion. Firstly, the model rests entirely on the correlation of archaeological evidence (the Cresswellian occupation at Gough's Cave) with a time unit defined by pollen analysis (the Younger Dryas). Radiocarbon dating has shown the dates of the Younger Dryas to be about 9000 to about 8000 B.C. The earliest Cresswellian deposits are not later than the eleventh or twelth millenium B.C., and the latest are dated about 6600 B.C. Thus, the correlation of Cresswellian deposits at Cheddar with the Younger Dryas is of dubious validity.

Secondly the model hinges on the assumption that Swildons discharges to Cheddar, or at least did so during the Pleistocene. This assumption is made on the basis of fairly good correlation between past "water tables" at Swildons and Cheddar, as opposed to poor ones at Wookey. The water tracing tests described above, however, conclusively demonstrate that Swildons discharges to Wookey. Although the tests were conducted under conditions of high stage, no spores from Swildons were recovered at Cheddar. The possibility of Swildons ever having discharged at Cheddar becomes unlikely in the opinion of the authors.

In addition to this evidence, it should be remembered that the sequence of events in the development of the risings at Cheddar proposed by Ford (1963) does not fully explain the roles of Coopers Hole and Sayes Hole. The discovery in 1966 of 200 ft. of submerged cave passage with a fast flowing stream, beneath the lake in Sayes Hole, further complicates the picture, and suggests that the full story at Cheddar may be more complex than that already described by Ford.

These facts must cause Ford's model to be viewed with suspicion. This conclusion agrees well with that drawn by Atkinson (in prep), based on the same, and additional evidence of a different kind.

A certain amount of controversy at present surrounds the concept of water table in karst areas. One of the present authors has already published on this subject (Drew 1966), and it is thought that some of the information gained during the Central Mendip tests is relevant to this question.

The altitudes of the principal risings on the south flank of the hills are as follows.

Cheddar	89 ft. O.D.
Rodney Stoke	180 ft.O.D.
Wookey Hole	208 ft.O.D.
St. Andrews Well	160 ft.O.D.

Two of these rise through non-Carboniferous rocks (Wookey and St. Andrews), and one (St. Andrews) through marls with a much lower Calcium Carbonate content than the Carboniferous Limestone or the Dolomitic Conglomerate. The concept of overflow springs related to a general water table within the hills therefore seems hardly applicable.

It is possible, however, that each rising has an associated "local" water table, and that the general water table is therefore a theoretical, undulating surface, fixed only at the risings. On East Mendip, the presence of discrete flow paths which cross without mixing invalidates this, if by a "water table" is meant a piezometric surface beneath which all the voids in the rock, whether related or not, are water-filled.

On Central Mendip, water tracing has so far failed to reveal crossing flow paths, but the tests of January 1967 do provide a certain amount of information which points against a water table concept of this type.

Firstly, the different times of arrival of spores at Wookey Hole rising suggests that the paths of streams from Swildons, Eastwater and St. Cuthberts, are discrete for the greater part of their lengths. (The evidence from Cheddar is equivocal here, but the time of 40 hours for the connection from G.B. Cave to Cheddar, using fluorescein (Ford 1963) suggests that the picture may be the same there). Secondly, the suggestion is made above (see Chapter Five) that Swildons is dominantly water-filled in its unknown sections, while St. Cuthberts is vadose. If this is accepted, then these two swallets, which drain to the same rising, must have entirely different flow characteristics at similar altitudes below 280 ft.O.D. Moreover, the time taken for the systems to become completely free of spores is four to seven days. This is under conditions of falling stage, so that initially optimum conditions existed for flushing the spores through quickly, but by January 4th, stage conditions were at a winter normal. This does not correspond with the prolonged arrival of spores which might be expected if a widespread, general, phreatic zone, through which water moves slowly in a mesh of cavities, were present.

Information obtained at Cheddar in the summer of 1965 suggests that even within a large cave system, submerged cavities are not always directly connected. During a flood in July, 1965, water samples were taken every day from both Feeders, and from Skeleton Pit, a large, flooded, shaft, 60 ft. deep, which discharges water into Gough's Cave at times of severe flood. While the Calcium Carbonate values for both Feeders showed an expected drop after the peak of the flood, those at Skeleton Pit remained constant throughout.

Similarly, the existence of a double rising at St. Andrews Well is not suggestive of a well integrated phreatic zone in this area.

In view of this evidence, it is the provisional opinion of the authors that there is no general water table, of the type envisaged in rocks with a high primary porosity (e.g. Chalk), in the Central Mendip area, and that "local" water tables are unlikely. Instead, it is thought that flow lines are contained in discrete cavities, and that even when these are water-filled, the voids in the surrounding rock need not necessarily be so, unless they are directly connected with the flooded cavity.

2). Practical

The information gathered so far is insufficient for any hard and fast conclusions to be drawn about likely volumes of water reserves in the Mendip Hills. However, three important conclusions may be drawn.

First, the apparent absence of any large body of standing water in the limestones in the East Mendip area indicates that water supplies drawn from this area are almost entirely dependent on rainfall and may be expected to diminish and possibly dry up in times of extreme drought.

Second, the suggestion that no water table exists in the Central Mendip area, causes a similar conclusion to be drawn there. Large flooded cavities are known, however, and the catchment area is far larger than on East Mendip, so that at the present rates of abstraction, the important risings should only fail in times of extreme drought.

Third, the high content of organic matter in some samples from some risings (see Table 5) and the short time in which the systems become free of spores, suggest that filtration of underground streams is in general very slight. Accordingly, untreated supplies from the limestone should be regarded with suspicion.

TABLE ONE Stream Connections, times, flow rates, amounts of spores

Swallet	Rising(s)	Times (hours)	Rates of Flow (ft. per hour)	Weights of spores (Kg.)
Pitten Street	Whitehole	4.5	600	2
East End	St. Dunstan W.	6.0	820	1
Stoke Lane	St. Dunstan E.	8.0	550	2
Brickdales	St. Dunstan E.	4.0	780	1
Withybrook	St. Dunstan E.	4.0.	700	2
	St. Dunstan W.	6.0	470	
Midway	St. Dunstan E.	2.5	1600	2
	St. Dunstan W.	4.0	730	
Larkshall	Ashwick Lower	4.0	750	2
Blakes Farm	Ashwick Lower	5.0	700	3
Springfield	Ashwick Lower	5.0	800	2
Oakhill	Ashwick Lower	5.5	900	2
Stout	Ashwick Higher	6.0	830	2
P1	Ashwick Higher	7.0	870	2
P2	Ashwick Higher	8.0	880	2
P3	Ashwick Higher	8.0	940	2
Little London	Ashwick Higher	8.5	945	2

TABLE TWO Swallet - Rising Gradients, East Mendip

	St. Dunstan	Lower Ashwick	Higher Ashwick	Whitehole
Pitten Street	1.35°	0.7°	0.5°	2.5°
East End	1.9°	1.0°	0.8°	1.7°
Stoke Lane	1.1°	0.4°	0.1°	1.4°
Brickdales	3.5°	1.9°	1.7°	0.95°
Withybrook	3.5°	2.9°	2.0°	0.8°
Midway	2.9°	3.2°	2.7°	0.8°
Larkshall	2.6°	3.1°	2.8°	0.8°
Blakes Farm	2.2°	2.8°	2.1°	0.7°
Springfield	1.7°	2.0°	2.2°	0.6°
Oakhill	1.85°	2.25°	2.2°	0.7°
Stout	1.6°	1.9°	2.0°	0.7°
P1	1.6°	1.8°	1.8°	0.7°
P2	1.5°	1.65°	1.6°	0.7°
P3	1.4°	1.55°	1.5°	0.7°
Little London	1.4°	1.55°	1.45°	0.7°

TABLE THREE Central Mendip Swallets, Times of Input, Amounts of Spores

Swallet	Time of input on 1/1/67	Amount and colour of spores
Longwood	1205 - 1235	12 Kg. Saffronine
Manor Farm	1200 - 1215	10 Kg. Methyl Violet
Swildons	1156 - 1210	16 Kg. Malachite Green
Eastwater	1200 - 1230	10 Kg. Bismarck Brown
St. Cuthberts	1200 - 1210	12 Kg. Undyed
Ramspit	1200	50 gm. Fluorescein

TABLE FOUR Central Mendip - Data Summary on all Risings

Rising	%age capped (by eye)	Nets used (L = large, S = small)	Lyco. trace	Fluoresc. trace
Axbridge	20 %	1 x L	Negative	-
Cheddar 1st Feeder	10 %	3 x L	Positive	-
Cheddar 2nd Feeder	15 %	1 x L 1 x S	Positive	-
Cheddar Lake Springs	1 %	1 x L	Positive	-
Laubram	33 %	1 x S	Negative	-
Bamet's Well	20 %	1 x S	Negative	-
Honeyhurst	100 %	1 x S	Negative	-
Rodney Stoke	10 %	1 x L	Negative	Negative
Springhead	20 %	1 x S	Negative	Negative
Westbury Main	20 %	1 x S	Negative	Negative
Westbury (Railway Inn)	50 %	1 x S	Negative	Negative
Hollybrook	33 %	1 x S	Negative	Negative
Easton	50 %	1 x S	Negative	Negative
Wookey Hole	5 %	3 x L	Positive	-
Glencot	33 %	1 x S	Negative	-
St. Andrews Main	25 %	1 x L	Negative	-
St. Andrews Scotland	20 %	1 x S	Negative	-

TABLE FIVE Central Mendip, Calcium Carbonate and Silt Content of Resurgence Waters, All Risings

Rising	Calcium Carbonate (parts per million) on 4/1/67	Silt Content and Type (%age figure indicates proportion of sample slide covered)
Axbridge	245	25 % all organic
Cheddar 1st Feeder	220	20-35 % angular calcite, 2/3 organic
Cheddar 2nd Feeder	215	30 % chiefly organic
Cheddar Lake Springs	-	40-60 % chiefly calcite
Laubram	268	15 % equal calcite + organic
Bamet's well	225	50 % all organic
Honeyhurst	350	40 % all organic
Rodney Stoke	248	75 % chiefly organic
Springhead	275	30 % equ. mineral + organic
Westbury Main	349	40 % organic w. fine hairs
Westbury (Railway Inn)	334	50 % all organic
Hollybrook	232	60 % equ. mineral + organic
Easton	254	25 % 3/4 organic
Wookey Hole	243	20 % chiefly organic
Glencot	275	20 % organic
St. Andrews Main	268	60 % all organic
St. Andrews Scotland	264	65 % all organic

TABLE SIX Flow Rates and Hydraulic Gradients, Central Mendip

Swallet	Distance to Rising	Drop to Rising	Travel Time	Flow Rate	Hydraulic Gradient
Longwood	8,800 ft.	611 ft.	20 hrs.	560 ft. p hr.	4.0°
Manor Farm	11,900 ft.	655 ft.	20 hrs.	660 ft. p hr.	3.2°
Swildons	10,800 ft.	570 ft.	25 hrs.	430 ft. p hr.	3.0°
Eastwater	8,900 ft.	571 ft.	16 hrs.	630 ft. p hr.	3.7°
St. Cuthberts	8,800 ft.	571 ft.	11 hrs.	860 ft. p hr.	3.8°

TABLE SEVEN Hydraulic Gradients, Central Mendip

	St. Andrews	Glencot	Wookey	R. Stoke	Cheddar	Axbridge
Longwood	-	-	-	1.7°	4.0°	1.9°
Manor Farm	-	-	-	1.8°	3.2°	1.7°
Swildons	1.9°	2.6°	3.0°	2.3°	1.7°	-
Eastwater	2.1°	3.0°	3.7°	2.0°	1.5°	-
St. Cuthberts	2.3°	3.0°	3.8°	1.9°	1.4°	-

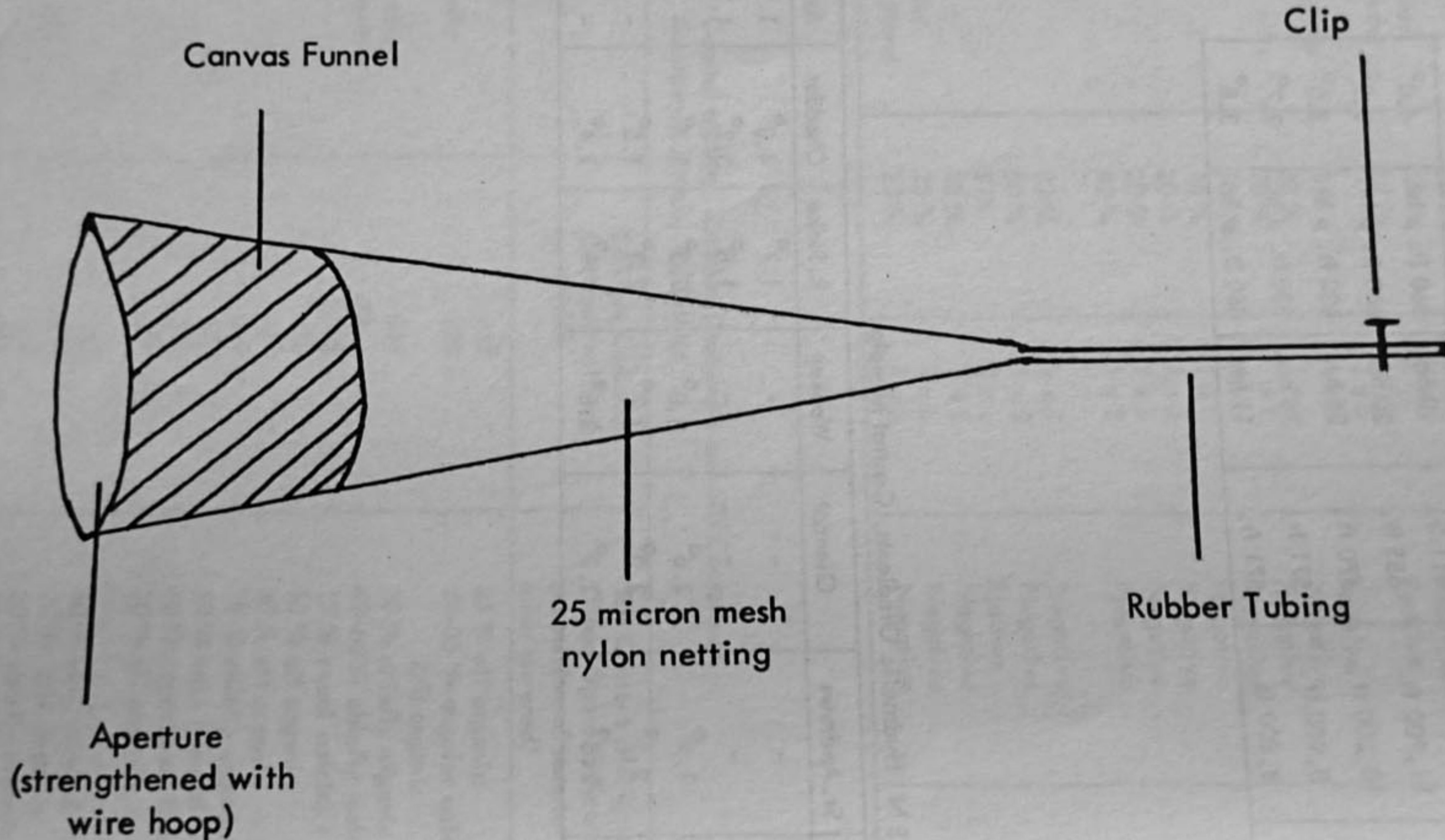
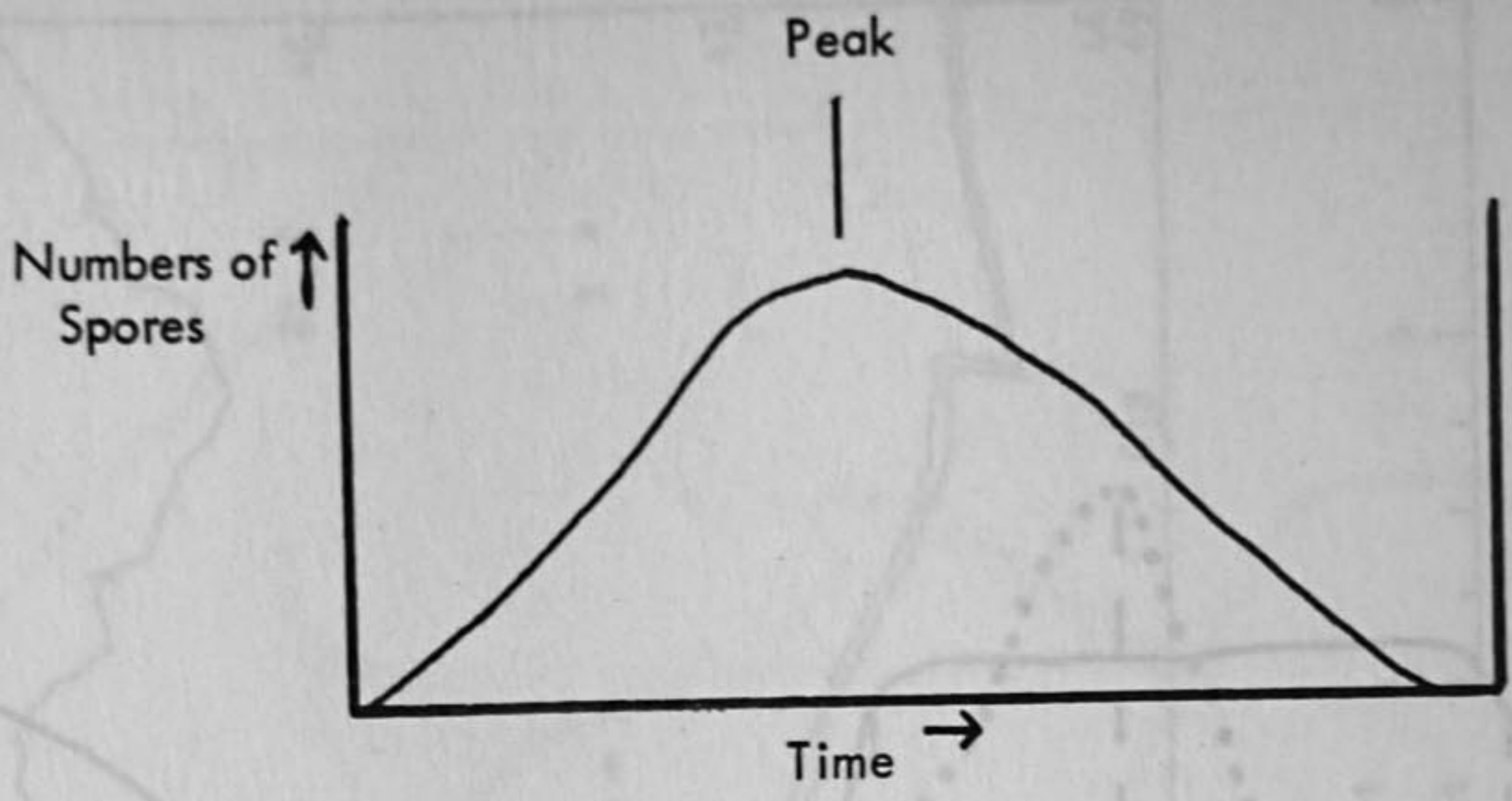
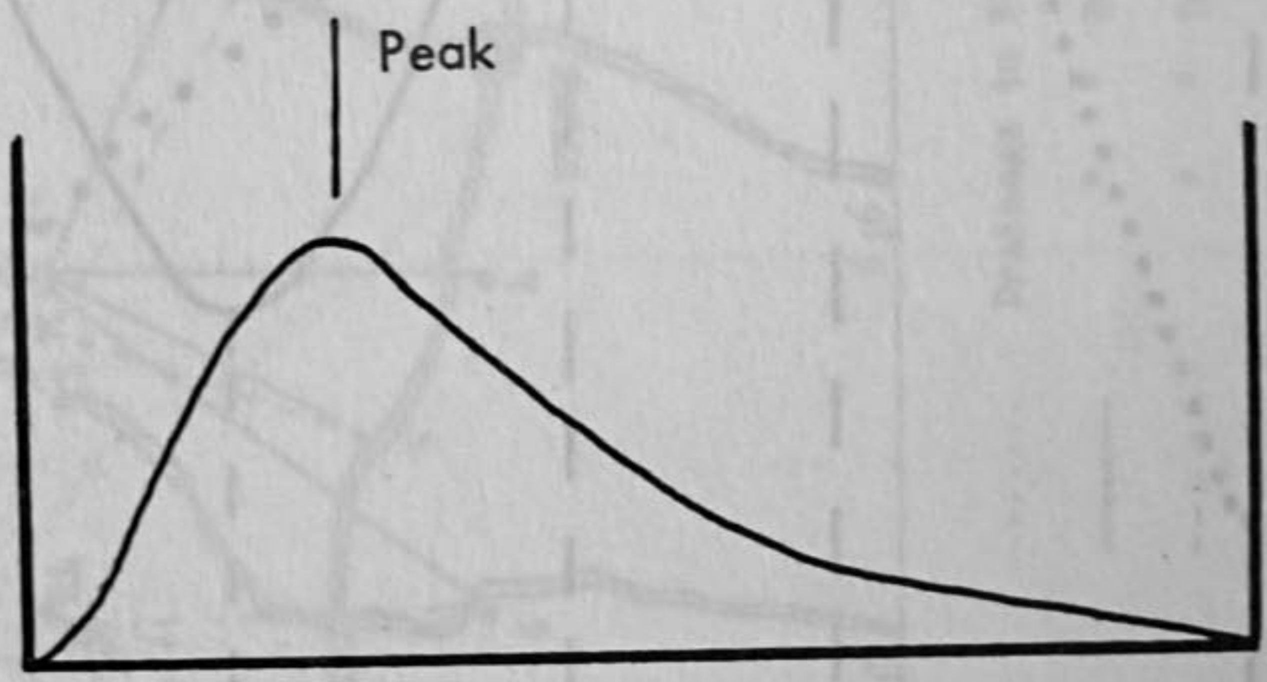


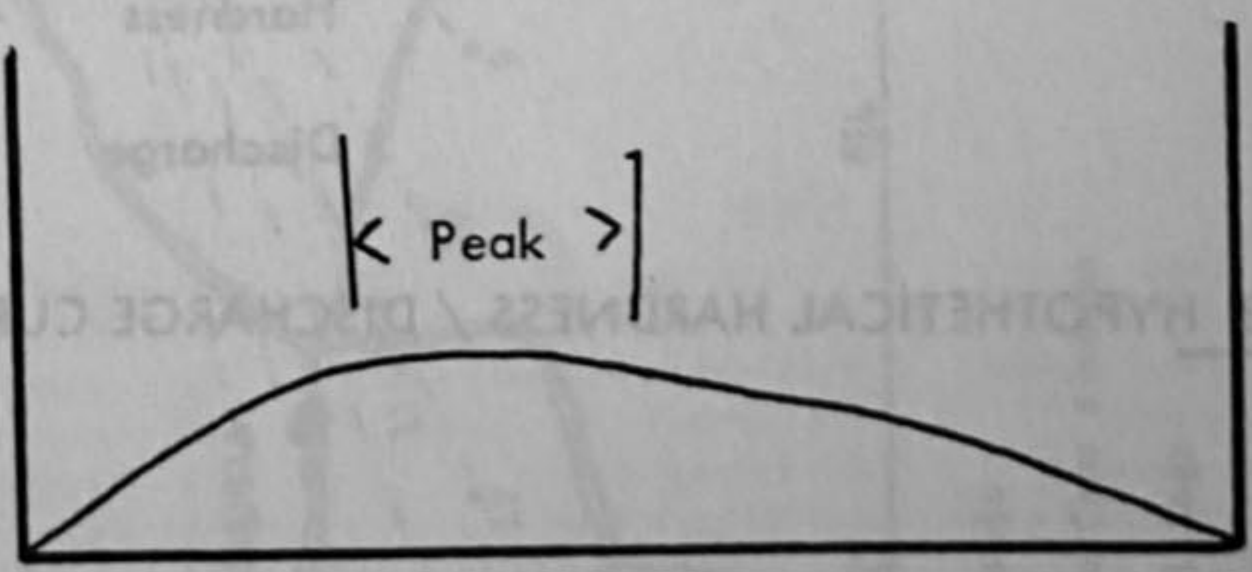
Figure 1 DESIGN OF A LYCOPODIUM NET



a). Normal Distribution Curve



b). Right Hand Skewed Distribution Curve



c). Flattened Peak on Concentration Curve

Figure 2 MODEL LYCOPODIUM SPORE CONCENTRATION CURVES.

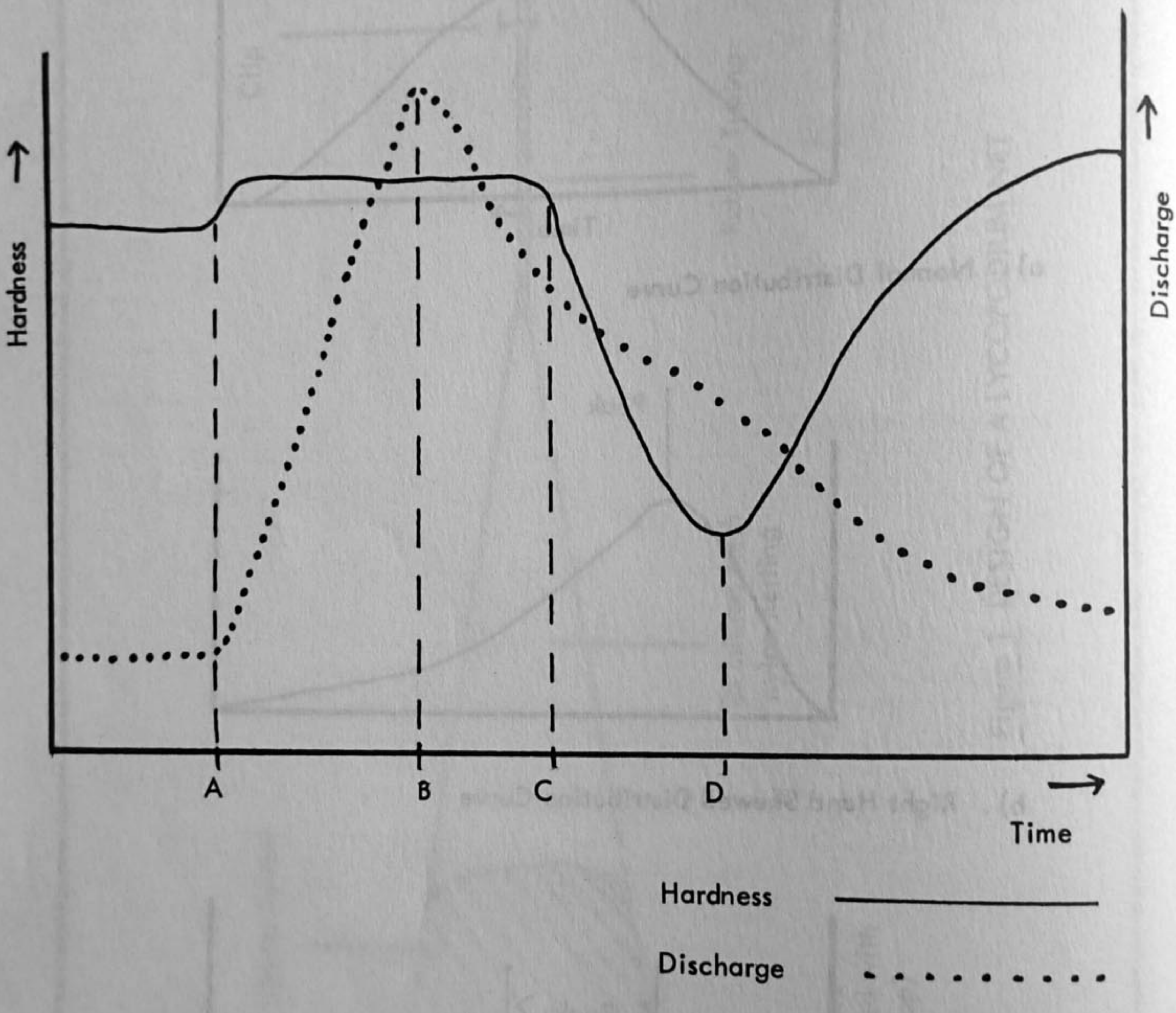


Figure 3 HYPOTHETICAL HARDNESS / DISCHARGE CURVES

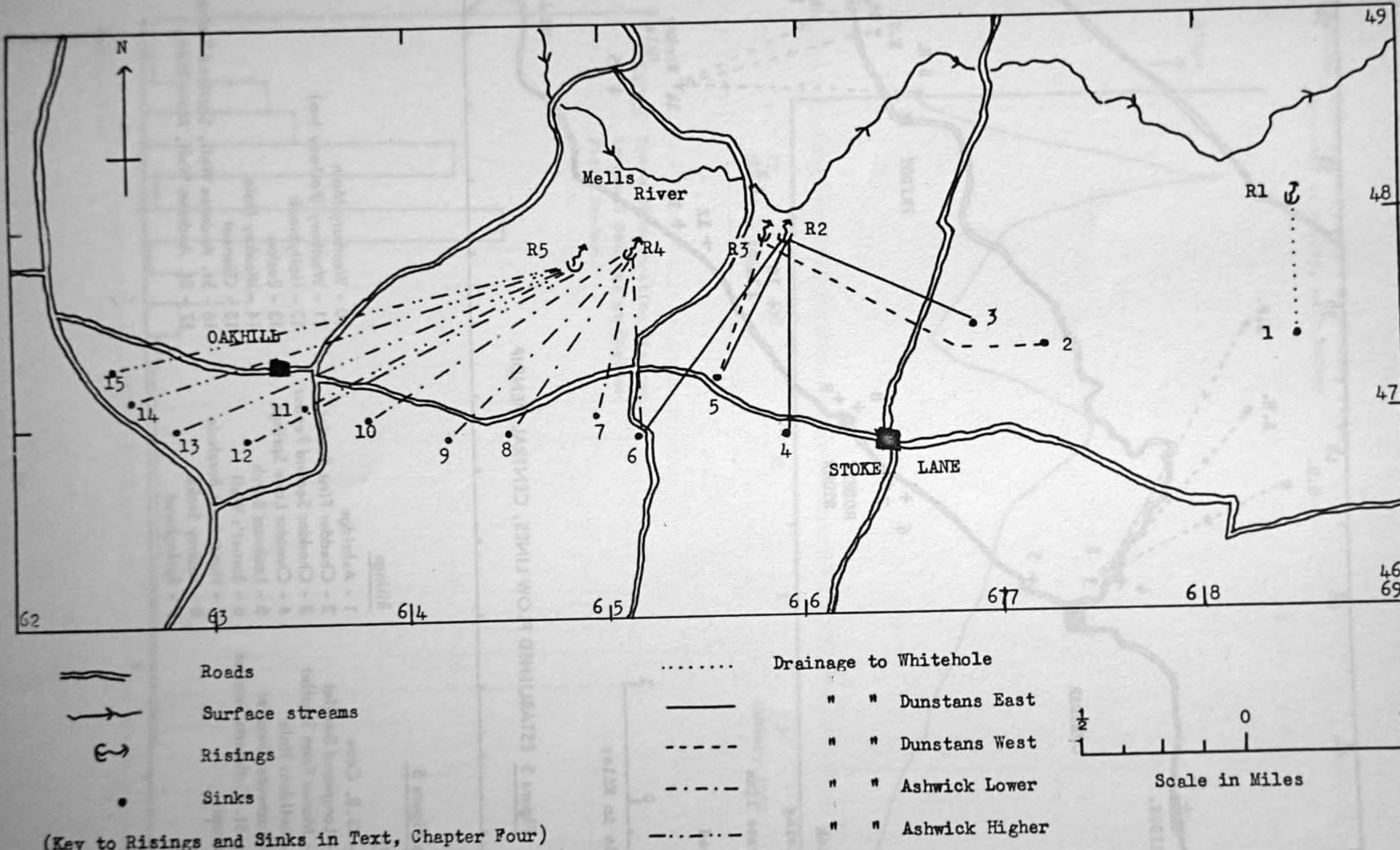


Figure 4 ESTABLISHED FLOW LINES, EAST MENDIP

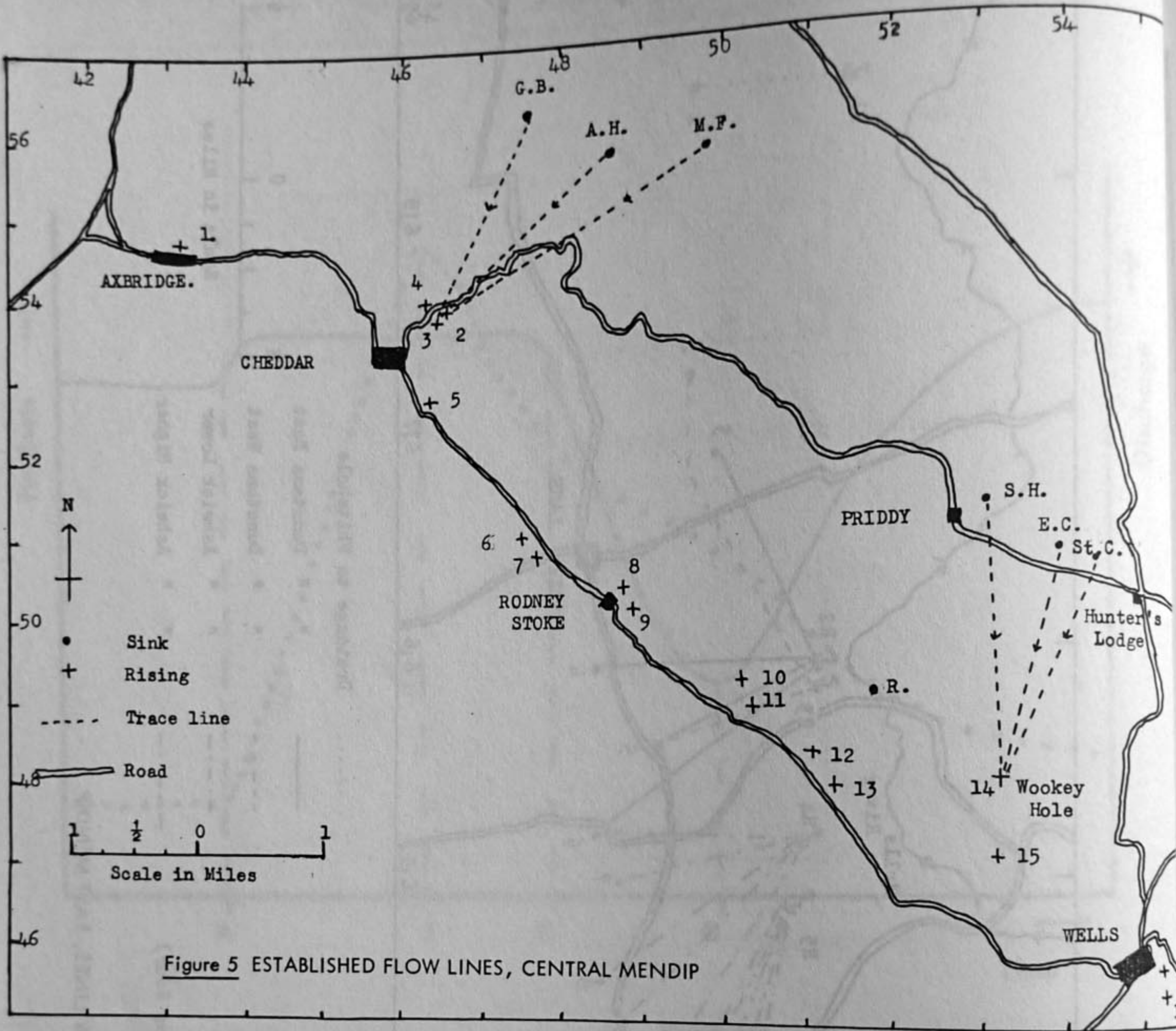


Figure 5 ESTABLISHED FLOW LINES, CENTRAL MENDIP

Key to Figure 5

Swallets

G.B. - G.B. Cave
A.H. - Longwood Swallet
M.F. - Manor Farm Swallet
S.H. - Swildons Hole
E.C. - Eastwater Swallet
St.C. - St. Cuthberts Swallet
R. - Ramspit

Risings

1 - Axbridge
2 - Cheddar First Feeder
3 - Cheddar Second Feeder
4 - Cheddar Lake Springs
5 - Laubram Batch
6 - Barnet's Well
7 - Honeyhurst Borehole
8 - Rodney Stoke
9 - Springhead
10 - Westbury Main
11 - Westbury (Railway Inn)
12 - Hollybrook
13 - Easton
14 - Wookey Hole
15 - Glencot
16 - St. Andrews Well, Scotland Rising
17 - St. Andrews Well, Main Rising

Figure 6 Hydrograph from BWW Continuous Stage Recorder at Henley, near Wookey

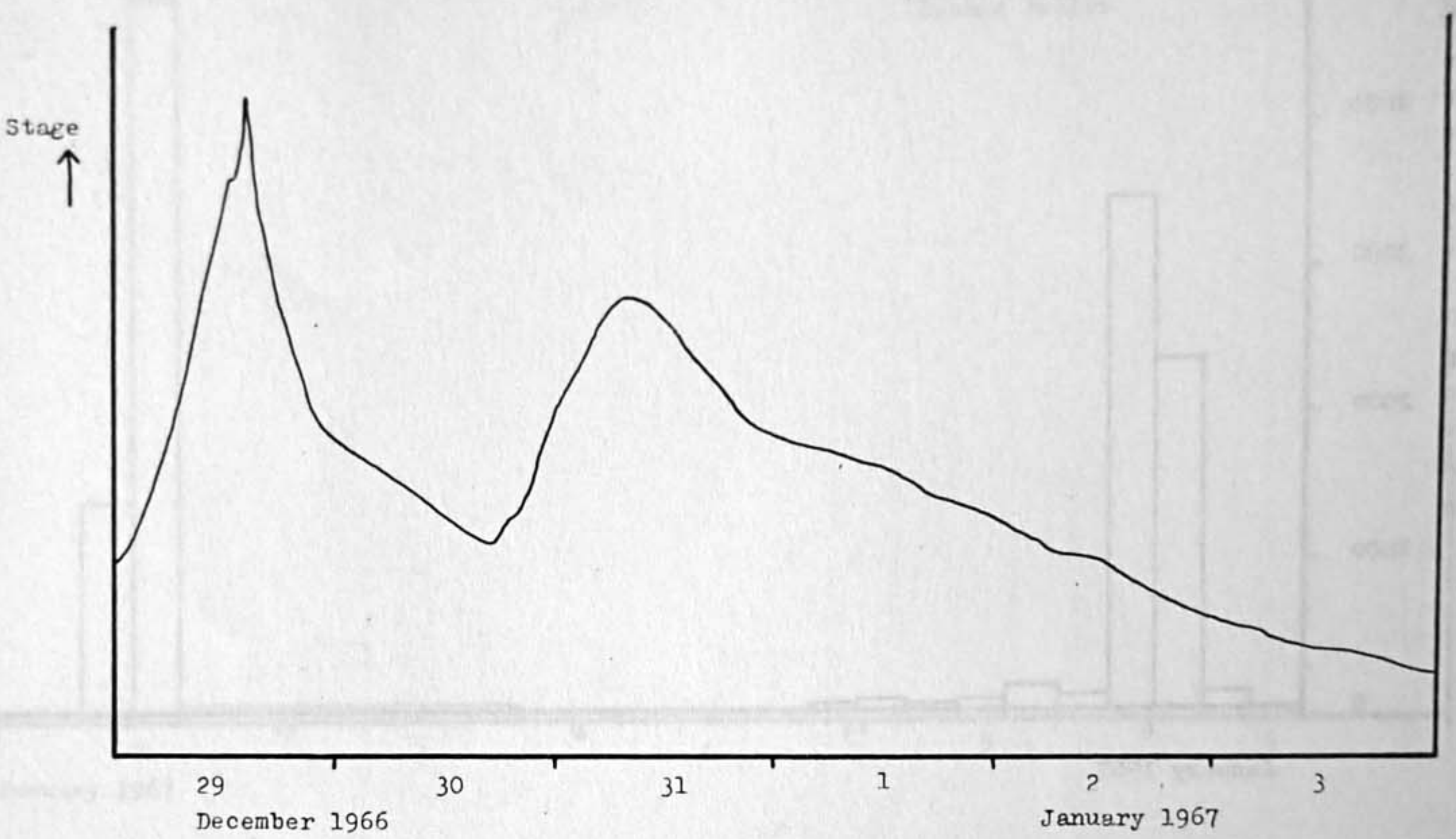
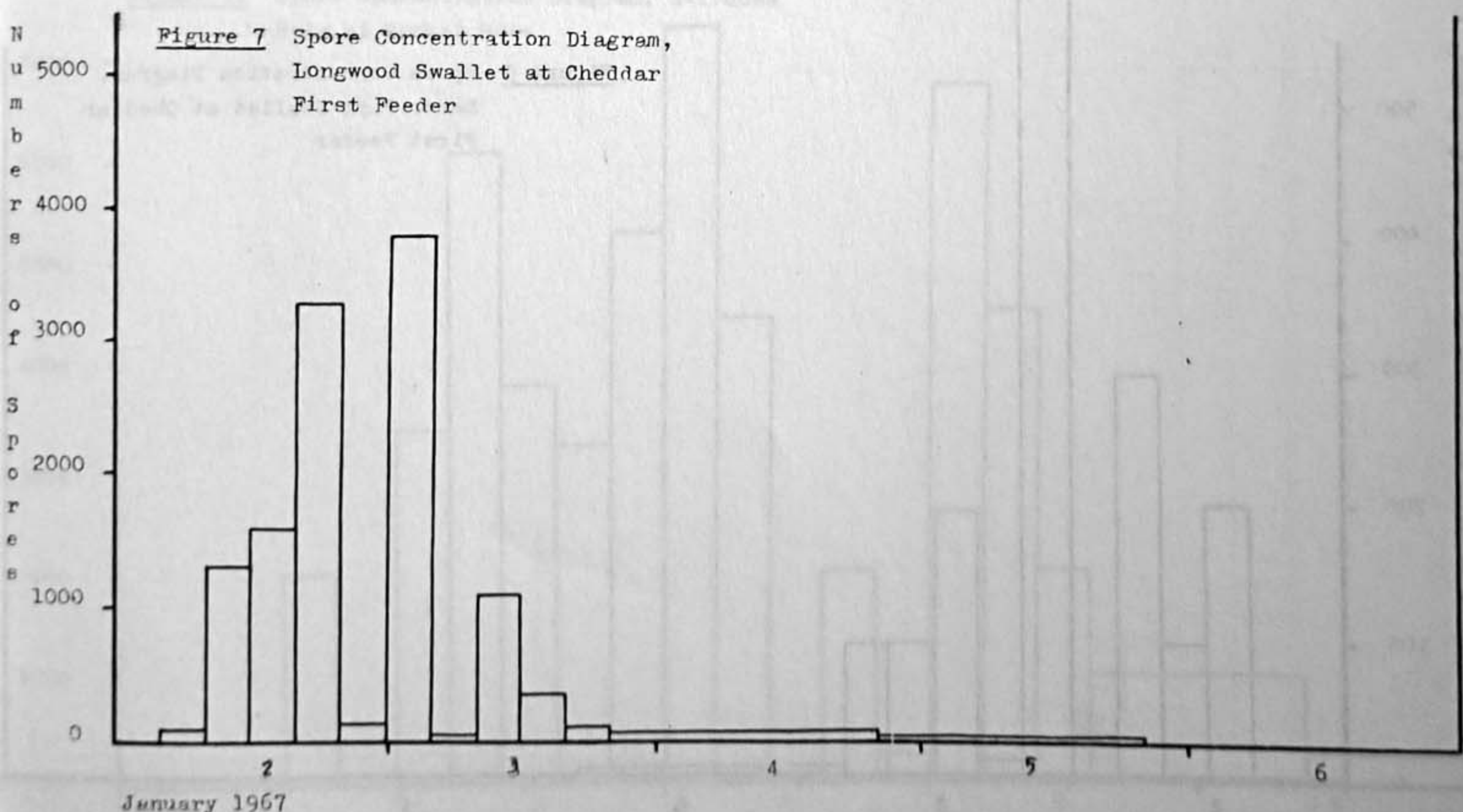


Figure 7 Spore Concentration Diagram, Longwood Swallet at Cheddar First Feeder



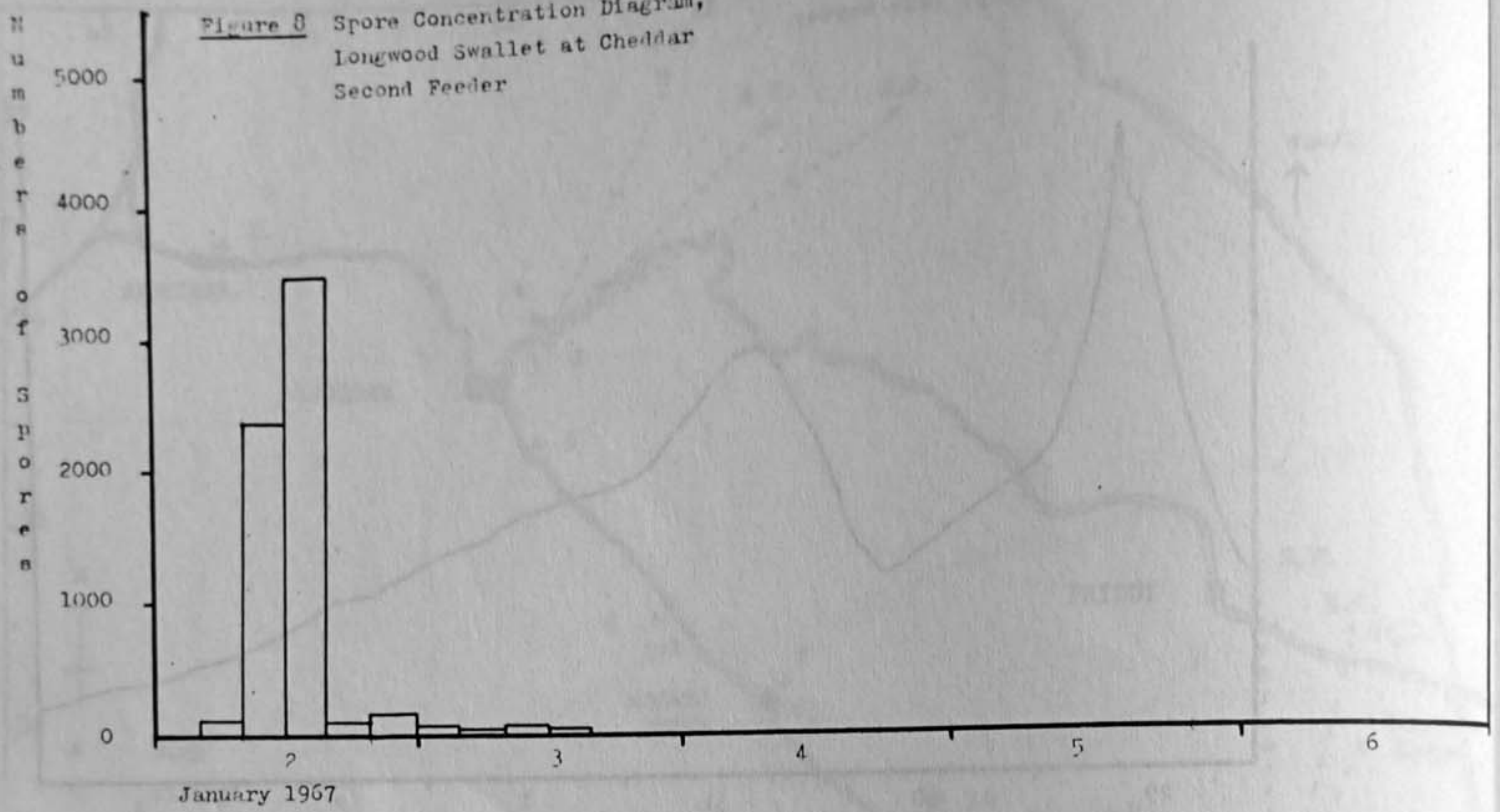


Figure 8 Spore Concentration Diagram, Longwood Swallet at Cheddar Second Feeder

Figure 9 Spore Concentration Diagram, Manor Farm Swallet at Cheddar First Feeder

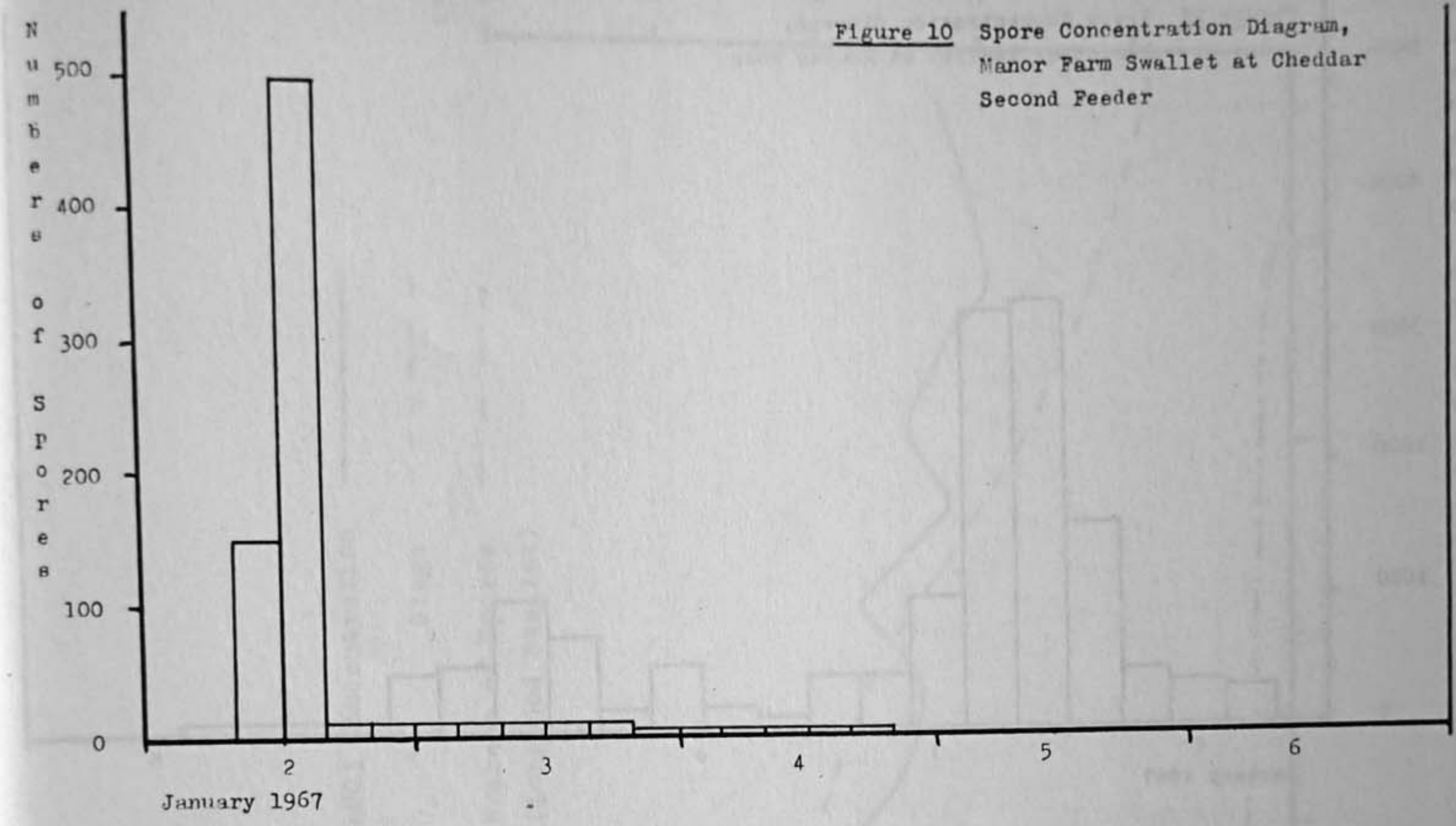
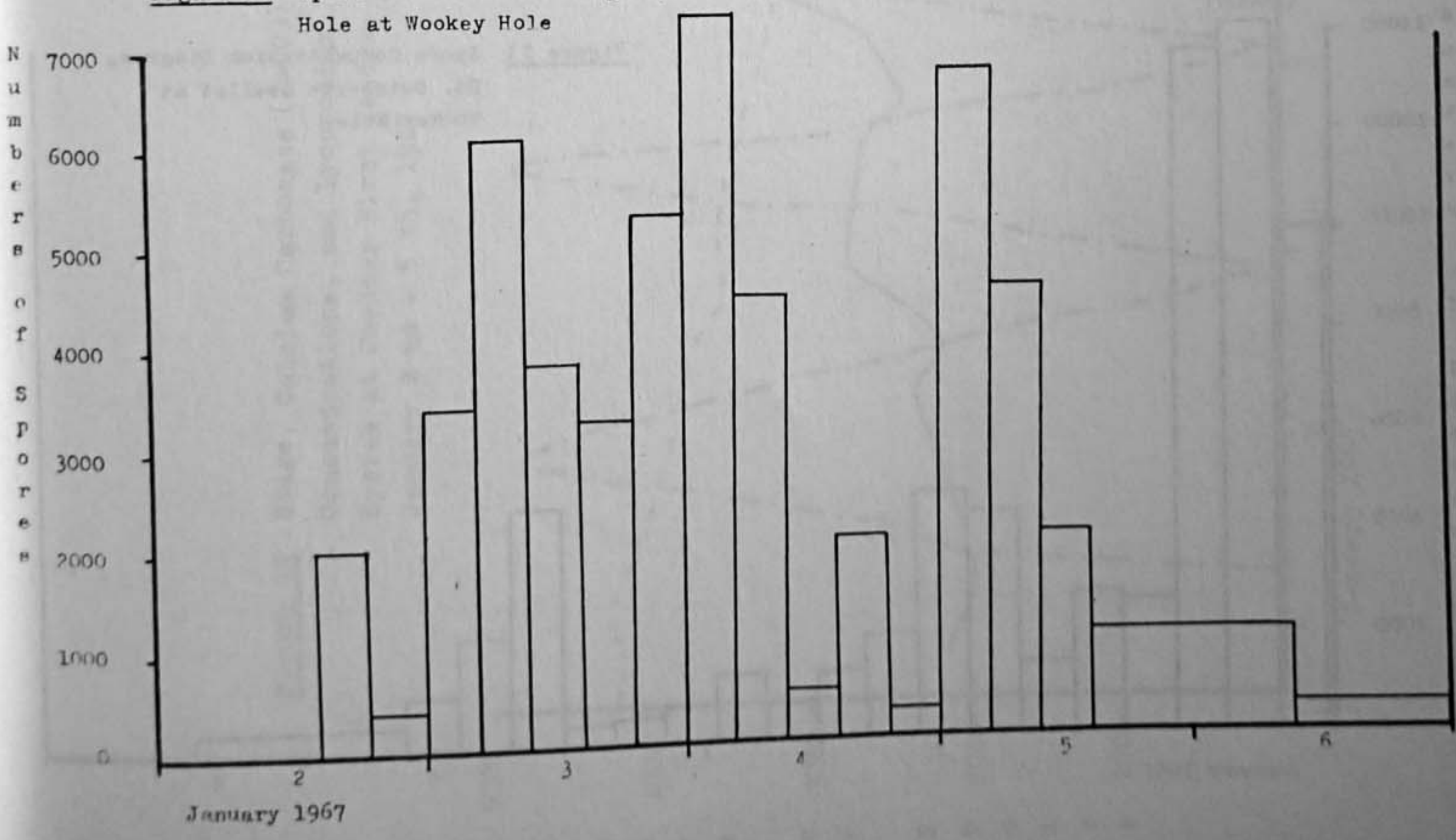


Figure 10 Spore Concentration Diagram, Manor Farm Swallet at Cheddar Second Feeder

Figure 11 Spore Concentration Diagram, Swildons Hole at Wookey Hole



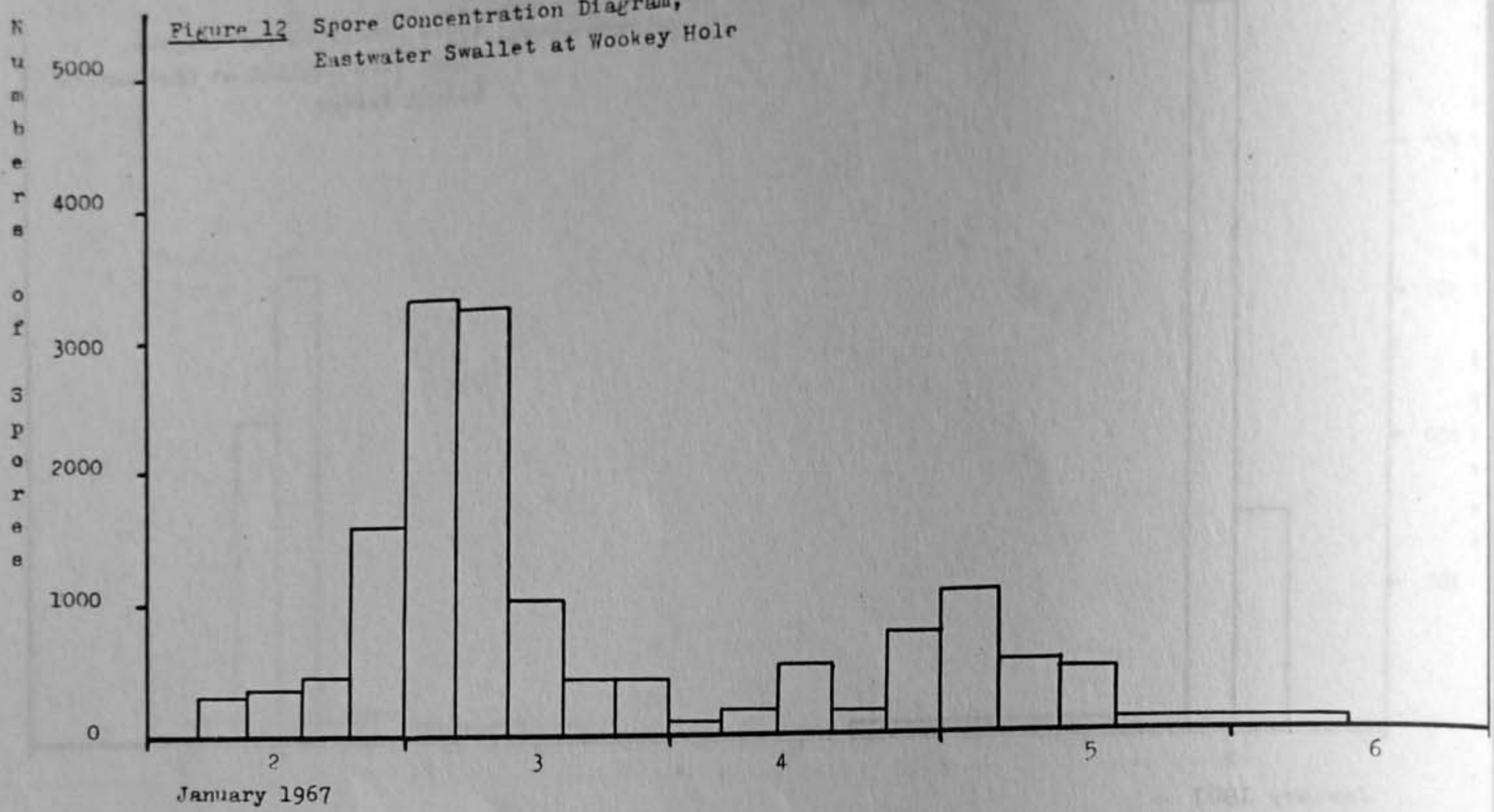


Figure 12 Spore Concentration Diagram, Eastwater Swallet at Wookey Hole

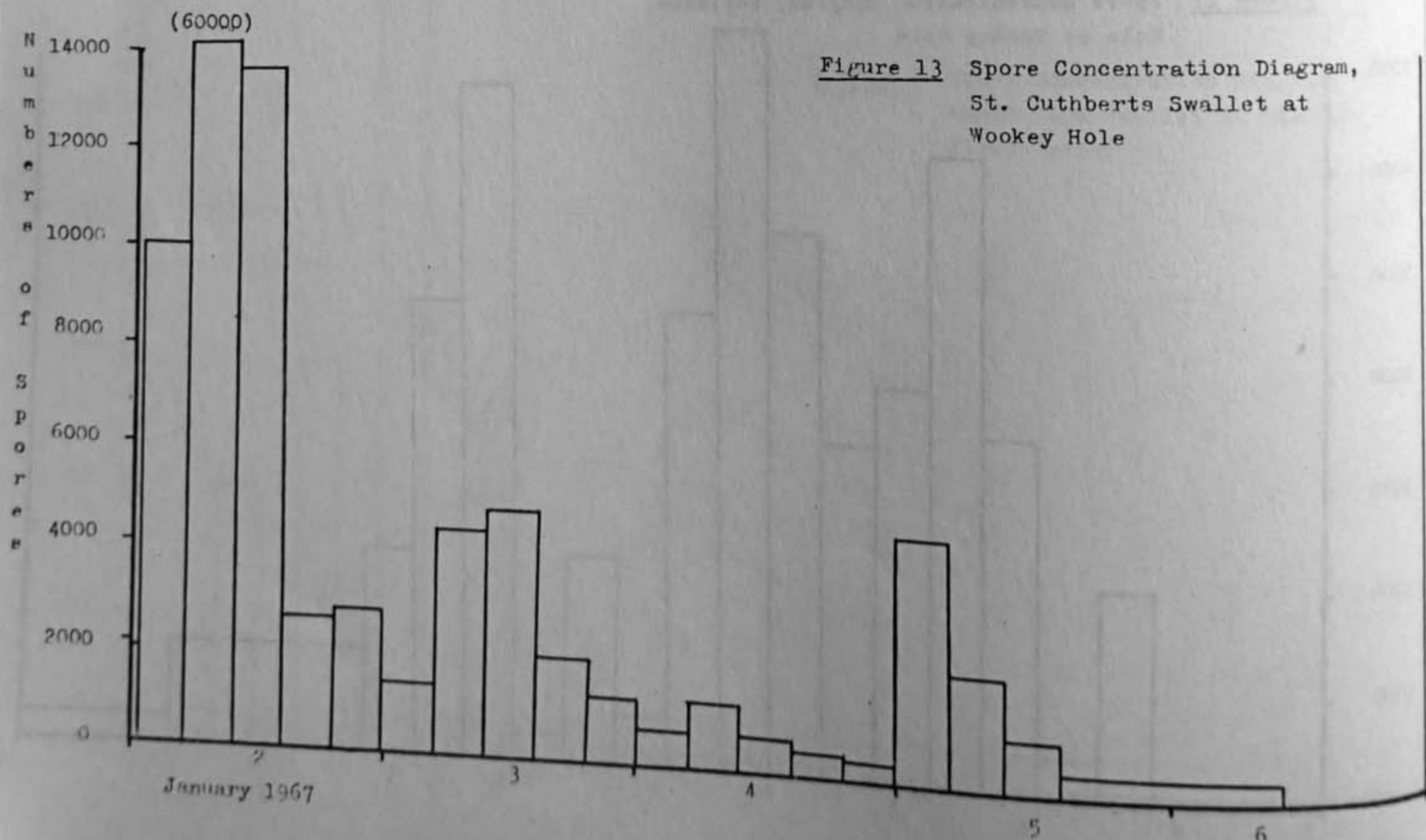
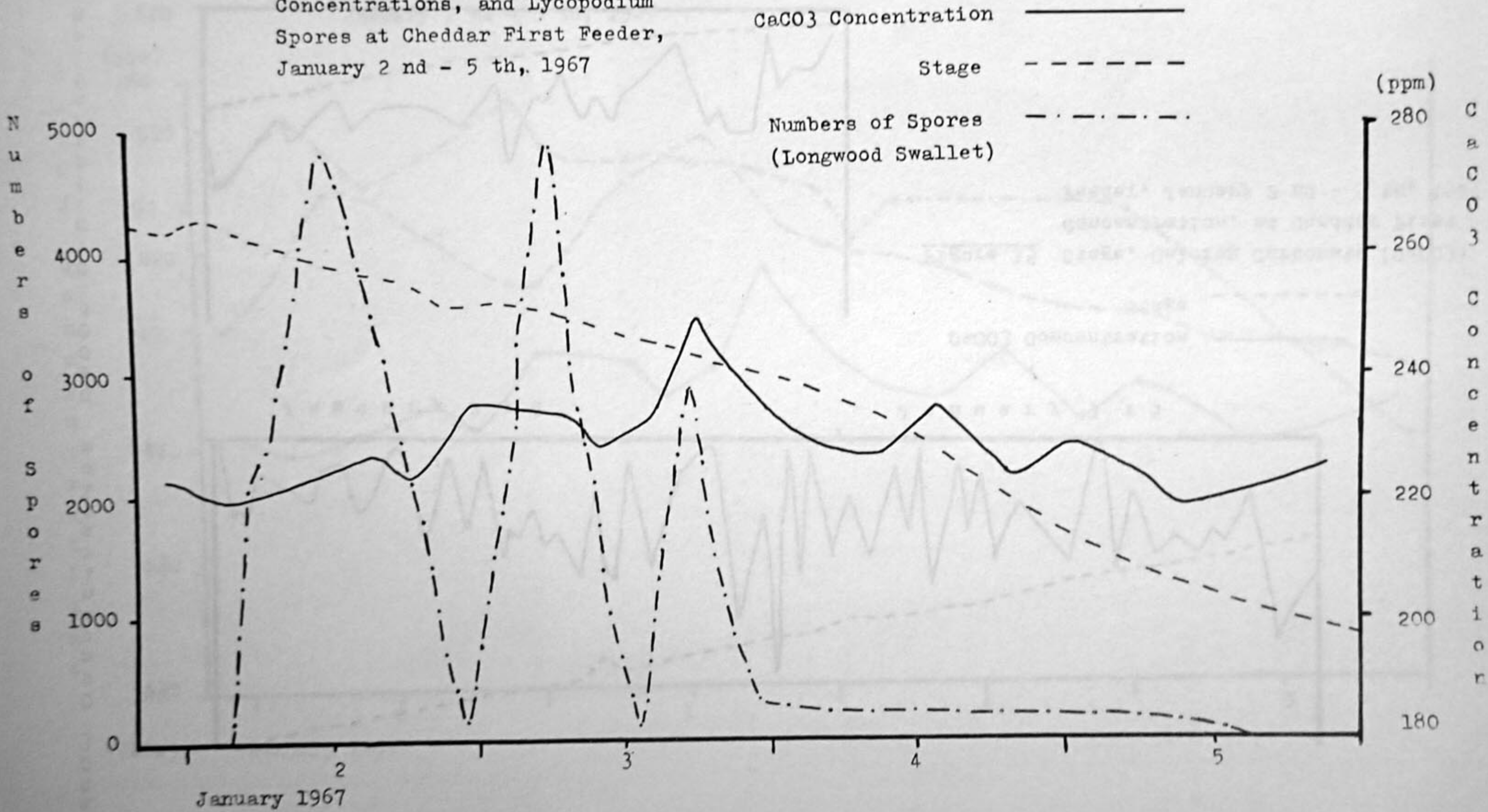
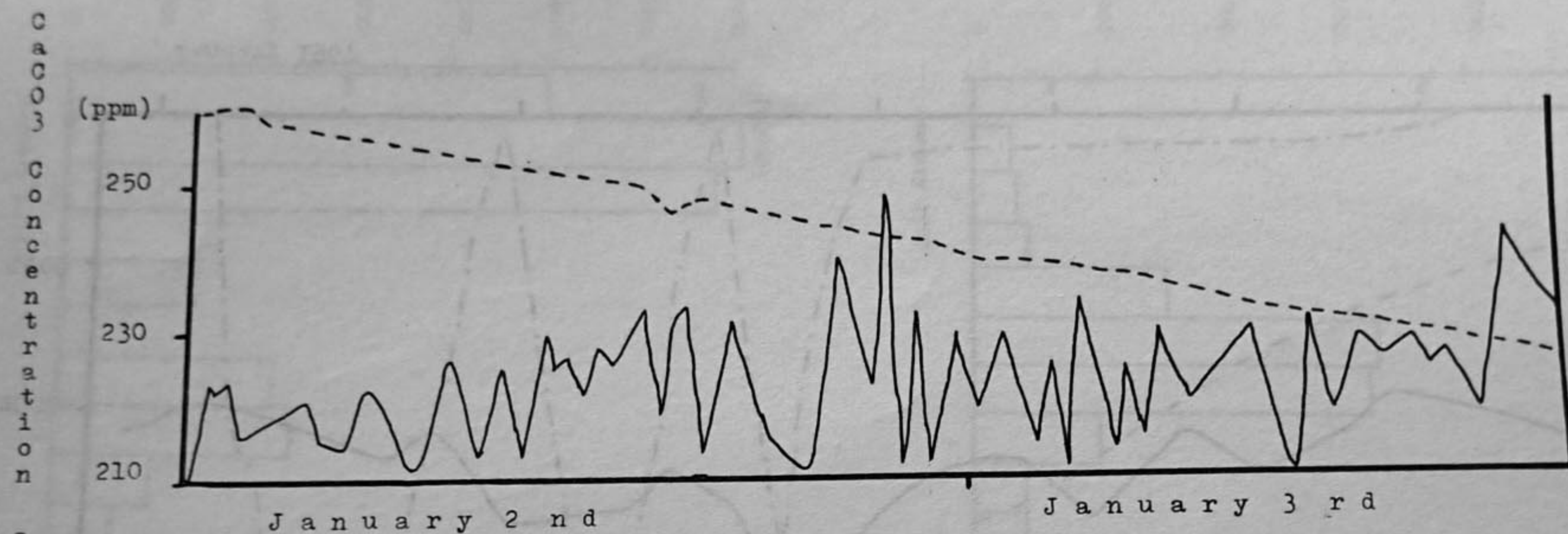
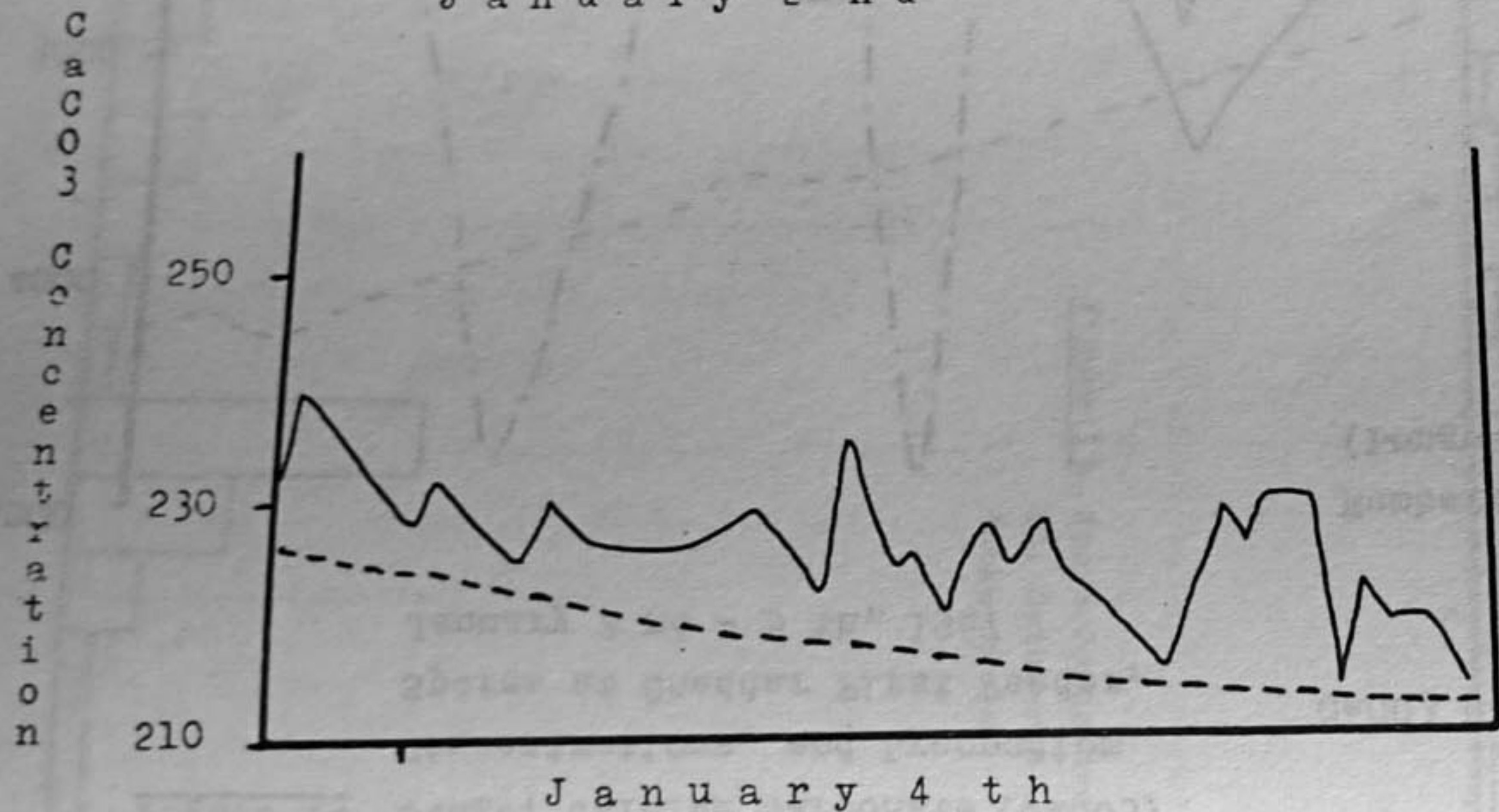


Figure 13 Spore Concentration Diagram, St. Cuthberts Swallet at Wookey Hole

Figure 14 Stage, Calcium Carbonate (CaCO3) Concentrations, and Lycopodium Spores at Cheddar First Feeder, January 2 nd - 5 th, 1967

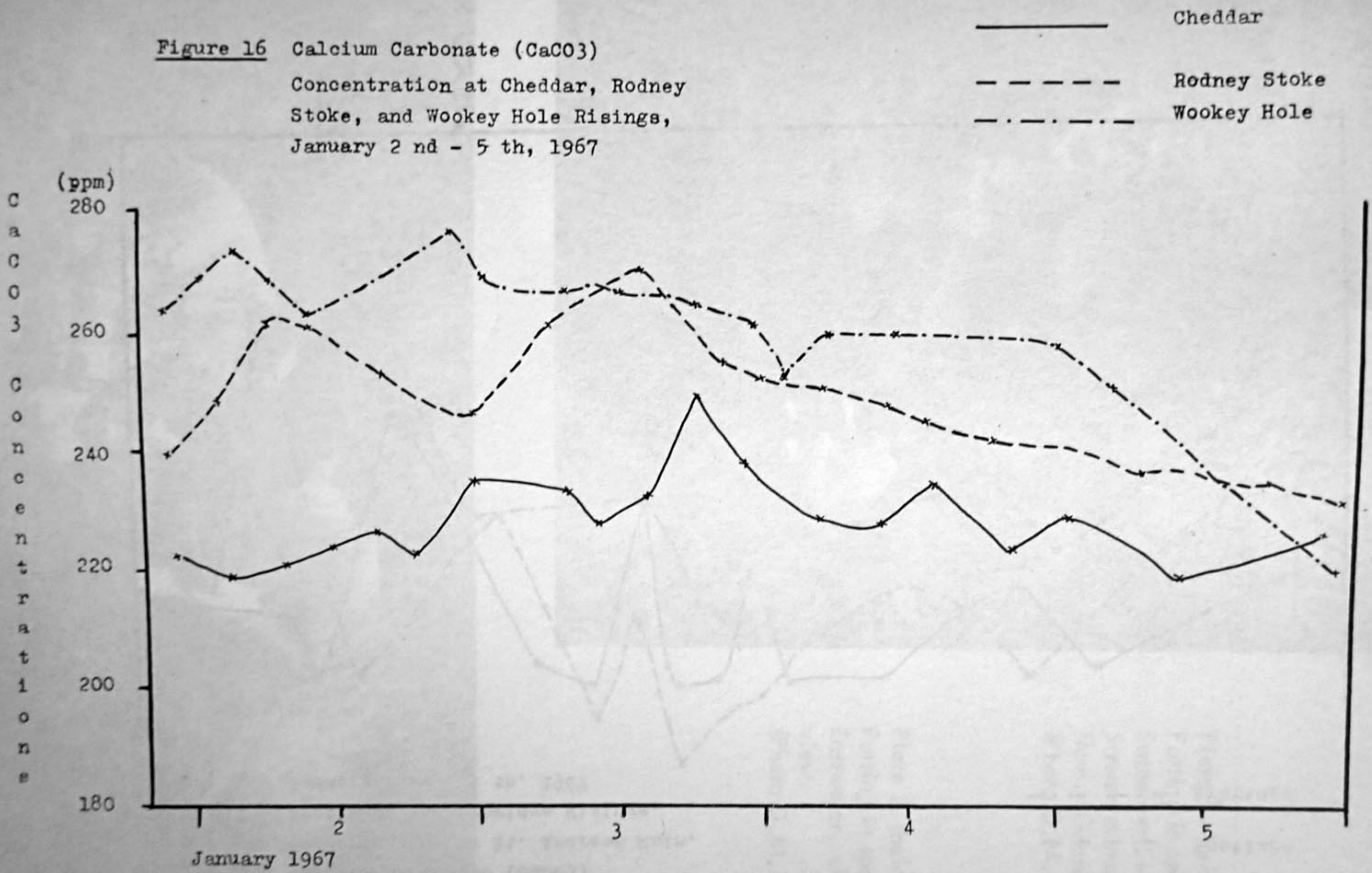






<u>Figure 15</u> Stage, Calcium Carbonate ($CaCO_3$) Concentration, at Cheddar First Feeder, January 2nd – 5th, 1967

Figure 16 Calcium Carbonate (CaCO3) Concentration at Cheddar, Rodney Stoke, and Wookey Hole Risings, January 2 nd - 5 th, 1967



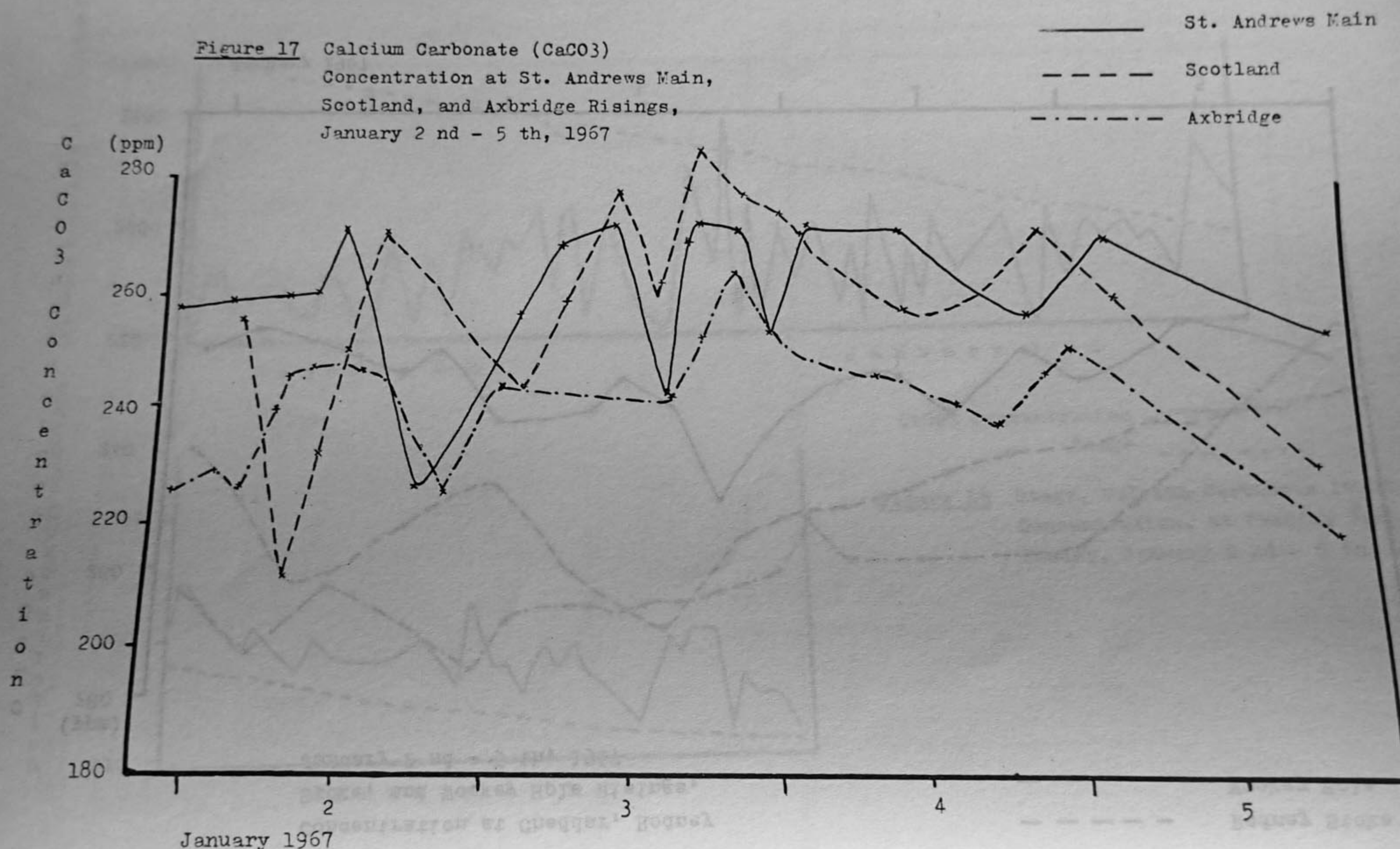


Figure 17 Calcium Carbonate ($CaCO_3$) Concentration at St. Andrews Main, Scotland, and Axbridge Risings, January 2 nd - 5 th, 1967

Plate 1. (left)
Putting in spores at Eastwater Swallet, Stream at moderate flow. General view.
(Photo D.M.M.T.)

Plate 2. (below)
Putting in spores at Eastwater, close-up view.
(Photo D.M.M.T.)

Plate 3.
Eight inch diameter lycopodium net on wooden frame at Springhead Rising.

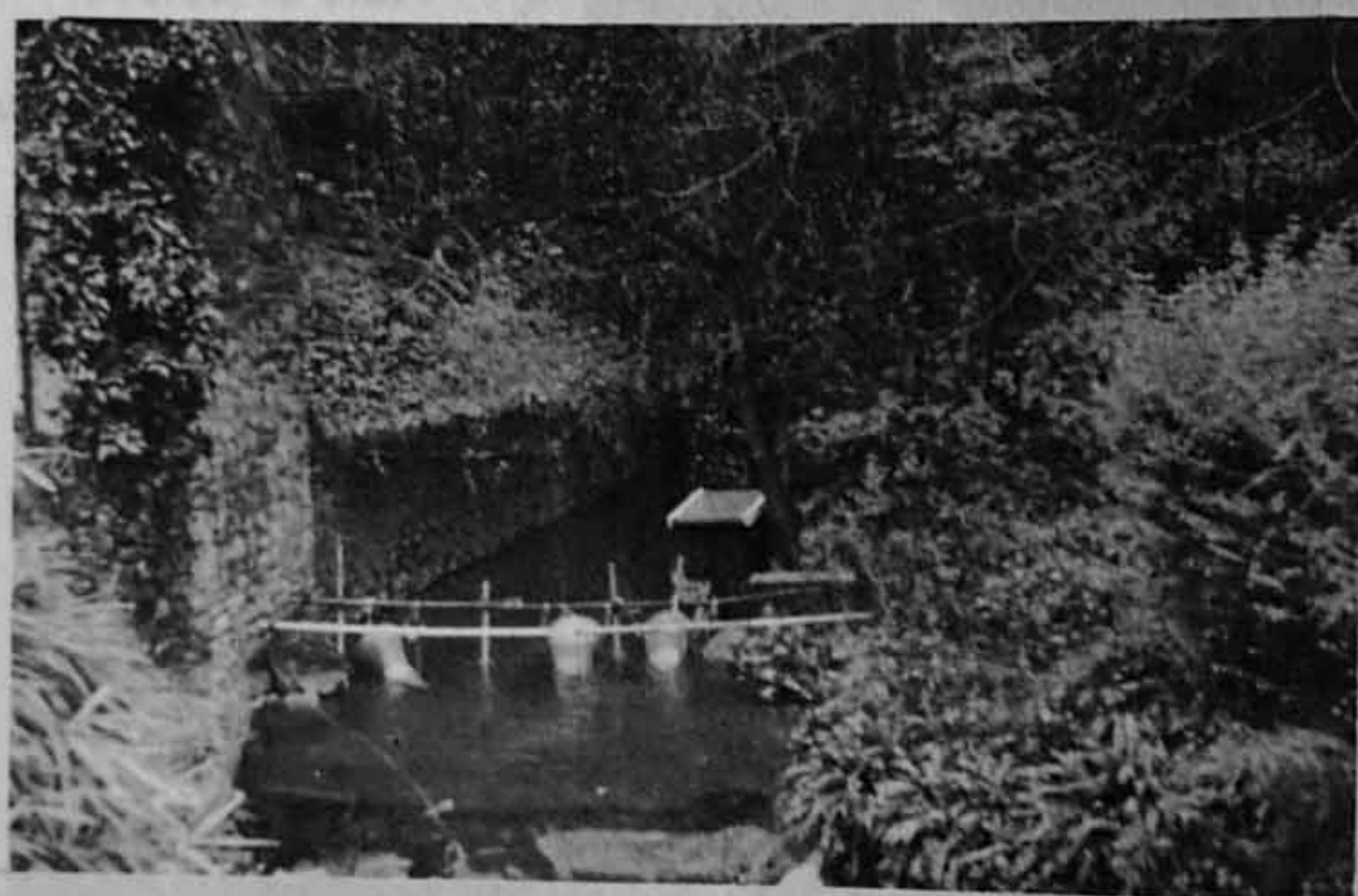


Plate 4.
General View of Cheddar First Feeder- three eighteen inch lycopodium nets in place. Continuous recorder in centre of photograph.

Plate 5.
Sampling the nets at Wookey Hole barrage (falling hydrograph).

Plate 6. Large net on Dexion frame in position at Axbridge.

Plate 7. Sampling the nets at Cheddar.

Plate 8. Close-up view of sampling technique, showing 50cc. specimen tube used for collection.

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