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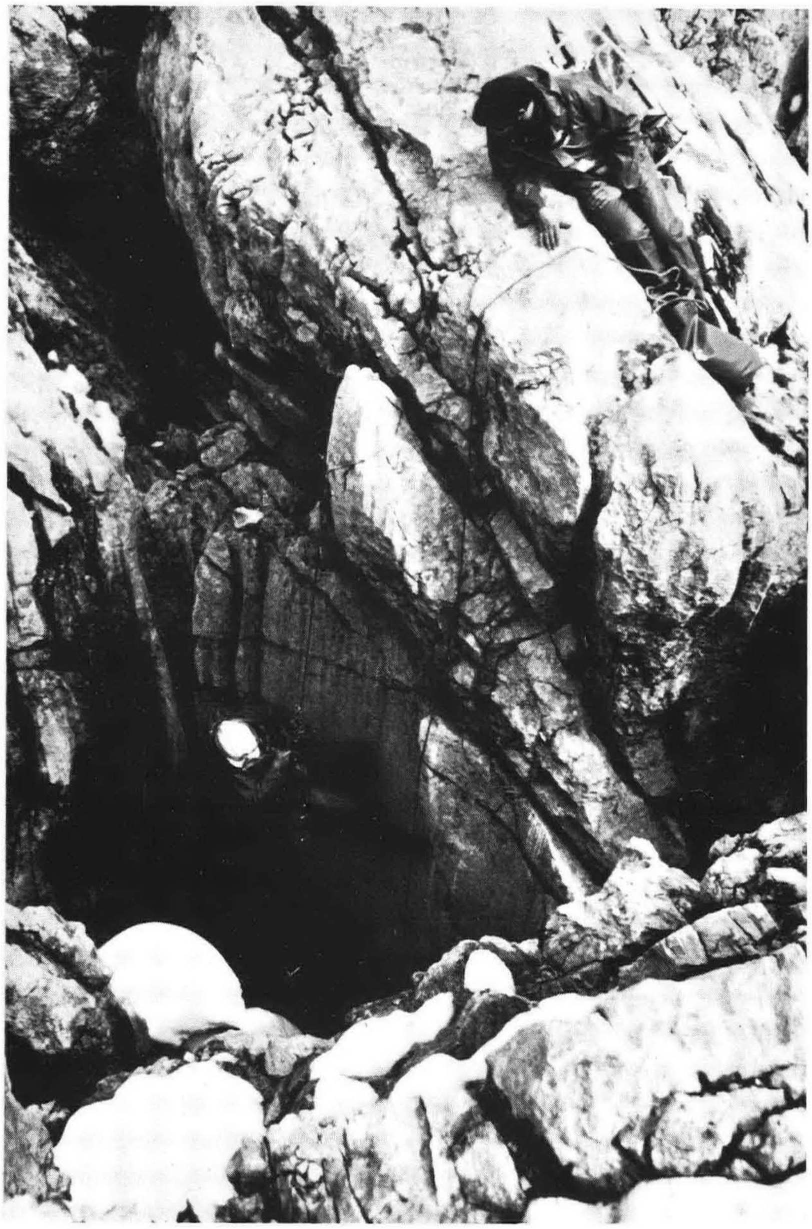

Bridge Cave, Steineresmeer, Austria

Russett Well Flood Pulse

Palaeokarst in Anglesey

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MUSS Expedition to Austria

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A PRELIMINARY FLOOD PULSE STUDY OF RUSSETT WELL, DERBYSHIRE

by N. S. J. Christopher

Abstract

A flood pulse study of Russett Well, Castleton has been performed based on a Classical Ashton type data analysis of flow patterns. In addition chemical variables including derived values and ionic ratios have been studied and the results show clearly that different bodies of water of either vadose or phreatic type have differing chemical characteristics and can be identified by these variables and ratios. Of particular value are potassium, Magnesium and silica concentrations.

Useful supporting information came from sulphate, Pco_2 and the Cl/Na + K ratio.

The overall results closely support existing ideas on the hydrology of the Russett Well system.

INTRODUCTION

The flood pulse technique was developed by Ashton (1966) and further refinements of the mathematical analysis made by Wilcock (1968). A complete analysis consists of studying the changes that occur in several variables during a flood event. In the original paper (Ashton 1966) these were limited to: flow, pH, total hardness, turbidity or suspended solids and possibly temperature. The variation in these variables is then related either by a mathematical analysis or, as in this case by inductive reasoning, to various expected responses based on a theoretical model which describes all possible combinations of phreatic and vadose configurations and factors to see which are present in the case studied.

Ashton's limitation on variables was not exclusive and in a later paper (1967) he used Mg/Ca ratio to characterize certain events during a flood pulse study. Part of the object of this study was to investigate fully other chemical variables to see which would be most useful as additional indicators, and to check that they did show variability with flow as some doubts have been expressed on this point. (L. G. Bray, personal communication).

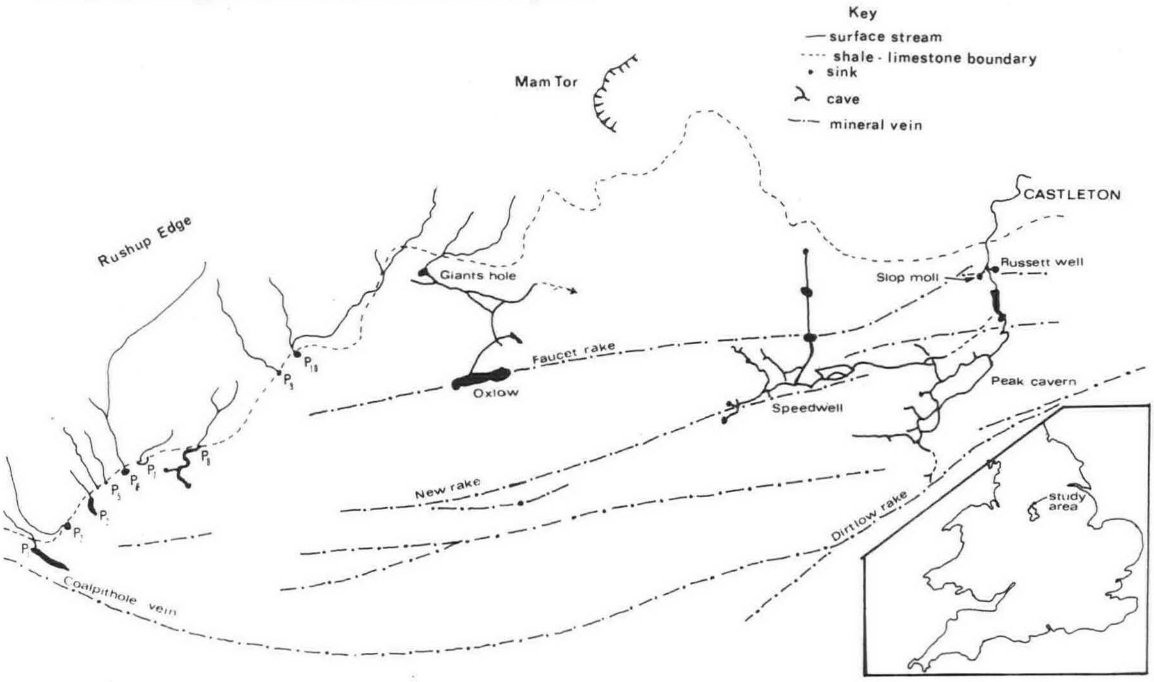
Although the potential of this powerful tool in karst hydrology had been recognised from the outset, there have been very few flood pulse studies reported in the literature.

Gascoyne (1974) studied several resurgences in Venezuela and concluded that the resurgences he studied responded rapidly to rainfall and their chemistry changed equally quickly initially. Flow rapidly returned to normal when the rain stopped but their chemistry took much longer to return to 'normal'. This conclusion was confirmed by Bray (1976) working in South Wales and he questioned whether reliable results could be obtained from chemical variables without a full understanding of the chemistry involved. Ashton (1967) reported the results of his work in Jamaica and drew meaningful conclusions from his observations based on both flow and chemical variables, particularly for the Black River; he has also (unpublished) predicted the shape and form of the Kingsdale Master Cave that was subsequently confirmed by exploration (Wilcock 1968). There have also been a number of studies of various areas, sometimes involving intensive sampling during a flood event, e.g. Chambers (1973), but these studies have principally been directed at deducing erosion rates, and general classification of resurgences by their response to rainfall. Flood pulse analysis of the type advocated by Ashton, and used here, was not included.

Ashton (1966; 1967) used only a limited suite of chemical variables; therefore, this work is the first to examine the variability of all the major anions and cations present in karst waters during a flood event of a British resurgence and to attempt to integrate their variations with a sequence of events deduced from flow measurements.

The karst hydrology of the Castleton area of Derbyshire has been described in some detail by Ford (1966; 1977) and figure 1 has been adapted from Ford (1966). The hydrology, in outline, is essentially a series of allogenic sinks at the limestone/shale boundary, taking water from streams running off Rushup Edge. These, with their associated caves, feed water underground into a complex system of bedding plane

FIGURE 1. Geology and caves of Castleton area, Derbyshire.



passages, joints and faults, some mineralised, and vein cavities. The general flow trend is eastwards, with the geological dip, under an apparent surface watershed to the all-weather resurgence of Russett Well in Peak Cavern Gorge.

Ford (1966; and figure 1) has identified three groups of sinks that probably have separate routes to Russett Well; these are, from west to east, P_1 - P_3 via Coalpithole vein, P_6 - P_8 via New Rake to Speedwell Main Rising and then to Russett Well.

All of the western catchment of Russett Well lies within the apparent surface catchment of the River Wye but the Monksdale-Haydale-Peterdale-Coombesdale tributary is now essentially dry and has been "captured" in its upper reaches by the subterranean cave system of the Peakshole resurgences, flowing via Peakshole water to the River Derwent.

The resurgence system in Peak Cavern Gorge is similarly complicated by the existence of three interrelated resurgences: Peak Cavern Water, Slop Moll and Russett Well. Slop Moll and Peak Cavern resurgence are both overflows for the Speedwell to Russett Well system. Slop Moll becomes active first when the flow at Russett Well exceeds 150 l/s, but much higher flows are needed for the Russett Well system to overflow via Speedwell pot or Treasury sump in Peak Cavern and thus combine with Peak Cavern Water. One observation showed this to be occurring when the discharge at Russett Well was approximately 750 l/s and Slop Moll was discharging about the same amount. To complicate the picture further, the Speedwell-Russett Well system connects with the Inner Styx in Lumbago Walk in Peak Cavern and at moderately high flow the overflow is via this route and down Swine Hole to join the Peak Cavern stream. Slop Moll also includes a component of wet weather flow and rapid percolation from Peakshole Sough, driven WSW along the foot of Cowlow. However, chemical analyses of Russett Well and Slop Moll have not shown any statistically significant difference between the two waters at all stages of flow; consequently this contribution cannot be large.

The Peak Cavern stream has three sources within the cavern; Far Sump, Ink Sump and Squaw's Junction, all three of which are thought to originate in the area of Dirtlow Rake and to be fed principally by percolation water as no sinks have been identified.

The area therefore provides a complex problem for flood pulse analysis and one well suited to the evaluation of different chemical indicators.

THE FLOOD PULSE STUDY

The winter of 1978/79 was particularly severe with over 90 cm of snow falling between February 12th and 16th; as recorded at the Buxton weather station. The snow remained until February 18th when a slow thaw began. Sampling of Russett Well began on February 21st when flow was low (80 l/s) and continued daily until February 27th; this revealed a very slow rise in water level which accelerated between February 26th and 27th. As rain was forecast for the next 24 hours, hourly sampling was begun at 3.30 p.m. on February 27th and continued until 10.30 a.m. on February 28th.

A field laboratory was set up in a nearby house and it was possible to carry out basic determinations there before removing the samples to the main laboratory for more complete analysis.

At the well pH, temperature and flow were measured hourly and two water samples taken. The pH was measured using a Chandos A47D digital meter with an Orion 91-06 combination pH electrode readable to 0.01 units. The electrode was buffered at the beginning of the study at pH7 but was thereafter left undisturbed. The electrode was placed in a relatively sheltered backwater of the well to reduce the streaming potential that can develop in flowing liquids (Barnes 1964). The meter, which was battery operated, was placed in a large clear polythene bag on a convenient ledge well above maximum flood level and left undisturbed for the duration of the study. Temperature was read to 0.1°C from a 0.40°C BS.593 Class A, laboratory thermometer calibrated for 100mm immersion left in the well for the whole duration of the study. Flow was measured as the level of the water below a reference point, to the nearest 0.5 cm, which had been previously calibrated for the flow/stage relationship using standard hydraulic formulae.

At each hourly sample the following procedure was adopted: read pH meter, thermometer, measure flow and take two water samples in clean dry acid-washed polythene bottles; a 500ml sample and a 250ml sample. The 250ml sample was treated with excess 'Analar' calcium carbonate slurry and both the sample bottles were filled completely by screwing the caps on underwater. An ordinary pair of household rubber gloves was found to assist operator comfort considerably with water temperatures of 5-6°C and to allow dry hands to be used for taking notes.

At the field laboratory a 250ml portion of the larger sample was filtered through a Whatman GF/C glass microfibre filter paper, with a mean particle retention of 1.2 microns, using a small Buchner flask and hand vacuum pump. The filter circle was retained to assess suspended solids. The filtrate was transferred to a clean 250 ml polythene bottle and acidified with 3-4 drops of concentrated hydrochloric acid. This sample was used for subsequent laboratory analysis. The remainder of the 500 ml sample was used unfiltered to determine: total hardness, alkalinity and chloride on site using standard methods. (Anon 1976).

The 250ml sample was allowed to stand for 2 hours, shaken periodically and then filtered through a Whatman 41 filter paper. The total hardness of the resultant solution gave a measure of the aggressiveness of the water to calcium carbonate (Stenner 1969).

The acidified sample was analysed in the main laboratory for calcium, magnesium, sodium and potassium by atomic absorption or flame emission spectrophotometry; for sulphate volumetrically, and for silica and nitrate colorimetrically using conventional methods (Anon 1976).

The raw analytical data was plotted against time and also used to compute several derived variables, which were saturation index (SIc), partial pressure of carbon dioxide (Pco_2), by a method already described (Christopher 1978) and a suite of fifteen ionic ratios, computed after conversion of the analytical data into milliequivalents per litre. This latter part was performed by a digital computer using a purpose-designed programme which also checked the analysis for cation-anion imbalance and performed a statistical analysis of the raw and derived data.

RESULTS

From the previous discussion it can be seen that the principal site in Peak Cavern Gorge for the study of the Rushup Edge to Russett Well system is Russett Well. Consequently this study was limited to recording the response of Russett Well to a flood event and no account is rendered of the parallel response of Slop Moll or Peak Cavern resurgence.

A representative selection of the data from this study is presented in figures 2, 3 and 4 and a summary of various variables compared to long term averages is given in table 1.

Table 1

Long term average values of chemical variables for resurgences in the Castleton Area compared to flood values of Russett Well from this study.

Site	Long term average values: Russett Well	Slop Moll	Peak Cavern	Flood values (this study): Russett Well
pH+	7.4	7.6	7.8	7.3
Temp. ^{o}C	7.8	7.1	8.0	6.4
Ca	76	74	86	68
Mg	2.1	2.2	1.4	2.3
Na	12.3	12.6	4.5	19.3
K	1.08	1.24	1.34	1.67
Hardness*	199	191	220	178
HCO_3*	142	133	166	122
Cl	29	30	15	43
SO_4	34	35	36	29
SiO_2	4.6	4.4	3.3	5.6
NO_3	12.8	13.7	10.7	12.7
Agg*	-1.9	-4.5	12	2
SIc+	-0.23	-0.1	0.38	-0.43
Pco_2	2.23	2.44	2.64	2.21

Note 1. All units are mg/l of the ionic species specified except those marked * which are mg/l $CaCO_3$.
Note 2. Those marked + are unitless numbers.

DISCUSSION

A. Flood Pulse Synthesis.

During this study the well rose from low flow to just below bank full discharge, a total of 28cm, which the flow graph shows to be equivalent to an increase in discharge of approximately 560 l/s. The flow maximum occurred at 05.30 on 28.2.79 when the measured discharge was 640 l/s. No measurements were made on Slop Moll or Peak Cavern but previous observations indicate that both should be active discharging at least as much as Russett Well.

The flow graph (figure 2) shows a steady rise from 15.30 on 27.2.79 until midnight with a few minor 'blips' and the first major pulse arrived at 01.30 and lasted until 03.30 on 28.2.79. A further major surge began at 04.30 and also lasted two hours, after which the flow gradually decreased.

It began raining lightly at Castleton at 16.30 on 27.2.79 but was dry from 18.30 to 20.30 when the rain began again; the intensity of the rainfall increased steadily to midnight, whereafter it decreased and stopped completely by 05.30 and it reamined dry to the end of this study.

Buxton weather station recorded 15.4mm of rain for the 24 hours ending 09.30, 28.2.79. There was in addition a considerable amount of drifted snow in the catchment area. Buxton records show that since February 16th, 97cm of snow had melted, equivalent to 81mm of rain. The ground was therefore probably completely saturated and any response to further thawing or rain would be very rapid.

Local knowledge (Ford, personal communication) indicates that Russett Well takes approximately 10 hours to respond after rain on Rushup Edge. The author has also noted, from his own observations during frequent visits to Castleton over the past few years, that it is frequently raining on Rushup Edge well before rain reaches Castleton and that up to an hour can elapse before the rain on Rushup Edge reaches Castleton. This is not surprising due to the 150m (500 ft.) difference in altitude and the more westerly location of the former closer to the Atlantic's westerly air flow which usually brings the rain. It is therefore significant that the first major pulse began at 01.30-02.30, 9-10 hours after it started rained at Castleton.

As will be seen the flow graph shows, apparently, only one flood pulse, but as we have seen the rain came in two periods separated by a two hour gap, and one would therefore expect two pulses. The presence of only one pulse is probably due to the continued and fairly rapid snow melt, which over the period of study visibly reduced the amount of drifted

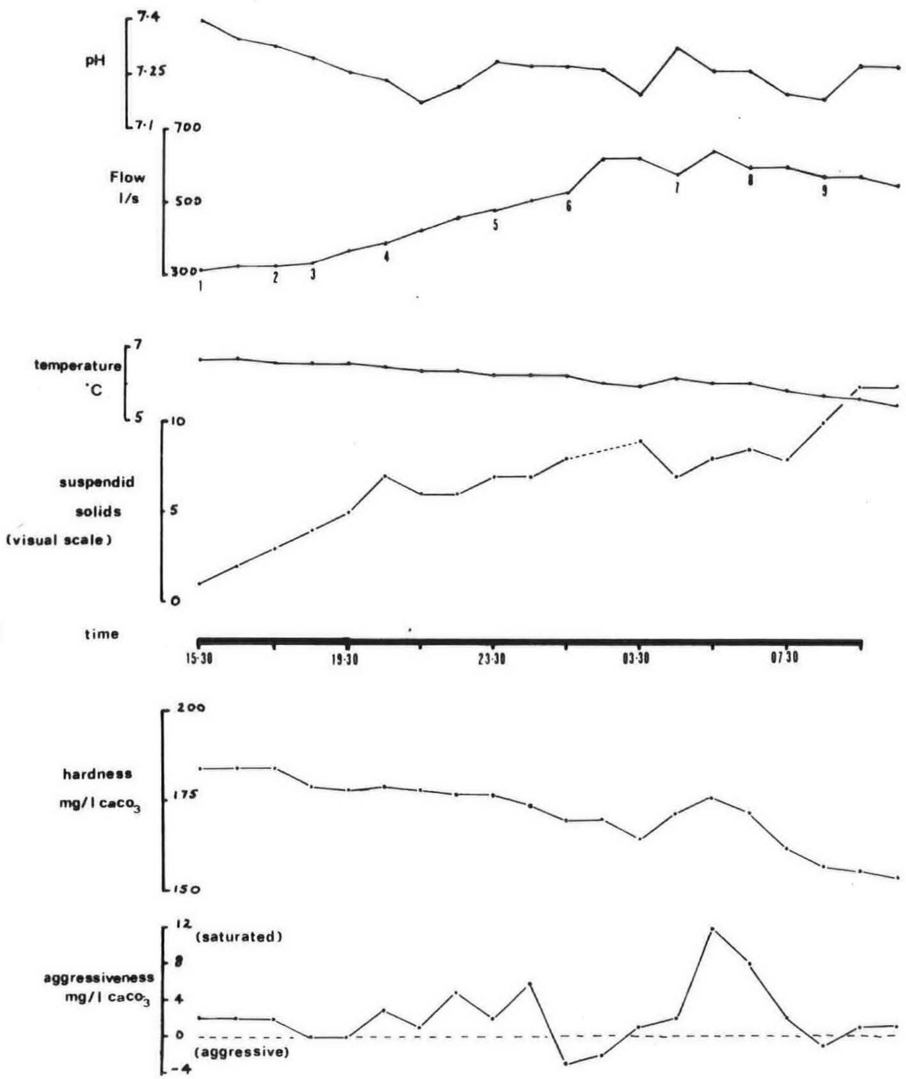


FIGURE. 2. Variation with time of the 'Ashton' variables.

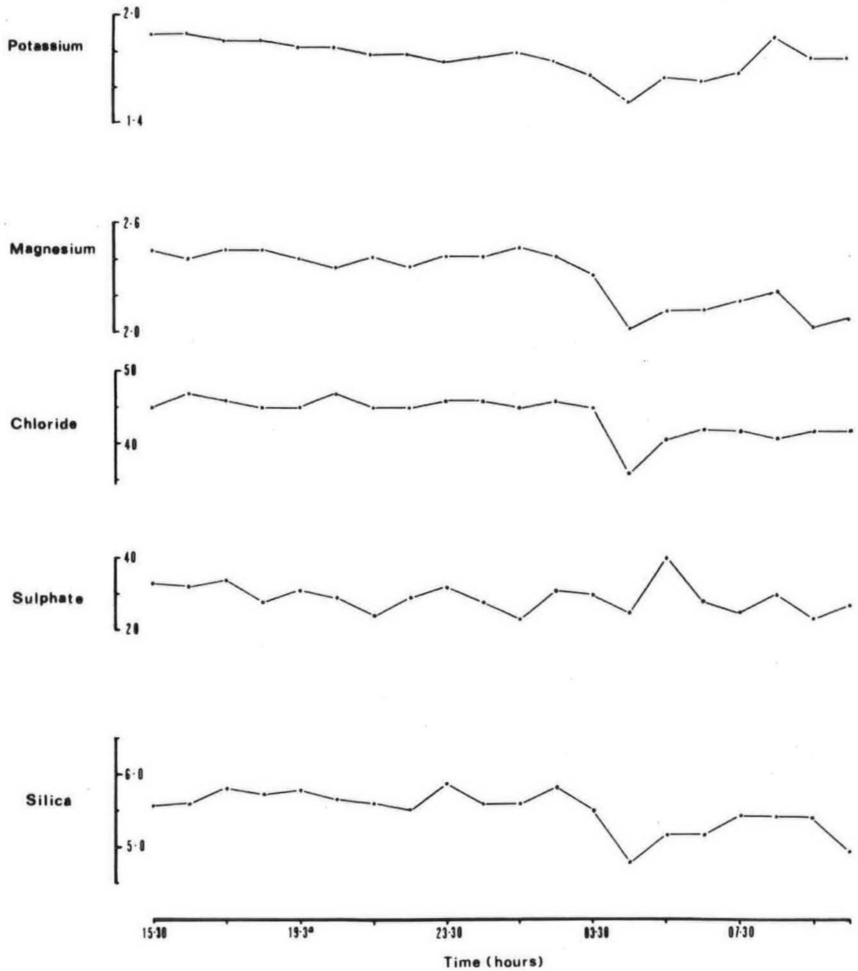


FIGURE 3. Variation with time of the chemical variables. (all units are mg/l of the ion specified)

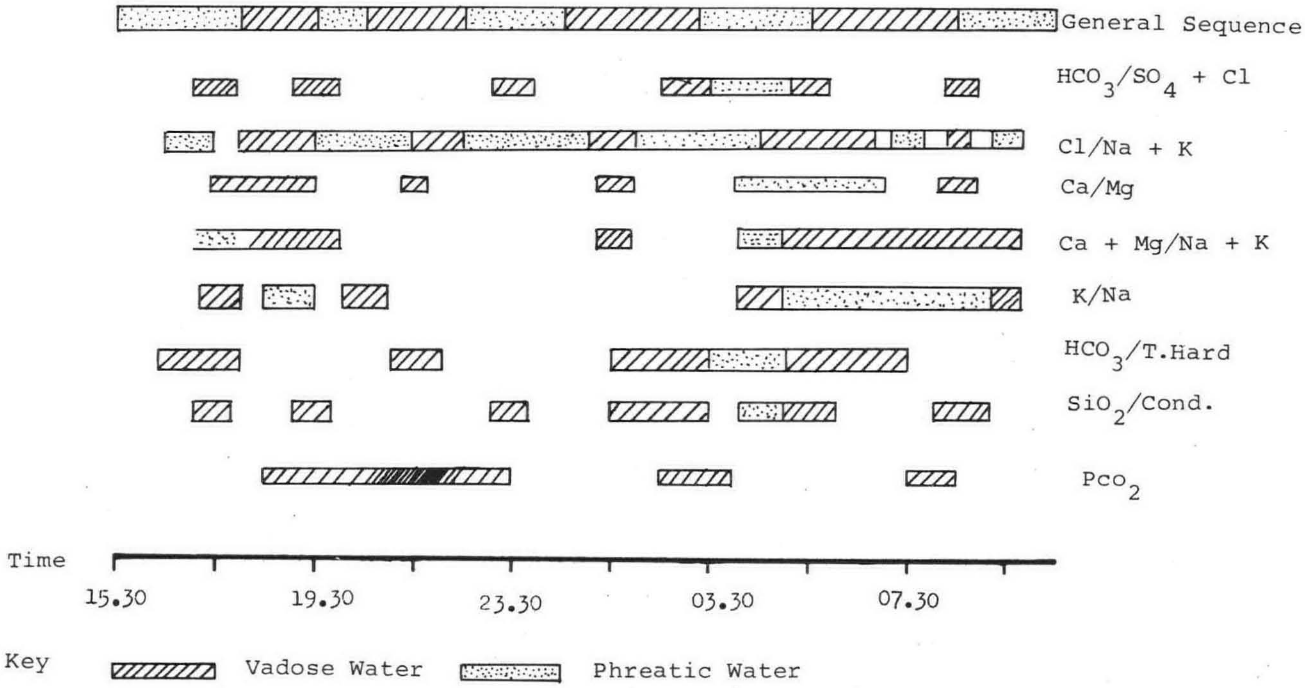


Figure 4. Water Types Characterized by Ionic Ratios and Pco_2 Values

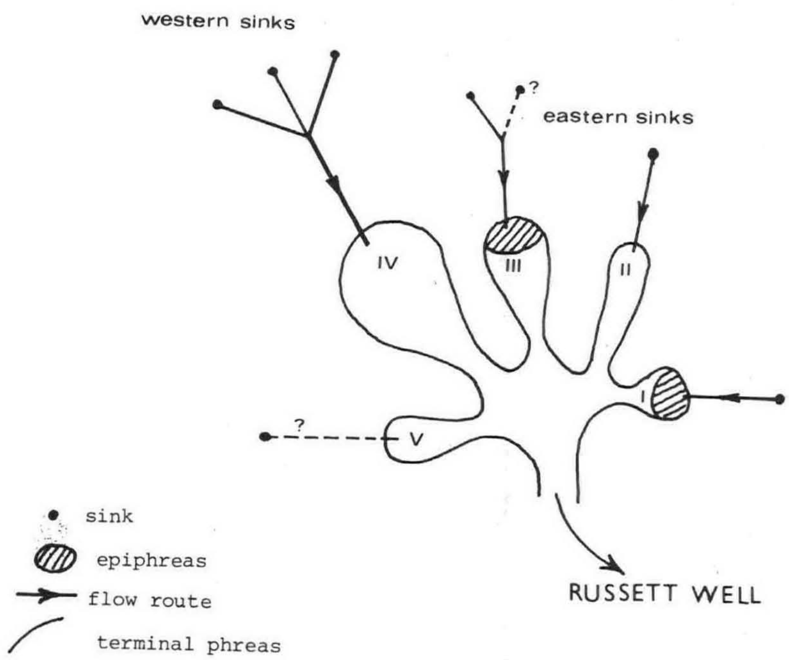


FIGURE 5. Diagrammatic representation of the Russett Well system.

snow in the catchment, and the pulse produced was augmented by the rainfall.

A flood pulse which develops on an impervious catchment passes into the vadose cave zone without modification unless there are oxbows present. However, when the pulse reaches a flooded zone (phreatic area) the pulse immediately increases the flow out of the phreas but the volume of the phreas requires time to be flushed clear of the resident phreatic water, which will be of a different chemical character to the incoming flood (vadose) water. Consequently a phreatic area will transmit a flow pulse instantaneously but delay the accompanying chemical pulse. This gives us a method of estimating the phreatic volume of a system by measuring the area under the flow graph between the first increase in flow and the arrival of the flood water. Multiple sinks, branching systems and oxbows complicate the overall pattern as do restricted phreatic areas which allow considerable backing up behind them in normally air-filled (vadose) passages. These temporary phreatic areas were termed 'epiphreatic areas' by Ashton (1966) and they produce a flattening of both flow and chemical pulses. A fuller discussion of these points is given by Ashton (1966).

Referring now to figure 2 and using the criteria developed by Ashton (1966; 1967) the following sequence can be deduced (events are numbered on the flow graph for convenience):

Time	Event	Comments
15.30	1	A small rise in flow and temperature; aggressiveness and hardness steady. The hardness is lower than 26/2 so this suggests a first phreatic flush superimposed on the snow melt water.
	2-3	Drop in temperature, hardness and pH; flow and aggressiveness increase. This indicates the arrival of the vadose water associated with event 1.
18.30	3	The continuation of 2 and the previous shape of the flow graph together with continued slow increase in flow is either a reflection of the snow melt or a result of backing up behind the first phreatic area.
20.30	4	An increase in suspended solids, hardness and pH with a decrease in aggressiveness indicate a second and separate small part of the phreas is becoming active.
20.30 - 23.30	4-5	At 21.30 pH reaches a minimum value, indicating the end of the vadose pulse associated with event 4 and the beginning of another phreatic pulse. At 22.30 an increase in suspended solids steadying in the hardness and temperature supports this showing the existence of a third phreatic area.
23.30	5	pH maximum reached, break in flow curve, temperature has dropped; this indicates arrival of vadose flood water.
23.30 - 01.30	5-6	Continued slow fall in pH, decline in total hardness which levels off after 6 indicates slow arrival of vadose water through a restricted phreas.
01.30	6	The sharp increase in flow with drops in temperature and hardness indicate increased arrival of vadose water either from a second and bigger pulse into this phreas or due to considerable backing up in the epiphreas possibly occasioned by the heavy rain of the last few hours. Flattening of flow graph suggests backing up in the epiphreas.
04.30	7	The rise in pH, temperature, hardness, with a decrease in aggressiveness to a minimum value, indicate that a fourth phreatic area is becoming active.
06.30 - 08.30	8&9	The fall in pH, hardness, temperature, etc. indicates vadose water associated with event 7 has arrived at the resurgence and the shoulders on the flow and pH graph suggest that the pulse was complex with three inlets.
09.30 - 10.30		The rise in pH and decrease in aggressiveness, together with a steadying in the decline in hardness suggests a fifth phreatic area is becoming active, but the study was terminated before it could be fully characterized.

The pattern of the flow graph after event 7 could represent a repeat of part or all of the preceding graph, but due to the much higher hardness displaced in this event this is thought unlikely.

In the succeeding discussion the five phreatic areas, which are shown up by the data analysis performed above, are referred to as phreas I, II, III, IV and V respectively. Estimates of the volumes of the first four phreatic areas were calculated by the method outlined above and are given in Table 2.

Table 2

Phreas	Approximate Volume in m^3
I	1200
II	2600
III	3300
IV	8700

B. Chemical Variations during a Flood Event.

As Ashton (1966) used chemical variations (pH and hardness) to characterize different water types it is difficult to see how the objections of Bray (1976) arise. However, to test out these objections thoroughly a comprehensive suite of major components was determined and various interrelations tested with a suite of 15 ionic ratios.

1) Calcium and Bicarbonate.

As calcium and bicarbonate are the dominant ionic species in karst waters and their geochemistry is closely related it is not surprising that these two ions show similar trends. It is also not surprising that as calcium is the biggest contributor to hardness they also show no trends not also demonstrated by the total hardness graph.

2) Magnesium, Sodium, Potassium, Chloride

These four ions are similar in their responses as shown in figure 3, and their concentrations expected in vadose and phreatic waters are expected to show similar variation.

Sodium and chloride are geochemically related in NaCl, which is a major pollutant in this study due to road de-icing. The mean concentration of these two ions during this study, Table 1, is 50% above the long term mean for Russett Well, and also considerably above the values recorded at the beginning of this study, indicating a high level of contamination. Apart from the large drop in concentration at 04.30 associated with the flushing of phreas IV, all the variation in these two elements could be attributed to experimental error. However, the chloride graph does show weak peaks associated with the major vadose pulses described above.

The concentration of potassium and magnesium in surface water is most probably controlled by the breakdown of the clay minerals, illite and chlorite respectively, which explains why these two elements usually have higher concentrations in surface waters than in limestone ground waters, and also these concentrations increase above the equilibrium value during a flood event. There is also probably, especially in the case of potassium, a certain degree of control by ion exchange reactions. (Christopher 1975).

The potassium graph in figure 3 shows there is a gradual decline in concentration from 1.9 ppm at 15.30 to 1.74 ppm at 23.30, but there are some minor peaks whose magnitude is well within the limits of experimental error. There is, however, a more substantial peak between 23.30 and 02.30, which coincides with the arrival of the flood water associated with phreas III. This is followed by a sharp decline associated with the flushing of phreas IV and the succeeding response supports the description of the feeder to this phreas as being complex.

Traces of potassium and magnesium are present in the salt used for de-icing but an analysis of salt taken from the Derbyshire County Council dump at Castleton had a K:Na ratio of 1:1224 and a Mg:Na ratio of 1:12,000. Consequently with a maximum sodium concentration of 21 ppm, the maximum potassium concentration from this source would be 0.02 ppm, only slightly above the potassium detection limit and 1% of the potassium concentration recorded at the beginning of this study. The magnesium concentration from this source is so small as to be negligible.

The magnesium graph of figure 3 shows a very similar pattern to the potassium graph after 23.30, but also shows two clear parks at 17.30-18.30 and 21.30 which are presumably associated with the arrival of magnesium-enriched flood waters through phreas I and II.

3) Sulphate and Silica

Both these ions show considerable variability; a certain proportion of which, particularly in the case of sulphate, is probably due to the lower reproducibility of the method used ($\pm$ 3 ppm), and also because of the more complex geochemistry of sulphur. It has generally been shown (Christopher 1977) that the sulphate content is high in soil waters, ground waters of long residence time and ground waters in contact with igneous rocks or areas of mineralisation.

This complex variability of sulphate probably explains why the sulphate graph shows peaks at all events described above, whether it is due to a phreatic or vadose pulse. There is one point of interest, however: the high sulphate value at 05.30 associated with the phreatic displacement water of phreas IV, suggests that this water has been in contact with sulphur-bearing rocks or minerals, most probably in a mineral-vein cavity system. All these results are in agreement with those of Jacobson and Langmuir (1974) who found that all chemical variables except sulphate had similar responses to conductivity and that sulphate showed almost no variability during a storm. They explained this apparent anomaly by postulating several sources of sulphur.

The silica graph is in close accord with the general picture developed above and the stream water geochemistry of silica (Kennedy 1971). There are peaks at 17.30 to 19.30, 02.30 and 06.30 - 09.30; the stepped nature of this latter peak lends support to the idea that this latter pulse is complex. Additionally, the major dip at 04.30 coincides with the flushing of phreas IV. All these peaks are in accordance with the Ashton type synthesis. There is, however, a peak at 23.30 coincident with a peak in the sulphate graph which also lends support to the idea that the vadose pulse of phreas III (event 4-6) is also complex. There is also some support for this on the temperature and aggressiveness graphs.

4) Derived Values and Ionic Ratios

A number of the fifteen ratios calculated present a very similar picture, so only seven of them are presented in figure 4 in summary form. The Pco_2 data is also presented together with a representation of the sequence deduced from the more conventional variables, for comparison.

As can be seen from figure 4, these ratios and the Pco_2 values support the general sequence of events quite closely, especially when it is realised that on a relatively coarse time scale of one hour it is difficult to establish the exact limits of a peak or trough.

The only major omission from figure 4 is the SIc data but this was done for convenience as these results are very similar to those of the Pco_2 data and would only duplicate the interpretation.

5) Chemical Responses

As has been noted above, several workers have commented on the rapid response of several karst resurgences to flood water but the slow chemical recovery. Whilst this study was not continued long enough to see if a similar result was obtained here the author does not doubt that it would have been found. This effect therefore calls for some comment.

It seems that this slow chemical recovery is due to the complex hydrology of a karst drainage system which is composed of three elements, conduit water, rapid percolation water and slow percolation water (Smith et. al. 1976). The conduit water is that carried in more or less penetrable cave systems, and has flow times measured in hours rather than days, and the percolation water is carried in fissures whose dimensions vary from mini-caves to microscopic; here the flow times vary from days to weeks. The <u>total</u> proportion of a karst resurgence water derived from swallets and thus cave conduits is certainly below 25% of the total annual discharge and is often less than 10%, but the swallet systems temporarily provide a much higher proportion when it starts raining and they provide chemically different water - quickly. This is the whole rationale of the flood pulse technique.

The percolation water systems also respond to increased input; the fastest percolation water may have similar responses to conduit systems, but over all they provide the bulk of the base flow, have a more subdued response and, when disturbed, take longer to return to equilibrium pre-flood chemistry.

Thus a combination of these responses is probably reason for the rapid initial change but slow recovery in karst water resurgences commented on by Gascoyne (1974) and Bray (1976).

THE HYDROGEOLOGY OF THE RUSSETT WELL SYSTEM

This section will attempt to draw together the arguments of the previous sections and to integrate the hydrological information with that of the geology.

The flood pulse analysis given above indicates four sequences of phreatic water being displaced, followed by the emergence of four pulses of vadose flood water; the shape of the flow graph indicates that those parts of the phreas associated with the first and third of these events have restricted outlets. Furthermore, the results indicate that the pulse coming from phreas IV is complex having three discrete input points. There is also a suggestion that the third pulse is also complex, but the picture is rather confused here. This synthesis is presented as a diagrammatic representation in figure 5. The size of the lobes I to IV is very approximately in accordance with the relative volumes given in Table 2, but the direction of entry of the various inlets has no geographic significance.

The first two lobes of phreas I and II are fairly small and difficult to assign with any certainty. Phreas I is apparently restricted, but phreas II reasonably open. Possibilities for either of these are: the inlets of Cliff Cavern in Speedwell Cavern, Bathing Pool in Speedwell, P_9 (Christmas hole) and P_{10} (Snelslow).

Phreas III is larger volumetrically than either I or II and also appears to be restricted in size or outlet; there is also some evidence particularly chemical to suggest that the input pulse is complex to this area with two separate input points. It therefore appears likely that it is one of the Rushup Edge sink groups.

As the eastern group is closer (3.7 km against 5.2 km) it would appear to be more likely. The known backing up of East Canals, Giants Hole and the restricted nature of presumed outlet via Whirlpool Rising in Speedwell Cavern, fits the flood pulse evidence. The other inlet to this part of the phreas could be either P_9 or P_{10}, but they do not enter the known part of Giants Hole. Alternatively, it could be a minor inlet of Giants Hole, e.g. Northeast Swallet inlet. A further possibility is that the delays imposed on the chemical pulse by the three sumps in the Giants streamway are confusing the picture, but these sumps are of very small volume.

Phreas IV is most probably the vein cavity system associated with the western sink group. There are three reasons for this assignment, which are: firstly, it appears to be the last major event and the western sink group is separated from Russett Well by the greatest distance of 5.2 km; secondly, the size of the phreatic displacement pulse and its radically different chemistry indicates a large phreatic volume which is in accordance with the distance, and what is known about the size of vein cavities from drained examples, e.g. Bottomless Pit, Speedwell or West Chamber, Oxlow. The phreatic volume estimated at 8700 m^3 (Table 2) and the plan distance of 3 km from Perryfoot to Speedwell Main Rising indicates an average passage-cross-section of 2.9 m^2 which seems reasonable for a hydrologic route via a mineral vein system as suggested by Ford (1966). Finally, the indications are that the pulse is a complex vadose pulse with three inlet points.

This final point and the estimated phreatic volume are the most important pointers to the origin of the water displaced from phreas IV. There is also supporting evidence in the sulphate content mentioned above.

The complex nature of the vadose pulse is probably the most interesting fact to come out of this study, because it confirms the views of Ford (1966; 1977) on the probable direction of drainage from the western sink group.

The three separate sink sub-groups are possibly P_1 and P_2, P_3 - P_5 and P_6 - P_8. The first of these sub-groups, P_1 and P_2, are known to combine very shortly after passing underground (Ford 1966). Not much is known about the drainage of the second sub-group, but the third sub-group, P_6 - P_8, is known to form one hydrologic unit. (Smith and Waltham, 1973).

Ford (1966) has suggested that P_3 drainage unites with P_1 and P_2; this study cannot confirm this without tagging of the individual sinks with various coloured dyes. P_4 is very small, the smallest of the Rushup Edge sinks, and so if P_3 does act with P_1 and P_2 this middle group would virtually be restricted to P_5.

The P_6 - P_8 complex may provide two of the three inlets with P_1 - P_5 acting as one unit. Support for this idea comes from the known hydrology of the P_8 cave system (Smith and Waltham 1973). The stream that goes underground at P_8 sinks in the cave at the bottom of the second pitch, and is not seen again in the known cave. The combined waters from P_6 and P_7 emerge within the cave to form the separate lower stream. However, it is known that in flood the sump at the bottom of the second pitch backs up and overflows into the lower streamway, thus recombining the waters, at least in part.

Phreas V is not sufficiently well established to be discussed further.

CONCLUSIONS

This study has confirmed, by an independent method, the nature of the hydrology of the Rushup Edge to Russett Well drainage system as proposed by Ford (1966 and 1977) based on the geology of the area, and outlined in figure 1.

The study has also confirmed, as originally proposed by Ashton (1966), that chemical variables show sympathetic variation with flow during a flood event and also that almost all the major ionic species can be used to differentiate water types provided that there is sufficient difference in composition between the separate water types.

Particularly useful results have been obtained, in this study, from aggressiveness, magnesium, potassium and silica and useful supporting evidence from sulphate and chloride.

Inter-ionic relationships as described by ionic ratios and the derived constants can also provide useful supporting evidence, particularly where the results of the individual ionic species are ambiguous; a good example here is the Cl/Na + K ratio (figure 4). Also the Pco_2 values are often good indicators of the nature of the water and give valuable clues as to its origin.

All this supporting evidence has, however, to be carefully weighed against the evidence from the conventional parameters of flow, hardness and pH. Contrary to what Ashton supposed, under the right conditions, temperature does give useful results and this supports the work of Halliwell in White Scar Cave, Yorkshire (personal communication).

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REFERENCES

Anon, 1976. *Standard methods for the Analysis of Water and Waste Waters.* 14 Ed. American Public Health Association. 1193 pp.

Ashton, K. 1966. The Analysis of flow data from a karst drainage system. *Trans. Cave Res. Gp. GB.*, Vol. 7, (2), pp 161-203.

1967. The University of Leeds Hydrological Survey expedition to Jamaica. *Trans. Cave Res. Gp. GB.*, Vol. 9, (1), pp. 36-44.

Barnes, I. 1964. Field measurement of alkalinity and pH. *US. Geol. Surv. Water sup. pap.* 1535-H. 17 pp.

Bray, L. G. 1976. Recent chemical work in the Ogof Ffynnon Ddu system: Conductivity recording at the Ffynnon Ddu Resurgence. *Trans. Brit. Cave Res. Ass.*, Vol. 3, (1), pp. 15-19.

Chambers, W. J. 1973. Limestone springs and individual flood events. *Trans. Cave Res. Gp. GB.*, Vol. 15, (2), pp. 91-98.

Christopher, N. S. J. 1975. The use of Saturation Index and Potassium to Sodium Ratio as indicators of Speleological Potential, with special reference to Derbyshire. *Trans. Brit. Cave Res. Ass.*, Vol. 2, (1), pp. 29-34.

1978. A simplified Method of Calculating Saturation Index and Partial Pressure of Carbon Dioxide for Karst Waters. *Trans. Brit. Cave Res. Ass.*, Vol. 5, (3), pp. 127-134.

Christopher, N. S. J., Beck, J. S., Mellors, P. T., 1977. *Hydrology* - Chapter 12 in *Limestones and Caves of the Peak District,* ed. T. D. Ford, Geobooks, Norwich. 469 pp.

Ford, T. D. 1966. The Underground Drainage Systems of the Castleton Area, Derbyshire and their Evolution. *Cave Sci.*, Vol. 5, pp. 369-396.

Ford, T. D. 1977. *The Castleton Caves* - Chapter 16 in *Limestones and Caves of the Peak District,* ed. T. D. Ford, Geobooks, Norwich. 469 pp.

Gascoyne, M. 1974. Hydrological investigations in Northern Venezuela. *Trans. Brit. Cave Res. Ass.*, Vol. 1, (3), pp. 169-179.

Jacobson, R. L. & Langmuir, D., 1974. Controls on the quality variations of some carbonate spring waters. *Jour. Hydrology,* vol. 23, pp. 247-265.

Kennedy, V. C. 1971. Silica variations in stream water with time and discharge, in Non-equilibrium Systems in Natural Water Chemistry, *Advances in Chemistry,* No. 106, *Am. Chem. Soc.* pp. 94-130.

Smith, D. I., Atkinson, T. C., Drew, D. P. 1976. The Hydrology of Limestone Terrains. Chapter 6 in *The Science of Speleology,* ed. T. D. Ford and C. H. D. Cullingford, Academic press, London. 593 pp.

Smith, P. B. and Waltham, A. 1973. The P8 Cave System, Castleton, *Cave Sci.* Vol. 7, (50), pp. 21-28.

Stenner, R. D. 1969. The measurement of the aggressiveness of water towards calcium carbonate. *Trans. Cave Res. Gp. GB.*, Vol. 11, (3), pp. 175-200.

Wilcock, J. D. 1968. Some developments in pulse train analysis. *Trans. Cave Res. Gp. GB.*, Vol. 10, (2), pp. 73-89.

Trans. British Cave Research Assoc., Vol. 7. No. 1 pp.13-30 March 1980

PALAEOKARST PHENOMENA IN THE CARBONIFEROUS LIMESTONE OF ANGLESEY, NORTH WALES

by D. J. Baughen and P. T. Walsh

ABSTRACT

At least seven horizons in the Carboniferous Limestone of Anglesey preserve a strong development of intraformational palaeokarst which takes the form of sandstone pipes in limestone host-rocks. It is concluded that palaeokarsts developed partly, if not completely, in a subaqueous environment, where deposition of non-calcareous fill-sediments, cavity development and subsidence were interactive processes. It is not thought possible to identify the analogue of the Anglesey palaeokarsts in modern coastal environments, if, indeed, the peculiar geographical conditions under which they formed exist at the present day.

INTRODUCTION

In contrast to the widespread occurrence of karst features in modern landscapes, palaeokarst phenomena are much less often encountered in the stratigraphic record (Quinlan 1972). The sandstone pipes in the Carboniferous Limestone of Anglesey, considered herein as strongly developed and possibly unique types of palaeokarst, may consequently have rather more scientific importance than has been accorded to them previously. The present study was undertaken with the intention of amplifying the data recorded by Greenly (1900 and 1919), who established their origins as solution subsidence phenomena, and to refute more recent opinion that they are of mechanical origins.

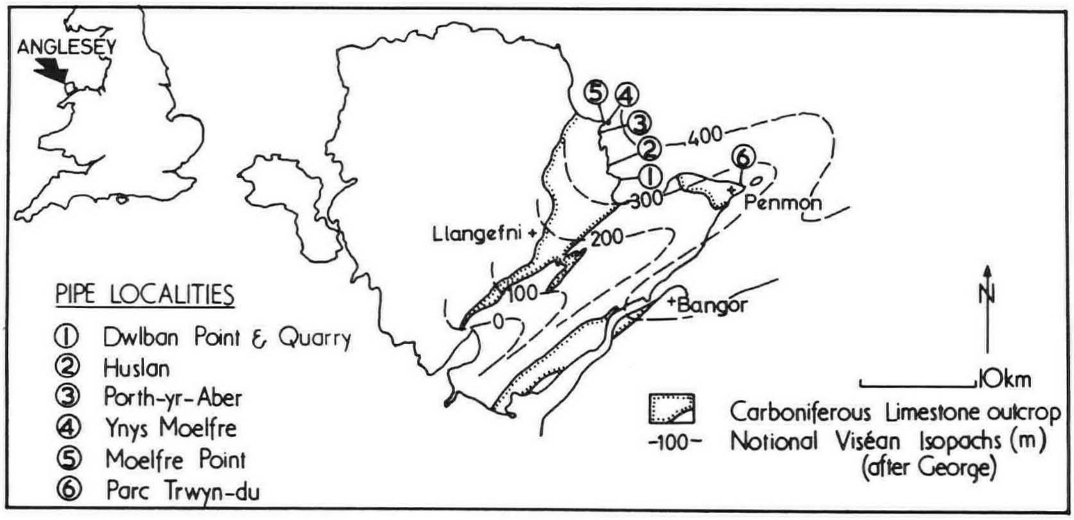

Fig. 1. Map to show (1) the Anglesey piped limestone localities and (2) thickness variations in the Carboniferous Limestone successions.

Piped limestones are known from several localities on the east coast of Anglesey (Fig. 1). Greenly described six of these and noted the following features which are common to all horizons he recognised:

1. Where a fill is preserved it is invariably a fine, white, hard, ganister-like sandstone, which may be contiguous with one of the next suprajacent layers. Such layers (termed 'source-sandstones' here in the absence of any appropriate technical terms), where preserved, are structurally quite conformable with the host limestone, except where bedding traces have been distorted by the cavity development processes and resultant infilling with sand. Occasionally lenses of quartz pebbles each up to 6 cm long are found in the pipe-fills and source-sandstone layers. At some localities, both host layer and pipes are truncated by an intraformational erosion surface.
2. Trace fossils (presumably annelid burrows) are occasionally visible in

the fill sandstones, but otherwise, there is no evidence of organic activity.
3. The structure of the sediment in the pipes appears to be quasi-horizontal, with gentle menisci axially within the pipes.
4. The walls and floors of the pipes are invariably smooth and the floors rounded.
5. In most of the pipes where a fill is preserved, there is a prominent radial jointing, which may extend laterally into the host limestone.

In his 1900 paper, Greenly concluded that the materials involved in the piping are marine in origin and that the piping must have taken place during an interval of shallowing (and perhaps exposure of the sea floor); but, except insofar as a chemical origin was implied, the mechanisms of cavity development were not discussed. Both Greenly and Challinor & Bates (1973) commented on the resemblance of the pipes to potholes, the latter proposing that the potholing on the foreshore at Porth-yr-Aber (exact location not specified) is a modern counterpart. However, Greenly had previously rejected a mechanical origin for the pipes..."there being no really coarse material/in the pipes/...pebbles, though present, being both rare and small". In the only other description of the pipes known to the writers, George (in Owen, 1974), in a review of the Anglesey Carboniferous Limestone, stated that the pipes were produced by "fresh-water solution", but no field details were given. Cope (1975) has identified what he terms a "neptunian dyke" palaeokarst close to the base of the Carboniferous Limestone succession at Careg Ddafad, Lligwy Bay, Anglesey (SH 498872). But as this is not strictly a sandstone pipe horizon, and, in any case, is described in detail by Cope, it is not considered further here. Its significance in the interpretation of the piped limestone phenomena is briefly discussed later.

STRATIGRAPHIC SETTING

While the main intention of this paper is to bring some interesting palaeokarst phenomena to the attention of karst geomorphologists, it is clearly necessary to try to place the Anglesey palaeokarsts into a regional stratigraphic framework. It is generally accepted that most members of the Lower Carboniferous of North Wales were deposited in a shallow-water, shelf sea environment - the Central Province Basin, which became established to the north of a persistent upland area across what is now Central Wales and the English Midlands - St. George's Land (George 1967). The distribution of the Viséan outcrops along the North Wales coast, dipping northwards and eastwards into the Liverpool Bay and Cheshire Basins broadly reflects the form of the North Wales cuvette of sedimentation, though the Corwen Outlier shows that, at its maximum, the Viséan shoreline formerly extended far beyond the main Welsh outcrops of the present day. Over what is now Anglesey, the transgression began in D_1 (Asbian) times and continued throughout D_2 (Brigantian) times (Cope, 1975), though there is some evidence that parts of western and northern Anglesey may never have been consumed by the transgression and remained as land areas throughout. In an embayment centred on Lligwy Bay, about 400 m of shallow marine and terrestrial sediments accumulated, the maximum development on Anglesey (George 1974, fig. 22). The most detailed existing account of the Anglesey Carboniferous Limestone is that of Greenly in his 1919 Memoir. It is generally acknowledged that this was the first description to synthesise reasonably accurately the considerable variations of lithology and thickness, both in time and space, and to identify the highly irregular nature of the landscape which became progressively enveloped by Visean sediments. The most recent summary of our knowledge of the Anglesey succession is that of George (in Owen 1974), who emphasised that the complexity of the stratigraphy was due to the position of Anglesey at the margins of the Basin ... "its present-day outcrops reveal the rapidly variable kinds of sedimentary relationships that characterise the immediate vicinity of a coastline" (George 1974, p.108). George regarded the sandstone intercalations in the Anglesey succession as resulting from the construction of lenticular spreads of terrigenous detritus onto the marine shelf.

Much recent work on the Viséan successions elsewhere in the Central Province (see especially Power and Somerville 1976; Walkden 1977 and Somerville 1979a and 1979b) has demonstrated the cyclic nature of Asbian and Brigantian sequences, with rhythmic sedimentation and non-sequences apparently being related to a cyclic rise and fall of sea level (see discussion in Ramsbottom 1973 and 1977, and George 1978). The same authors have demonstrated that strong developments of palaeokarst (often associated with palaeosols) mark emergent phases of the cyclic successions. Somerville (1979b) has suggested that, as the palaeokarsts/palaeosols are so persistent, they may shortly assume as great an importance in regional stratigraphic synthesis as faunal evidence, which, being largely facies controlled, can be notoriously unreliable.

It seems probable that detailed remapping of the Anglesey Viséan will eventually reveal that the major palaeokarst developments in the succession (as described herein), and, possibly other lesser developments, are the homologues of some of the palaeokarsts described elsewhere in the Central Province; i.e. they are not simply local manifestations of phases of coastal shallowing, but variants on the now widely recognised stratigraphic breaks in the Central Province successions (Power and Somerville 1976). However, it should be remembered that, overall, the Anglesey sequence represents a more marginal facies than is preserved elsewhere in the Central Province (George 1974, p.114). Moreover, there is considerable evidence, documented in Greenly (1919, p.612 et seq), of much contemporaneous structural deformation of the Shelf and its sedimentary cover in Anglesey (intraformational faulting, angular unconformity, slide breccias etc); this indicates that local tectonism could well have had as important an effect on the development of the Anglesey palaeokarsts as any wider control, such as an eustatic rise and fall of sea level. Fig. 2 shows the approximate stratigraphic positions of the piped sandstone palaeokarsts in the Anglesey successions. The correlations call for little comment: plainly, the Parc Trwyn-du horizon in the 'D_{2b}' zone could be the lateral equivalent of one or other of the Dwlban horizons, but it must be younger than any other in the Lligwy Bay - Berw Fault sequence. However, according to George (1974, fig. 21), though the section at Careg Onen represents much the same stratigraphic sequence as that between Lligwy and Berw, no piped sandstone has yet been reported there.

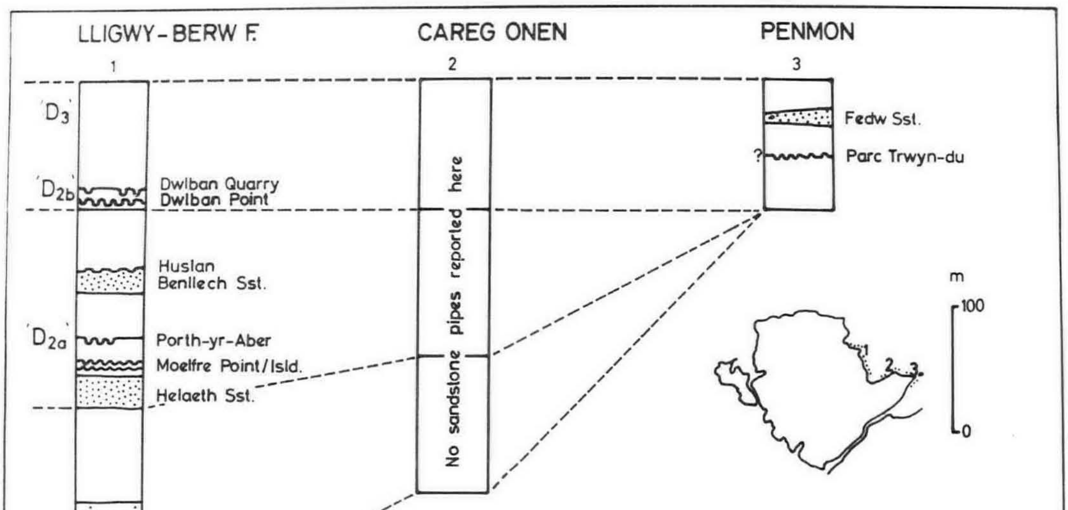

FIG 2 COMPARATIVE SECTIONS OF THE CARBONIFEROUS LIMESTONE OF THE EAST COAST OF ANGLESEY SHOWING THE STRATIGRAPHICAL RELATIONSHIPS OF THE PIPED SANDSTONE HORIZONS
(Freely adapted from George 1974)

FIELD DETAILS

Field Surveys

Piped sandstone horizons in the Carboniferous Limestone of Anglesey are now known from seven localities: i) Dwlban Point (Trwyn Dwlban) (SH 532819) ii) Dwlban Quarry (532817) iii) Moelfre Point (516869) iv) Ynys Moelfre (Moelfre Island) (519868) v) Porth-yr-Aber (515858) vi) Huslan (522834) and vii) Parc Trwyn-du (637814). The last named is the only one not

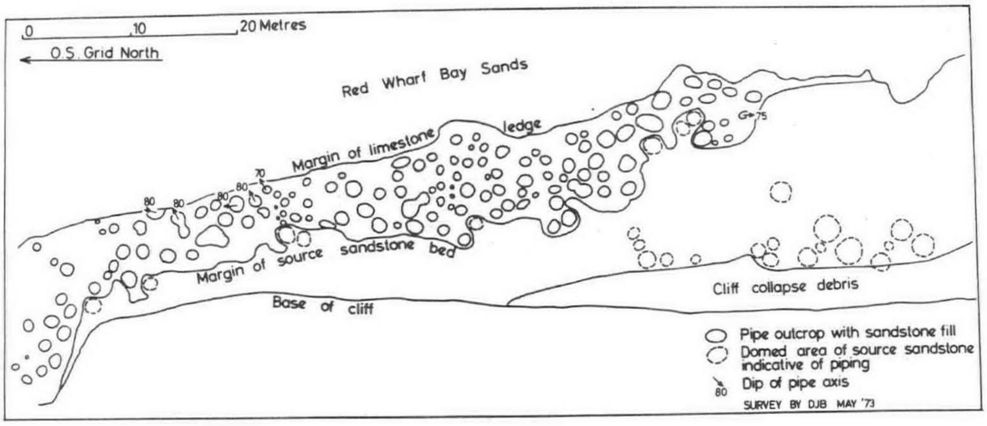

Fig. 3. Map to show the locations of sandstone pipes on the Dwlban Point ledge.

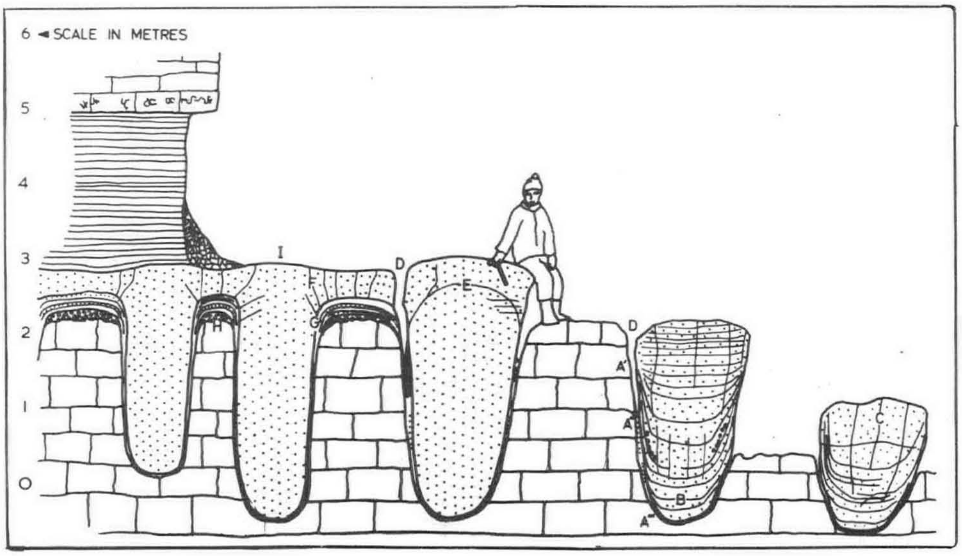

Fig. 4. Section to show the main structural and stratigraphic features of the pipes of the Dwlban Point Horizon (for explanation, see text).

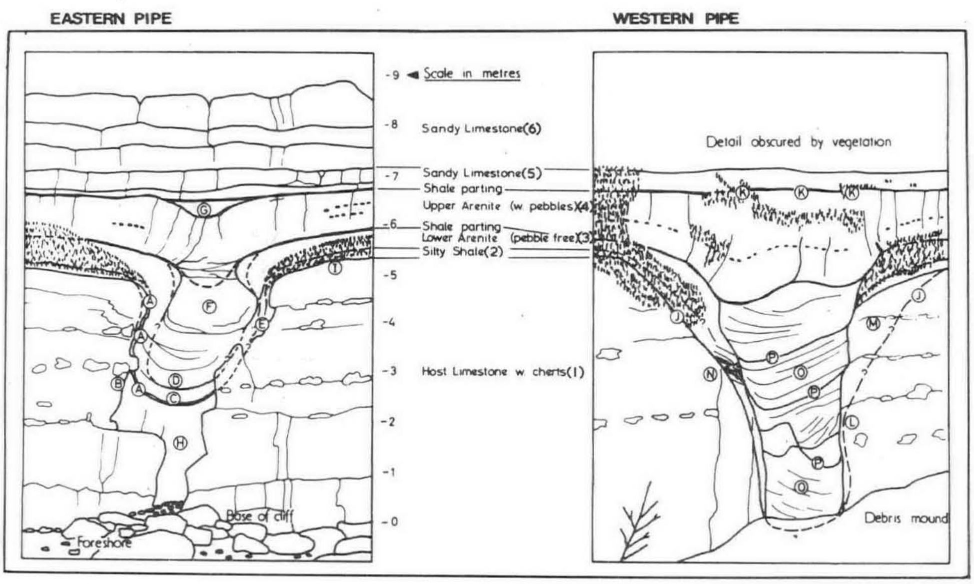

Fig. 5. Section to show the main features of the eastern and western pipes of the Dwlban Quarry Horizon (for explanation see text).

described by Greenly (1919). At each locality, the dimensions of each pipe were measured, and at localities where large numbers of pipes were present, pipe loci were surveyed, using a simple base-line and triangulated offset technique. Apart from the common structural and lithological details noted above, there are distinct differences from horizon to horizon; no two are identical. Salient comparative details are given below.

Dwlban Point

The Dwlban Point palaeokarst is well exposed on a wide, gently-sloping rock ledge which dips into the sands at the north-western corner of Red Wharf Bay. On parts of the ledge which lie above the seaweed-strewn intertidal zone there is effectively 100% exposure over an area of 225 m^2. At least 154 pipes are present here, many of which are spectacularly exposed in profile at the edges of the ledge (fig. 3).

The form and stratigraphic relationships of typical pipes at Dwlban Point are depicted in fig. 4. The host-rock is a massive, pale grey, cherty calcarenite. The pipes are over 2.7m deep in some cases, while the average depth must be of the order of 2 m. The largest is about 2 m in diameter. The pipe walls and floors are invariably smooth and there is no trace of honey-combing (or any other obvious change) in the host rock adjacent to individual pipes.

The pipes are invariably cylindrical, and have circular outlines at all levels. The oldest layer involved in the piping is a thin, calcite-cemented quartz-pebble conglomerate, up to 6 cm thick, which adheres strongly to the upper surface of the host limestone (H). The quartz pebbles are markedly angular. The conglomerate appears to be rather patchy in its distribution, though it covers most of the ledge. It grades up into a silty shale which, on average, is about 30 cm thick where not involved in the pipe structures, but whose thickness attenuates where it acts as a lining to the pipes. The attenuation appears to correspond directly to the depth to which the layer has been stretched by the descending plug of sand above (A^1 = 9 cm; A^2 = 3 cm; A^3 = 2 cm). This feature, while obviously critically important in understanding the fill mechanism, was not commented upon by Greenly. The involution of the shale lining is often quite abrupt at the rim of the pipe (G).

The fill-sandstone of the pipes is a pale yellow quartz arenite with occasional strings of angular quartz pebbles, the clasts being up to 6 cm long. The sandstone forms a continuous layer and, on average, is about 30 cm thick where not involved in the piping. It is well-stratified and bedding surfaces are quasi-horizontal near the pipe axes (B). Near to the margins, however, the stratification is abruptly contorted to a layering subparallel with the walls, the surfaces there showing frequent traces of polishing and shearing. The upper bedding surface of the sandstone source rock is conspicuously domed, the apices of the domes being co-axial with the pipes (I). There is no sign of subsidence at the interface between the source sandstone and the overlying 2.2 m-thick pyritic shale. Of the post-subsidence effects noted at Dwlban Point, the most prominent are a well developed scale-like jointing across the top of some of the pipes, (E) (presumably due to the effects of differential compaction) and the radial jointing (F) which is common to all pipes at all locations (again, presumably, a lithification-induced structure).

Where the pipes have been attacked by marine erosion at the foreshore level, the shale linings have been easily eroded and there is usually a conspicuous annular hollow between host rock and sandstone plug (D). This shale has been carefully examined for both macrofossils and microfossils; unfortunately, it appears to be entirely unfossiliferous.

Dwlban Quarry

A number of pipes were once exposed in the old blockstone quarry to the rear of Dwlban cliffs. This horizon lies about 11 m above that at Dwlban Point. Only two (termed here the eastern and western pipes) are now exposed but both of these are spectacularly exposed in profile and their internal structure is clearly revealed. Fig. 5 presents the stratigraphic profiles of the two pipes. Access to the base of the eastern pipe is facilitated by a cave (H) opened up by wave erosion at high water mark. Whereas the eastern pipe is markedly bulbous, with a near-hemispherical floor, the western pipe is distinctly funnel-shaped (J & L). The host limestone is a cherty pale-grey calcarenite (1); chert growth postdated the piping and at (B) nodules have grown into the pipe lining. The junction with the silty shale (2) is quite sharp and there is no obvious evidence that the latter represents a solution residue. As in the case of the

Dwlban Point horizon, this shale lines the cavities and the envelope has evidently thinned commensurately with the depth of penetration; whereas it is 17 cm thick at the rim of the western pipe it is only 5 cm thick at its base. In the eastern pipe the shale is brecciated (A) and sheared (E). At (A) small irregular solution channels disposed subparallel with the bedding of the host limestone ramify into the walls of the pipe. In the western pipe the shale is much sheared and convoluted, apparently by downwards piercing of older fill sediments by younger ones (N). At (M) in the western pipe detached blocks of sandstone have become embedded in the distorted shale lining (detail hidden from front view).

The main part of the pipe fill is a complex arrangement of at least three and probably more arenite layers which are separated by prominent shale partings. Some, but not all, of the fill is derived from the layers which form the unpiped stratigraphic sequence. Layer 3 is non-pebbly whereas Layer 4 has prominent strings and lenses of quartz pebbles; this helps to relate the fill materials to the source layers. In the case of the eastern pipe the outermost "skin" of the "onion structure" is pebble-free and equates to Layer 3; the next innermost skin (D) is pebbly and either represents a subsided extension of Layer 4, or, more likely, it is considered, a pebbly sandstone which is absent from the unaffected profile (i.e. one stratigraphically intermediate between Layers 3 & 4). The sandstone masses at (D) and (F) in the eastern pipe and at (O) in the western pipe have no counterparts in the normal stratigraphic profile. In both pipes, the pebbly strings in Layer 4 and the shale parting at its base show only a small subsidence effect, and indicate that the descent of the bulk of the fill into the pipe was earlier than the deposition of that layer. A small lens of a third arenite (G) is preserved only in the axis of the eastern pipe and shows that a mild subsidence effect was still active locally before lithification of the Layer 4 Arenite. Certainly subsidence was complete by the time the next overlying layers were formed and the prominent shale parting (K) shows no downwards inflection. It is very difficult to summarise the general structure of the plugs of sandstone in the central parts of the two pipes. In the eastern pipe the sand masses are roughly meniscoid in form, but in the western the sand bodies are separated by several major shale partings (P) across which there are marked fluctuations of dip, both in terms of inclination and direction. This indicates that, while piping was operative, there was a repeated accumulation of widespread layers of sand, each many decimetres thick, which, penecontemporaneously, were removed by erosion, except for the small plugs which descended into the growing cavities. There can be no doubt that sedimentation, erosion and cavity development were closely interrelated processes here.

The fill bodies evidently descended as masses of unlithified wet sand and clay partings between these bodies show much evidence of slickensiding and polishing.

Apart from the common annelid burrows already noted in the sandstone, no new evidence of organic activity was found in any of the layers affected by the piping except for the presence in the shale lining of numerous small calcite rods (?brachiopod spines) and, in one instance, a small fragment of a double-ribbed bivalve shell. However, no microfossils were present in samples taken from this layer.

Down the dip, close to where the source rocks disappear beneath the sands of Red Wharf Bay, cratering effects in the sandstone source rocks and thickening of the upper Arenite indicate that several more pipes occur at this horizon. However, erosion of these is not sufficiently far advanced to be able to observe the internal form. At least seven are present, some only a little distance behind the cliff face, so we see only the outer edge of the crater, whereas others have been removed from foreshore exposures by recent marine erosion.

Moelfre Point

The Moelfre Point palaeokarst horizon is well exposed on a wide, near-horizontal rock ledge, just above normal high tide level (fig. 6); 168 pipes have been located there, most of which are visible only in plan. More often than not, the sandstone fill has been removed by modern marine erosion, leaving only the funnel-shaped cavities, which are typical of this horizon.

In contrast to the pipes at Dwlban, those at Moelfre are appreciably smaller and often much less circular in plan. As depicted on Fig. 6, many of the Moelfre pipes are quite angular, sometimes reflecting the coalescence of a number of adjacent pipes during their lateral enlargement.

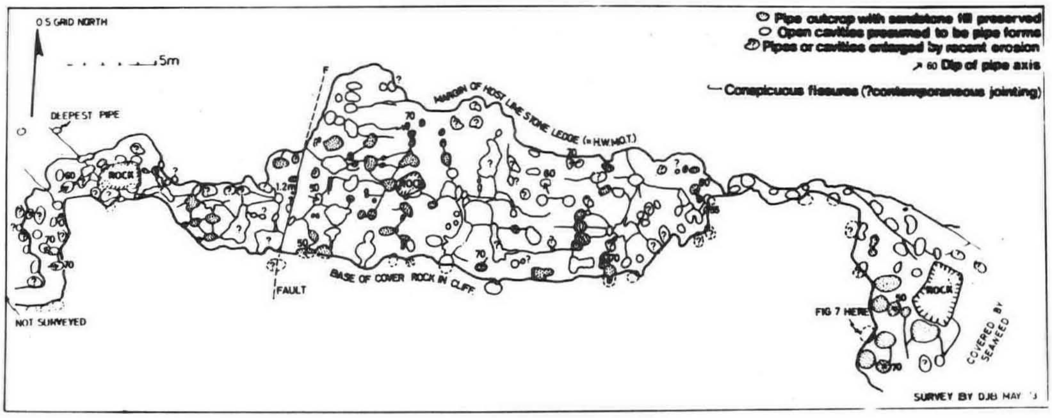

Fig. 6. Map to show the locations of sandstone pipes on the Moelfre Point ledge.

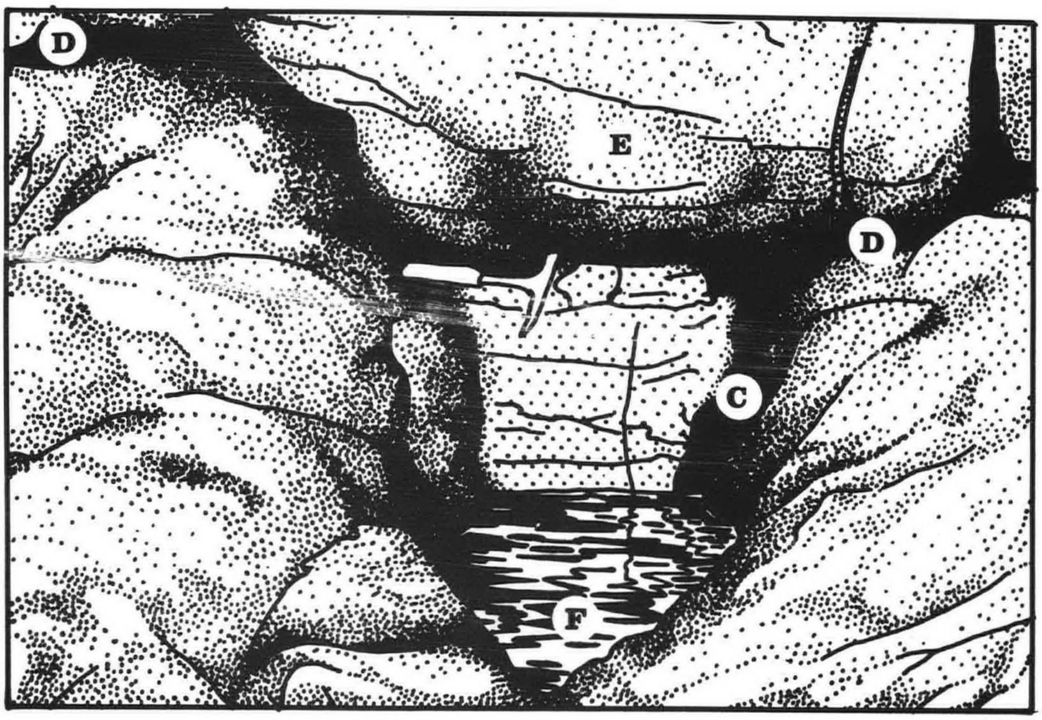

Fig. 7. Sketch to show the relationships of host-rock, pipes and cover-rock at the Moelfre Point Horizon (for explanation, see text).

Pipe axes are usually normal to the bedding but can be inclined at up to 30° from this in exceptional cases. Where a sandstone plug has been preserved, an annular hollow has been eroded out between the plug and the host limestone. The lining material is however, rather more silty than is typical of the Dwlban pipes; it often shows distinct concentric laminations which appear to be shears produced by subsidence. The maximum depth of piping is of the order of 2.2m.

An attempt is made in fig. 6 to record some of the more conspicuous fissures which ramify across the rock ledge between the pipes. The fissure network differs from that present in the cover rock and it seems to be too irregular to represent a tectonically-induced joint system. In view of the presence of an undoubted syngenetic joint system associated with the Huslan pipes (see below), it seems likely that the Moelfre Point fissures are, likewise, a lithification-induced set produced prior to and/or during the piping process; however, in no instance was any fissure observed to contain a sandstone fill. The interpretation of the age of the Moelfre Point fissures is complicated by their obvious enlargement by modern marine erosion; they are no longer seen in their original condition.

Fig. 7 shows a sketch of one of the pipes in the Moelfre Point horizon where it is overlain by the cover rock. The host limestone is a massive brownish-grey calcarenite which is sharply truncated by an intraformational erosion surface (D) from the cover rock limestone (E). During the intraformational erosion period the hollows occupied by the sandstone fill of the pipes were evidently deeply scoured and the cover rock sediments, on being deposited, first came to fill these depressions with festoons of crinoidal debris. The source sandstone, (if one ever formed here), was removed by the intraformational erosion without trace.

The pipe shown in fig. 7 displays the characteristic meniscoid bedding and radial jointing; its lithology is the usual fine-grained, yellowish-white quartz arenite, which is occasionally pebbly. Like most of the others, this pipe has been hollowed out along the shale lining (C) by modern marine erosion, which has also substantially removed the fill from an adjacent pipe (F), now filled with spray-water to form a small rock-pool.

Ynys Moelfre (Moelfre Island)

Owing to difficulties of access, the two Ynys Moelfre horizons, (the one about 3m above the other), have been examined only briefly. The pipes are similar in size and shape to those on the adjacent mainland at Moelfre Point, and it is possible that the upper horizon at Ynys Moelfre is the homologue of that at the Point. (That the lower horizon does not appear on the mainland is presumably due to faulting immediately west of the headland, which has eliminated its outcrop). Recent erosion has removed the sandstone fills in practically all cases. The mean diameter and depth of the Ynys Moelfre pipes are of the order of 30 cm and 40 cm respectively. The lower horizon is associated with a sandstone source rock.

Porth-yr-Aber

At least 35 pipes are present on a narrow sloping ledge in the foreshore/cliff section at Porth-yr-Aber. Vertical profiles through a dozen or so pipes are well displayed in the upper part of the ledge, but where it dips into the foreshore, it is seaweed strewn and details are difficult to discern. The pipes range from 0.6 to 3.0 m in diameter and their depth to more than 1.7 m. The walls are generally smooth. The ledge is not broad enough to discern if there is any pattern of piping, though, close to high tide mark, four pipes lie in a line in close proximity to each other. For the same reason, the density of piping cannot be determined, but the over-all development is very reminiscent of that at Dwlban Point, both in terms of the size of individual pipes and the density.

The pipe fills are contiguous with two sandstones in the "normal" succession. The host is a light-grey calcarenite, which is over 3.6m thick; this is separated from the lower arenite by a prominent shaley parting which averages 4 cm thickness. (Owing to its vulnerability to erosion, the latter is rarely seen in the cliff section; its outcrop is marked by a deep cleft). The lower sandstone averages about 22 cm in thickness; it is unlike most of the source rocks in the Anglesey succession in being a coarse gritty siltstone which shows much evidence of bioturbation. The lower and upper sandstones are separated by a mammillated surface which contains a very thin clay parting, about 1 - 2 cm thick. The upper sandstone is a typical ganister-like sandstone, and is about 16 cm thick where not involved in the piping process. The total thickness of the sandstones and shale partings in the "normal" sequence is thus about 44 cm. All four layers descend into the pipes, the lower parting acting as a lining in the usual way. Whereas, at least in theory, the lower parting (as at Dwlban) might have formed in part as a residue from the solution process which produced the piping, this cannot, of course be true for the upper parting.

Although some of the Porth-yr-Aber pipe population are very nearly cylindrical and have axes which are normal to the host-rock bedding, there is a wide variation in ovateness of plan (up to a maximum of about 5:3); also, many of the pipes are clearly not developed on C-axes normal to the bedding and there are a number of cases where the pipes have wormed their way downwards during growth in a corkscrew fashion. The relationships are complex: some pipes are nearly cylindrical but are developed on inclined C-axes, whereas other pipes are markedly ovate in plan,but have normal C-axes. Where the pipes are markedly ovate (seldom is this more than 4:3), the A-axes trend within a few degrees of N-S, and all lie within the NW-SE to NNE-SSW sector. There is no evidence that the host rock was fissured at the time of piping. Many of the pipes are markedly bulbous, with sides appreciably steeper than the vertical.

The subsidence mechanisms were evidently equally complex: in some cases, the upper sandstone can be seen to descend sharply and deeply into the pipe cavity, and, in some of these, it can be seen to pierce the lower sandstone, which then forms only a discontinuous lining to the pipe. In other cases the pipe form which had already been established before the upper sandstone was deposited, was not reactivated, and the upper sandstone passes over it without deflection. Likewise there is evidence of a similar selective reactivation of the piping processes after the upper bedding surface of the upper sandstone had formed: in some cases this is cratered by later subsidence and the cover rocks fill the depression without themselves being affected by subsidence; in others, the upper bedding surface passes over the pipe without inflection. The cratering amounts to several decimetres in some cases. Thus, locally, subsidence was operative before the upper sandstone was lithified but was complete before the cover rock had formed (in this case a sandy limestone, bearing brachiopods). It is obvious that, as at Dwlban, deposition of the sandstone, their resorting by bottom currents and gravitational settling into the growing pipes were concomitant (or at least closely interactive) processes. As at Dwlban, it is reasonable to conclude that a great deal of sand in the pipes (mostly of the nature of the lower rather than the upper sandstone) does not have any stratigraphical counterpart in the "normal" succession i.e. the clay partings, or the surfaces bounding them, represent significant non-sequences. Indeed, in some pipes, one can observe that lenticular bodies of sandstone wedge out against the lower surface of the upper arenite in the margins of the pipes. Of critical importance to the interpretation of the palaeoenvironment in which the pipes formed is the statement by Greenly (1919, p.614) that the sands found in the Porth-yr-Aber pipes contain ... "a few" .. brachiopods (which would, of course, identify them as marine layers). This evidence is completely contrary to most modern opinion about the arenites, which holds that the sandstones are freshwater in origin. A search was made for marine fossils in the Porth-yr-Aber sandstones but none was forthcoming.

Huslan

In terms of depth/diameter ratio, the Huslan pipes are the shallowest of the entire series and are better described as dish- or bowl-shaped rather than cylindrical. In diameter they range from 0.4 to 1.3 m; the maximum observed depth was 60 cm, though most are much shallower. Practically every hollow contains a fill of hard white fine-grained silty sandstone. This is nowhere more than a few centimetres thick and it is clear that the hollows were not filled completely at the time of the marine transgression which deposited the cover rock of marine shale, the latter about 70 cm thick. At the edge of the rock platform which exposes the Huslan pipes the cover rock is seen to pinch and swell over a highly mammillated surface. The sandstone is fused to the limestone host and no shaley material intervenes as it does in all other cases. On a medium scale, the pipes are markedly circular in plan, but, on a small scale, the sandstone/host rock interface is a highly frilled and sutured contact. It is at Huslan that we have the clearest evidence that the host rock was deeply fissured by an intraformational joint system developed either before or during the piping episode. In numerous instances, the fissures (up to about 6 cm wide) contain bodies of sandstone fill which link adjacent pipes. Owing to the limitations of exposure the depth to which this fissuring was developed cannot be ascertained, but it was at least as deep as the piping (60 cm+). Clearly, as at Moelfre, the cover-rock/host-rock interface is an important intraformational erosion surface, which reflects an interval during which any source rock layer(s) which may have been deposited was removed.

Parc Trwyn-du

A remarkably extensive ledge of limestone which dips at 18° in a 040° direction, exposes over 20o pipes at Parc Trwyn-du, near Penmon Point. As at Moelfre and elsewhere, the pipes have mostly been hollowed out by recent erosion, but preserved sandstone plugs are not uncommon. There is no trace of any suprajacent source-sandstone layer and it is difficult to estimate how much of the upper part of the original pipe profile has been removed by intraformational erosion; the average depth of what remains below the erosion surface is about 80-100 cm. The most notable feature of the Parc Trwyn-du pipes is that the plan forms of the majority are distinctly ovate (the A:B axes averaging roughly 3:2), while the A-axes are, with very few exceptions, subparallel within the range of $164-184^{\circ}$ (fig. 8). This trend is not matched by any joint set developed in the host limestone. A-axis length is ca.90 cm (range 15 - 200); the mean B-axis length is 60 cm (range 10-80). The fill material is again a pebble-free fine sandstone and silty or shaly material again forms a lining. Unfortunately, there is no clear section to show the exact nature of the contact between a pipe and the next suprajacent layer, which is a 90 cm-thick marine shale. Unlike Moelfre and Huslan, the interface is quite flat.

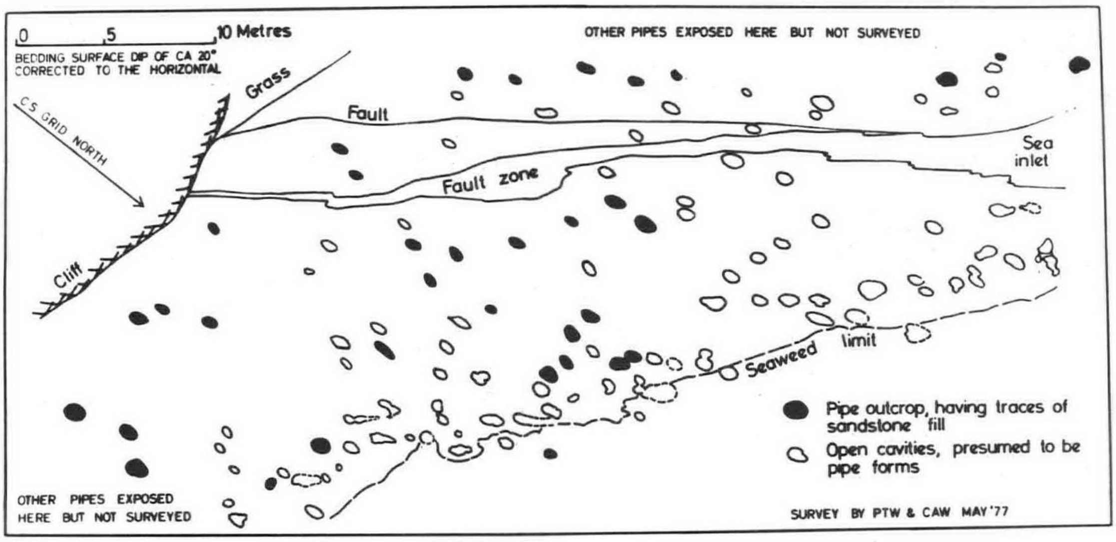

Fig. 8. Map to show the locations of sandstone pipes on the Parc Trwyn-du ledge.

PETROGRAPHICAL EVIDENCE

No systematic petrographical analysis of the fill rocks and host rocks has been attempted, this being beyond the scope of the present study. A number of thin sections of the fill and host rocks at Dwlban Point and Parc Trwyn-du have been made, however, the former being selected as typical of the whole series, the latter because of the unusual ovate form of the pipes there. It should be noted that, macroscopically, the fill rocks are practically identical from horizon to horizon; likewise the host rocks.

Both the Dwlban Point and the Parc Trwyn-du fill rocks appear to be very pure orthoquartzites, the quartz grains being predominantly silt size. The coarsest grains in the non-pebbly masses are about 2 mm in diameter, but only about 20% of the grains are of sand grade. The bulk of the cavity fills is therefore better described as sandy siltstone than sandstone. The fabric is a tighly-packed mosaic of intergrown quartz crystals. In the Parc Trwyn-du samples, less than 5% of the grains are non-quartzose; of these, felspars are the commonest. The Dwlban Point lithology is virtually 100% quartzose except for a few grains of an iron oxide. As revealed by occasional indistinct haematitic haloes, much secondary overgrowth of quartz in optical continuity has taken place. As far as can be determined, the original grain outlines appear to have been neither markedly angular nor markedly well-rounded. Cementing of these sandy siltstones was partly effected by the growth of inter-particulate films of haematite, which may locally form about 5% of the bulk of the rock. The well sorted, monomineralic nature of the fill sediment indicates that the material might well have been a beach sand (Pettijohn et al. 1972), but there is yet no supporting evidence of an organic or structural nature.

In the case of the Dwlban Point host limestone, samples taken from between 50 cm and 1 m below the upper surface reveal it to be a fine-grained biosparite. There has been much diagenetic alteration and the original grains, such as crinoid stems and bivalve shell fragments, are now revealed only as dusty inclusions in irregular sparry grains which vary in size mainly between 0.2 and 0.05 mm. The largest recognisable fragments still more or less representing the original grain size are the occasional slightly abraded Foraminifera up to 0.4 mm long. The allogenic bioclastic debris apparently contributed about 80% of the sediment, the remainder being a very fine-grained microspar which possibly represents something like the original pre-lithification fabric. No terrigenous detritus was noted. Some sections reveal occasional ooliths.

The Parc Trwyn-du host-rock has a broadly similar fabric though there is a notable ($>$15%) content of silt-size quartz grains. Samples taken at Parc Trwyn-du were carefully orientated, but a comparison of thin sections cut parallel with A & C axes and B & C axes revealed no significant differences in the present, and, by implication, the original fabric. Fragments which were spicular, discoidal or ovoid at the time of deposition do not seem to be markedly parallel with either A- or B-Axes. Thus, petrographical evidence adds very little at present to what can readily be deduced from field studies. Whether the recrystallisation/lithification processes were fully developed before piping began is not yet certain.

SPATIAL RELATIONSHIPS OF THE PIPE FORMS

It is possibly of interest to stratigraphers and karst geomorphologists to calculate just how much of the limestone host-rock has been removed at each of the palaeokarst horizons described here, and how each of the pipes is related to the others at any one horizon. This can be achieved with a reasonable accuracy at the Dwlban Point, Moelfre Point and Parc Trwyn-du horizons, but limitations of exposure make such analysis meaningless elsewhere. The basic statistics of the solution subsidence are as follows:

<u>Dwlban Point (fig. 3)</u>
Total area mapped: 450 m^2 (area piped at least 1000m^2)
Total number of pipe axes mapped: 154
% area piped: 20
% range of piped areas in any arbitrarily selected area of about 25 m^2: 10-40

Total volume of limestone removed: 270m^3
Solution factor: (Volume/area): 1m^3/1.7m^2

<u>Moelfre Point (fig. 6)</u>
Total area mapped: 281m^2
Number of pipe axes mapped: 168
% area piped: 10
% range in any arbitrary 25m^2 area: 5-30

Total volume of limestone removed: 20m^3 (possibly double this before intraformational erosion)
Solution factor: 1m^3/14m^2

<u>Parc Trwyn-du (fig. 8)</u>
Total area mapped: 630 m^2
Total number of pipe axes mapped: 120 (survey selective, only the central part of this outcrop was mapped)
% area piped: 5
% range in any arbitrary 25m^2 area: 0-15

Total volume of limestone removed: 16m^3 (possibly double this before intraformational erosion)
Solution factor: 1 m^3/39m^2

Thus the palaeokarst development at Dwlban Point can be shown to be of the order of eight times more voluminous than that at Moelfre Point and twenty times than at Parc Trwyn-du. The density of piping on the Dwlban Point ledge is such that one square kilometre of such a surface would contain about 300,000 pipes, representing the solution of 500,000 m^3 of limestone.

The authors have not been able to detect any trace of a distribution pattern for any part of the pipe population at any of the three localities; indeed the spatial position of any specific pipe seems to be totally random with regard to its neighbours and to the population as a whole. On the other hand, by any statistical yardstick, the population is evenly distributed across each of the three surfaces considered. Clearly, whatever solution process was responsible for their formation it was evenly effective, area for area, across them. Individual pipe loci, once established, were evidently maintained throughout the piping, and whereas, often, there is mutual interference of pipes which have enlarged laterally, individual pipe axes were not deflected by such interference; moreover, at any one horizon all pipes seem to have grown at roughly the same rate.

The circularity of plan for the pipes at Dwlban Point, as depicted on fig. 3, is not a cartographic convenience; horizontal profiles through the pipes at all levels show them to be remarkably circular. Except at Parc Trwyn-du, and to a lesser extent at Porth-yr-Aber, a circularity of form appears to be the general case and the chief source of an irregular plan is where adjacent pipes have coalesced. It is evident that, in most cases, the fabric of the host-rock and/or the processes which produced the pipes selectively promoted a circularity of form (i.e. this outcome was neither inevitable nor accidental).

The growth of some otherwise circular pipes at Moelfre and Porth-yr-Aber on axes which are inclined at angle of 20^{o} or more to the normal to the bedding of the host-rock is puzzling. This probably indicates that the long-term flow of solvents through the host-rock was itself other than normal to the bedding, rather than that there were selectively susceptible zones thus disposed owing to the chemical or physical nature of the host-rock fabric; however, there is no evidence to explain why it developed thus, nor why only in certain instances in these particular pipe populations.

It is interesting to note that the largest pipes of the Anglesey palaeokarst developments, those of the Dwlban Quarry horizon, are not apparently related to the most strongly developed karstic surfaces; indeed the Dwlban Quarry pipes are striking in their isolation. The eastern and western pipes are about 55m apart and the eastern and beach level group of pipes a similar distance; in between there is little evidence of piping. Admittedly, the Dwlban Quarry horizon is little more than a two-dimensional cliff profile, but, by way of comparison, an arbitrarily drawn section through the Dwlban Point ledge would intersect at least 20 pipes in the same distance.

The two Ynys Moelfre palaeokarst horizons are interesting in respect that, whatever processes were responsible for their formation, the effects were locally repetitive within a mere few metres in the depositional sequence; there is certainly no trace of interconnection between them.

In the case of the markedly ovate pipes of the Parc Trwyn-du horizon (fig 8), there is a clear parallelism of the A-axes, but, elsewhere, neither in groups of adjacent pipes, nor in populations as a whole can any pattern of growth be discerned, whether linear, concentric, radial or other. It is perhaps paradoxical that, whereas the Parc Trwyn-du host-rock was unjointed at the time of piping, at Moelfre Point and Huslan the host-rock was fissured, but in neither case were markedly ovate pipes produced.

SUBSIDENCE MECHANISMS

It is readily demonstrable that the pipes of the seven palaeokarst horizons described here are not "potholes" in the sense that they were mechanically-formed cavities (compare Challinor and Bates 1973 p.163). Apart from the fact that no corrasion fragments have been preserved in the floors of the pipes, it is obvious that the argillaceous linings could not have been preserved under such conditions. The structural form of the shale linings shows that cavity development did not commence until its deposition was complete, i.e. at a time when the host limestone was protected from subaerial destruction, at least from corrasive action. On the other hand, where source sandstones have been preserved, the lack of cratering of the upper bedding surfaces of these layers indicates that the piping processes were complete by the cessation of deposition (or at least the resorting) of these layers. By extension, it is obvious that the host limestone was susceptible to solution only while the sandy sediments of the source rocks were being formed, or that solution took place penecontemporaneously in the interval before the cover rocks were formed. Cavity development therefore, must have taken place at least several decimetres below the local depositional surface. A subrosive origin for the pipes is indicated and the pipe systems may be regarded as small-scale covered-karst landscape forms. Presumably, the local water table was sufficiently close to have risen through the growing cavities while they were developing, possibly repeatedly.

The structure of the bedding traces within the sandstone fills, (quasi-horizontal axially, but subparallel with the walls marginally), suggests that the fill sediments moved downwards into the growing cavities as semi-coherent plastic bodies and in the absence of irregular slump structures it is reasonably certain that at no time could there have been open cavities in the host-rock, the roofs of which eventually collapsed to admit the plugs of sand. Evidently the mechanism was essentially a gentle gravitational settlement of the plastic fill bodies concomitant with space being made available by subrosion of the host-rock. The corrosion of the host-rock must have been virtually 100% effective at the pipe margins; so much is indicated by the invariably smooth walls and near perfect cylindrical shapes. However, as noted above, the descending plugs of sand at Dwlban Quarry and Porth-yr-Aber were sufficiently rigid to cause geopetal piercement structures, with slickensided shear surfaces at the contacts of the diapirs.

Having concluded that the seven horizons of the Anglesey Carboniferous Limestone described here show a broadly similar origin as covered karst forms, it now becomes necessary to consider the source and nature of the solvent in each case. As a general consideration, the corrosion process would obviously have been aided by the puncturing of the shale lining, though no punctures have so far been observed; moreover, it may be presumed that, the deeper the subsidence, the thinner the lining became and the more freely permeable it became. At the time of the initiation of the solution process(es), however, the clay-rich lining layer, 30 cm thick at Dwlban Point, must have acted as a barrier to the fast migration of groundwater. It is considered that the sandy fills were fairly freely permeable at the time of piping, being well-sorted silty sand. It is presumed that the host rock calcarenites were also freely permeable.

With regard to the direction of movement of the solvent, there are, of course, four theoretical possibilities:

1. flow was entirely downwards through both sandstone fill and shale lining (which may be presumed to be the simplest explanation).
2. flow was upwards through the pipes due to release of artesian water previously flowing through the host.
3. flow was entirely lateral through the host limestone, the descent of the pipes being due entirely to gravitational settling.
4. any two or all three of these flows acting in combination or alternation.

Unfortunately, in the case of the Anglesey piped sandstones, there is no evidence from any source which points to one or other of these proceses operating exclusively. Obviously, the simplest way to interpret the Anglesey palaeokarsts is to assume that they formed in much the same way as the pipe forms which have developed in, say, the Chalk outcrop of many areas of western Europe and which are open at the ground surface at the present day, (though this presupposes that chalk pipe phenomena are both well understood and non-controversial, which the authors do not accept). Most karst authorities believe that chalk pipes originate through solution of chalk by downward-percolating vadose groundwater of low pH, most of the subrosion taking place close to the interface with the overlying non- calcareous Cenozoic cover; the loci of solution subsidence are determined initially by irregularities on that interface or by areas of more frequent or more open jointing and with linings of insoluble clay and flint solution residues produced as an inevitable by-product. Meniscoid fills of the Cenozoic fill rocks then slump into the growing pipes under gravity. The activity is commonly thought to be typical of Chalk areas where the ground surface lies considerably above the water table and developments are favoured by a position at the edge of an overlying cover of low permeability rocks.

Such a model, borrowed from the Chalk areas of, say, SE England broadly fits the observed details of the Anglesey palaeokarst, but there are features about the latter which indicate that the model cannot be accepted unreservedly. Firstly, it would require a considerable elevation out of the Carboniferous shelf seas at a time when the structural details of the Anglesey pipes indicate that sedimentation and cavity development were closely linked processes. Secondly it does not explain why, as at the Dwlban Quarry horizon, individual pipes are so large and deep, but are otherwise isolated on a surface which shows no trace of karst development (why not many more smaller holes, much more closely spaced, as in chalk-areas?). Thirdly, it must be remembered that the 30 cm-thick shale lining (at Dwlban Point) must have had a considerable retarding, if not insulating effect on the solution process, at least in the early stages of pipe growth. This is not normally present in chalk pipes. Indeed, there are many significant differences in the structure of chalk pipes from Anglesey Carboniferous pipes (see, for instance, Prestwich 1855; Kirkaldy 1950; Bonte 1963; Thorez et al. 1971; Walsh et al. 1973).

The markedly ovate pipe forms at Parc Trwyn-du hint strongly at a lateral component of groundwater flow at this locality, though it is not apparently possible to prove this. By implication, the flow here had either a northwards or southwards or an alternating N-S direction.

From the foregoing discussion, the Authors feel that, in the almost total absence of model studies of such phenomena, the possibility that solution was produced by an upwards moving groundwater flow should not be dismissed out of hand. It should be remembered that there are many well documented instances of freshwater springs in shallow coastal environments, indicating artesian conditions in modern seas off the Italian, Yugoslavian, Persian, Vietnamese, Irish, Florida and Mexican coasts (Sweeting 1972, p.214). One might reasonably postulate a significant uplift of some nearby area of the Anglesey Carboniferous coast so as to produce a recharge zone (in an area which shows much evidence of tectonic activity in Visean times). Connate and meteoric groundwater might then travel down the hydraulic gradient toproduce corrosion in the coastal sandflat areas. There are two immediate objections to such an hypothesis: firstly, it is difficult to explain why the postulated artesian waters became aggressive to the host-rock only at the place where they are about to leave the karst regime. Secondly, if solvent action was taking place due to upwelling artesian flows through the pipes, it was not so rapid as to have destroyed the meniscoid fill structure of the growing pipes, which is present in almost all cases.

Whether the solvent flow was upwards, downwards or lateral, it is clear that the Anglesey Viséan pipes were formed in response to a highly unusual and probably very complex interplay of chemical and hydrological factors. Possibly a mischungskorrosion effect (the enhanced solvent aggression induced by the mixing of groundwater flows of differing bicarbonate saturation) (Bögli 1971) is partly responsible for these spectacular effects.

COMPARISON WITH PALAEOKARST FORMS ELSEWHERE

It was expected at the outset of this study that a knowledge of palaeokarst forms elsewhere might afford valuable clues regarding the origins of the piped sandstone palaeokarsts of Anglesey. But the authors do not possess first hand knowledge of similar forms and a literature search has not offered any firm evidence that homologues have ever been identified elsewhere. Indeed, the converse seems to be true; the literature review indicates, if anything, how diverse the physical features of palaeokarsts can be.

In this context, therefore, it is considered pointless to categorise a long list of the many different kinds of palaeokarst; only those whose age, geographical proximity or broadly similar form are included here. Comparisons are drawn, firstly, with other palaeokarsts of the Anglesey Carboniferous Limestone; secondly, with palaeokarsts described elsewhere in the Carboniferous Limestone of Central England and, thirdly, with any others which appear to have even a remote bearing on the problem of the origin of the Anglesey structures. The palaeokarst surface at Careg Ddafad, Lligwy Bay, near the base of the Carboniferous Limestone of Anglesey (Cope 1975) appears to be comparable in scale though not in form with the sandstone pipe palaeokarsts described in this paper. The fill sediments at Careg Ddafad were interpreted by Cope as littoral quartz-pebble conglomerates and the karst forms described as "neptunian dykes"; the latter follow master joints running vertically through the host limestone but also (as in the case of the eastern pipe at Dwlban Quarry) lateral offshoots are seen to penetrate along the bedding. Cope (p.21) was in no doubt that the diagenesis of the host-rock had already taken place by the time the karst processes were active ... "the limestones behaved in much the same way as they would do today"; he concluded that lithification must have taken place at shallow depth below the water/ sediment interface and must have reached completion in a relatively short time. Owing to incomplete exposure, the depth to which the host limestone was fissured is not known; indeed, the Careg Ddafad palaeokarst is only intermittently exposed at times of heavy beach scour at Lligwy Bay. The Careg Ddafad palaeokarst clearly denotes an open, rather than a covered karst development and it is not therefore strictly comparable with the piped sandstone horizons.

35 Km. to the east of Anglesey, the large quarries near Llanddulas, Clwyd, show numerous infilled solution channels in the porcellanous, pale-coloured limestones which lie roughly in the middle of the 420 m-thick West Clwyd Viséan succession (Institute of Geological Sciences, 1965, p.57). The channels appear to be infilled phreatic tubes and the structure of the silty or sandy fill sediment indicates that it was washed into cave systems and settled quasi-horizontally. As possibly in

Anglesey, the Llanddulas palaeokarst suggests the former presence of extensive freshwater subsurface flows, and, in turn, that there must have been significant marginal uplifts to produce the required hydraulic gradients. Beyond this they obviously have little in common.

Extensive palaeokarst surfaces have been widely recognised in the D_1 and D_2 subzones of the Carboniferous Limestone sequence of NE Wales and Derbyshire (Walkden 1974 and 1977; Power and Somerville 1976 and Somerville 1979a and 1979b). These consist of potholed or mammillated surfaces which often underlie thick beds of K-rich bentonite clay, the latter being regarded by all three authors as palaeosol developments derived from the weathering of volcanic ash. It is considered that the palaeokarst and palaeosol horizons were developed during long periods of emergence of the sedimentary pile out of the marine shelf. All three authors agree that the limestones bearing the karst surfaces must have been lithified very quickly, certainly prior to karst development. Walkden stated that the depth of cavity development is commonly up to 1m depth in Derbyshire and he quoted Geikie's (1897) observation of a clay filled cavity ... "several yards deep" in Great Rocks Dale, Derbyshire. Somerville recorded that in the Clwydian Range the pipes are of the order of 1.5m deep. Some of Walkden's photographs of typical funnel-shaped pits (1974, fig. 5) are remarkably like those of the Moelfre and Huslan horizon. Again, comparable with the Moelfre and Parc Trwyn-du horizons, some of the Derbyshire clay-fills are restricted to the lower and middle levels of the pipes, the host-rock and the cover-rock being otherwise in direct contact.

Walkden regarded the Derbyshire palaeokarsts as covered karst developments, and remarked on certain similarities with the marine aeolianites and buried palaeosols of the late Pleistocene of Bermuda (Land et al 1967; Bricker and MacKenzie 1970). By analogy with the modern solution rates measured on limestone pavements in areas such as Florida and the Yucatan (which Walkden considered to have much the same climate as had the Central Province Basin in Asbian and Brigantian times), the palaeokarst/palaeosol developments are considered to have taken between 30 and 100 thousand years to form.

A number of palaeokarst developments have been described in the Carboniferous Limestone of the South West Province, none of which appears to represent a covered karst, and so they are not strictly comparable with the Anglesey developments. At a number of localities along the North Crop of the South Wales Coalfield the junction between the uppermost member of the Carboniferous Limestone is corroded below the overlying Millstone Grit, in some cases to a depth of 3m, the cavities being filled with the basal Millstone Grit conglomerate and, less commonly, bodies of sandstone which appear to have no counterparts in the overlying succession (Owen and Jones 1961). In areas where the uppermost Viséan limestone is a D_1 oolite there is some controversy regarding the origins of the pipe forms. Robertson (1933) thought that the interface represented a major non-sequence and that the corrosive forms were a pre-Millstone Grit karst. Owen and Jones agreed that a pre-Millstone Grit karst had developed here, but pointed out that there is considerable evidence that the limestone host was not indurated at the time of the karst development, and that, in any case, it is not unusual for the conglomeratic fill to have a meniscoid structure in the pipes. They further noted that there is no strong development of any residual clay and therefore conclude that the time interval was short. They concluded that elsewhere along the North Crop, where an S_2 zone limestone forms the uppermost Carboniferous Limestone member, subrosion is due to an intra-Namurian subsurface solution which has accentuated an already corroded pre-Namurian surface which relates to earlier secondary dolomitization. None of their figures show anything comparable to the near cylindrical, smooth-sided forms of the Anglesey piped sandstone palaeokarsts. A similar irregular junction of the Carboniferous Limestone/Millstone Grit interface was described by Dixon (1909) from near Ifton, Gwent. In the same paper Dixon described pipes of dimensions and form similar to those of Anglesey at West Williamston, Dyfed. The piped horizon lies at the junction of limestones marking a break in sedimentation between the upper and lower *Syringothyris* zones. But the pipes here are stated to be older than the infilling, which lies in "... an undisturbed state" (Dixon 1909, p.515).

Bretz (1940 & 1950) has described several instances in the U.S.A. of solution subsidence beneath non-calcareous cover rocks in which cavernisation of the host limestone was concomitant with descent of the cover rock, the structures so produced often possessing a meniscoid form. In the case of the north-eastern Illinois palaeokarst, where freshwater Pennsylvanian shales infill subrosion hollows in a Silurian host-rock, several figured (1940, figs. 27 & 28) possess a size and form similar to those of the larger Anglesey pipes. Cavernisation here is reasoned to have been produced by artesian flow. But both in this case and the other, the so-called "filled sinks" of the Ozark Dome of Missouri, which involve Mississippian and Pennsylvanian fill sediments, the cavities have no regularity of size, form or fill characteristics. In both cases cavernisation is inferred to have taken place "at depth". In these respects neither situation seems to be closely comparable with the Anglesey palaeokarst.

A so-called syngenetic karst, with large scale karstic cavernisation associated with the freshwater lithification of South Australian coastal calcareous aeolianites of late-Pleistocene age has been described by Jennings (1968). The situation described is interesting in respect of the short time scale involved in the production of such a well developed karst but no non-calcareous rocks are reported to have been involved in the solution process. Similar coastal karst developments have been described by Swinnerton (1929) from Bermuda.

In terms of the size and shape of cavities and density of piping, perhaps the palaeokarst systems most closely comparable with those described here are those marking depositional breaks in the Pleistocene limestone sequence of South Florida (Perkins, in Enos and Perkins, 1977). Photographs published by Perkins show remarkable similarities of form (his fig. 19 to those of Moelfre Point and fig. 21 to the ovate pipes of Parc Trwyn-du). Perkins reasoned that the host-rock was fully lithified at the time of piping and that the source of the solvent was organic acid derived from associated soil covers (the latter occasionally preserved as infillings); there is no report, however, that quartz arenites are preserved in the Florida succession. The Florida palaeokarsts have been traced over hundreds of square kilometres. The mechanism of piping is not discussed, though a covered karst system is inferred.

CONCLUSIONS

In conclusion, the authors propose a reconciliation of existing data in the following way: they envisage that the pipe systems were formed in coastal sandflat (possibly intertidal, possibly deltaic) conditions which may have some similarities, in modern analogy, to the Persian Gulf or Bahama Banks areas. The sand flats were periodically emergent, setting up an hydraulic head which drained connate and meteoric waters into an underlying calcarenite host. There is ample evidence to indicate that the Anglesey area of the Central Province Basin of Viséan times was tectonically unstable, and intermittent earthquake activity probably vibrated the soft sand fills of the growing pipes causing pressure surges in the local ground water system. Subsidence may have been promoted in this way. At each horizon, subsidence was eventually terminated by a widespread marine advance, which led either to the deposition of covers of shale (as at Dwlban Point) or to further erosion of source rocks, sandfills and the upper surface of host limestones (as at Moelfre Point). As the influence of mobile groundwaters ceased, so, in turn, did cavernisation and subsidence. At Dwlban Point, the whole process lasted for only as long as it took for the deposition and resorting (following subsidence into the pipes) of a layer of sand, of average thickness about 50 cm.

Certainly, it is hard to think of a way of proving any geographical analogue at the present day. Since the cavity development in the Anglesey Viséan is considered to have been a subterranean effect without any surface expression, one would simply not be aware that a similar subsurface process was taking place in a modern shallow sea coastal environment. Presumably, the first place to look would be in areas such as the Persian Gulf, where an emergent coastal sandflat of quartz sand is known to overlie recently-lithified carbonates (see, for instance, Bathurst 1976 p. 371 et seq.)

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An earlier version of the manuscript of this paper was read to the Regional Meeting of the Engineering Group of the Geological Society of London at its conference at Cardiff, September 1977 (Walsh & Baughan 1978). Many of the helpful comments made at that meeting have been incorporated into the present manuscript. We are grateful to Drs. J. Soyer and M. Blaszak and Mrs. E. G. Niemcynow-Burchart for their comments in the field; to Drs. J. G. Capewell and T. D. Ford for helpful criticism of the manuscript; to Miss C. A. Walsh for assistance in the field and to Miss P. A. Scantlebury, Miss S. B. Jones and Mr. M. Ijtaba for laboratory assistance. Mrs. C. Dublin and Mrs. L. Gilroy have kindly typed the manuscript.

REFERENCES

Bathurst, R. G. 1976. *Carbonate sediments and their diagenesis.* Elsevier Scientific Publishing, Amsterdam.

Bögli, A. 1971. Corrosion by mixing of karst waters. *Trans. Cave Res. Grp. G.B.* vol. 13, pp. 109-114.

Bonte, A. 1963. Les remplissages karstiques. *Sedimentology,* 2, 333-340.

Bretz, J. H. 1940. Solution cavities in the Joliet Limestone of north eastern Illinois. *J. Geol.,* Vol. 48, pp.337-384.

Bretz, J. H. 1950. The origin of filled sink-structure and circle deposits of Missouri *Geol. Soc. Am. Bull,* Vol. 61, pp.789-834.

Bricker, O. P. and Mackenzie, F. T. 1970. Limestones and red soils of Bermuda. *Geol. Soc. Am. Bull.,* Vol. 81, pp.2523-2524.

Challinor, J. and Bates, D. E. B. 1973. *Geology explained in North Wales.* David and Charles, Newton Abbot.

Cope, F. W. 1975. The age of the Lower Carboniferous conglomerate at Lligwy Bay, Anglesey, *Geol. Jour.,* Vol. 10, pp.17-22.

Dixon, E. E. L. 1909. Limestone unconformities and their contemporaneous pipes and swallow holes. *Geol. Mag.,* vol. 6, pp.514-516.

Enos, P. & Perkins, R. D. 1977. *Quaternary sedimentation in South Florida.* Geol. Soc. Am. Memoir, No. 147.

Geikie, A. 1897. *Ancient Volcanoes of Great Britain* 2 Vols. (v.2 p8-22), London.

George, T. N. 1967. British Dinantian Stratigraphy. *Six. Cong. de Strat. Carb., 1,* 193-218.

George, T. N. 1974. *Lower Carboniferous rocks in Wales.* Chapter 5 (pp. 85-115) in *Upper Palaeozoic and post-Palaeozoic rocks of Wales.* (Editor T. R. Owen) University of Wales Press, Cardiff.

George, T. N. 1978. Eustasy and Tectonics: Sedimentary rhythms and stratigraphic evidence in British Dinantian correlation. *Proc. Yorks. Geol. Soc.,* Vol. 42, pp. 229-262.

Greenly, E. 1900. On sandstone pipes in the Carboniferous Limestone at Dwlban Point, East Anglesey. *Geol. Mag.,* Dec. 4, Vol. 7, pp.20-24.

Greenly, E. 1919. *Geology of Anglesey.* Mem. geol. Surv. Gt. Britain, 2 volumes.

Institute of Geological Sciences, 1965. Annual Report: Part 1 Summary of progress etc. (p.57).

Jennings, J. N. 1968. *Syngenetic karst in Australia: Contributions to the study of karst.* Res. School of Pacific stud. Dept. of Geog. Publication G/5 Canberra, pp.41-110.

Kirkaldy, J. F. 1950. Solution of the chalk in the Mimms Valley, Hertfordshire. *Proc. Geol. Assoc.,* Vol. 61, pp. 219-224.

Land L. S., Mackenzie, F. T. & Gould, S. J. 1967. Pleistocene history of Bermuda. *Geol. Soc. Am. Bull.,* Vol. 78, pp.993-1006.

Owen, T. R. & Jones, D. G. 1961. The nature of the Millstone Grit and Carboniferous Limestone junction of a part of the North Crop of the South Wales Coalfield. *Proc. Geol. Assoc.* Vol. 72, pp.239-250.

Pettijohn, F. J., Potter, P. E. & Siever, R. 1972. *Sands and Sandstones.* Springer Verlag, New York.

Power, G. & Somerville, I. D. 1976. A preliminary report on the occurrence of minor sedimentary cycles in the Middle White Limestone (D_1, Lower Carboniferous) of North Wales *Proc. Yorks. Geol. Soc.* Vol. 40, pp. 491-497.

Prestwich, J. 1855. On the origin of the sand and gravel pipes in the chalk of the London Tertiary district. *Quart. J. geol. Soc. London.* vol. 11, pp. 64-84.

Quinlan, J. F. 1972. *Karst-related mineral deposits and possible criteria for the recognition of paleokarsts: a review of preservable characteristics of Holocene and older karst terrains.* 24th International Geological Congress, Montreal. Section 6 Stratigraphy.

Ramsbottom, W. H. C. 1973. Transgression and regression in the Dinantian; a new synthesis of British Dinantian Stratigraphy *Proc. Yorks. Geol. Soc.,* Vol. 39, pp. 567-607.

Ramsbottom, W. H. C. 1977. Major cycles of transgression and regression (mesothems) in the Namurian. *Proc. Yorks. Geol. Soc.* Vol. 41, pp. 261-291.

Somerville, I. D. 1979a. Minor sedimentary cyclicity in the late Asbian (Upper D_1) limestones in the Llangollen district of North Wales. *Proc. Yorks. Geol. Soc.* Vol. 42, pp.317-341.

Somerville, I. D. 1979b. A cyclicity in the early Brigantian (D_2) limestones of the Clwydian range, North Wales, and its use in correlation. *Geol. Jour.* vol. 14, pp. 69-86.

Sweeting, M. M. 1972. *Karst landforms.* McMillan, London.

Swinnerton, A. C. 1929. The caves of Bermuda. *Geol. Mag.* Vol. 66, pp. 79-84.

Thorez, J., Bullock, P., Catt, J. A. & Weir, A. H. 1971. The petrography and origin of deposits filling solution pipes in the chalk near South Mimms, Hertfordshire. *Geol. Mag.,* Vol. 108, pp.413-423.

Walkden, G. M. 1974. Palaeokarstic surfaces in the Upper Viséan (Carboniferous Limestones of the Derbyshire block, England. *Jour. Sediment. Petr.*, Vol. 44, pp. 1232-1247.
Walkden, G. M. 1977. Volcanic and erosive events on an Upper Viséan Carbonate platform in North Derbyshire. *Proc. Yorks. Geol. Soc.*, Vol. 41, pp.347-366.
Walsh, P. T., Edler, G. A., Edwards, B. R., Urbani, D. M., Valentine, K., & Soyer, J. 1973. *Large-scale surveys of solution subsidence deposits in the Carboniferous and Cretaceous Limestones of Great Britain and Belgium and their contribution to an understanding of the mechanisms of Karstic subsidence.* Proceedings of the I.A.E.G. Conference 'Sink holes and subsidence', Hanover.
Walsh, P. T. & Baughen, D. J. 1978. Solution subsidence phenomena in the Carboniferous Limestone of Anglesey. (Abstract) *Quart. Jour. Eng. Geol.*, Vol. 11, pp. 329.

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Leif Engh - Solutional erosion formula

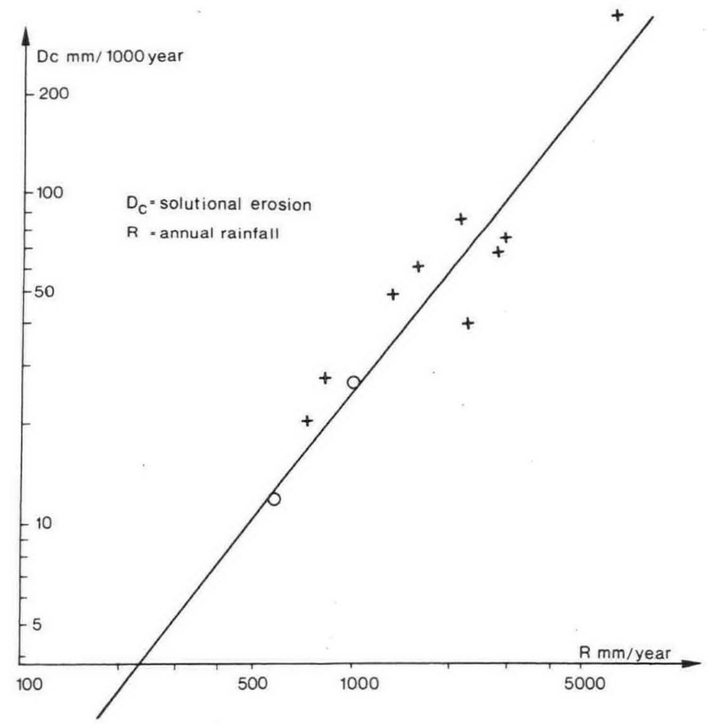

Fig. 1. The curve describes the equation $Dc=0.0043\ R^{1.26}$ which is supposed to be a linear relationship between karstic solutional erosion and annual rainfall.

Trans. British Cave Research Assoc., Vol. 7. No. 1 pp.30-32 March 1980

CAN WE DETERMINE SOLUTIONAL EROSION BY A SIMPLE FORMULA?

by LEIF ENGH

Abstract

A formula and a diagram describing the relationship between precipitation and solutional erosion, constructed by Sandor Lang are discussed. The formula is found to be incorrect for it will not give rise to the proposed curve. Two values from Sweden fit well into the curve.

At the 7th International Speleological Congress in Sheffield (1977), Sandor Lang from Hungary presented a paper concerning the "Relationship between world-wide karstic denudation and precipitation".

I found the article rather interesting, because if what Lang said is correct, then we do not have to bother any more about the time-consuming hydrochemical analyses for the purpose of calculating solutional erosion. By hydrochemical analyses I mean different ways to determine the total water hardness, e.g. by titration with Titriplex solution (manufactured by Merck, Germany) which today is the most used method in Sweden. Maybe a more up to date, and faster method, is the conductance method described by Allbutt (1977). The hydrochemical methods are time-consuming because they have to be carried out over a long period. Carbonate hardness has to be determined for different water discharges, including the maximum and the minimum flows of the year, and both water discharge and the temperature must be estimated at the same time. Markowicz and Glazek (1973) pointed out the importance of a long series of measurements and Helldén (1974 a) said that the measurements have to be carried out over at least a whole year. This must be done because the water hardness varies with the water discharge and the temperature. After the measurements have been carried out the average hardness can be calculated for different water discharges. Knowing the annual run-off and the distribution of the run-off during the year, the load of carbonates in the water can be calculated for the different run-off periods during the year and the total annual transport of carbonates in the stream can be estimated. In addition the catchment area, and the fraction of the catchment area which is occupied by limestone has to be known, as well as the bulk density of the limestone. Those values can then be put into the formula proposed by Corbell (1957) and modified by Helldén (1974b):

$$X = Tr\ (D\ A\ 10^{6})^{-1}$$

where X is the mean solutional erosion rate in mm/1000 years (= m^3/km^2 year), Tr is the total transport of carbonates during a year in grams/year, D is the bulk density of the limestone in g/cm^3 and A is the limestone area in the catchment area in km^2. From the obtained value of X the total carbonate transport from the non-limestone area in the catchment area must be subtracted as suggested by Smith and Atkinson (1976).

Thus the hydrochemical method is rather complicated and time consuming. And I am sorry to admit that most values of solutional erosion rates which are reported in the literature are not carried out with the accuracy described above.

In the paper presented by Lang there is a diagram illustrating the relationship between solutional erosion and the annual precipitation (fig. 1). The curve in the diagram was described by the formula:

$$Dc = 0.08R^{0.8}$$

where Dc is the rate of the solutional erosion and R is the annual precipitation. The data needed for the construction of the diagram were collected by Dr. Balazs from karst areas from all over the world. Some data collected by Lang himself were marked in the diagram (marked with a cross in figure 1).

After having checked the formula against the diagram, by taking two points on the curve and using their x and y values in the formula, I realized that the formula could not produce the curve in the diagram. I then chose two values of solutional erosion determined in Sweden and put them into the formula and the existing diagram as well. The two values I had at hand were obtained by Helldén (1974a and b), 27.9 mm/1000 year and 1009mm/year, and by Jasinski (1978), 13.5 mm/1000 year and 554 mm/year, both calculated by hydrochemical methods. The measurements were carried out with great accuracy during a period of at least one whole year. Therefore they must be considered to be reliable estimations of the corrosion intensity. The two values fitted extremely well into the curve constructed by Lang when plotted by using the diagram.

For this reason, I deduced that the empirically derived curve in Lang's diagram is more correct than the formula. The formula, which I suppose Lang has constructed from the diagram, is probably incorrect because of a slight mathematical error.

As there seems to be a relationship between the solutional erosion (y) and the annual precipitation (x) and this relationship seems to be best described by the function $y = ax^b$ all I had to do was to find the best values for a and b. This I did by taking two x and two y values from the existing diagram and put them into a standard computer program for the function $y = ax^b$. Those new values for a and b describe the existing curve better than the values given by Lang. The new mathematical description of the curve reads:

$$Dc = 0.0043R^{1.26}$$

This formula consequently describes the curve shown in figure 1.

Now the question is: was it a mere chance that the two Swedish values fitted so well into the curve, or is there a relationship between precipitation and the solutional erosion? The coefficient of correlation (r) for the two Swedish values and for the nine values given by Lang will be around 0.8, but of course those eleven values are far too few to be used as statistical evidence.

To assume, like Lang, that the formula applies to the whole world is perhaps to exaggerate. Other important factors, such as evapotranspiration, have to be taken into account, but eventually we might find the curve applicable in temperate areas. It is my hope that other karst researchers will put their values of solutional erosion into the same diagram to test the validity of this argument, but the values ought to be derived from measurements carried out with the accuracy described above.

REFERENCES

Allbutt, M. 1977. An appraisal of the conductance method for the in situ measurement of total hardness and agressivity. *Trans. Brit. Cave Res. Assoc.*, Vol. 4, no. 4, pp. 431-439.

Corbell, J. 1957. Les Karst du nord-ouest de l'Europe. *Mem. Inst. Etudes Rhodaniennes*, No. 12, 544 pp.

Helldén, U. 1974. a) *Karst*. Ph.D. Thesis. Dept. of Physical Geography, Lund University, 191 pp.

" 1974. b) Limestone solution intensity in a karst area in Lappland, northern Sweden. *Geogr. Annaler*, Vol. 55 A, pp. 185-196.

Jasinski, H. 1978. *Korrosionsberakningar fran tva karstomraden*. M.Sc. Thesis. Dept. of Physical Geography, Lund University, 46 pp.

Lang, S. 1977. Relationship between world-wide karstic denudation and precipitation. *Proc. 7th Intern. Speleol. Congr.* Sheffield, pp.282-283.

Markowicz-Lohinowcz, M. and Glazek, J. 1973. Remarks on the quantitative methods of karst denudation velocity estimation. *Proc. 6th Intern. Speleol. Congr.* Olomouc. Vol. 4, pp.225-230.

Smith, D. I. and Atkinson, T. C. 1976. *Process, landforms and climate in limestone regions*. In *Geomorphology and Climate*, ed. by E. Derbyshire. pp.367-410.

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MANCHESTER UNIVERSITY SPELEOLOGICAL SOCIETY EXPEDITION TO AUSTRIA

by S. H. Foster, K. C. Plumb and D. R. Hanson

Abstract

The 1979 Austrian Expedition organised by MUSS explored the extensive plateau area of the Steinernes Meer. Several new caves and potholes were discovered, but nothing deeper than 100m was found in spite of a depth potential of 1600m. Only a small portion of the total area was explored, but this was studied intensively.

INTRODUCTION

The original aims of the expedition were twofold:
1) to visit and explore the Wiesserloch, a 580 m deep pothole situated in the Nebelsbergkar region of the Leoganger Steinberge, a mountain range 50 km south of Salzburg (figs. 1 & 2).This pothole was partially explored by MUSS in 1978;
2) to search for new caves on the Steinernes Meer, a neighbouring mountain range.

The latter objective became the main aim of the expedition due to a misunderstanding between Salzburg Caving Club (Landesverein für Höhlenkunde in Salzburg) and ourselves. When an advanced party of three arrived in Salzburg they found that, although we had hoped for a joint expedition to the Wieserloch with a group of Polish cavers from Krakow, this would not be possible. However the advance party were able to make arrangements for the expedition to go straight to the Steinernes Meer.

On Sunday 19th August 1979 the remaining nine members of the group arrived in Austria. After a night's stop in Salzburg the expedition moved over to Weissbach to begin moving equipment onto the Steinernes Meer.

The members of the expedition were:- K. C. Plumb (Leader), S. H. Foster (Secretary), D. Hanson (Treasurer), P. D. Gelling, D. Howard, S. Lenartowicz, J. Pettitt, T. Pettitt, R. Riley, J. Stell, and P. Sweetman.

DIARY OF EVENTS

Tuesday, 14th August
Advanced party arrived in Salzburg.

Friday, 17th
Main party travelling to Austria.

Sunday, 19th
Main party arrive in Salzburg.

Monday, 20th
Two people walked up to the Ingolstadter for reconnaisance.
Rest of group sort out gear and establish camp at the Gasthof Lofheyer (in the Weissbach valley above the village of Weissbach).

Tuesday, 21st
Using the taxi at the Gasthof Lofheyer most of gear was moved up to the Deissbehstausee. Most of this equipment was then carried to the Ingolstadter hut cable car and thence up to the hut. Four people slept in the hut, the rest of the group camped by the stausee.

Wednesday, 22nd
Camp site by Rotwasserquelle established and all the gear moved to it.

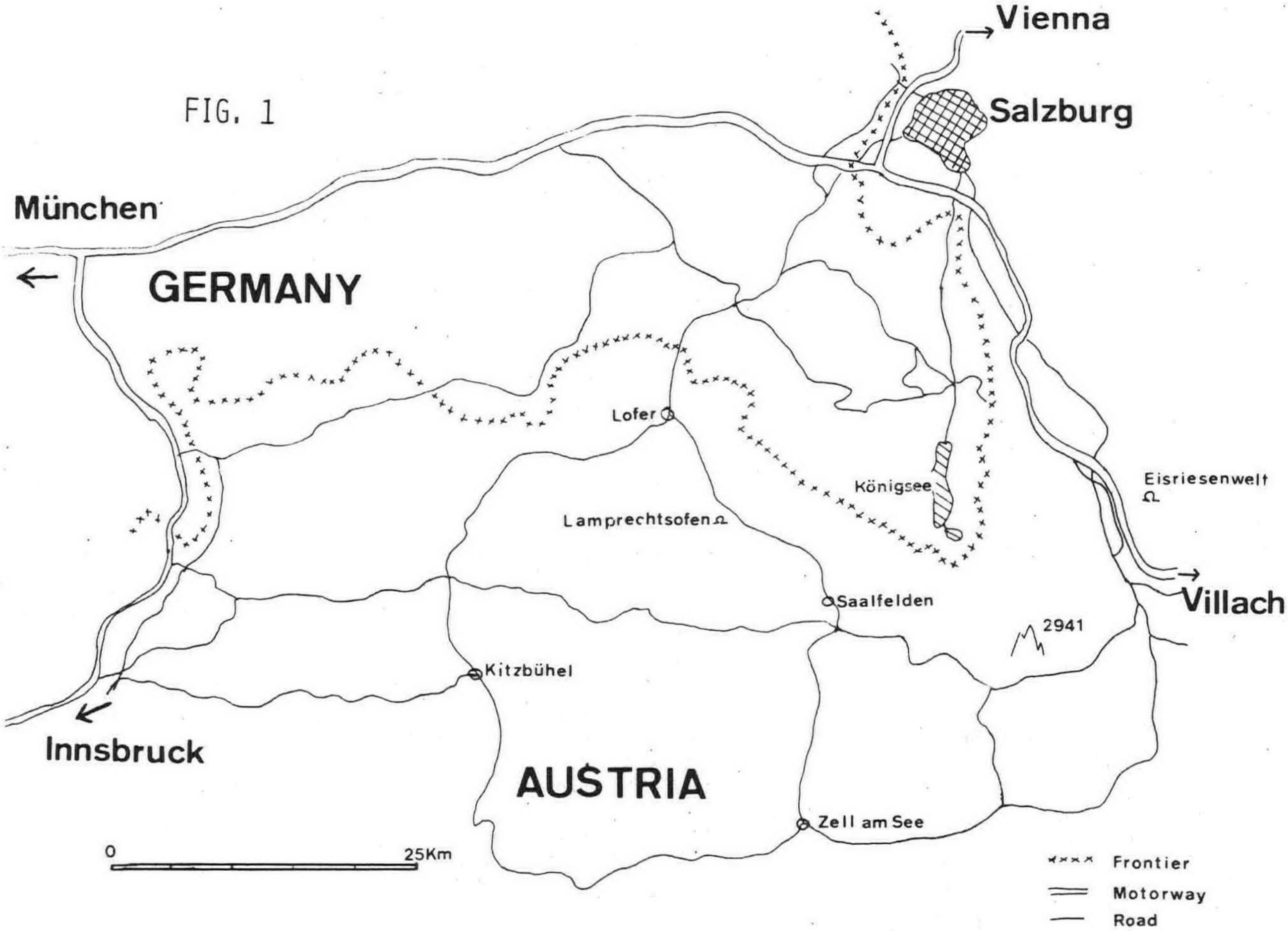
Thursday, 23rd
Told to move camp site as we were disturbing a group of marmots. Three groups went out prospecting, some new caves were found and a superb new camp site at Hochwiesalm. That evening half of the camping gear was moved to the new camp site.

Friday, 24th
Hochwiesalm camp established. Weather started to deteriorate rapidly and heavy snow fell during the night.

Saturday, 25th
All expedition members except for two retreat to the valley and go shopping in Lofer.

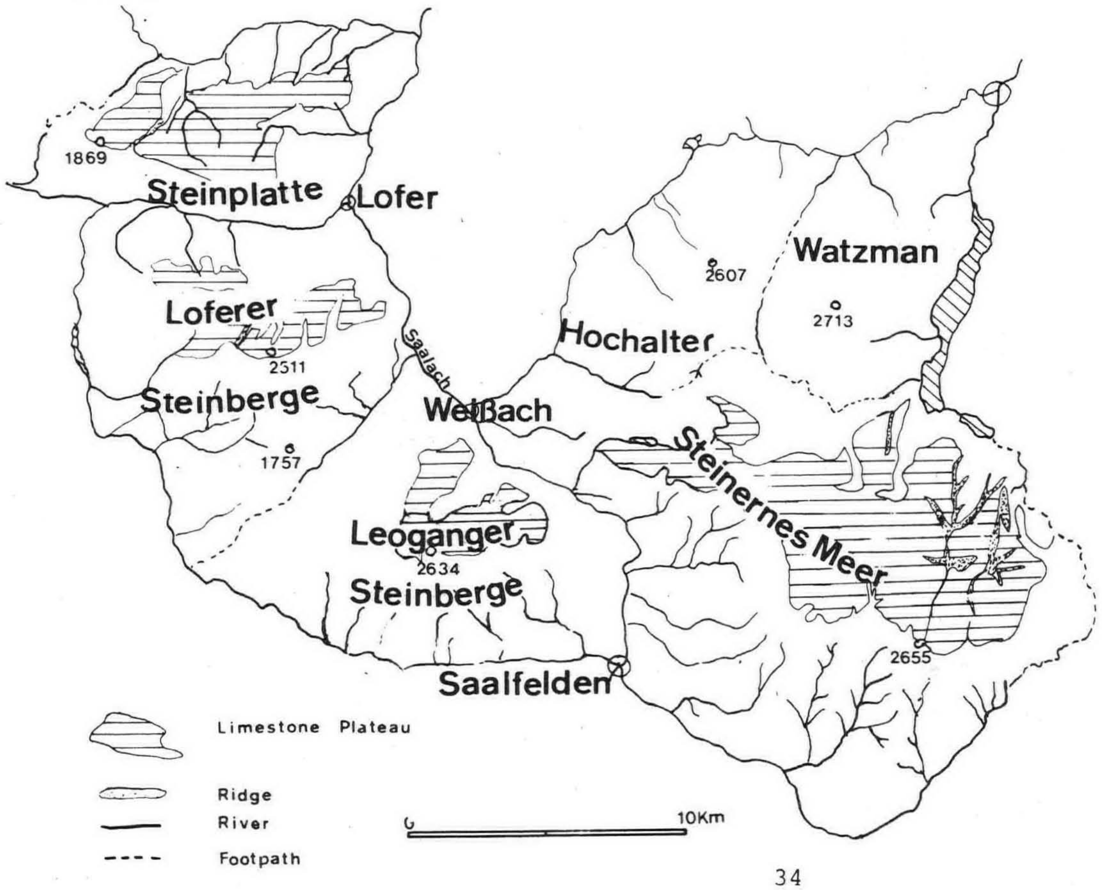
Sunday, 26th
Fine weather returns, expedition returned to the stausee using the taxi. Extra gear and food was carried to the camp site and some prospecting done on Seehorn.

FIG. 1



Vienna
Salzburg
München
GERMANY
Lofer
Königsee
Eisriesenwelt
Lamprechtsofen
Saalfelden
Villach
2941
Kitzbühel
Innsbruck
AUSTRIA
Zell am See
0
25Km
Frontier
Motorway
Road

FIG. 2



1869
Steinplatte
Lofer
Watzman
2607
2713
Loferer
Saalach
Hochalter
2511
Steinberge
Weißbach
1757
Steinernes Meer
Leoganger
2634
Steinberge
2655
Saalfelden
Limestone Plateau
Ridge
River
Footpath
0
10Km

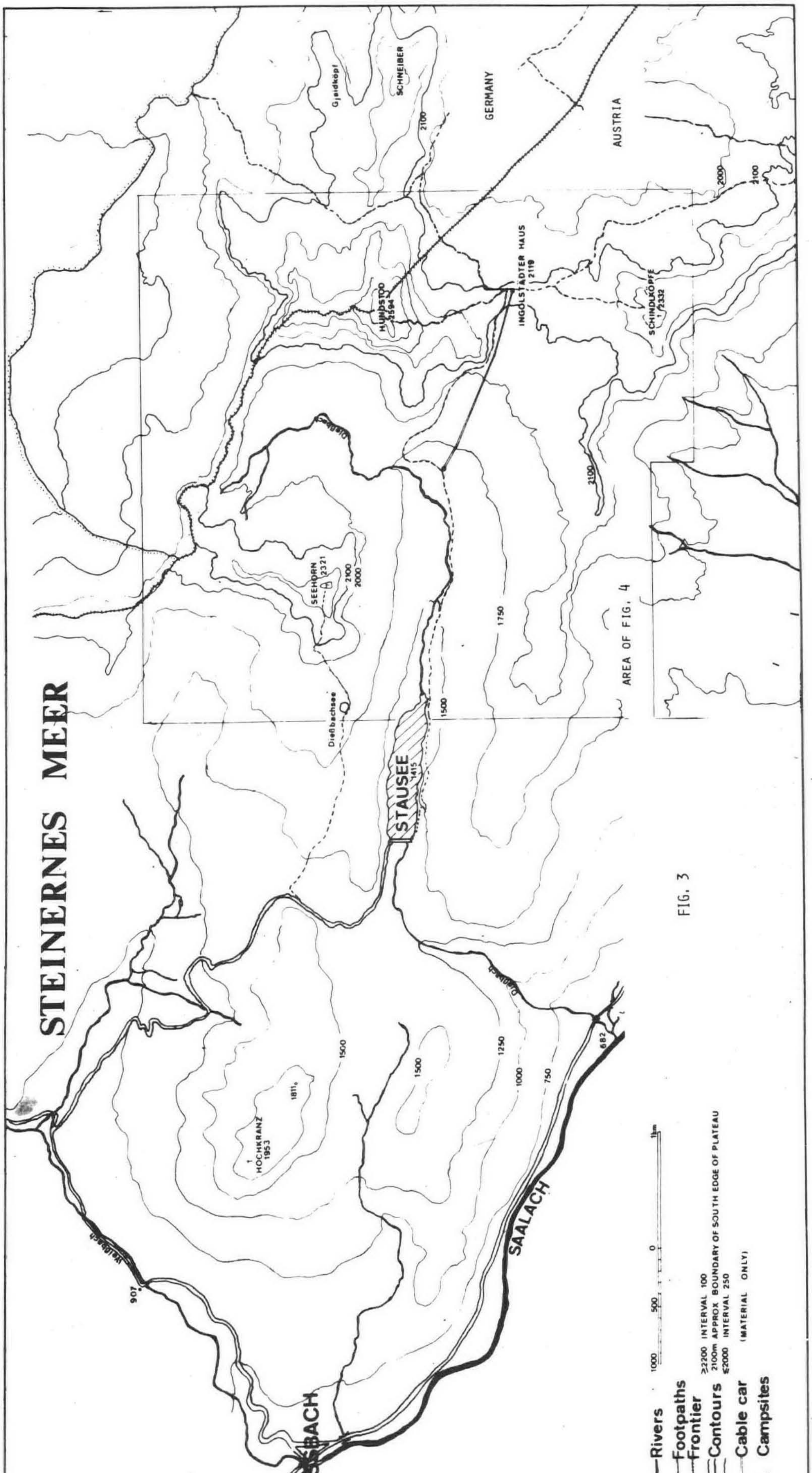

STEINERNES MEER
Gjaidkopf
SCHNEIBER
GERMANY
AUSTRIA
HUNDSTOD 2594
INGOLSTÄDTER HAUS 2119
SCHINDLKÖPFE 2332
SEEHORN 2321
2100
2000
Dießbachsee
STAUSEE 1415
1500
1750
AREA OF FIG. 4
HOCHKRANZ 1953
1811
1250
1000
750
682
907
WEISSBACH 665
SAALACH
Rivers
Footpaths
Frontier
Contours ≥2200 INTERVAL 100
2100m APPROX BOUNDARY OF SOUTH EDGE OF PLATEAU
≤2000 INTERVAL 250
Cable car (MATERIAL ONLY)
Campsites
1000 500 0 1km

FIG. 3

Monday 27th to Thursday 31st
Prospecting on Seehorn, Rossel and Kuhreitenschied, Hundstod East and South.

Friday, 1st September
Due to hunting we have to move camp site again.

Saturday, 2nd
Move all the gear to the Ingolstadter hut and look for new camp site. Meet the chief hunter for the Steinernes Meer and discover that it is illegal to camp anywhere on the mountain without a special permit. However, he arranged for us to stay in the winter room of the hut.

Sunday, 3rd
Move all the gear from temporary camp site to Winter room. Prospecting on Hunstod and Schindlköpfe .

Monday 4th to Thursday 7th
Exploration and surveying of many caves on Hundstod and Schindlkopfe. Thursday evening 6 people left leaving 5 members on the mountain.

Friday 8th
Surface surveying.

Saturday 9th
Very heavy carry to get all gear to stausee.

Sunday 10th
All gear transported to the valley using the taxi.

Monday 11th
Remaining members of expedition set out to visit other caving areas in Austria.

THE STEINERNES MEER

The position of this mountain range can be seen on figs. 1 & 2 whilst the 1:25000 map (fig. 3) covers the area in greater detail. We had consulted Walter Klappacher (L.V.H.K.Szb.) who suggested that we base our expedition at the Ingolstadter hut. The Salzburg cavers are in the process of publishing a series of books which describe all the known caves, the geology, hydrology, etc. of a particular area. Volume 2 of the Salzburger Höhlenbuch deals with all the areas marked on fig. 2 and was to form an important part of our prospecting, as it avoided duplicating work.

The Höhlenbuch gives the following boundaries to the Steinernes Meer: Weissbach-Kematenalm-footpath to Wimbachscharte-footpath through the Loferer Seilargraben past the Wimbachgries hut to the Hachelklause-Schrainbach-Königssee-Obersee-Fischunkelalm-Röthbach-footpath to Neuhüttenalm-Blühnbachtörl-Valley side over Hinteralm to the Blühnbach-Seichenbach-Bohlensteig-Torscharte-footpath to the Ursulabach-Saalfolden-Saalachtal-Weissbach. This gives the region an area of 209 km^2 of which approx. 62 km^2 can be described as an alpine karst plateau. In 1977, when the Höhlenbuch was published, nearly 200 caves were known of which only 4 could be described as having major development. The biggest system is the important resurgence cave, the Salzgrabenhöhle, near the Königsee. This system is over 7 km long and has a vertical range of -90 to +180 m, with the main plateau 1000m higher a vast depth potential exists. In fact the greatest depth potential from the plateau at ca.2100 m to resurgences along the Königssee is 1500m, and this was one of the reasons this area interested us.

The plateau is at a fairly constant level of 2100m $\pm$100m; however, several peaks rise to over 2500m, the highest being Selbhorn at 2655m. From this plateau the valleys to the north, east and south lie at the base of very steeply sloping terrain; only to the west, to the Weissbach, is the terrain less precipitous. Due to these steep valley sides, approaches to the main plateau are limited, the only easy routes being well marked footpaths, so most attempts at reaching the plateau not utilising these paths would be extremely serious. Although we did not realise it at the time camping is forbidden almost everywhere on the mountains; due to this most earlier exploration had occurred within a maximum of a couple of hours walk from any one of the several mountain huts.

Above 1800m vegetation is extremely sparse, as is water, our three camp sites utilised 3 of the 4 places where camping was possible and only at two of these sites was water easily accessible. In the area we looked at to the south-west of the Ingolstadter hut only one source of water was found and this only flowed after rain had fallen.

There can be little doubt that the Steinernes Meer has tremendous speleological potential but, although finding new caves is extremely simple, as the lapiaz is riddled with shafts, many hours must be spent looking at small uninspiring caves for every reasonable new discovery. Combined with the difficulties of crossing this inhospitable terrain, exploration involves a lot of hard work interspersed with moments of excitement.

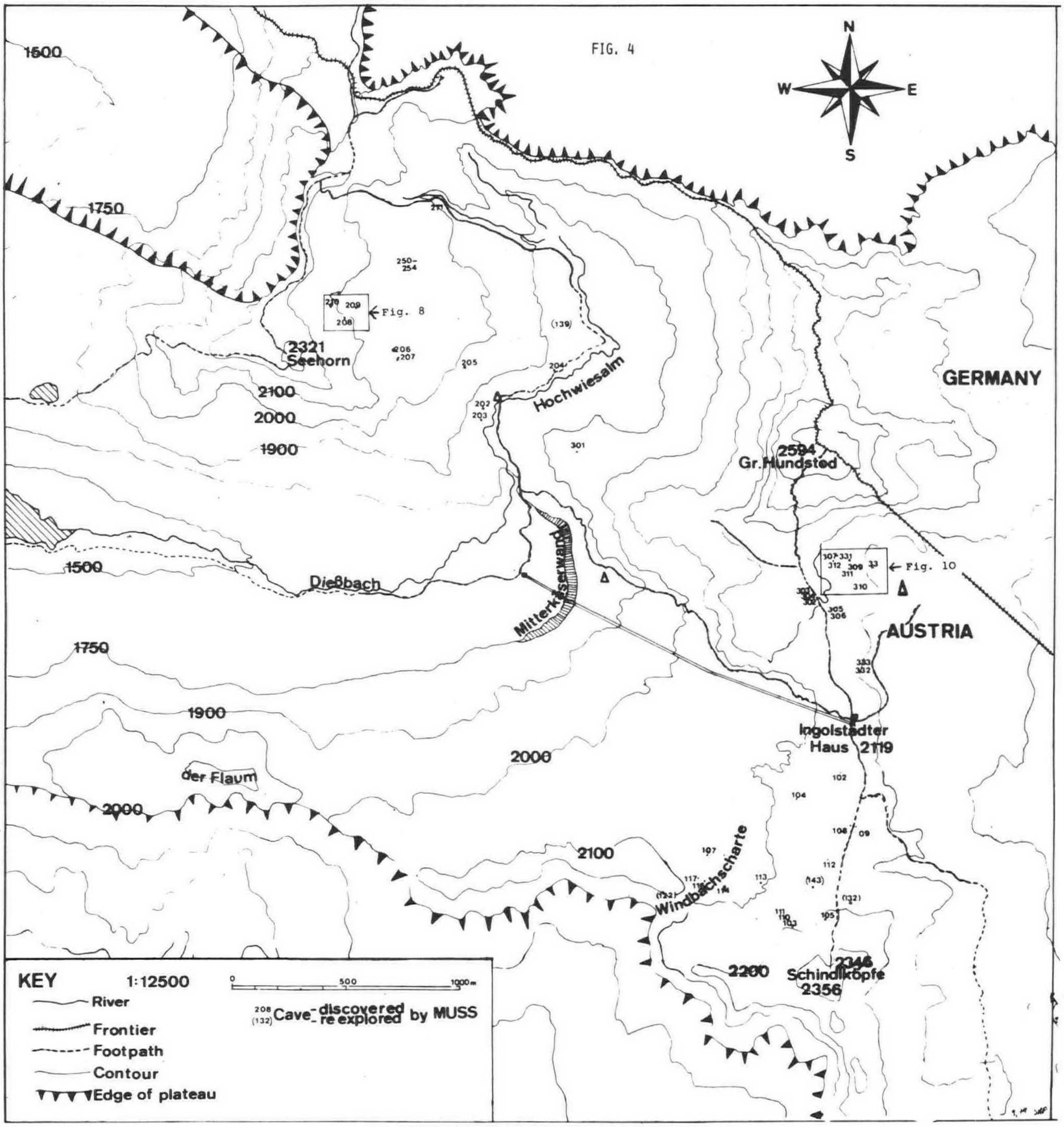


FIG. 4
N
W
E
S
1500
1750
2321
Seehorn
2100
2000
1900
1500
Dießbach
1750
1900
2000
der Flaum
2000
2100
Windbachscharte
Hochwiesalm
Mitterkaserwand
2594
Gr. Hundsted
GERMANY
AUSTRIA
Ingolstädter
Haus 2119
2200
2346
Schindlköpfe
2356
← Fig. 8
← Fig. 10
KEY 1:12500
0 500 1000m
River
Frontier
Footpath
Contour
Edge of plateau
208 (132) Cave - discovered - re explored by MUSS

SYSTEM FOR IDENTIFYING NEW CAVES

For the purposes of documentation the Austrians have split up the various mountain areas into smaller groups, e.g. Leoganger Steinberge, Steinernes Meer, etc., with defined boundaries and a "Kataster" number. The kataster archives provide a central reference for all discovered caves. The Steinernes Meer has been given the number 1331 and all speleological sites are numbered 1331/ followed by a number. All these sites are marked on the 1:25000 Map (fig. 4). As we were unsure as to how many sites were known, our identification was to number the site M followed by a three digit number. The first digit defining the area as follows:

M1 - Schindlköpfe: M2 - Seehorn: M3 - Hundstod.

All groups going prospecting took note books with them and recorded details of any hole where more than a cursory inspection was required to decide its extent. Also all entrances obvious from a distance were investigated where possible.

SCHINDLKÖPFE AREA

The boundaries of this area were arbitrarily defined as follows:
- to the west the Mitterkäserwand, a 100m cliff face,
- to the north, the Stausee-Ingolstadter hut footpath,
- to the south, the edge of the plateau at c.2100m,
- to the east, the Ingolstadter hut-Schindelköpfe footpath.

The lapiaz slopes gently but continuously to the Mitterkäserwand. At its eastern extreme two hills rise above the general plateau level, Schindlköpfe and, nearer the hut, an un-named hill covered with dozens of cairns. The most noted karst feature of this area was the enormous closed depression of Schindlköpfgruben, presumed to be a polje. Only one site of any note was discovered in the depression, M107, nearly all the cave development occurring on the rim, on the flanks of Schindlköpfe and the un-named hill and on the valley sides on the edge of the plateau. This area which was only looked at in the final week, after we had moved into the hut, proved to be the most interesting. Several sites with a strong draught issuing from very narrow rifts had to be left as we didn't have any chemical persuasive with us.

Description of caves.

M101/1331-143. 2160m altitude. *Steinweiberlschacht.*
100m north of Schindlköpfe west of the footpath. 50m surface shaft (3 bolts) to a boulder-covered floor. From the base of the shaft two ways on were possible up a slope of loose boulders or down through the scree. A slight draught was noted but not strong enough to warrant further work.
The Höhlenbuch was consulted on the return of the explorers and it was found that the Salzburg cavers had explored this cave in February '75.

M102, 2150 m altitude
35m S.W. of top of cairned hill near Ingolstadter hut. The entrance is at the bottom of a chimney. A climb down and around several blocks leads down through boulders to the first pitch. This pitch, of 20 m, drops into a chamber with large blocks. The second pitch (undescended) is between the blocks in the middle of the chamber.

M103, 2180 m altitude
On the West face of Schindlköpfe at the bottom of a large snowfield. A slope over ice leads to a passage 1m high with a small hole to surface. The continuation of the passage leads to a crawl over a pool which was not pushed.

M104, 2140 m altitude
Horizontal opening, 1m high, 5m wide, in small valley leading down from cairned hill to the Schindlköpfe polje. Horizontal passage for 10m leads to an aven to the surface and several short low crawls, all blind.

M105, 2180 m altitude
On the west face of Schindlköpfe, 35m and 220° from M106, and approximately 150m below the summit (Fig. 5). A 51m deep clean washed shaft, with 2 bolts at -26m and -34m, lands on a boulder floor with a snow pile. A large rift 1-2m wide leads off after an initial climb down boulders on the east side of the shaft. A boulder slope leads from here to the 6m second pitch. The rift continues to another 6m pitch onto boulders and then to a 10m pitch which drops into a chamber. Two ways on are possible, either by following the obvious boulder floor 4m down the pitch, then traversing forward to a 10m pitch or continuing down the pitch into a

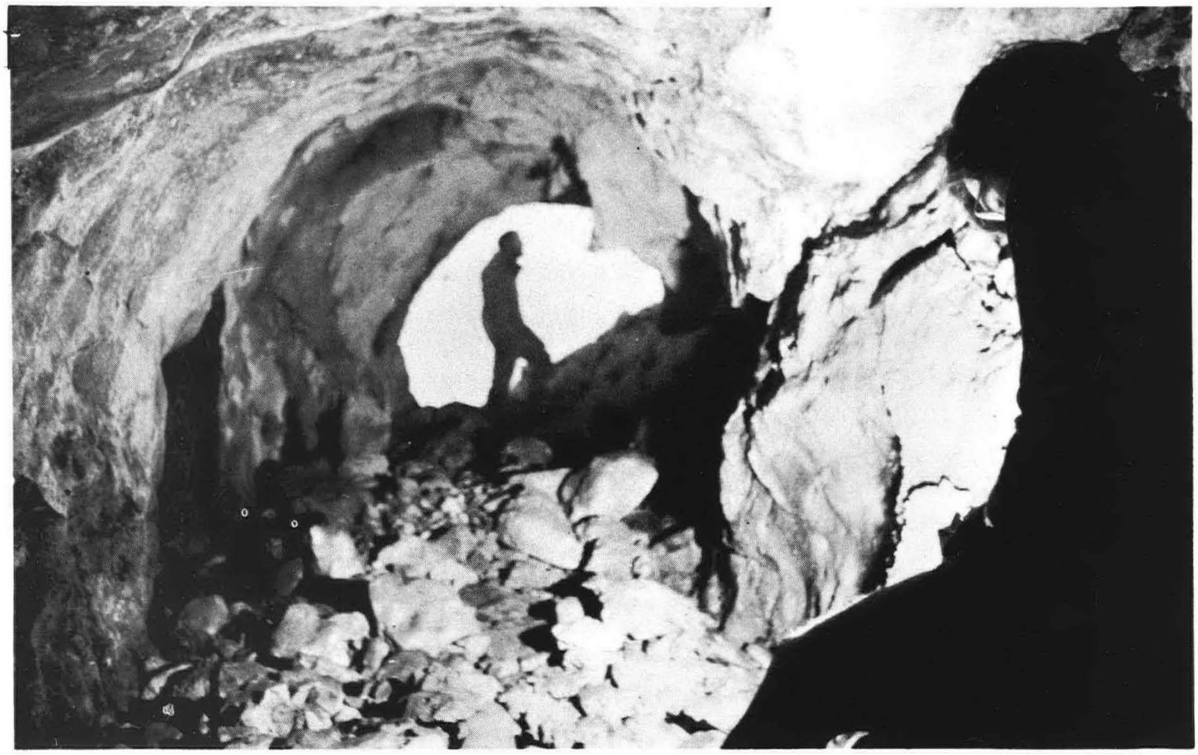
Plate 1

1. Gt. Hundstod from Schindlkopke.

2. Kl Hundstod from Seehorn-Rossl area, with camp at foot of snow-slope at bottom.

3. Mitterkaserwand from Hochweisalm footpath.

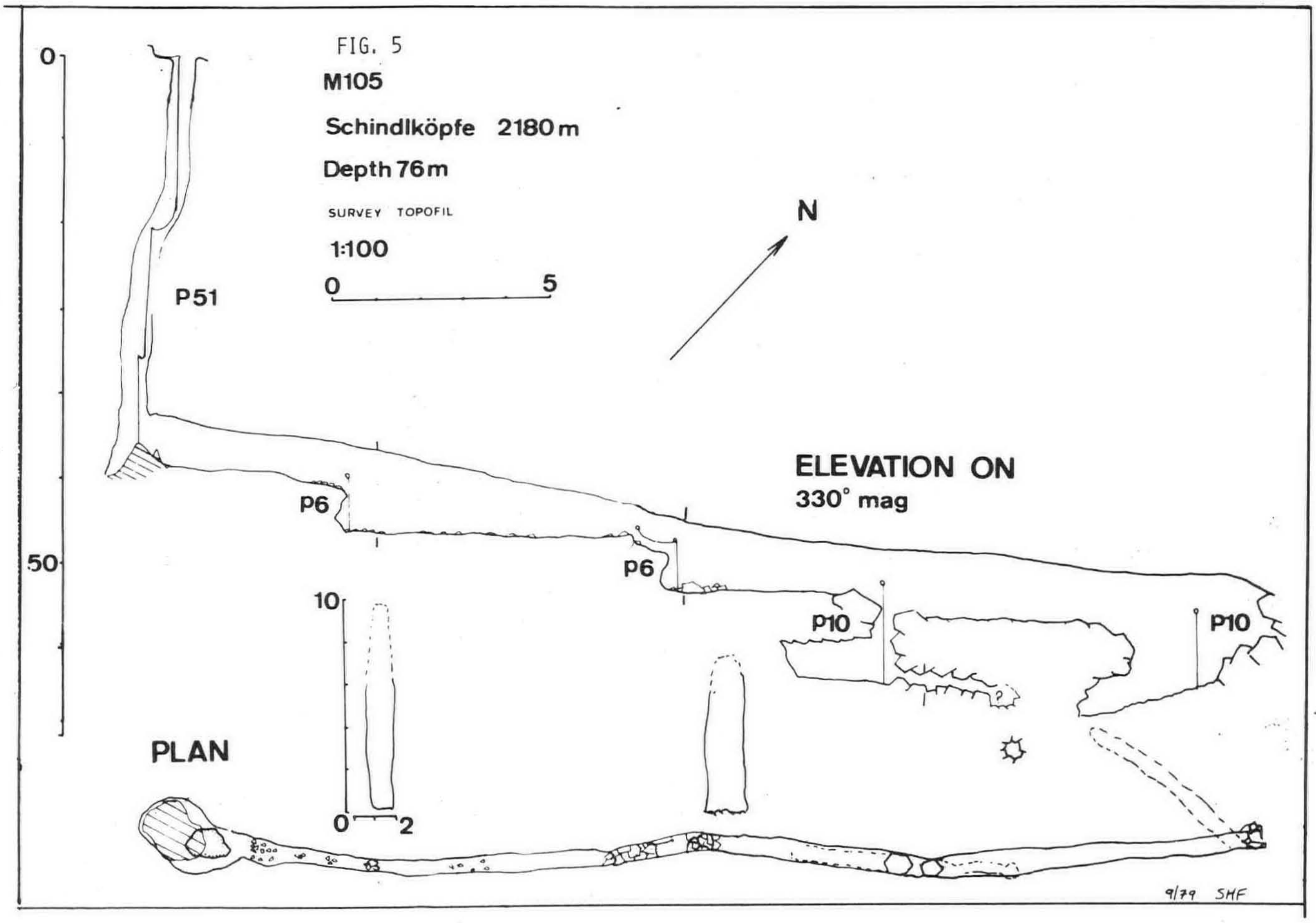
Plate 2



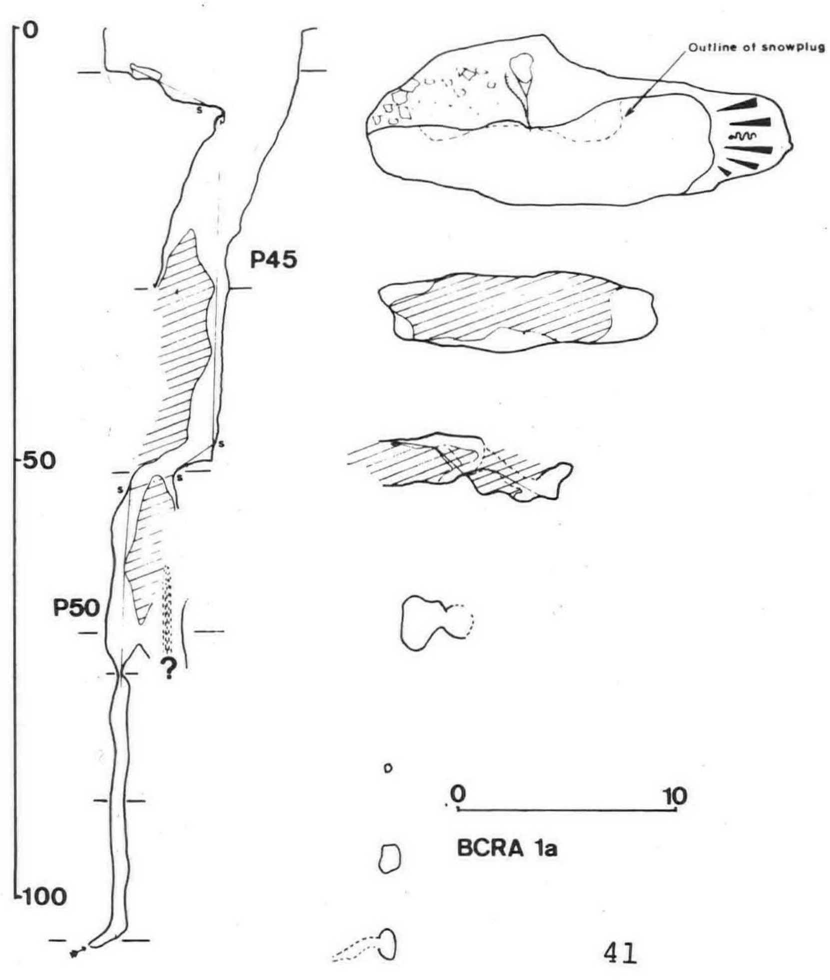
1. Phreatic tube in M254.

2. Entrance to M105.

3. Tunnel between snow and cave wall.



RIESENDOLINE AM SCHINDLKÖPFE FIG. 6
1331/132 M106



chamber with a crawl leading off under and through very loose boulders. The final 10m pitch lands in a rift chamber with a crawl between boulders which soon chokes with fill.

M106 = 1331/132, 2220 m altitude *Riesendoline am Schindlköpfe* (fig. 6)
This cave was listed in the Höhlenbuch as unexplored; the imposing shaft was easy to locate as it lies only 5m to the east of the Ingolstadter hut-Schindlköpfe footpath. The 20m by 8m entrance shaft was almost full of snow but at least two ways on could be seen. A bolt was placed in a rock wall beside the minor of the two inlet streams (this stream is only active in very wet conditions) enabling a 45m abseil past the snow plug to be made. The way on was under the snow plug for 5m to a short drop onto another snow plug. A bolt was placed and the descent to the snow made; a gulley was dug to allow easy access to the other side of the snow plug. A 2m gap between the snow and the wall allowed a further descent to be made. After 15m a rock floor was reached, the way on being open in two directions, back under the snow plug in a 3m diameter shaft which was very wet or down to the right in a much smaller but drier shaft. After 5m an extremely tight section was passed and eventually the bottom of the shaft reached, what had been thought to be a 15m shaft turned out to be nearer 50m. A stream flowed across the snow covered floor and sank; no apparent way on in the snow and ice could be found although a strong draught was noticed. The ascent of the shaft proved very unpleasant due to it raining on the surface making the squeeze desperate and the entrance pitch very wet.

A return was made two days later and the gulley through the snow at the top of P50 was completely iced over giving some idea of the draught. We concluded that it was a very promising hole, as it takes a lot of water in wet weather, mainly from the waterfall at the eastern end. The complex nature of the snow plug makes it very difficult to be sure that all the possibilities had been looked at. Only in cool dry weather should a descent of this shaft be made as all the pitches, especially P50, become extremely wet. If it rains, surface run off causes the two waterfalls to become active, when it is very warm the snow plug melts enough to cause P50 to be wet.

M107, 2050 m altitude
On the northern side of the small hillock in the bottom of the Schindlköpfe polje. The entrance is approximately 1 m square. From the entrance the passage drops approximately 3m in a distance of 10m. The passage then turns sharply left and a pool of water 3m long is encountered; after 10m a junction is reached. To the left and downhill leads immediately to a choke, Turning right leads to a frozen pool and then after 10m to a shaft to the surface which was blocked by ice.

M108, 2150 m altitude
By the path to Schindlköpfe under a snowfield leading down from the cairned hill. The cave had two entrances, one at the top of the snowfield and climb down at the base of the snowfield. The top entrance lead to a scree slope under the ice which entered a rock passage sloping at an angle of 30°. The bottom entrance involved a 2m climb onto a snow pile; climbing down the snow pile leads to the bottom end of the sloping tube from the top entrance. The cave then descends a steep ice slope for about 12m where a 6m high chamber is entered. The chamber was approximately 15m long with no ways on.

M109, 2150 m altitude
Directly across the Schindlköpfe path from the bottom entrance of M108. A 5m climb down lands on an impassable snow plug.

M110, 2150 m altitude
91° to first peak on the north side of Windbachscharte and 151° to Schindlköpfe. Series of shafts connected by a southward trending hading rift, all snow plugged a few metres down.

M111, 2150 m altitude
The entrance is 40m north of M110, a 5m oval shaft down to snow in an East-West rift. The east end is blind butthe west end lead to a 2m drop into small chamber. However, the way out of the chamber is choked.

M112, 2150 m altitude
The entrance is on the west side of a hillock between Schindlköpfe and the cairned hill, approximately 40m from the path. 5m shaft to a boulder-floored chamber, shaft undescended.

M113, 2080 m altitude

272° to first peak on north side of Wimbachscharte OII° to Gt. Hundstod summit.

Oval entrance hidden in side of rift on rim of Polje is a bedding plan dipping at 15° to 2m climb where a narrow vadose trench increases in width to where a 2.5m pitch lands on ice slope (rope essential) and ends in shaft. The way on is a traverse over the shaft to another much larger hole (15m pitch, bolt belay), landing in a large chamber with thick ice on the floor. No way on was found at this level, but a ledge at -8m led into an ascending rift. This was followed to a low tight sharp bedding, on the other side of which a 2m climb brought one into the top of an 8m deep 1.5 m wide vadose canyon. This was traversed along and down to where a small shaft was met. At the base of this shaft (free climbable) a route was forced through a boulder choke down into a narrow rift passage. At one extremity the passage choked whilst in the opposite direction a narrow rift down was reached. A very strong draught issued from this but no progress downwards could be made. This was probably the most promising find that was made, but explosives or smaller cavers would be needed to continue exploration.

M114, 2100 m altitude

2I4° to first peak on North side of Wimbachscharte.

02I° to Gt. Hundstod summit.

Entrance shaft 8m x 3m is 10m deep and free climable landing is on floor of boulders. Bedding plane crawl connects with large c. 25m x 30m low-roofed bedding plane chamber which drops about 30m to its lowest end. A descent through unstable-looking boulders connects with another chamber of smaller dimensions which is conclusively choked.

M116, 2080 m altitude

213° to the first peak on the north side of Wimbachscharte and 010° to Gt. Hundstod.

Entrance shaft leads after 8m free climb to a crawl on a pebble floor into a chamber. Due to the unstable nature of this crawl further exploration was not carried out.

M117, 2080 m altitude

213° to the first peak on north side of Wimbachscarte and 113° to Gt. Hundstod.

Ca. 8m square 2m deep shakehole to an ice-floored passage 1m high 0.6m wide leading to an undescended shaft extremely tight at the top.

1331/122, 2094 m altitude *Obere Höhle in der Windbachscharte*

Located on the north side of Wimbachscharte 50m below the upper level of the col. The cave has long been known as the entrance is an enormous oval orifice easily seen from the edge of the plateau near Wimbachscharte. A descent of 15m down a steep ramp and final vertical section lands on a boulder floor. The only way on is a narrow rift which after 10m descends very steeply into a large chamber. A large (2m wide, 10m high) rift leads off to the west but ends in a climb up into a boulder-filled passage. An active stream trench was followed to where further progress was too difficult.

SEEHORN-ROSSL AREA

Looking up from the Diessbach Stausee there are two obvious mountains, Gt. Hundstod to the east and the Seehorn-Rossl group to the north. The Seehorn area was reached by ascending a track up a hanging valley. At the top of this valley a large alp opened up (Hochwiesalm) consisting mainly of boggy meadow land but providing a dry comfortable campsite at its southern end. The dog-legged alp was terminated by one ridge of Seehorn sweeping down and joining another knife edge ridge from Gt. Hundstod. A long hard day's walking or climbing can be had traversing this ridge between the two summits.

There are basically three areas to explore from this campsite, the sinks of the valley floor, the small caves and rock shelters some 20m above the valley floor, and an inclined plateau area 300m above the campsite. The hillside rose steeply from the campsite to the plateau area and then very steeply to the top of Seehorn. This 'back wall' being mainly composed of dolomite and yielding one surface stream which sank under a snow bank into a cave, M209. The 'plateau' area consisted of stepped beds of limestone dipping into Seehorn at an angle of approximately 10°. The surface of the beds were pitted with choked shafts, the main cave development being found from entrances in the walls on the edge of the beds.

Hochwiesalm Low Level Area

Due to the valley floor being covered with a layer of glacial clay, permanent streams are present in the valley. The hydrology of the valley is very complex, with streams sinking and resurging in several places. After heavy rain a stream flows continuously from its resurgence in the Kuhreitenschied, past the campsite and on to the Stausee. In normal conditions this stream sinks where it meets the alp, reappearing some 300m further down the valley at the 'elbow'. A second permanent stream resurged just below the 'elbow' on the Western side of the alp, and after flowing for 100m, sinks again. The resurgence of this stream was never found, but is believed to be above the Stausee on the flanks of Seehorn. Several old phreatic tubes just above the valley floor level were investigated, along with various other caves all no more than 20m above the valley floor.

Hydrology of the Seehorn Rossl area (fig. 7)

The possible drainage routes are:

1. S.W. to Lahnkarquelle (1620m): potential altitude change c.500m; temperature of resurgence water 2.5°C; indicating fast flow through from high level sink.
2. S.E. to resurgences in Diessbach group in Hochwiesalm (1850m); potential c.250m. (Same comments as for 1 above).
3. N to Wimbachquellen (780m); potential c.1300m thought to be unlikely due to presence of dolomitized limestone band only 100m north of M208 (see fig. 7); however, if sufficient depth were attained the flow could follow the direction of a dye trace from Diessbachsee (1780m) to the Wimbachquellen.

Hydrology of the Seehorn Kuhreitenschneid area

The same three possibilities as above but different priorities:

1. Potential c.400m; flow would have to pass south through or under dolomitised limestone band.
2. Potential 150m: the most likely drainage route would take similar course to surface stream (one of the tributaries that form Diessbach).
3. Flow would have to pass under Diessbach. If sufficient depth were gained, perhaps via a series of pitches at the start of the cave, then this route is likely.

Several cave features were represented in this area. On the lower steep slopes of the valley there were many immature streamlets which ran in small rills before sinking in tight 2m deep shafts, only to re-emerge a little lower down. The upper plateau in the area of M206 and M207 was covered with many small braided streams, which sank very quickly into the rock. There were also many large snow-plugged shafts of 10m depth which had no other obvious source of water other than their snow fill. In the col between Seehorn and Kuhreitenschneid a band of dolomite gave rise to the only permanent surface streams, which then sank on the limestone-dolomite boundary (M209, M210). In the area around M250 to M255 there were indications of older cave development which had been uncovered at a more recent date. Several deposits of what appeared to be calcite were found in trenches which were reminiscent of cave profiles. Also two large phreatic tubes were found (M254, M255) coming out of the hillside down the bedding, and ending in prominent cave-like valleys.

Description of caves

M201, 1331/139: 1970 m altitude.

50m above a lone pine tree on the flanks of Hochwiesalm above 'elbow' in valley. A low chamber splits into several small phreatic tubes heading up and into the hillside.

M202, 1860 m altitude.

A short sloping shaft choked by boulders.

M203, 1860 m altitude.

30m south of M202 the furthest entrance to left in a line of entrances along a horizontal bedding plane. A 3m climb down to ledge leads to two small drops of 1.5 and 6m into a chamber. A crawl under one wall leads into small rift choked after 3m by a wall of loose rocks.

M204, 1860 m altitude.

2m above valley level on right (west) bank, 100m upstream of nick point. The entrance tube leads as a crawl into a chamber, the only way on being a low crawl in water, not pushed.

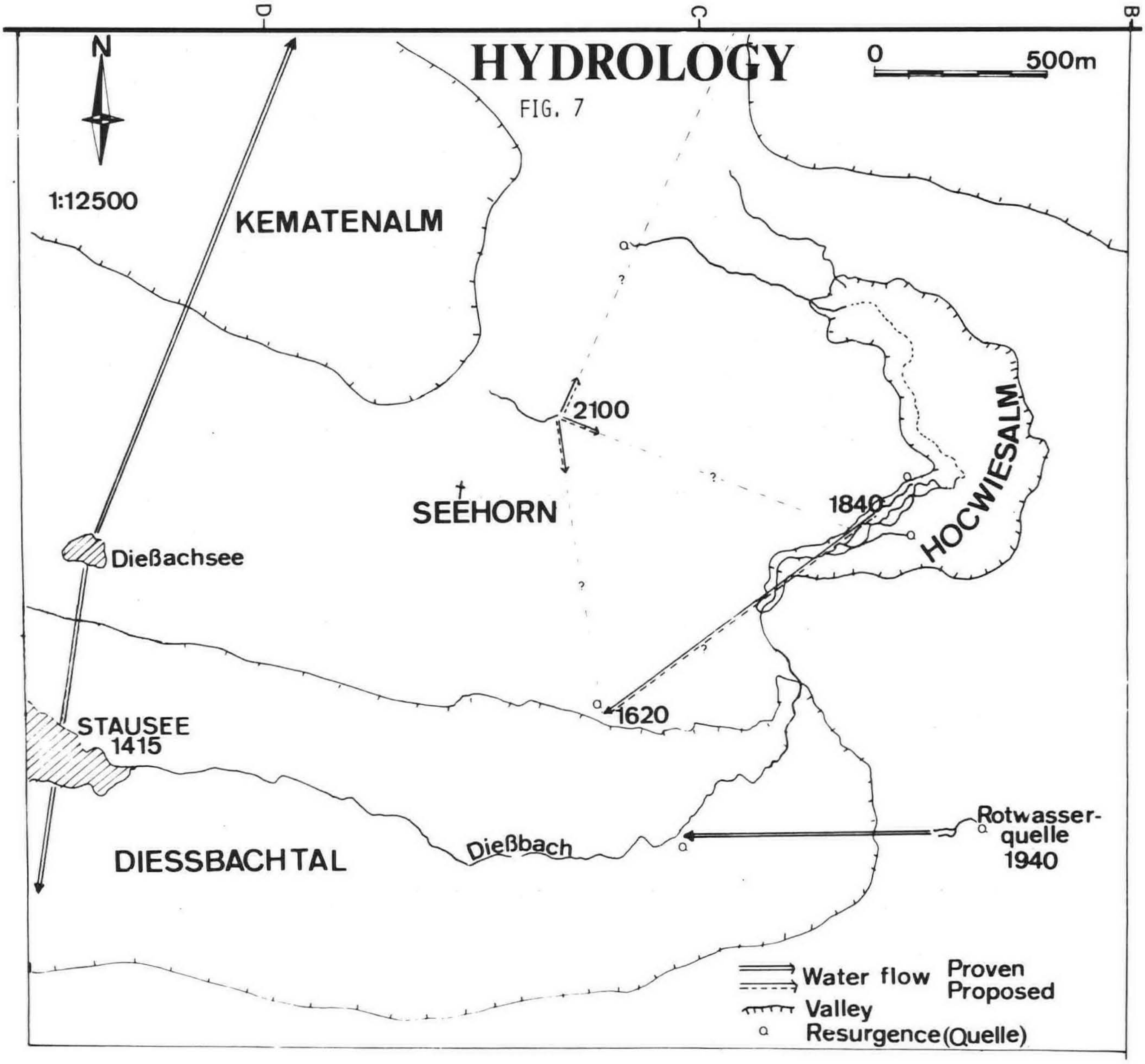
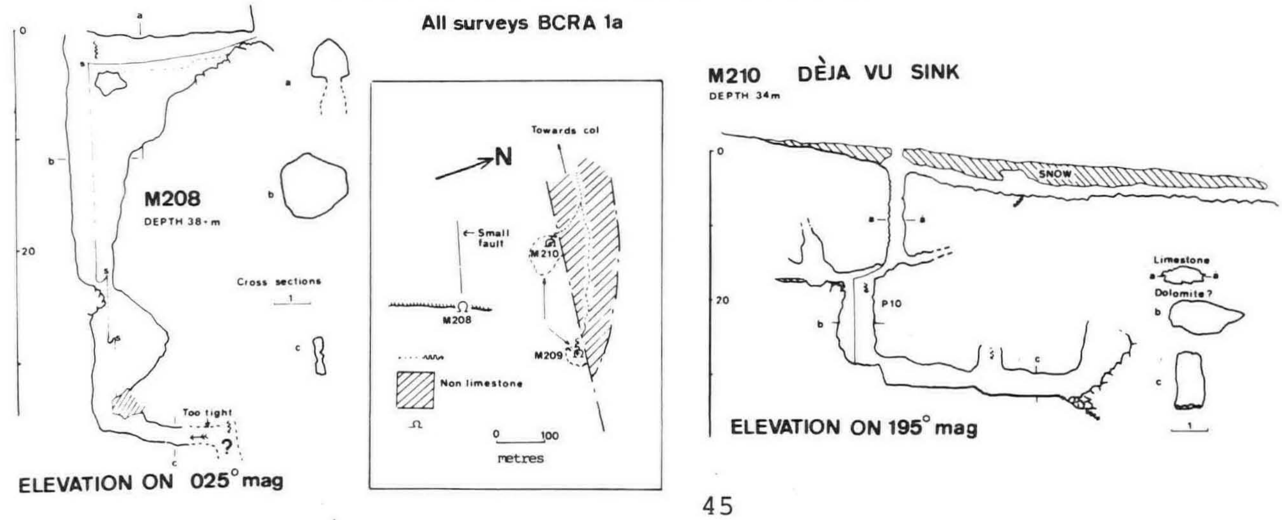


FIG. 8

CAVES OF THE SEEHORN-ROSSL AREA



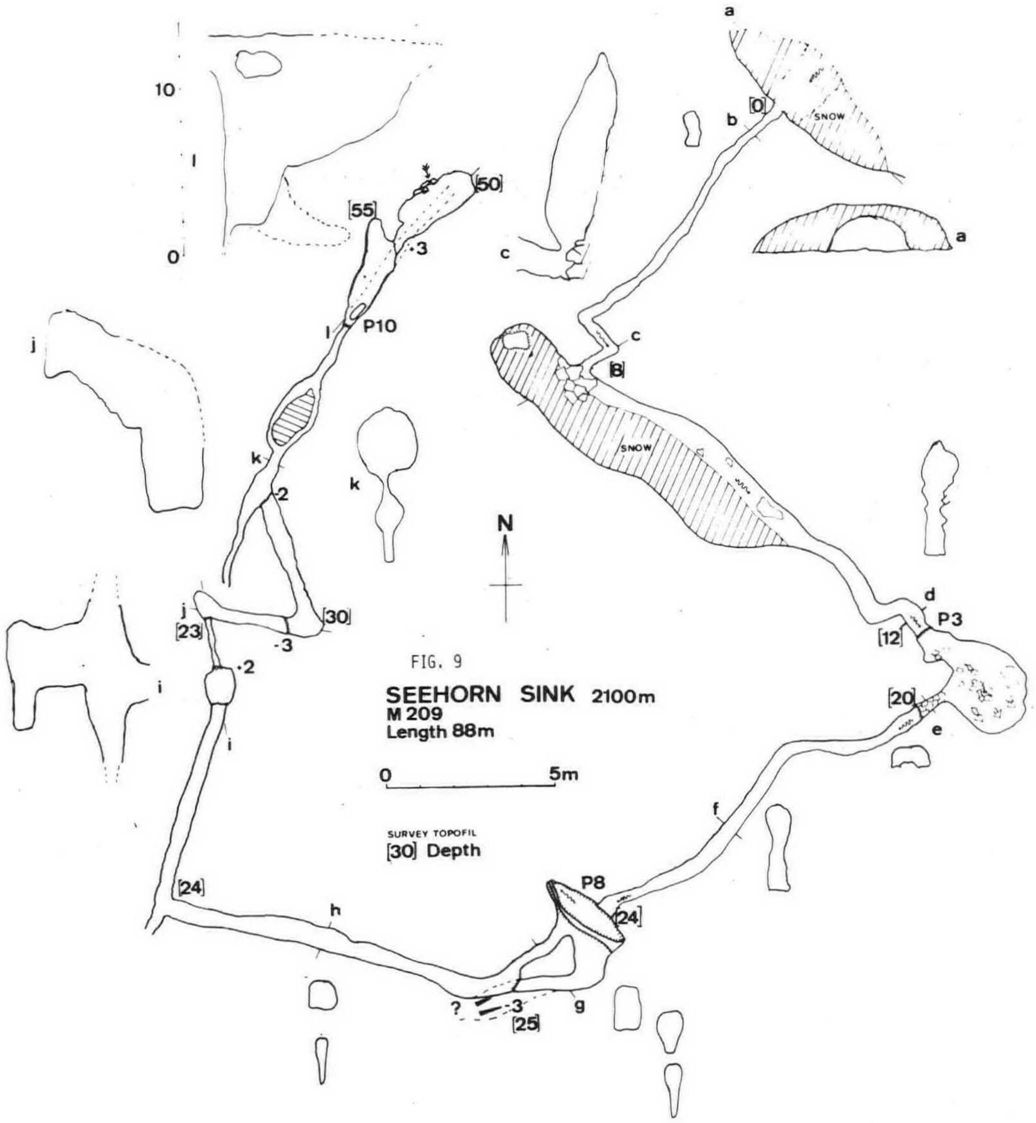


FIG. 9

SEEHORN SINK 2100m
M 209
Length 88m

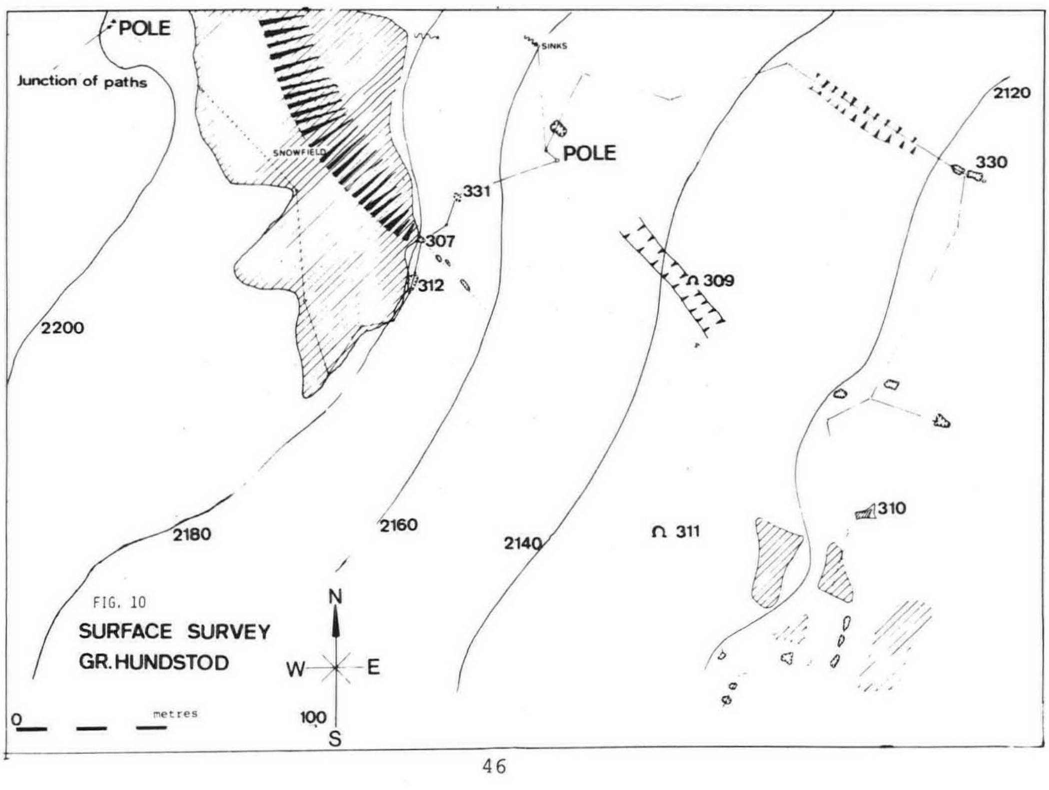


FIG. 10

SURFACE SURVEY
GR.HUNDSTOD

M205, 1960 m altitude
100m, vertically, above campsite (nick point of stream) bearing 334°: 6m deep sharp tight shaft in clints, too tight at bottom. Typical of drainage on flanks of Seehorn above Hochwiesalm.

M206, 2060 m altitude
On main plateau area, bearing 082° from Seehorn summit cross. 12m deep shaft which gets too tight, basically an oversize clint.

M207, 2060 m altitude
Just over crest of hill from M206 on same bearing from Seehorn. A large lens-shaped opening 15m long with a maximum width of 1.5m. At the widest point a 15m pitch lands onto a snow plug, no way on.

Seehorn-Rossl area

M208, 2100 m altitude Depth 38m+ Length 15m (fig. 8)
Approaching from Hochwiesalm the local plateau at c.2100m is crossed heading towards the col to the NNE of Seehorn. The entrance to M208 lies to the right (north) end of a 6m wall after a series of 1m steps in the limestone pavement. The triangular 1m high entrance lies on a bearing of 290° (mag) from Gr. Hundstod.

From the entrance a 2m crawl over loose rocks leads to a climb down a larger boulder overlooking the impressive first pitch. A traverse forward on a ledge on the left hand wall leads after 3m to a large jammed block. A 15m pitch (bolts on left and right hand walls) in an impressive shaft drops one onto a snow-covered floor. A small hole below the snow bank marks the start of the 2nd pitch. Passing loose blocks at the top, this 10m drop ends on a large snow block. A further 2m drop into a small chamber with the way on back under the snow block leads to a narrow rift. Several hours digging in an ever tighter rift led to a point where further progress would require explosives; however, the noticeable outward draught, the sound of running water and an estimated 20m shaft only 2m further on made the digging seem worthwhile. The cave is developed on a small fault with the size of the entrance disguising the quite major development. A large number of small streams, surface runoff, sink just before the 6m wall, so if the next shaft, which appeared to be a rift, could be reached the possibilities of further development would seem good.

M209, 2100 m altitude, Depth 55m, Length 88m *Seehorn Sink* (fig. 9)
The entrance was found while people were digging in M208. A small surface stream disappeared under a snow-field. A tunnel led off under the snow and was duly followed into a sporting stream cave.

Crawling under the snowfield leads to several squeezes and a water chute; climbing up between boulders one emerges in a sizeable chamber. One side of the chamber consists of a large mass of snow, daylight entering from a tight shaft connecting with the surface. The stream can be followed downstream to a 3m drop, handline essential, into a small chamber where it sinks between boulders. Facing the pitch a small draughting hole on the left marks the way on. A 2m climb down brings one back to the stream. This can be followed for a short way to where it disappears down a blind 8m drop. Two ways on are possible from the top of this pitch, either down or across. Both ways unite in a tall narrow phreatic passage, the only passable route being the uppermost of three interconnected tubes. A junction is soon reached, left closes down after a few metres whilst right continues as a walking size passage descending a sandy ramp to a small pit. A trickle of water enters from the roof to disappear down the too tight shaft. The way on is 2m higher through a 2m long slot, an awkward climb down lands on a small ledge. A delicate climb down on sloping razor sharp flakes led to a 3m free climbable drop. Squeezing through a slot led to another climb down to a water-floored chamber. A further narrow passage led to a shaft into a chamber. This proved extremely awkward to descend as the top of the drop was in a narrow rift. The only way on that could be found in this chamber was through a wall of unstable boulders after a climb of 3m. Although a noticeable draught was felt this was not pushed.

M210, 2120 m altitude
100m upstream of M209 where stream again sinks under snowfield (fig.10). Although it is possible to crawl under the snowfield to where the stream sinks and on to where a 3m climb rejoins the stream, the normal entrance was in the middle of the snowfield. A 15m chimney with razor-sharp walls ends in the streamway 2m upstream of a 10m shaft. A bolt was placed and a 10m descent made beside the waterfall, at the base of the shaft a climb down of 3m led into a walking size passage. This

lowered where a further short climb down into a chamber had to be made. A small stream entered from the roof and the united streams sank between boulders at the far side of the chamber. The cave is developed almost entirely along the limestone-dolomite boundary, resulting in the extremely jagged and sharp rock of the entrance chimney. The cave was named Deja Vu sink due to the similar mode of discovery to M209, i.e. following a surface stream to where it disappears under a snow bank.

M250, 62° from Seehorn and 305° from Gt. Hundstod. 150m South West of Diessbach. Circular depression in rock 2m diameter and 2m deep just up hill from prominent East-West fault line. Entrance over boulders in one corner of depression leads to a sloping ramp. 2m along this ramp a twisting spiralling tube led to a pitch of 12m to a small chamber. Not descended due to lack of tackle.

M251, 238° from Watzmann (to East of Kuhreitenschneid) and 298° from Gt. Hundstod. On skyline when seen from below. Long rift or trench with several small ways in, non deeper than 20m. Distinguishable by pumice-like infill.

M252, Hole in cliff face above M251. A large entrance with arched roof leads to a 5m pitch (free climbable). Around the next corner a 7m pitch is descended to a chamber where the way on enlarges to a 8m pitch. The passage then becomes too tight.

M253, 204° from Watzmann and 200m from Diessbach. Figure-of-eight-shaped hole with a rock bridge across the centre. The eastern end of hole has a small entrance which is soon choked. The western entrance is a flat-out crawl for 10m over sharp scree to a larger passage which soon divides. To the right was tight for 25m before a chamber was entered with three ways on. Two choked almost immediately, but the third led to a 10m shaft. This was blind at the bottom, but a passage lead off 2m above the floor, only to choke. Left hand passage zig-zagged about to the head of a shaft. Two large boulders blocked the way on, but they could not be moved so the shaft was left undescended.

M254, Large obvious entrance 100m to West of M253. Phreatic tube 3m wide by 2m high dipping down under Seehorn at 30°. The floor was broken boulders, and after 30m infill reduced the height of the tube to 15 cm leaving no way on without substantial digging.

M255, 10m to west of M254, and very similar to it.

HUNDSTOD SOUTH AREA

To the South of Great Hundstod this area (fig. 10) is bounded to the north by the steep south face of Hundstod, and to the west by the col and ridge into the Hochwiesalm. The southern boundary was arbitrarily defined by the line of a footpath running between the Ingolstadter hut and Funtensee as the plateau slopes all the way down to Funtensee. The limestone strata are inclined at an angle of 30°, and an exposed bedding planeforms the ground surface. There were several snow fields on the slopes of Hundstod, and much frost-shattering of the rock. The 'egg-box' karst was broken occasionally by obvious trenches, which contained what appeared to be calcite deposits.

All the caves in this area were surface shafts which contained snow plugs at the bottom. Where a way could be found past this now plug the caves tended to be very unstable, the rock being highly shattered.

M301, 1900 m altitude. Approximately 300m on bearing 298° from Hochwiesalm campsite. 3m deep to a small chamber, no way on.

M302, 2180 m altitude. *Arch Hole.* . 20m West of Gt. Hundstod path on bearing 216° from a prominent pole. A large open shaft approximately 10m x 5m, with a rock arch across the middle. Descended 10m to snow plug, no way on.

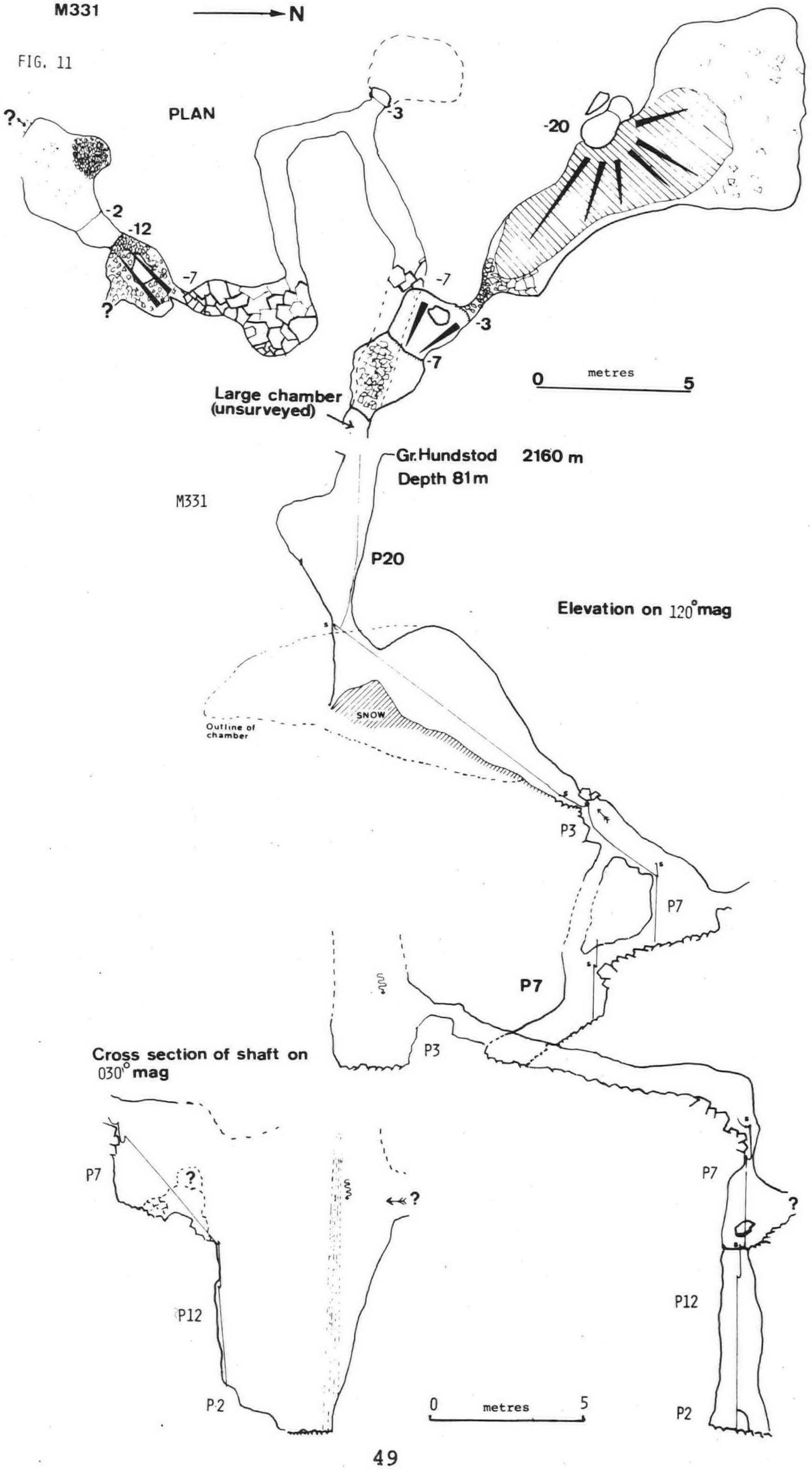
M303, 2180 m altitude.
On bearing 215° from prominent pole. 20m from Arch Hole. An open shaft. 12m descent to a floor choke.

M304, 2180 m altitude. 5m from M303 in direction of pole.
7m climb to boulder choke. Small draughting hole bearing East

M305, 2180 m altitude. *Eishöhle*
On right hand side of path ascending Gt. Hundstod. Large snow plugged shaft. A tunnel running through the snow had ice-scalloping on walls. Off the ice tunnel two small shafts in rock connected with the surface.

M306, 2180 m altitude.
Bridge Cave. Left hand side of path ascending Gt. Hundstod, 20m above Eishohle. Large 12m x 4m shaft with rock bridge across middle. 12m descent to snow plug. A small 3m deep hole in snow led 15m down a 45° slope. Snow finally fills the passage. Two blind avens noted. Passage ended under the snow plug of the adjacent shaft.

FIG. 11



M331
N
PLAN
?
-2
-12
?
-7
-3
-7
-3
-7
-20
0 metres 5
Large chamber (unsurveyed)
Gr.Hundstod 2160 m
Depth 81m
M331
P20
Elevation on 120°mag
SNOW
Outline of chamber
P3
P7
P7
P3
Cross section of shaft on 030° mag
P7
?
?
P12
P2
0 metres 5
P7
?
P12
P2

M307, 2180 m altitude
30m North East of path. Large fault near snowfield. Fault trending East-West with several shafts typically 2m x 7m. All now plugged.

M309, 2140 m altitude
50m below pole in obvious rift. Sloping entrance down 5m ramp over loose boulders to chamber. Enter chamber 8m above floor. Hole in floor dropped a further 5m. Slight draught felt.

M310, 2110m altitude
100m South East and below pole. A large sloping hole with a snow bank for first 20m but the bottom was snow filled. A small hole 5m from top headed towards the pole, with a squeeze through to a chamber followed by a squeeze over sharp rock directly onto a 10m pitch. Shaft 2m diameter choked at bottom.

M311, 2130 m altitude
Diagonally across and up snowfield from 310. Two entrances unite and descend 20m down a steep snow slope. Two small passages lead off, both containing ice formations. One passage led to a sloping squeeze over ice to the top of a drop. Stones fell 5m to floor. Descent not made due to lack of tackle.

M312, 2180 m altitude
10m South of fault containing M307. Entrance under the edge of the snowfield. Descent around a complex snow plug possible for 40m until the way on is snow choked. A small muddy passage leads off 20m below the entrance in direction of M307 and M331. The passage was choked with boulders after 5m.

M330, 2120 m altitude
A system of three interconnected shafts. The prominent middle shaft has a snow slope down to a small hole which has daylight entering from the western (highest) shaft. The ways down the side of the snow plug are choked. Eastern (lowest) shaft starts as a narrow inconspicuous rift which slopes down 5m to head of 14m underground pitch (bolt belay). 7m down the pitch daylight can be seen through a small phreatic tube from the base of the middle shaft. The bottom of the pitch is a boulder floor, with no way on. A boulder slope and aven enter from the direction of the central shaft.

M331, 2170 m altitude
Open shaft west of large snow field 20m from an obvious pole on a bearing of 245° from it (fig. 11). A 20m shaft to a snow plug forms the entrance to this interesting cave. The snow plug forms one corner of a large low-roofed chamber. The way on lies down this snow plug to a small hole with an unstable rock bridge (insecure belay for next pitch). From this hole a descent of 3m leads to a large rock bridge and at the far end a further dop of 7m lands on a boulder slope. Facing up slope a 2m climb leads after 5m into a large chamber. Down the boulder slope several large jammed blocks mark the top of a further drop, P7 (bolt belay), again landing on a boulder-strewn floor. Down slope a junction is reached; right leads after a climb up and down into a high chamber with a trickle of water entering from high up. Left leads down yet another boulder-strewn passage until some larger boulders are met where the noticeable draught issues from a narrow rift. An 8m descent (2 bolts) in a narrow rift lands on a steeply sloping boulder floor and a furtherdrop of 17m, bolt belay, in a very much larger shaft (10 x 5m). A small stream enters from high in the roof and disappears between boulders in the floor. Opposite the top of the 17m drop a hole was noticed, as the draught appeared stronger here, the main way on was presumed to be through this hole. The quantity of water present would have made bolting up the wall extremely unpleasant. The only other way on was up a 3m climb halfway down the boulder slope; due to the extremely loose nature of the rock, this was not undertaken.
It was initially thought that the stream entering this final shaft originated from the large surface snow field, however this seems unlikely having drawn up the relevant surveys.

M332, 2100 m altitude
Within 3m of the Ingolstadter hut-Königsee footpath on west side just before path turns to the east.

A scramble down the side of a snow plug leads into a chamber. The way on to the right, through an awkward shaped passage, is a hands and knees crawl for 5m. The passage continues as a tortuous walking-size rift, with several scrambles over boulders. A snow plug enters from the right 30m from the entrance at a large chamber. The snow was ascended but no connection could be found with the surface. Several routes around the snow led to a 3m free climb out of the chamber. The way on was over two more 3m climbs to a three way junction. The passage at floor level dropped 5m to end as a window, too small to pass through, 4m above the floor of a chamber. A 2m climb up to the rightonto a shelf revealed two more ways on. To the left is a steeply sloping rift which is impassable 5m on. A chamber can be seen. The way on is the horizontal 0.5m diameter tube to the right. A ladder or rope should be belayed in the chamber and pushed through first as 3m along the tube suddenly increases in gradient to become a 12m pitch. The pitch lands in the same chamber as could be seen from the other two routes. A further 3m climb down leads to a rift which was too tight to follow.

SURVEYING

All the surveying on the expedition was carried out using a Topofil (fig. 12). This is an ingenious survey unit which combines tape, compass and clinometer. The one we used was purchased from Groupe Vulcain in Lyon.

The basis of the system is a reel of cotton, A, which is mounted in a box. The cotton runs through a guide G and around a rev-counter wheel C. The cotton then runs over the top of a compass and out of the box. The cotton is kept under tension by a spring loaded level B pressing on the cotton reel and friction through a spring-loaded guide D. The cotton is aligned over the compass by guide D and by a small U-shaped hole throughout the cotton passes. On the base of the Topofil is cemented a protractor F with a brass pin, H, located at the origin of the protractor. Also located on the base of the Topofil is a small spirit level E.

Surveying is carried out using the normal leap-frogging technique. One person has the Topofil and the other person has the end of the cotton. The person with the cotton walks from station 1 to station 2 and pulls the cotton taught, the distance being measured by the rev. counter. The bearing is then read by lining the cotton up with a red line across the compass. The clinometer reading is taken by wrapping the cotton around the brass pin H, whilst holding the clinometer vertical, and keeping the cotton taught. The Topofil is then moved in the vertical plane until the bubble in the spirit level is centralised and a reading is taken by lining up the cotton and the protractor.

The person with the Topofil then leap-frogs to survey station 3 whilst the other person reels in the cotton. When the person with the Topofil passes survey station 2, the person with the cotton takes hold of the cotton as close to the Topofil as possible, so that the distance from station 2 to station 3 can be measured. The bearing and clinometer reading are taken as before. The survey carries on until all the cave is surveyed.

One small problem with the Topofil is that the readings are in grad., instead of degrees so either a calculator with grad on it must be used, or the grad have to be converted to degrees to that an ordinary calculator or tables can be used. All bearings quoted in this report are magnetic, magnetic variation in this area is $17^{\circ}40'$: East (August 1979). (100 grad = 90°)

CONCLUSION

Although diverted from its original main aim of exploring the Wieserloch, the MUSS Expedition spent a useful and eventful 3 weeks on the Steinernes Meer. Much was learnt about the problems involved with prospecting for new caves on high level lapiaz. Also we believed that we did some useful work in furthering the knowledge of cave development in the areas studied. Perhaps the greatest lesson learnt was the problems of working with foreign cavers where it is all too easy to tread on people's toes without realising it. The Steinernes Meer is an area of great speleological potential and is certainly worth further visits.

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REFERENCES

Salzburger Höhlenbuch - Vol. 2. W. Kappacher, H. Knapezyk. Landesverein für Höhlenkunde, Salzburg, 1977, pp.145-297.

MAPS
Austrian Alpine Verein Karte 1:25000 *Steinernes Meer* covers the majority of the area.
Austrian Alpine Verein Karte 1:25000 *Hochkönig-Hagen-gebirge* covers the area to the east of the Steinernes Meer map.

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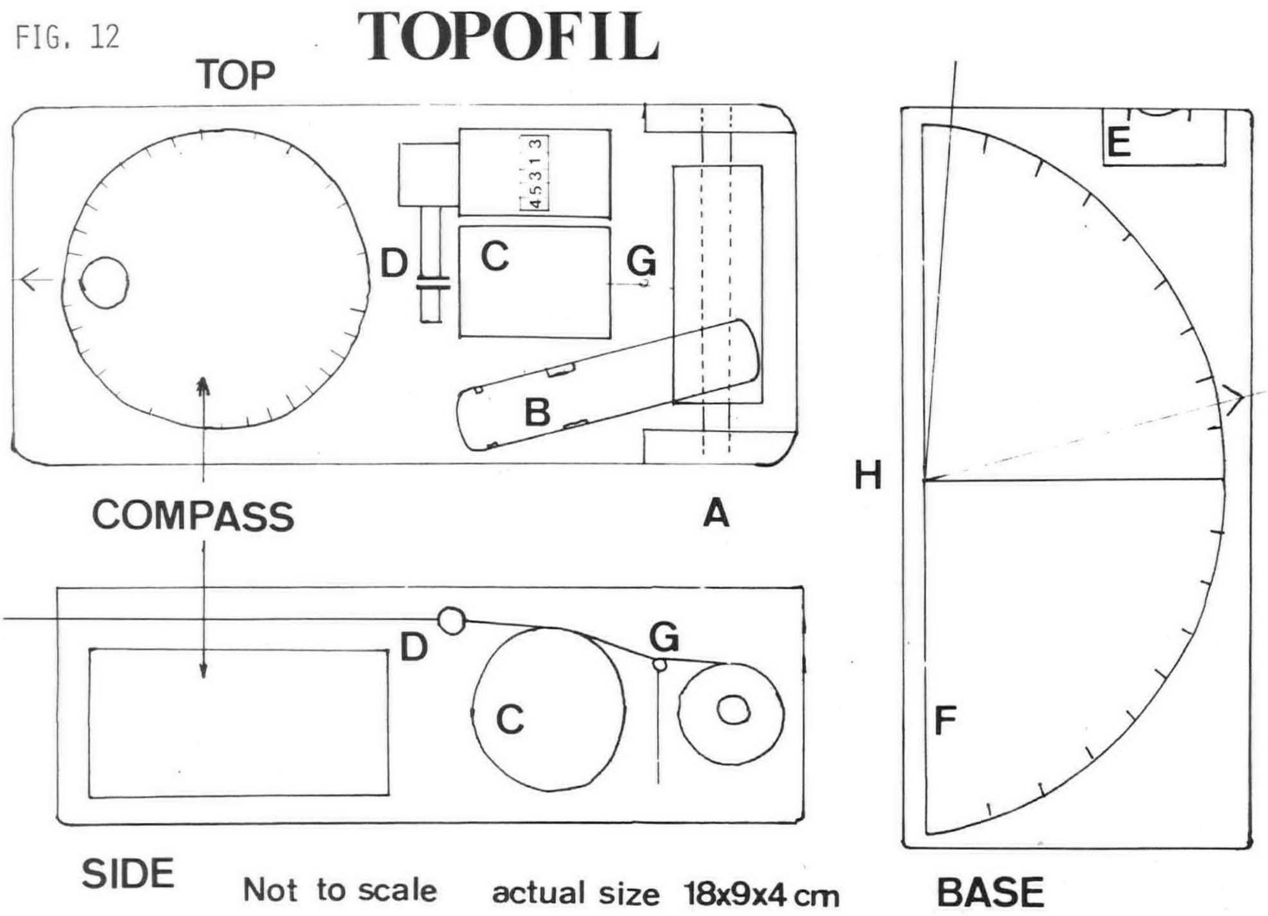
FIG. 12



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