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Descending the Moulin, Canadian Rockies.

Denudation in the Burry catchment, Gower

Sampling at a Karst Spring, Leason, Gower

Computer Program for Cave Surveying

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Caves of Leck Fell

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DENUDATION RATES IN THE RIVER BURRY CATCHMENT, GOWER, GLAMORGAN

by W. Chambers

ABSTRACT

A study of denudation in the predominantly limestone River Burry catchment of Gower, South Wales, based on one year's data revealed a denudation rate of 30mm per 1000 years which is below that of other karst areas of the British Isles. There was little temporal difference in denudation when the summer and winter six months were compared (48% and 52% respectively); however, at the most extreme 7.5 times as much denudation occurred during February as October. Spatially, denudation was dominated by one spring which contributed 58% of total denudation, whilst only 11% was from allogenic or non-discrete limestone seepage.

The study of solutional denudation in predominantly limestone areas has increased in frequency and sophistication since the pioneer work of Corbel (1957). The aim of the present account is to describe denudation rates in a peninsular catchment in lowland South Wales. The analysis is based upon discharge records and water sampling throughout the 1971-2 water year. (Chambers, 1976).

The River Burry (Fig.1) is the dominant stream of the Gower Peninsula, an area of Devonian and Carboniferous sandstones, shales and limestones, projecting westwards from near Swansea into the Bristol Channel. The Burry catchment, whilst complicated in detail by subterranean river capture, is a basically simple system. It rises on isolated 183 m denudation surfaces of Devonian sandstones(quartz conglomerate and mudstones) and crosses Carboniferous Limestone plateau surfaces at 122 m and 61 m O.D. allogenically to reach the sea at Cheriton. The catchment is dominated by Carboniferous Limestone although the sandstone watersheds and the Ryers Down - Cefn Bryn sandstone ridges add diversity to the hydrology and denudation rates. Glacial and periglacial deposits mantle the surface of the catchment; the former, predominantly Older Drifts, are of a non-calcareous lithology, whilst the latter are locally derived and tend towards a higher limestone content (Griffiths, 1937).

During the study period of 1971-2 three clear rainfall periods were noted. Between October and January dry conditions prevailed with 10% less rain than the 35 year mean; from February to June the weather was rainy with 75% more rain than the mean; and from July to September another dry period occurred during which 36% less rain than the mean fell. Two official droughts occurred, in August and September; however, overall the year was wet with 9% more rain than the 35 year mean.

Products of contemporary denudation in limestone environments are transported in solution and suspension but this study is concerned with solutional transportation only.

DENUDATION INPUTS

Precipitation during the water year was entirely in the form of rain.

As can be seen from Table 1, rainfall decreases south and west of the line connecting Llanmadoc, Penmaen, and Swansea (Oliver, 1971). Conversion of the point data to areal data by the Thiessen polygon method (Thiessen, 1911) gave an average precipitation input to the Burry Basin of 1049.38 mm during the water year and a total volume of 28,039,433 m^3.

Table 1

Station	N.G.R.	Height (m)	Precipitation (mm)
Penmaen	532888	85	1203.9
Burry Dairy Farm	458903	38	1049.0
New Henllys	452892	49	1032.5
Moorcorner	464864	81	988.8
Reynoldston	481901	107	1026.5
Llanmadoc	437940	8	1193.4
Swansea	642922	8	1191.3

The quality of atmospheric input is frequently omitted from consideration in the calculation of denudational rates. Whitehead and Feth (1964) noted that the atmospheric contribution was of two main types: 'dry fallout' such as dust and other fine particles and precipitation; these together constitute 'bulk precipitation'. Except in unusually affected examples (Stevenson, 1968; Tamm and Troedsson, 1955) bulk precipitation is usually 'a dilute solution in all but dilute natural waters' (Janda, 1971). Both Williams, (1968) and Imeson (1973) discount the importance of precipitation input of dissolved salts. Since Gower is almost completely vegetated and no part of the Burry catchment is further than 5 km from the coast, it is suggested that a large proportion of any recorded calcium and magnesium is oceanic in origin and non-denudational. Samples of bulk precipitation were taken throughout the water year giving a mean concentration of 2.3 mg/l of calcium and magnesium.

In addition to the non-denudation input described, other possible sources for the discharge and chemical load of the Burry catchment are seepage beneath the surface watershed and artesian flow from elsewhere. Seepage across the watershed is considered to be negligible because of the geological structure and the closeness of fit of the water budget, whilst artesian flow from the Brecon Beacons, as once suggested by George (1944), is similarly rejected. Thus, it is concluded that input components to the denudational system of the River Burry are limited exclusively to precipitation. Given a total surface area of 26.72 km^2 and an annual precipitation of 1049.38 mm with a mean hardness of 2.3 mg/l the total amount of input of calcium and magnesium amounted to:

$$26.72\ km^2 \times 1049.38\ mm \times 2.3\ mg/l = 64{,}000\ \text{kilograms}$$

DENUDATION OUTPUT

The flow of water and solutes from the Burry System is dominated by two outputs, evapotranspiration and discharge, although abstractions by water authorities must also be considered.

EVAPOTRANSPIRATION

The measurement of evapotranspiration is notoriously difficult and introduces a large element of inaccuracy into a water budget calculation. Indirect calculation of actual evapotranspiration using the Meteorological Office formula (Min. Ag. Fish & Food, 1967) based upon Penman's work (1948, 1949, 1950) and using rainfall data from Penmaen, potential evapotranspiration from Mumbles and the soil moisture deficit as calculated by the South West Wales River Authority gave a value of 610.9 mm (16323248m^3). When adjusted (Min. Ag. Fish & Food, 1967) for the height difference between Mumbles (30.48m) and the mean height of the Burry Basin (70.18m) the actual evaporation is calculated as 599.3mm (16013296m^3). It is worthy of note that, as Howe (1956) also found for Swansea, precipitation exceeded evapotranspiration in 10 out of 12 months of the year. Only in the mid-summer months of July and August was evapotranspiration dominant.

ABSTRACTION

The West Glamorgan Water Board abstracts water from the Devonian sandstone aquifer of Cefn Bryn. The major source is Holy Well (SS 498 901), from which 84316m^3 of water was utilised. However, only some 16% of the Cefn Bryn upland is within the surface catchment of the River Burry and thus it is calculated that 13,727m^3 was removed from the catchment by abstraction during the 1971-2 water year. This is equivalent to 0.5mm over the whole drainage basin. Mean hardness of this water was 76 mg/l and thus total calcium and magnesium removal was 1,043 kilograms.

DISCHARGE

Discharge from the Burry Basin was measured at Cheriton Bridge (SS 451 932). The total discharge from the catchment for the water year was 11,504,236m^3 which is equivalent of 430.5mm rainfall.

HARDNESS

In addition to total annual discharge, information concerning the solute concentration of the streams is necessary, in order that the total solutional denudation of the River Burry basin be calculated. In the absence of continuous monitoring equipment, Drew (1974 p.97) discussed the derivation of a satisfactory mean hardness value, and noted that "... differences in total limestone loss is considerable..." when utilising weekly, monthly, and annual mean figures. He concluded that "... one to two day intervals are necessary to provide an accurate estimation of solution rate...". In the present study a composite approach was employed, base flow hardnesses were related to the annual hardness cycle, whilst flood flow hardnesses were calculated by regression analysis using the empirical formula:

$$y = 446 - 141.7 \log 100x$$

where y = total hardness in mg/l
x = flood discharge in m^3/sec

When the solute concentration is combined with the discharge, the total solutional load, in terms of kilograms of calcium and magnesium, for the 1971-2 water year is 2,289,503.

TEMPORAL DISTRIBUTION OF DENUDATION

The temporal distribution of denudation is a function of water hardness and discharge. Whilst there is a significant (at the 0.001 level) correlation between hardness and discharge, the range of hardness for the water year (from 59 to 259 mg/l) was far less than that of the discharge (from 0.04 to 4.2 m^3/sec). Thus the dominant influence upon temporal variations in denudation was discharge; as discharge rose, total solute transport increased and solute concentration fell slightly. Seasonally, there was little difference between winter and summer solutional denudation, winter accounting for 52% and summer 48%. This reflects,

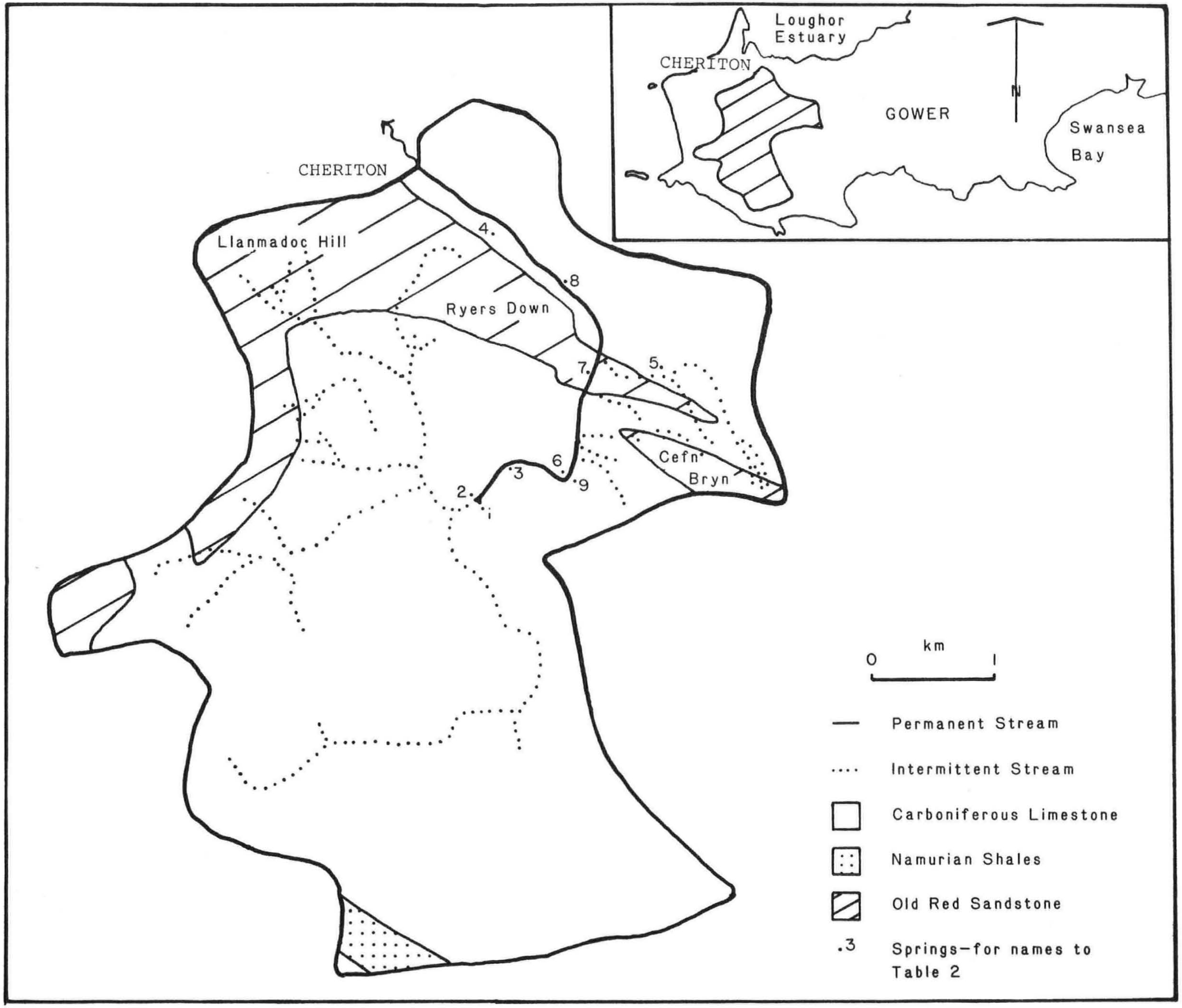

Fig. 1. Sketch map of the River Burry catchment. Localities are listed in Table 2.

primarily, the difference between the seasonal discharges (winter 57%, summer 43%) and, secondarily, the winter coincidence of discharges with generally lower total hardnesses whilst the summer discharges coincided with relatively higher total hardnesses; thus, winter values are depressed and summer values increased.

The most important single months were February, March and June, with, respectively 15%, 14% and 12% of the annual denudation, whilst the least important months were September, October and November, with respectively 3%, 2% and 3% of the annual denudation. Thus, at the most extreme, seven and a half times as much denudation occurred during February as during October. This compares with data from Williams (1968) where the most intensive month was four times as effective as the least intensive.

When the vagaries of individual dry and wet months are removed with the use of 3 month running means, the most effective denudation period was January to April, whilst the least effective was from October to December.

AREAL DISTRIBUTION OF DENUDATION

In additionto measurement of the discharge and solute concentration, and total solute load at Cheriton Bridge, similar measurements were made at each of the discrete springs in the Burry Valley. Since all the springs had large percolation components, hardness values were constant (Burry Head 9mg/1σ and Whitewells 5mg/1σ) thus there was little need to produce discharge/concentration rating curves. Weekly denudation was calculated by multiplying weekly spot hardness figures by weekly spot discharge readings.

Throughout the year, 89% of the total denudation was derived from the springs sampled but only 69% of the total discharge was thus derived, the difference being related to the high hardness values of the springs in the valley. The remaining 31% of the discharge and 11% of the total denudation was derived from tributaries running allogenically from the Old Red Sandstone watersheds, at low hardness values, and non-discrete seepages (in the valley) at higher hardnesses. The contribution of individual springs to the denudation load of the River Burry is dominated by Burry Head (58% of total solute load), Whitewells (20%), Burry Valley Pond (4%) and Burry Dairy Farm (3%), none of the other springs contribute more than 0.5%.

The total contribution of each spring to the basin solutional denudation is largely related to its discharge for the reasons outlined with reference to the total basin output. This figure however, takes no account of the catchment area of each spring and thus the overall rate of denudation over its entire basin. When this was calculated the following rates of denudation in terms of millimetres of surface lowering per 1,000 years were derived for each spring catchment. It is not suggested that rates of denudation are uniform within each spring catchment (see Mandel, 1967).

Table 2

	Spring	Denudational Rate (mm/1,000 yrs)
1.	Burry Dairy Farm	47
2.	Burry Head	39
3.	Burry Valley Pond	48
4.	Cheriton Woods West	26
5.	Mansel Fold	40
6.	Old Quarries	50
7.	Stackpool Mill	33
8.	Stembridge Mill	51
9.	Whitewells	43

THE WATER BALANCE, TOTAL DENUDATION AND DENUDATION RATES

Having reviewed the inputs and outputs to the Burry karst denudation system it is possible to calculate the water balance and denudational balance for the water year 1971-2. (Fig. 2).

Table 3 Precipitation, Discharge and Solute Data

	mm	Discharge (m^3)	Total Solutes (g)
Input	1049.38	28,039,433	64,000,000
Evapotranspiration	599.30	16,013,296	-
Abstraction	0.50	13,727	1,043
Output	430.50	11,504,236	2,289,503,000

The water balance simply expressed is:

Run off = Precipitation - evapotranspiration - abstraction ± storage.
431 = 1049 - 599 - 0.5 - 18.5 (mm)

The storage change volume is the remainder after other components of the budget have been calculated. In the Burry Catchment storage equalled 2% of the annual run-off. Storage may be soil moisture or ground water. Figures from the Meteorological Office (1971-2) show that soil moisture deficit at the beginning of the water year (29 September 1971) was 13.0mm in the South West Wales River Authority area, and that by the end of the water year (27 September 1972) this value had increased to 36.8mm. Thus during the water year the net soil moisture storage value had decreased by 23.8mm. Groundwater storage

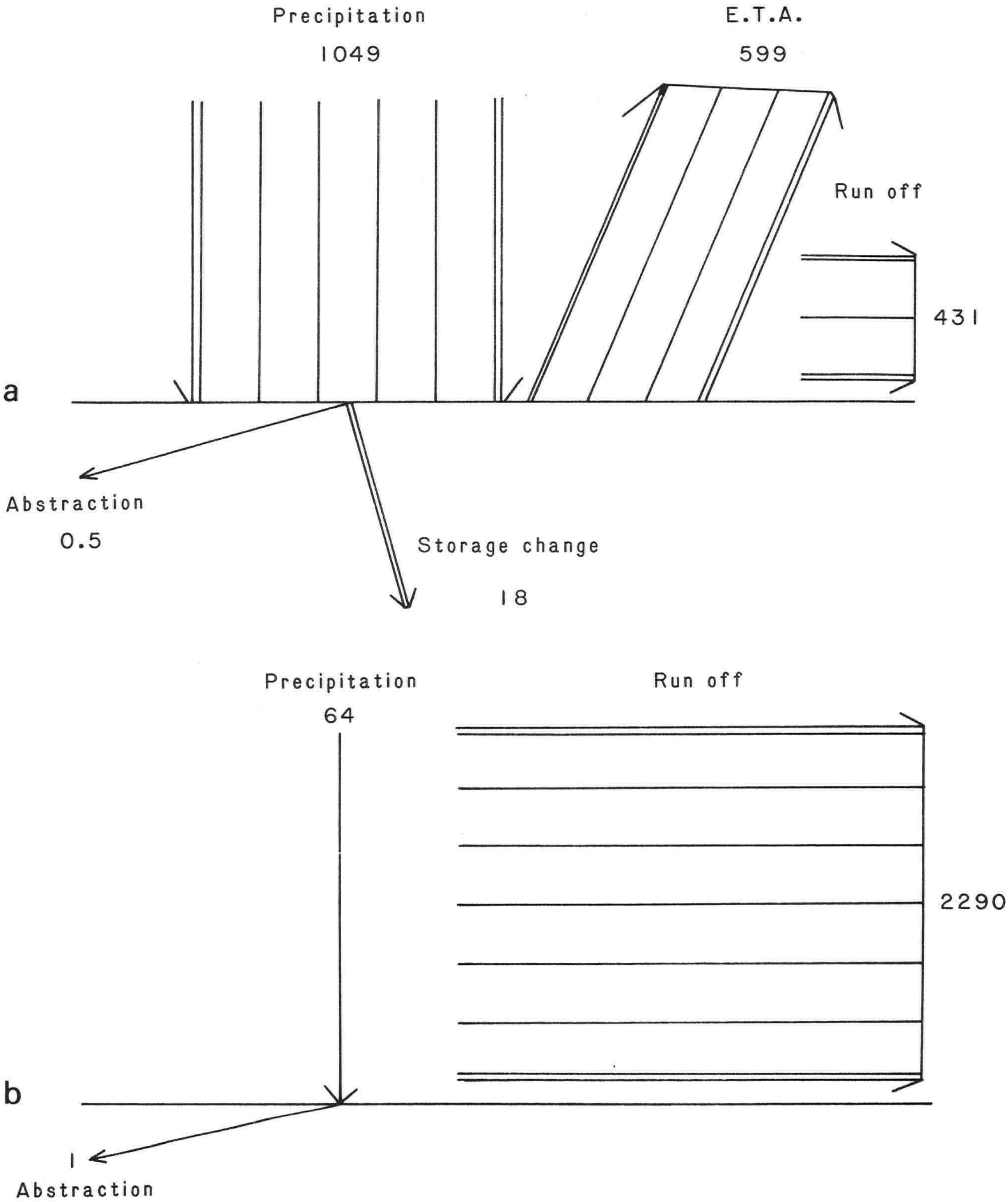

Fig. 2. The River Burry catchment: (a) water-balance 1971-2; figures are in millimetres of water depth equivalent; (b) Denudational balance: figures in grammes of solutes. The inclined lines represent directions of flow, i.e. inputs or outputs from the ground surface.

information is equivocal. Four of the sampled springs had larger discharge at the beginning of the hydrological year, whilst six had the opposite. If it is accepted that this indicates an approximate balance in groundwater storage then storage changes during the year represent a decrease of 24 mm; this relates clearly to the water balance equation as quoted above.

Total denudation and denudation rates have been variously calculated (Corbel, 1959; Williams, 1963; Groom & Williams, 1965; Williams P.W. 1968). In the present study the formula of Groom & Williams (1965) is used

$$X = \frac{Mr - Mp}{D \cdot A \cdot 10^6}$$

Where

X = rate of limestone solution in mm/1000 yrs or $m^3/yr/km^2$
Mr = mass of limestone run-off in one year in grams
Mp = mass of limestone input as precipitation in one year in grams
D = density of limestone
A = area of catchment in km^2

thus for the water year 1971-72 the following substitutions give:

$$X = \frac{2,289,504,043 - 64,000,000}{2.8 \times 26.72 \times 1,000,000} = 29.75 \text{ mm/1,000 years}$$

where Mr = the sum of the discharge at Cheriton Bridge and the abstraction at Holy Well.

Some 9% more precipitation occurred in the study year than during the 1915-1950 thirty-five year period. The hydrological systems studied respond in various ways to increased precipitation; if run-off is increased as a result of increased precipitation (not necessarily the case if precipitation occurs during periods of soil moisture deficit), the chemical concentration of the run-off may be expected to be more dilute. In the absence of long-term evapotranspiration data it is impossible to state whether this parameter was greater or less than average during the year of study. If it assumed that evapotranspiration is responsible for 50% of precipitation, then of the extra 9% input to the system, half would be lost to evapotranspiration. Thus 4.5% more than the mean run-off would have occurred in the water year. If it is assumed that a 4.5% increase is minimal and unlikely to affect the overall relationship between discharge and solute concentration then the increased discharge is likely to be reflected in increased overall total solute load of a similar magnitude. It is suggested that a negative adjustment of 4.5% could be made to give a truer long term value. The overall rate of lowering would be

$$x = \frac{2,186,475,000 - 61,000,000}{2.8 \times 26.72 \times 1,000,000} \text{ mm/1,000 years}$$
$$= 28.41 \text{ mm/1,000 years}$$

The net denudation rates of 29.75 and 28.41 mm per 1,000 years relate to the entire catchment area of the River Burry. Since denudation is not equally distributed over the whole of the basin because of the 18% cover of non-calcareous bedrock it is necessary to estimate solutional denudation from the calcareous section of the basin. This may be effected by the addition of a $\frac{1}{n}$ factor where n equals the proportion of limestone exposed in the basin.

This gives:

$$\frac{2,289,504,043 - 64,000,000 \times 1.22}{2.8 \times 26.72 \times 1,000,000} = 29.8 \text{ mm/1,000 years}$$

for the 1971-72 water year and

$$\frac{2,196,475 - 61,000,000 \times 1.22}{2.8 \times 26.72 \times 1,000,000} = 28.4 \text{ mm/1,000 years}$$

for the mean water years.

CONCLUSIONS

Only two other published estimates of denudation rates in South Wales are known to the author. Williams (1963) and Groom and Williams (1965) noted a rate of 15.77 mm per 1,000 years in the Mellte Basin of the North Crop of the South Wales limestone for the water year 1960-1, by water sampling. Direct measurement of the surface lowering of limestone pavements of the North Crop by Thomas (1970) indicated a rate of denudation of between 25 and 75 mm per 1,000 years depending upon lithology. A mean figure derived from these two estimates is probably premature although Atkinson (1972) allocated South Wales a mean areal rate of denudation of 32mm per 1,000 years. However, it is interesting to note that the present estimate is intermediate between Williams and Thomas. This would probably indicate that solutional losses in South Wales are less than other well-developed karst Carboniferous Limestone areas of the British Isles such as Yorkshire, Derbyshire, the Mendips, and County Clare, Ireland.

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INTENSIVE SAMPLING AT A KARST SPRING SYSTEM: LEASON, GOWER, SOUTH WALES

by W. J. Chambers

ABSTRACT

Intensive discharge and water chemistry studies of the Leason sink-resurgence spring system in Gower, South Wales, indicate that at the sinks drought discharge and water chemistry are constant, whilst during floods four dilution models apply. During the transition from summer to winter conditions total hardness levels and variability in hardness levels during storms are reduced. At the spring increased discharge correlated with dilution although some storm events exhibit concentration preceding dilution. During drought conditions the sinks contributed 3.2% of spring discharge and 0.7% of total solute load, whilst in storm conditions the respective figures are 58% and 14%.

Studies of karst drainage systems have changed in emphasis from extensive spot sampling to intensive regular sampling. The spot sampling approach of Corbel (1952, 1957) has been successively replaced by monthly (Pitty, 1966), fortnightly (Ternan, 1974), weekly (Ede, 1972) daily and hourly sampling intervals (Newson, 1970; Drew, 1974; Glover & Johnson, 1974). The present paper presents some approaches and results from the intensive study of one karst spring and its sink feeders (Chambers, 1976).

LEASON SPRING: EXPERIMENTAL SETTING

i) Location: The Leason system is located in the Gower Peninsula, South Wales. It rises on the northern slopes of Cefn Bryn, the central, east-west, watershed of Old Red Sandstone, and flows northwards to the Carboniferous Limestone outcrop. Soon after reaching the limestone, the numerous sink streams disappear to re-appear at Leason Spring at the foot of the pre-glacial cliffline overlooking the Loughor estuary (Fig. 1).

ii) Hydrology: the catchment area of the Leason system is approximately 1.75 km^2, although it is difficult to ascertain precisely because of its marshy, featureless headwater area where water tributary to Leason and the adjacent Llanrhidian and Burry catchments rises. The system has been studied by Corbel (1957), Baynton (1968), Taylor (1967), Ede (1972a) and Chambers (1973, 1976); water tracing tests employing fluorescein (Drew & Smith, 1968) and Leucophor B.S. (Crabtree 1970a, 1970b, 1971; Glover, 1972) have indicated the connection between three sinks at Freedown (N.G.R. 491915), Llwyn-y-Bwch east (484915) and Llwyn-y-Bwch west (483916) and Leason Spring (484927). Additionally, two other small, intermittent sinks in the vicinity of Freedom Farm contribute to the spring. Connections and flow-through times from the sinks to Leason have been measured by Baynton (1968), Ede (1972) and the present writer. Baynton quoted a four-day flow-through between Llwyn-y-Bwch and Leason, whilst Ede found times of less than twenty-four hours. Work by the present writer using both tracing and flood pulse techniques shows considerable variation directly dependent upon the antecedent precipitation index ($r = -0.89$), the minimum time period being 7 hours, maximum 36 hours and mean of 20 hours for ten storms.

iii) Meteorological Conditions: The experiment was run for ten weeks from 9th September 1972 to the 19th November 1972. In terms of precipitation and hydrology the period was divisible into two sections: the driest conditions of the calendar and water year between 9th September and 26th October, and the onset of winter conditions with the replenishment of soil moisture deficit between 26th October and the end of the experimental period. During the former period system discharge occurred and, during the latter, system recharge. At the start, soil moisture deficit was 47 mm, the year maximum, at the end it was less than 1 mm similarly the antecedent precipitation index started at 0.00 mm, rose to 67.1 mm on 13th November and was 42.1 mm at the end of the study period.

iv) Sampling Constraints: The timing of the experiment was related to the need for comparison between contrasting hydrological and seasonal conditions. Analysis of data from within the experimental period was dependent upon the satisfactory operation of equipment and the choice of contrasting conditions yielding data susceptible to analysis. Thus volumetric water hardness data was from 24th September - 9th October for drought conditions, and from 4th-19th November for floods. Numerous individual storms were also analysed and these were on 9th October, 6th, 10th, 12th, 16th and 17th November.

EQUIPMENT AND PURPOSE

Intensive sampling equipment was utilised in order that a detailed study of the sink-spring system and its response to meteorological variables could be made. Volumetric inputs and outputs were measured by means of autographic stage recorders in conjunction with V-notch weirs, rectangular weirs and stage boards at the sinks and spring. This was to assess the water budget of the system during specific periods, the effect of floods, the sources of flood water and to trace flood pulses through the system.

Water samples were collected by a fixed interval vacuum sampler at time intervals ranging between one and four hours depending on conditions. The samples were analysed by titration and allowed the calculation of denudational budgets during differing flow conditions and analysis of water flow history.

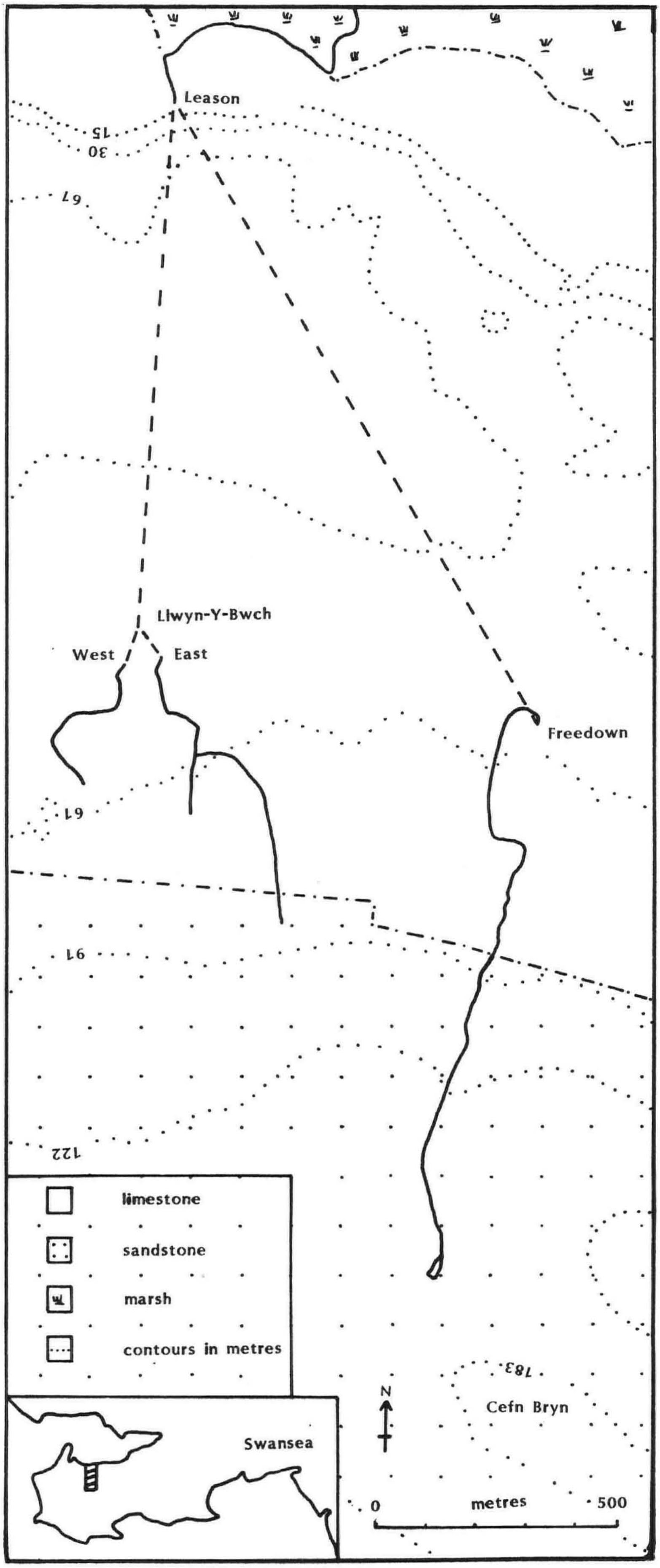

Fig. 1. The Leason Spring System

WATER HARDNESS RESULTS

Variations in water hardness at the sinks and the spring of the Leason system are clearly distinct and are considered separately:

i) Water Hardness at the Sinks:
In terms of hydrology and water chemistry a sink stream may be considered as any other surface stream. Most workers report an inverse relationship between hardness and discharge (Douglas, 1964). Increasingly, however, exceptions and modifications to this relationship have been noted (Hendrickson & Krieger, 1960; Toler, 1965; Gunnerson, 1967; Douglas, 1968; Hem, 1970) and numerous explanations and models have been applied. The basis of the inverse relationship is the difference in hardness between the highly mineralised groundwater and the dilute surface run-off components. Thus, the changing relative contributions of groundwater and surface run-off produce an inverse relationship between discharge and water hardness. The recognition of the simplified approach of Horton (1945) to run-off generation and the many groundwater paths available for subsurface flows (Kirkby & Chorley, 1967) has facilitated the acceptance and interpretation of the increased number of exceptions to the inverse relationship.

The inapplicability of the inverse relationship is a major problem in calculating total denudation. In view of the relatively high solute concentrations input by sink streams in limestone areas (ranging from 10% to 30% of the limestone spring water concentrations discharged (Table 1)),

Table 1

Author		Area	Sink hardness
Drew	1967	Mendips	89 ppm $CaCO_3$
Ford	1966	Mendips	119 ppm $CaCO_3$
Ede	1972	Gower	31 ppm $CaCO_3$
Chambers	1976	Gower	63 ppm $CaCO_3$ + $MgCo_3$

and since the main fluctuations in sink water hardness occur during times of flood it is apparent that an accurate consideration of the sink solute input variation is necessary for the accurate determination of denudation rates in karst drainage systems (Newson, 1971).

a) Water Hardness variation during a Drought Period 24th September - 9th October 1972.
Water samples were taken infrequently during drought conditions at the sinks; however, hardness values tended to be constant and high with the exception of conditions immediately preceding total drying-up of the sink streams when hardness values rose greatly. Thus Llwyn-y-Bwch east sink was at a hardness of 85 mg/l on 28th September and had risen to 105 mg/l by 5th October.

b) Water Hardness variations during flood periods.
Five storms were analysed at Freedown sink and three at Llwyn-y-Bwch west between 9th October and 20th November 1972. This period included the end of the summer flow regime and the establishment of winter flow conditions. The total hardness to discharge relationship at each sink was poor, whether analysed as all storms combined, individual storms, or all rising and falling limbs. Only at Freedown sink for all storms (significant at the 0.01 level) and for all rising limbs (significant at the 0.05 level) were any significant inverse relationships found between total hardness and discharge. Thus during the storms analysed there was no consistent relationship between discharge and total hardness except at Freedown where the relationship was weak. This is probably because the storms extended over widely different summer and winter flow conditions and also because different sources of water arrived at the swallet in rapid temporal succession. However, this does not explain the lack of correlation between similar limbs.

Whilst linear relationships between discharge and chemical parameters were not obvious, cyclic relationships of the type described by Toler (1965) and Hendrickson & Krieger (1960) were more apparent. By plotting discharge against total hardness and linking sequential measurements four types of response to precipitation were discernible at the sinks (Fig. 2).

TYPE 1. Exemplified by Llwyn-y-Bwch west on 12th and 17th November 1972, and Freedown on 10th November 1972. Initially a short-lived increase in chemical concentration coincided with a rise in the hydrograph; following this concentration fell rapidly, possibly coinciding with peak discharge. This was then followed by an increase in hardness or a constant hardness accompanied by a fall in discharge.

The initial stage may represent the 'flushing out' of the system of the products of evapotranspiration, atmospheric dust and stagnant pools (Hendrickson & Krieger, 1960). Stage two represents the arrival of the run-off from the storm, whilst stage three reflects the reassertion of a replenished groundwater, or the discharge of soil interflow, (Stenner, 1970) or a mixture of both. This form of response is associated with a short period of dry weather antecedent to a storm amidst an otherwise wet period. This would account for the concentration effect, the rapid dilution and the assertion of groundwater or interflow water immediately after the event.

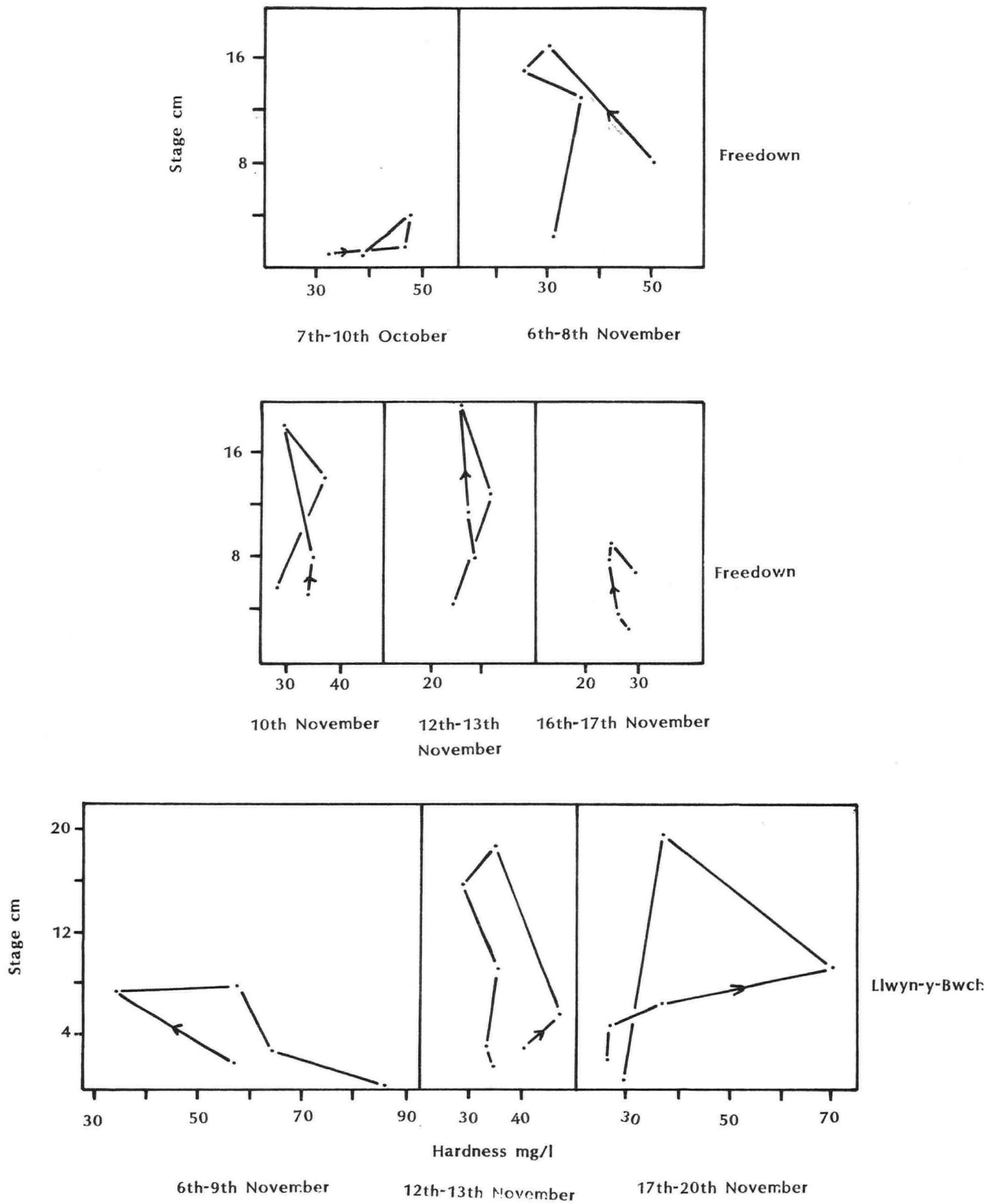

Fig. 2. Water hardness and discharge at the Sinks during flood conditions.

TYPE 2. Exemplified by Freedown sink on 9th-10th October, 1972; this model was also divisible into three distinct phases. An initial stage was characterised by a long slow rise of the hydrograph and chemical concentration. This was followed by or merged into a peak of discharge and chemical concentration persisting after the fall in discharge. Finally, when base flow had almost been re-attained, the chemical concentration fell fairly rapidly. This model was interpreted as characteristic of medium storms following a prolonged period of drought. The gradual rise of both parameters reflected the nature of the storm as it extended the headwater of the sink stream. The extended peak of chemical concentration reflected the large amount of mobile evaporation residue and dry fall-out available even after discharge fell. The final stage represented the termination of the residual solute transport and its substitution by baseflow of greater dilution than that existing before the storm.

TYPE 3. Exemplified by Freedown on 16th November, 1972 and Llwyn-y-Bwch west on 6th November; this simple model is one of dilution, and is the one most easily and consistently revealed by long interval sampling. The initial stage was a rapid increase in discharge accompanied by an equally rapid fall in concentration. This was followed by a gradual fall in discharge and rise in chemical concentration.

This model is interpreted as representing the rapid run-off of precipitation from ground already at or near saturation, consequently there is no increase in chemical concentration initially (i.e. no concentration effect). The subsequent rise in concentration simply reflects the re-establishment (at a slightly lower concentration) of groundwater or interflow conditions. This corresponds to Hendrickson and Krieger's 'anticlockwise' model (1960).

TYPE 4. Exemplified by Freedown sink on 6th-8th November and 12th-13th November, 1972; this model is basically one of dilution. Initially there was a rapid rise in discharge and an immediate dilution effect. This was followed by a slow decline in discharge accompanied by a fairly rapid rise in concentration or a levelling off of the dilution process followed by a rise in concentration. The effect of this was a peak concentration during the falling limb, clearly delayed after the peak discharge. This was then followed by a slow decline in concentration with the decline in discharge.

The model is interpreted as an initial dilution stage as a result of intense rain upon already saturated ground conditions. The second stage of falling discharge and a fairly rapid rise in concentration could be related to a 'flushing effect' delayed after the flood peak, but since the model requires an already saturated ground the source of the concentrated body of water to be flushed is problematic. An alternative explanation is that the increased hardness represents the re-assertion of the groundwater regime, but does not explain the subsequent dilution of run-off. Another possible explanation in view of the intensity and heaviness of both storms (41 mm and 29 mm respectively) is that a rapid rise in discharge occurred causing surface run-off and dilution. This masked any concentration effect for the duration of the flood peak, although the concentration effect was felt later with the removal of salts from the more distant parts of the catchment. With the flood recession, a dilution caused by shallow interflow (Stenner, 1970) occurred, which had not been replaced by deeper and more concentrated groundwater flow of longer residence time by the end of the experimental sampling.

c) Water Hardness Variations with the Onset of Winter Flow.

With the onset of winter flow conditions two clear changes were noted in the hardness of the sink streams; a decrease in total hardness and a decrease in total hardness variation within each storm. The general lowering of hardness at the sinks was measured in two ways: baseflow samples were taken immediately preceding each flood, and a varying number of samples taken through each storm were averaged to give a mean storm hardness. With the former method there is a decrease in total hardness at both sinks.

Table 2.

Water hardness before storm	Summer	→			Winter	in mg/1
Llwyn-y-Bwch west	86	-	40	-	30	
Freedown	38	49	33	28	29	

Similarly with the second method there is a decrease:

Table 3.

Mean storm hardness	Summer	→			Winter	in mg/1
Llwyn-y-Bwch west	59	-	36	-	38	
Freedown	39	34	33	27	26	

These results are attributed to dilution of groundwater and soil water by increased volume and lower concentration of precipitation with a short residence time, and also to the rapid succession of storms during this period which reduced the 'recovery period' for equilibrium conditions and thus baseflow conditions were not completely reattained before the onset of the next storm.

The second trend, of a generally decreasing magnitude of total hardness variation for each storm with the onset of winter conditions was noted at Freedown sink. Thus despite increasingly rainy conditions and higher antecedent moisture conditions, the degree of dilution decreased because of the generally lower mean hardness recorded above and because the easily soluble salts had been removed earlier in the wet period.

ii) Water Hardness at Leason Spring:
Two forms of short-term variation have been noted in the literature; flood and siphon effects. The latter have short periodicities (Drew, 1967; Atkinson, 1968) and are usually attributed to the 'siphoning-off' of phreatic water trapped in pockets and therefore harder (Waltham, in Atkinson 1968); the former are related to storm effects and are genetically similar to the flood effects noted at the sinks. Of the two, only flood effects have been detected at Leason Spring.

Ashton (1966) suggested that, depending upon the aquifer and underground configuration of the drainage system, two forms of chemical response are predictable at any one karst spring for any one storm. Thus dilution will almost certainly occur with the passage of flood water and concentration may occur depending upon the nature of the phreatic zone. Further, Ashton has shown that the temporal relations between dilution and concentration and various other parameters including storm discharge, water temperature and turbidity may be useful in the description and interpretation of the underground system.

a) Water Hardness variation during Flood Periods

Three storms on the 10th, 12th and 16th November 1972, each characterised by simple hydrographs and chemographs, were analysed (Fig. 3). The three storms were, respectively, of 12 mm, 25 mm, and 13 mm, with a maximum hourly rainfall intensity of 3.3 mm, 6.6 mm, and 2.25 mm.

As at the sinks, Leason Spring exhibited a poor correlation between short-term pairs of total hardness and discharge values. Thus whilst samples collected weekly for one year correlated significantly at 0.1% level (r = -0.68), the values for complete individual storms and for individual storms split into rising and falling limbs and for the three storms combined are low.

Unlike the sink streams however, the variations in spring hardness during one storm may be explained with recourse to a single simple cyclic modelafter Hendrickson & Krieger (1960). All three storms at the spring (Fig. 4) may be included within the anticlockwise model outlined earlier. In the case of the underground aquifer however, the concentrated reservoir of phreatic water is always available and thus the model operates following wet as well as dry weather.

A complication to the simplistic inverse correlations between water hardness and discharge at Leason was the existence of a very brief period of markedly increased concentration of water hardness with discharge on the 12th and 16th November storms. Thus in the eight hours immediately preceding the concentration effect of 12th November, the increase in water hardness per two hours was 1 mg/l, 2 mg/l, 3 mg/l, and 2 mg/l. This was then followed by an increase of 8 mg/l (154-162 mg/l) before the rapid decrease attributed to dilution occurred. Similarly immediately preceding the 15th November concentration effect the two hourly increases in total hardness were 1 mg/l, 1 mg/l, 1 mg/l and 0 mg/l, to be followed by an increase from 172 mg/l to 178 mg/l.

Table 4 Changes in water hardness in mg/l per 2 hours immediately preceding start of dilution

Storm	10-8 hrs	8-6	6-4	4-2	Concentration effect	Start of dilution
12/13th November	146-147	147-149	149-152	152-154	154⟶ 162	162-141
15th November	169-170	170-171	171-172	172-172	172⟶ 178	178-174

The increase could be attributed to the re-establishment of baseflow during the recession limb of the preceding storm, however the rapid concentration immediately preceding dilution would seem to indicate a marked concentration effect. Since this coincided with the increase in discharge (i.e. the flood pulse) it was attributed to the 'flushing out' of phreatic water as the flood pulse was transmitted from the epiphreatic surface to the spring opening.

In all three storms a rapid extreme dilution followed the concentration effect:

Table 5 Changes in water hardness in mg/l per two hours following the concentration effect: the dilution effect.

Storm	Concentration effect	0-2 hrs	2-4	4-6	6-8
12th November	154⟶ 162	162-141	141-81	81-68	-
15th November	172⟶ 178	178-174	174-156	156-107	107-90

The greatest dilution was achieved on 12th-13th November when a 60 mg/l dilution occurred in two hours, within four hours of the concentration effect. The peak dilution rate of the 15th/16th November storm was 4-6 hours after the concentration effect when a 49 mg/l dilution occurred. All three storms caused water hardness dilution of between 49% and 58%, the amount depending upon rainfall amount and maximum intensity.

TOTAL DENUDATION IN THE LEASON SYSTEM IN VARYING HYDROLOGICAL CONDITIONS

A sink-resurgence karst system of the Leason type is characterised by rapid and large changes in its physical and chemical parameters following storm rainfall. The changes are largely the result of the interaction between sink water and percolation water, during differing flow conditions. Attempts have been made to classify springs within this conceptual framework and thus two polar types have been recognised, karst springs fed by discrete conduits and those fed by diffuse percolation. Clearly the majority of karst springs occur on the discrete - diffuse, or sink - percolation continuum, as was recognised by Newson (1971). He proposed that any spring be attributed a 'swallet percentage contribution value', since all springs had a measurable component of their discharge and solute load supplied by swallet or sink water. The analysis of the Leason spring system during autumn 1972 exemplifies the various problems involved in this approach.

i) The Leason System in Drought Conditions: 24th September - 9th October 1972.

This period was the driest of the 1971-2 water year; with the exception of 2.2 mm on 13th September and 1.8 mm on 1st October, no rain fell from 8th September until 9th October. As a consequence Llwyn-y-Bwch west sink was dry and the other two sinks were very low in discharge at the start of the period. Freedown sink had a discharge of 2.4 litres per second and a total hardness concentration of 43 mg/l; thus 103 mg of calcium and magnesium were input per second. Llwyn-y-Bwch east was even less significant with a discharge of 0.2 litres per second and a total hardness of 66 mg/l giving a total input of 13 mg/sec. Simultaneously, Leason spring was discharging 33 litres per second at a concentration of 222 mg/l, giving a total solute discharge of 7326 mg/sec. Thus at the start of the drought period the sinks contributed 7.8% of Leason's discharge and 1.8% of its total solute load. System discharge was occurring and the system was dominated by percolation (diffuse) water.

By 9th October both the Freedown and Llwyn-y-Bwch east contributions had decreased to very insignificant amounts to the Leason system. Freedown had a discharge of 0.3 l/sec at a hardness of 41 mg/l giving a total input of 14 mg/sec, whilst Llwyn-y-Bwch east was almost dry with a discharge of 0.01 l/sec at 105 mg/l giving a total input of 1 mg/sec. At the same time, Leason spring discharge had not measurably decreased and remained at 33 l/sec whilst the total hardness had increased marginally to 224 mg/l giving an overall discharge of 7392 mg/sec. Thus by the end of the drought period sinks contributed 1% of Leason's discharge and 0.2% of its total solute load.

The total water and solute budget during the entire fifteen day period was:

Table 6

		Litres	%	grammes	%
Inputs	(i) Freedown	1,235,520	2.9	53,223	0.55
	(ii) Llwyn-y-Bwch each	133,056	0.3	10,065	0.15
Total input		1,368,576	3.2	63,288	0.70
Total Output	Leason	42,769,000	100	9,577,449	100
Unknown Input		41,400424	96.8	9,514,161	99.30

Thus the sink contributions to Leason spring were minimal over the fifteen day drought period with a mere total discharge of 3.2% and 0.7% of the total solute load. A considerable volume of water and solute load must therefore have been derived from alternative subterranean sources. Assuming a uniform homogeneous source some 41.4×10^6 litres of water with a total solute load of 9.5×10^6 grammes were provided from groundwater sources at a concentration of 225 - 230 mg/l. This was exactly the hardness of the water issuing from Leason spring during the drought period.

Thus as the drought period continued, the contribution of sink recharge to spring flow decreased and the relative contribution of percolation recharge and groundwater discharge increased. At no time was the 'swallet percentage contribution value' in excess of 3.2% for volume of water or 0.7% for total solute load.

ii) The Leason System in Flood Conditions: 4th November - 19 th November 1972.

The flood period was composed of four identifiable storms on the 7th (5 mm), 10th (12 mm), 13th (25 mm) and 16th November (13 mm); these followed a period of replenishment of soil moisture deficit between 26th October and 3rd November when a total of 38.3 mm of rain fell. During the flood period 148 mm of rain fell compared with 17 mm during the drought period, it is thus apparent that groundwater recharge occurred.

At the onset, Llwyn-y-Bwch west sink was dry and did not begin functioning until 6th November. Since discharge and solute values varied considerably during the period conditions at the beginning and end were not compared but rather a total mass balance of water and solutes for the period was measured. Additionally, maxima and minima were recorded at Llwyn-y-Bwch west and Freedown sinks and Leason spring:

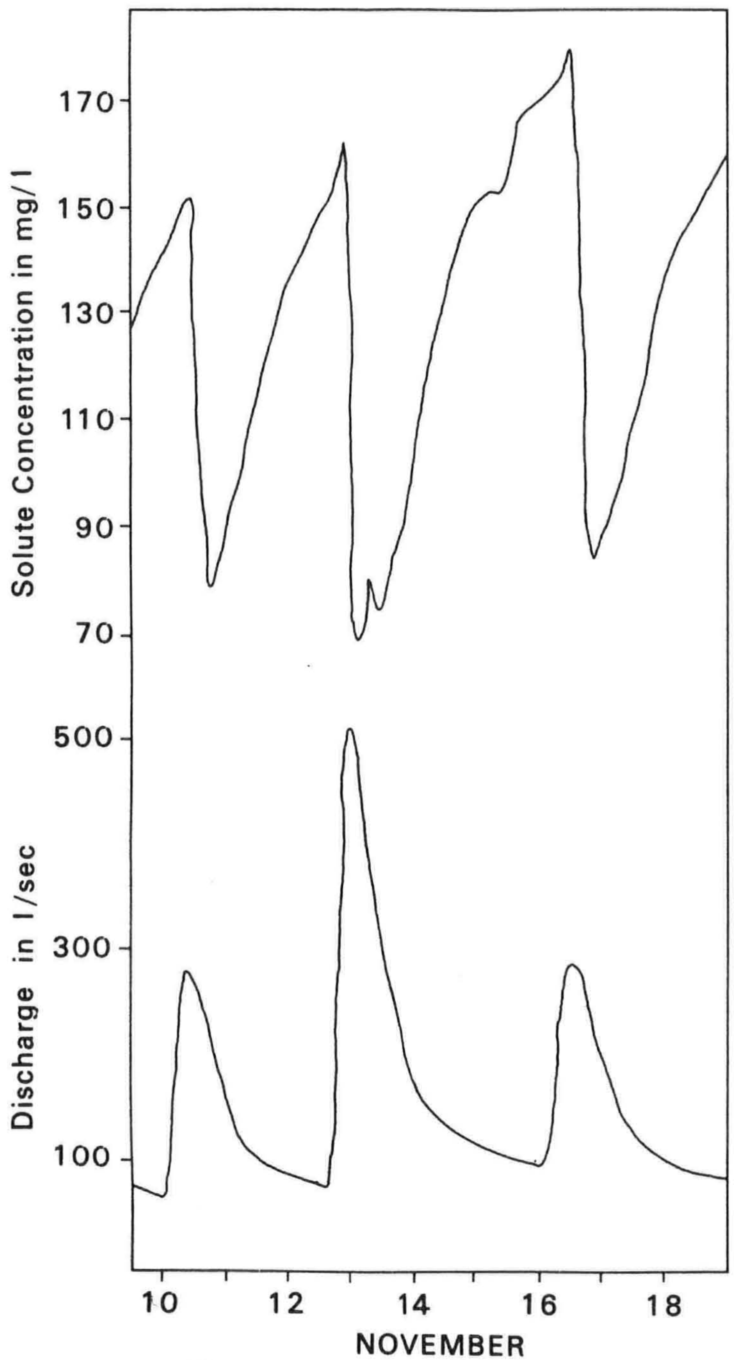

Fig. 3. Water hardness and discharge at Leason Spring during flood conditions.

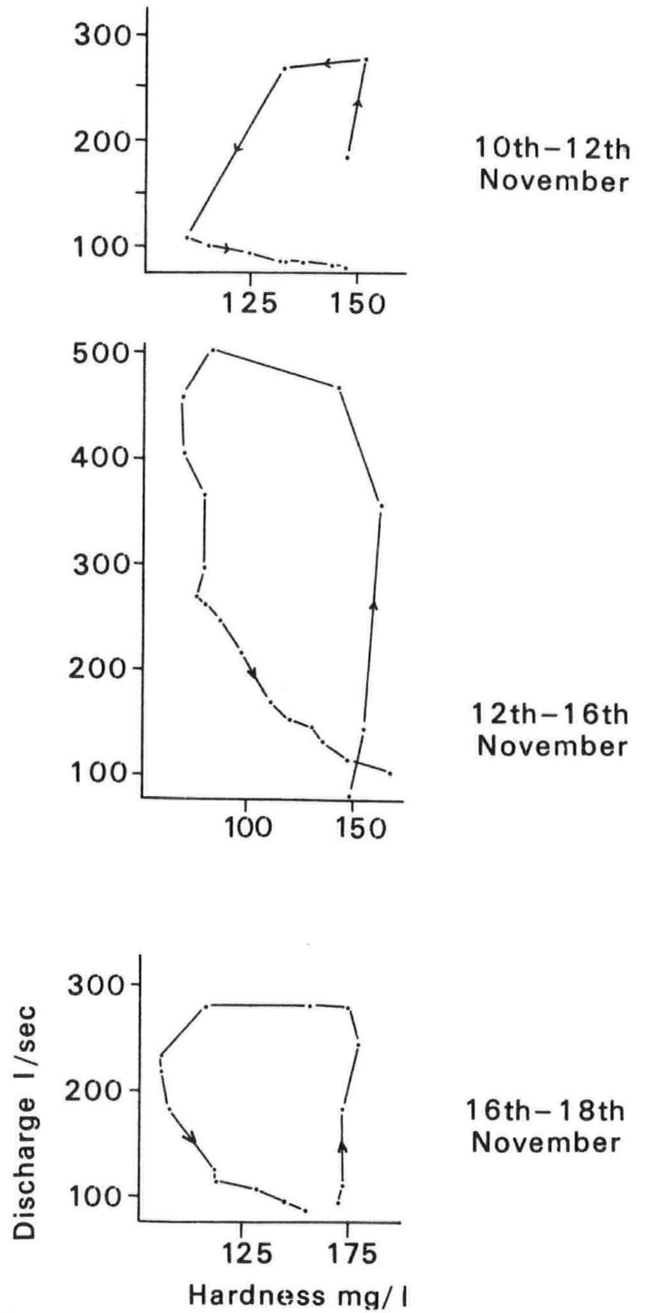

Fig. 4. Water hardness and discharge chemographs at Leason Spring during flood conditions.

Table 7

Site	Max. discharge litres/sec	Min. discharge litres/sec	Max. Solute Conc. mg/1	Min. Solute Conc. mg/1
Llwyn-y-Bwch west sink	400	1	86	27
Freendown sink	345	5	50	24
Leason spring	502	38	208	66

It is apparent that at times of high flood, input (recharge) to the system via sink water alone (i.e. not including overall percolation) exceeded output (discharge) from Leason spring.

The water and solute budgets for the system during the 15 day flood period are shown below in tabular form:

Table 8

	Water litres x 10^6	Budget %	Total Solute grammes	Budget %
Inputs: Freedown	78.9	40	2,508,608	9.2
Llwyn-y-Bwch east	3.3	2	106,927	0.4
Llwyn-y-Bwch west	31.8	16	1,240,842	4.6
Total Input	114.0	58	3,856,377	14.2
Output: Leason	193.8	100	27,146,000	100
∴ unknown output	79.7	42	-	-
∴ unknown input	-	-	23,290,000	85.8

Thus the three sinks accounted for 58% of the total water and 14% of the total solute input to the Leason system; this left 42% (81.4 litres x 10^6) of the water, and 86% (23.3 grammes x 10^6) of the dissolved calcium and magnesium unaccounted for. Apart from measurement error, two sources were likely; either unrecorded sink input from numerous ephemeral sinks or groundwater and percolation input. Baseflow separation of the flood hydrograph prior and immediately following the storms gave a mean baseflow of 60 litres per second during the storm period which gave a total baseflow contribution of 77 litres x 10^6. This was equivalent to 40% of the spring output and left a 2% unknown component: attributed to small ephemeral sinks known to exist in the catchment.

The total solute load was derived from sink input and underground solution. As noted above, 14% was input by the three major sinks and 86% from other sources dominated by groundwater. If it is assumed that all the 86% is groundwater, the concentration may be calculated by use of the mass balance equation:

Output from Leason = Sink input + groundwater input

27.1 grammes x 10^6 = 3.9 grammes x 10^6 + 23.2 grammes x 10^6

Thus the unknown input concentration had a concentration of:-

$$\frac{23.290 \text{ milligrammes x } 10^6}{81 \text{ litres x } 10^6} = 286 \text{ mg/1}$$

This value, 286 mg/1, is high compared with extreme drought hardness values recorded at Leason (225-230 mg/1); however, when compared with the hardness of neighbouring percolation springs (Landimore, Mansel Fold, Stembridge Mill) ranging between 280 and 325 mg/1, this value is credible.

The total effect of the storm period upon the discharge and total solute load of Leason spring may be calculated by multiplying the mean baseflow discharge for the period by the baseflow water hardness. This gives the total discharge and solute load assuming no storm event. This may then be compared with the measured values for the storm period and the effect of the storm calculated:

Table 9

Flow condition	Discharge (litres x 10^6)	Solute load (mg x 10^6)
Baseflow	77.8	17.5
Flood	193.8	27.1
Increase of flood period over baseflow	+149%	+55%

Thus the storm period was responsible for the removal of 55% extra solutes at the Leason system.

In addition to the description of 15 day storm period and drought periods, it should be noted that the effects of individual storms within the 15 day storm period may vary considerably from the mean values. When each of the five storms constituting the storm period are analysed individually marked differences in the sink input percentage occur:

Table 10

Period	Sink % contribution to a) Spring discharge	b) Spring total solute load
Drought	3.2	0.7
Flood	58.0	14.0
5th-7th November storm	91.8	27.2
7th-9th November storm	61.8	20.5
10th-12th November storm	55.2	14.9
12th-14th November storm	39.8	11.0
16th-17th November storm	40.5	9.0

iii) The Leason System: A Comparison of Drought and Flood Conditions

Considerable differences existed between drought and flood conditions. Despite identical time periods, significant differences were noted in the water volume and dissolved solids passing through the system. Four and a half times as much water passed through the system in the flood period, whilst 2.8 times as much solutes passed through. The contribution of the three major sinks in discharge increased 82 times, and their total solute load increased 61 times. The sink percentage contribution to flow varied from 3.2% to 58% during the 15 day periods, and instantaneously from less than 1% to more than 100%. From the speleological viewpoint total limestone solution during the flood period was the equivalent of a circular passage of 20 cm diameter and 26490 cm length, whilst that during drought conditions was equivalent to the solution of a passage of 20 cm diameter and 10821 cm length.

CONCLUSIONS

This study has shown the many differences which exist within one system in different hydrological conditions. Flood conditions are usually the more disruptive water hardness parameters, a result of the rapid changes experienced at the feeder sinks.

Relationships between sink discharge and hardness seem to be poor when correlated linearly, although cyclic models are more accurate.

The use of a 'sink percentage contribution' index to classify karst spring systems is seen to be difficult when the contrasts between drought and flood conditions, and between floods are noted.

The use of intensive and continuous sampling techniaues at a karst spring system gives a clearer picture of the great variability experienced within that system, and shows the danger of oversimplification of the karst hydrological systems.

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CAVE SCIENCE

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A MORPHOMETRIC AND GEOLOGICAL STUDY OF LIMESTONE PAVEMENTS IN SOUTH WALES

by K. Lewis

ABSTRACT

A study of fifteen small pavement areas in South Wales showed that pavements in the area were characterised by small clints averaging 88cm in length and 49cm in breadth. Grykes were wide and shallow. Both grain size and purity of the limestone appear to be significant controls of pavement morphology with large clints occurring on limestones with larger grain size and higher acid-insoluble residue content.

In the past few decades much has been added to our knowledge of limestone pavements. Most work has been carried out in northern England and western Ireland. In contrast very little research has been carried out on the pavements of South Wales. These are more broken up in appearance than their counterparts in Northern England and Western Ireland. Thomas (1969) stated that 95% of the South Wales pavements fall into the thinly-bedded type as defined by Sweeting (1966). Thomas (1969) also noted the importance of minor fracture planes in affecting the rate of solution of each pavement in South Wales. Sweeting (1972) described the pavements of South Wales as being poorly preserved and accounted for this by acid waters draining from glacial deposits and peat accomplishing much solution of the limestone.

The work reported in this paper aims to describe the morphology of selected pavements in the limestone area to the north of the South Wales coalfield (Fig. 1), and to investigate in particular the effect of various geological factors influencing pavement development and morphology.

The pavement-bearing outcrop of limestone forms a broad arc around the north outcrop of the South Wales coalfield (Fig.1). It reaches a maximum width of 4.5 km east of Ystradfellte. Most of the outcrop is buried beneath a cover of stiff impermeable boulder clay which Thomas (1969) considered to protect the underlying rock from solution.

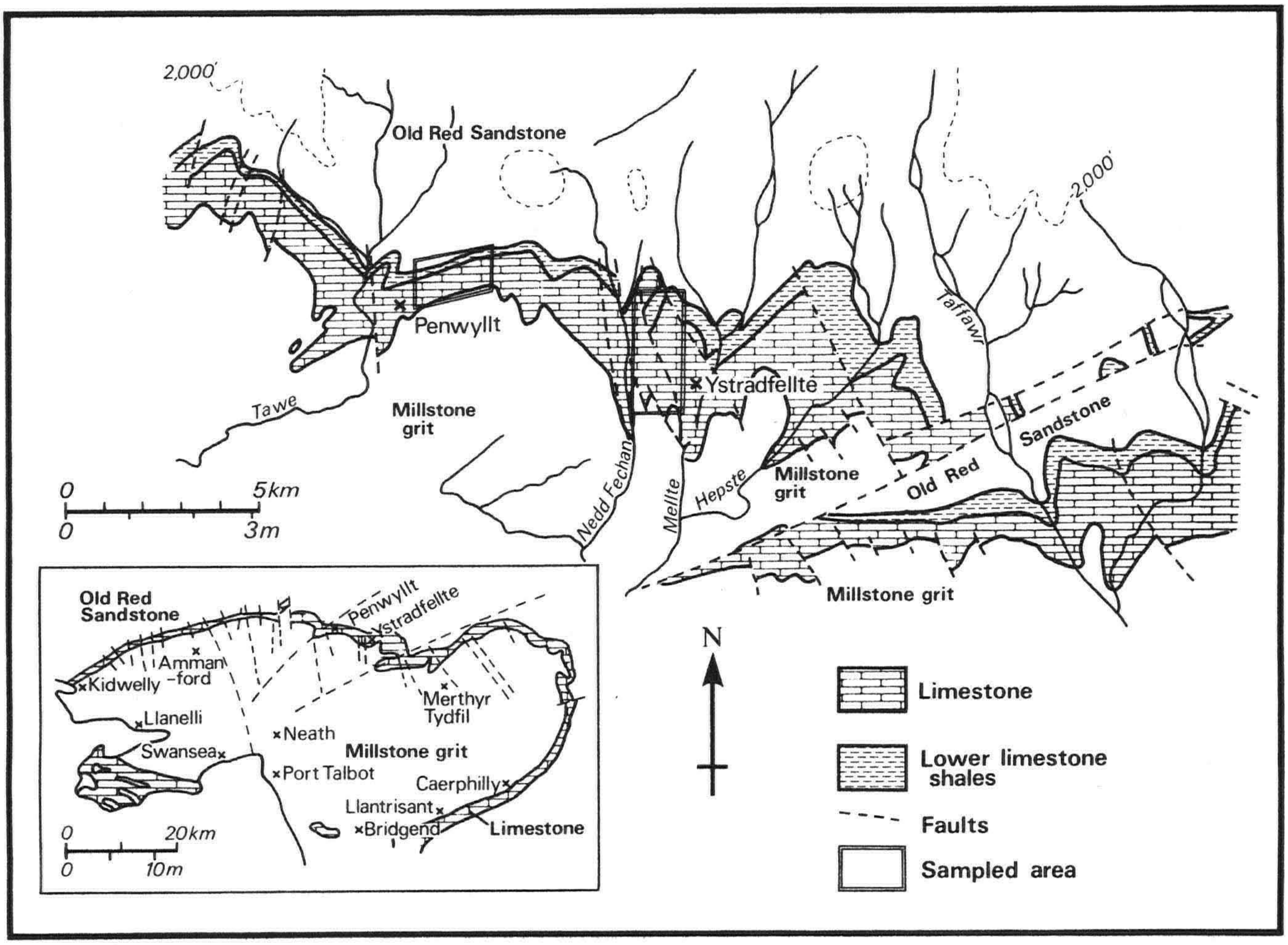

Fig. 1 Location map of the Carboniferous Limestone outcrop lying north of the central sections of the South Wales coalfield. (After Thomas, 1969).

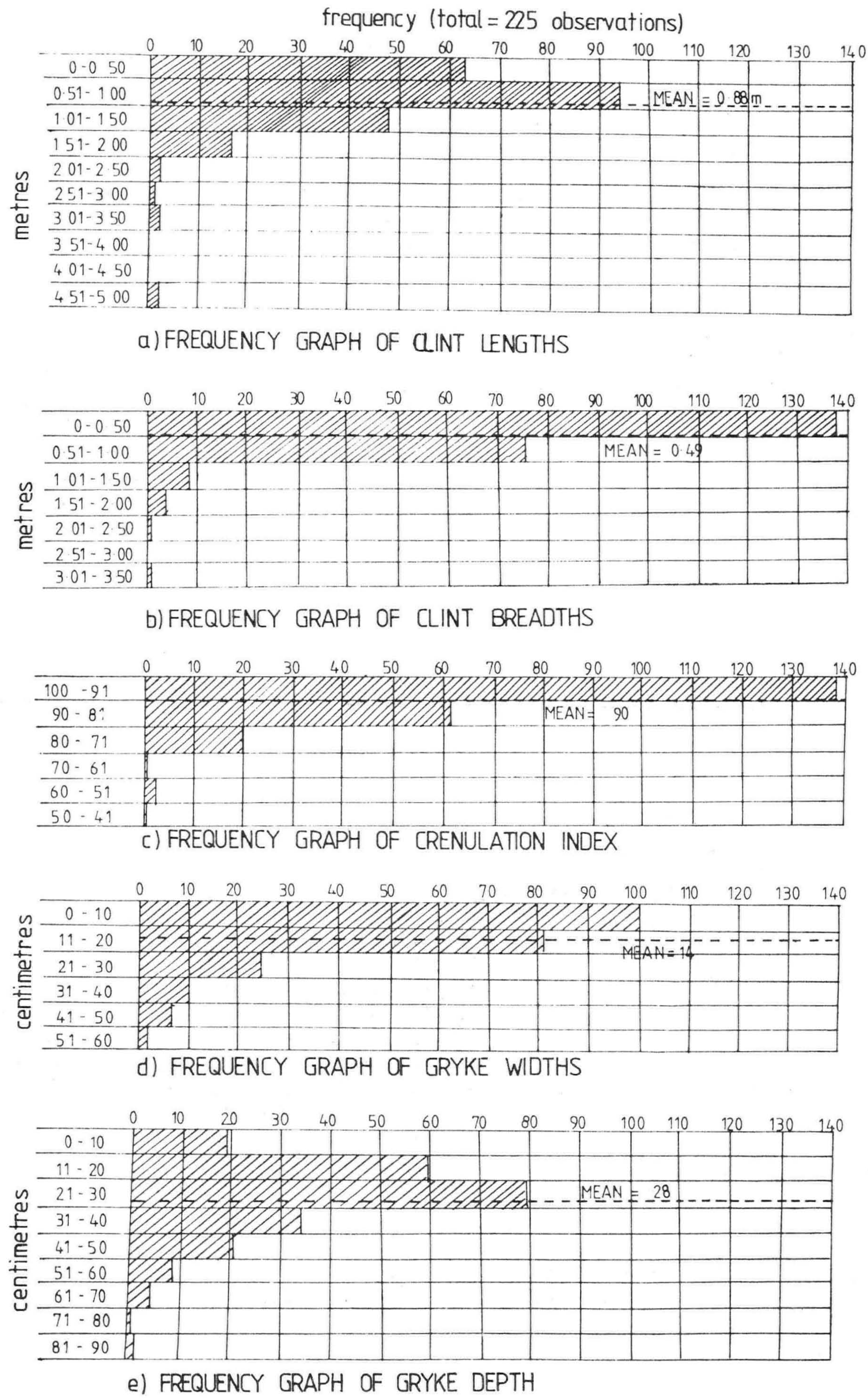

Fig. 2 Frequency histograms of the measured components of morphology of the South Wales pavements.

The limestone is of Carboniferous age and can be divided into the Lower Limestone Shales, the Main Limestone and the Upper Limestone Shales, with only the Main Limestone supporting pavements. The Main Limestone is made up of a number of different types of limestone. These are a dark sandy limestone, a light oolite, a coarse crinoidal limestone and a dark massive limestone and oolite. The dark massive limestone and oolite is the thickest of these limestone types, having a thickness of between 91 and 106 m. The dip of the outcrop is southerly, decreasing from 20^{o} to 30^{o} in the west to 5^{o} to 10^{o} in the east. The studied area is believed to have been glaciated during the last glacial phase (Bowen, 1971).

In total 15 areas of pavement were investigated, eight located near Ystradfellte on a spur between the Mellte and Nedd-fechan valleys at 370 to 400 m O.D. and seven near Penwyllt at 480 to 520 m O.D. (appendix). No pavement investigated was greater than 1.8ha in area. The dips of the pavements varied between 6^{o} and 8^{o}S near Ystradfellte, and between 10^{o} and 14^{o}S near Penwyllt.

PAVEMENT MORPHOLOGY

A number of components of pavement morphology were measured. These included clint length and breadth, gryke width and depth, clint crenulation and area of exposed rock and area of loose flaggy rubble known as shillow (Sweeting, 1966).

a) Clint length and clint breadth:

Clint length was taken as the maximum dimension of the clint surface. The majority of the measured lengths were less than 2 m with a mean value of 88 cm (Fig. 2.a). Clint breadth was measured normal to clint length and had a mean of 49 cm (Fig. 2.b). These low values relate to the closeness of joint spacing in the sampled area, and to the destruction of clints by frost-action, aided by the presence of minor fracture planes.

b) Clint crenulation:

This is the ratio of the clint length to the clint surface length (Fig.3). A value of 1.0 denotes a perfectly plane surface. Most values obtained were between 0.9 and 1.0 (Fig. 2.c) showing that most clints were relatively plane. Pavements with a high degree of crenulation, denoted by low values, were usually associated with overhanging trees, or tall overhanging grasses, which channel rainwater onto the clint surface. This chemically aggressive water accomplishes much solution where it comes into contact with the clint surface and where it runs off, forming a runnel.

c) Gryke widths and depths:

Grykes in the sampled area were both narrow and shallow. Gryke widths were generally less than 30 cm with an overall mean of 14 cm (Fig. 2.d). Gryke depths were usually between 11 and 50 cm with a maximum measured depth of 86 cm (Fig. 2.e). These shallow grykes are the result of frost action reducing clint size and infilling the grykes with debris.

d) Area of exposed rock:

This was taken as being the area covered by clints plus the area covered by shillow. It was obtained by sampling at regular intervals along a number of transects across each pavement. The values of the area of exposed rock ranged from 18% of the total pavement area at Ystradfellte pavement number 5, to 93% at Penwyllt pavement number 12 (Fig. 4).

Statistical analysis of these data showed a significant negative correlation ($r = -0.47$, significant at the 0.05 level), between the area covered by shillow and clint length. This showed that pavements with a larger area of shillow had smaller clints. Shillow is believed to be formed through frost-action on clints. Thus the above findings demonstrate the importance of frost action on South Wales pavements.

South Wales limestone pavements are for the most part characterised by small clints with a low degree of surface crenulation, and shallow grykes. There is strong evidence that the pavements have been severely broken up, probably by frost action aided by the presence of the numerous minor fracture planes.

GEOLOGICAL FACTORS

In order to account for the variations in morphology recorded between the 15 pavement areas, rock samples were collected from the pavements for laboratory analysis. The percentage acid in soluble residue was determined by the technique devised by Molnia (1974) and grain size characteristics obtained from photographs of thin sections. The results are summarised in Table 1.

a) Grain Size:

Grain size ranged from less than 2μm to over 100μm with a mean of 24μm. This large range can be accounted for by the presence of a number of different limestones. Statistical analysis showed a significant positive correlation, at the 0.05 level, between the mean clint surface area (clint length x clint breadth) and mean grain size. Thus limestones with larger grain sizes give rise to clints of greater area. This accords with Sweeting's (1979) observations that large-grained limestones are less soluble than fine-grained limestones.

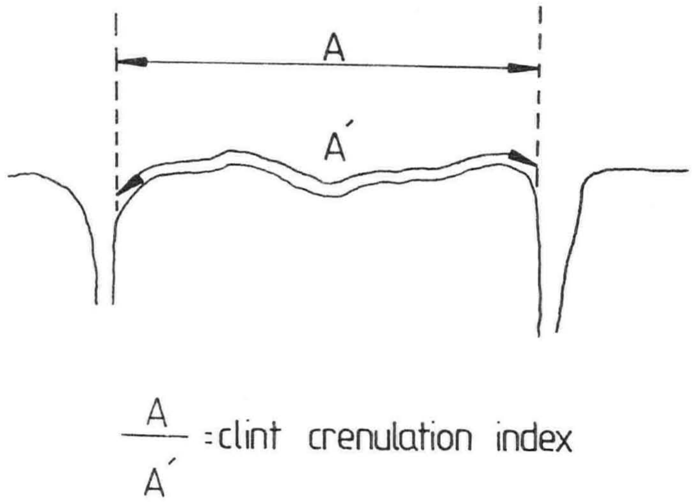

Fig. 3   Diagram to illustrate the crenulation index.

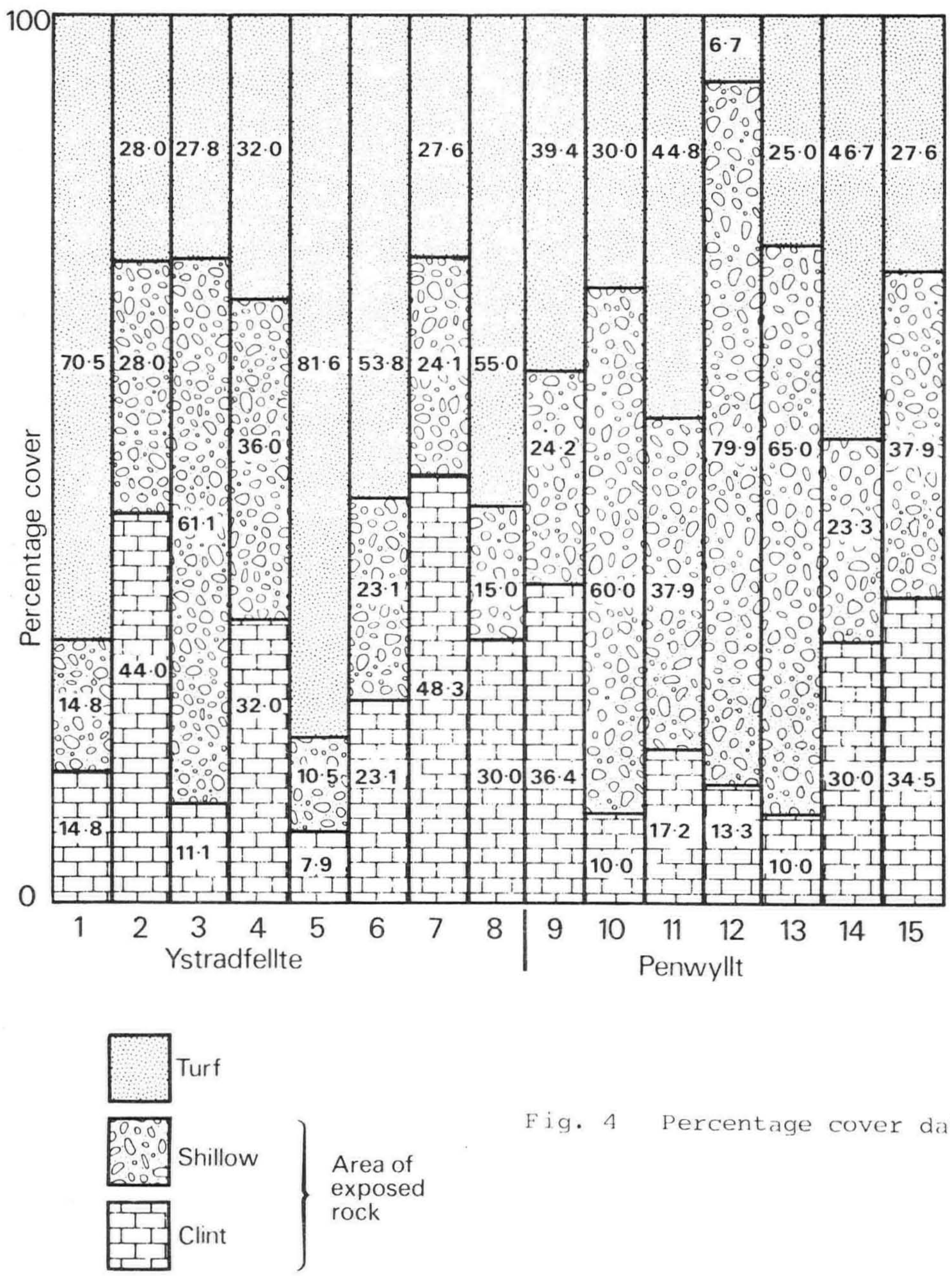

Fig. 4   Percentage cover data.

Table 1.

Pavement Number		Grain Size (Microns) Mean	Range	Standard Deviation	% Insoluble Residue	Dip
Ystradfellte	1	35.12	91.0	23.68	4.53	6°
"	2	26.05	57.0	12.37	7.26	6°
"	3	16.34	57.0	13.99	5.79	6°
"	4	10.21	26.0	6.72	8.24	6°
"	5	11.74	27.0	5.98	5.42	9°
"	6	26.46	72.0	12.76	4.84	8°
"	7	29.22	81.0	20.99	6.27	8°
"	8	33.07	104.0	20.00	5.70	6°
Penwyllt	9	30.36	61.0	14.42	6.66	10°
"	10	<2.00	<2.0	<2.00	5.01	14°
"	11	23.88	63.0	12.39	6.20	12°
"	12	25.94	66.0	14.63	5.58	12°
"	13	17.66	32.0	6.75	4.72	12°
"	14	26.62	81.0	14.64	5.02	10°
"	15	<2.00	<2.0	<2.00	4.66	7°

b) Acid Insoluble Residue:

This ranged from 4.5 to 8.2%, again accounted for by the presence of different limestones. A statistically significant positive correlation, at the 0.05 level, was obtained between the total clint area and the percentage insoluble residue, the more impure limestones having a larger clint area. The more impure limestones appear therefore to be less susceptible to solution.

This conclusion was confirmed by acid digestion analysis of rock samples from a limestone outcrop between two pavement surfaces at Ystradfellte (Fig.5). The highest insoluble residue values tended to be associated with the pavement bearing horizon, with the lowest values occurring midway between the two pavement surfaces. Pavements therefore appear to be associated with the more impure limestones with the highest insoluble residue content.

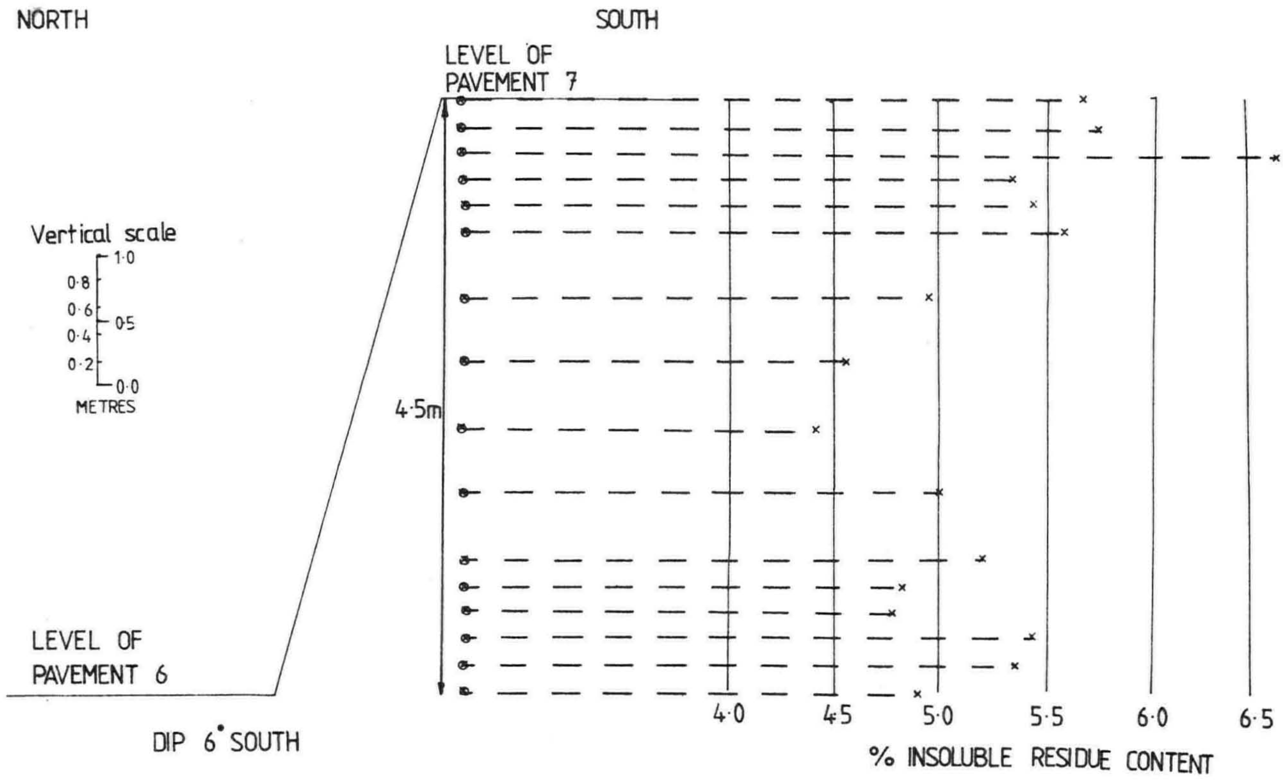

Fig. 5 Diagram to illustrate insoluble residue content between two pavements at Ystradfellte.

c) Dip:

Dip varied quite substantially with the highest value being 14 degrees, at Penwyllt and the lowest being 6 degrees at Ystradfellte. All dips were to the south. Dip showed no significant relationship with any measured component of pavement morphology.

CONCLUSION

The pavements of South Wales are characteristically of broken up appearance and have small clints and wide shallow grykes. Both grain size and purity of the limestone appear to be significant controls of pavement morphology with large clints occurring on limestones with larger grain sizes and higher acid insoluble residue content. The dip of the limestone strata appears to have little influence on pavement morphology.

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I would like to express my thanks to Dr. L. Ternan for supervising my undergraduate dissertation and for supplying invaluable help in the preparation of this report. I would also like to thank the staff and technicians of the Department of Geographical Sciences, Plymouth Polytechnic for their help and advice. This work was carried out as part of an undergraduate dissertation as a student in the Department of Geographical Science, Plymouth Polytechnic.

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APPENDIX

PAVEMENT NUMBER	GRID REFERENCE	PAVEMENT NUMBER	GRID REFERENCE
Ystradfellte 1	SN 923141	Penwyllt 9	SN 867159
Ystradfellte 2	SN 921143	Penwyllt 10	SN 868163
Ystradfellte 3	SN 916146	Penwyllt 11	SN 870165
Ystradfellte 4	SN 916143	Penwyllt 12	SN 872165
Ystradfellte 5	SN 916142	Penwyllt 13	SN 873164
Ystradfellte 6	SN 917141	Penwyllt 14	SN 875164
Ystradfellte 7	SN 917140	Penwyllt 15	SN 872162
Ystradfellte 8	SN 914141		

CAVE SCIENCE

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A COMPUTER PROGRAM TO AID CAVE SURVEYING

S. Reid

ABSTRACT

The increasing availability of modern computers now means that surveyors can take advantage of their capabilities to process raw survey data in a reasonably comprehensive manner. The program presented has been written to be compatible with most makes of computers, rather than dedicated to any particular one, and calculates values for a centre line survey in plan and section, plus other features.

This article stems from the rapid growth in popularity of micro and mini computers. The increasing availability of these, particularly in the domestic field, means that cavers are now able to take advantage of the capabilities of these machines. Probably the most useful application for cavers is that of surveying, where there is a requirement for repetitive calculations to be performed, which can be tedious, even with the assistance of a pocket calculator. Computer programs to aid cave surveying are not new but most are too basic, i.e. for programmable pocket calculators, or too complex and require access to larger computers not generally available.

The program presented here has two main objectives:

(i) To produce the data required for a centre line survey in plan and section.

(ii) For the program to be written in a form that is compatible with most of the common varieties of the B.A.S.I.C. language, and to be used without the need to become too involved with the details of computer operation and programming.

Extra features are included which are described later.

It is aimed at machines using the B.A.S.I.C. language, (Beginners All Purpose Symbolic Instruction Code), such as Sinclair, Commodore, Apple, Dragon, etc. and machines at the bottom end of the industrial and commercial range, such as the Hewlett Packard HP 85 (on which this program was developed).

Unfortunately, since B.A.S.I.C. instructions can vary slightly between similar types of machine, the program is written as simply as possible, so that conversion can be effected with minimal difficulty. This results in a program that a professional programmer would regard as untidy and long-winded; however, in the interests of simplicity for the non-computer-oriented person, it is considered that this approach is valid.

The theories of cave surveying and computing are adequately covered in the existing literature (see references) so discussion of these subjects is limited to points necessary to explain the program.

Hardware Required

A computer system is required: for example, if a Sinclair is purchased, the package contains the computer and keyboard only. To be viable a display, program storage device and printer are required. The display is a television set (mono or colour) and the program storage is usually by means of a cheap cassette recorder. The printer appropriate to the computer used is necessary to give a hard copy of the data. If a printer is not available, an alternative program is provided. (Appendix 5).

The program requires a memory capacity of 23 Kbytes; however, methods will be described of using the program in an abbreviated form for computers with less memory.

What the Program Will Do

From three basic parameters, distance, bearing and inclination, the program will give ten values for each survey station:

1.	Ordinate East)	enable a plan survey to be drawn
2.	Ordinate North)	
3.	Horizontal Change	Note - horizontal, not necessarily the leg length measured.
4.	Vertical Change	
5.	Altitude	
6.	Length	
7.	Depth	Cumulative totals of each (Items 6 and 7)
8.	Distance	
9.	Bearing	the original data entered, plus any correction factors (Items 8, 9 and 10)
10.	Clinometer	

Note that items 3 and 6 are not incremented if a vertical pitch is encountered, i.e. if the inclination is $\pm 90^{o}$.

The facility for correction values for compass and clinometer are incorporated, as are values for depth correction and grid correction, the latter three enabling closed loop errors to be distributed.

Having calculated the data for each survey station, the computer will give the straight line horizontal distance and bearing from the first to last set of data entered. The surveyor can then request sections on any bearings he chooses, (projected sections).

All the above can be achieved from either the "forwards only" method of surveying, whereby the surveyor measures in front of himself for each leg, or the "leapfrog" method where the instruments are used at alternate survey stations and reverse/forward legs measured from one position.

Entering the Program Into Computer Memory

For Hewlett Packard machines using B.A.S.I.C. language, the program is entered via the keyboard, exactly as published. For other machines, minor difference in syntax will exist, primarily connected with the printer instructions; some reference to the manual may be necessary for these. For the remainder, Appendix 4 lists the equivalent key words. It must be emphasised that once the program is permanently stored on a cassette (or disc), then no special knowledge is required to use it. Methods for storing the program on tape vary so much that again reference to the manual will be necessary; however, on most machines this is a simple operation.

If the available computer does not have a 23 Kbyte memory, the best way of condensing the program is to reduce the number of survey stations that can be processed. As written it is 150 but the value 153 in lines 60 to 90 and all following lines containing the value 153, such as 1440 and 2150, can be reduced to a lower figure plus 3. For example, for 50 stations (or legs) change the values 153 to 53; the program will then require a memory of 15.2 Kbytes.

Running the Program

When the RUN key is pressed, the display will give a prompt reminding the user that the maximum number of survey stations that can be used is 150 and instructions for the entry of the grid ordinates, then the instruction to enter the survey title. When this is done, the title will be printed, the display will clear and then request the compass correction value. When this is entered, the display will again clear, then request the clinometer correction value, which should then be entered. This procedure will continue for all the datum and correction values. If some are not known, or required, then enter zero (Ø). (When the grid ordinates are requested, values for any grid may be entered).

When the initial base data has been entered, the display will show:

NOW BEGIN TO ENTER STATION DATA

STATION No. ?

The station number is then entered, e.g. 1 or 2 if the leapfrog method is used. The display will then show:

DIRECTION F/R

Enter F for the forwards method, or R if the leapfrog method is to be used. The display will then show:

DISTANCE ?

This value should be entered, then the same will apply for values of bearing and inclination. The display will then show:

MORE DATA Y OR N ?

(next station no.) X

Enter Y if you want to enter more station data, otherwise N. The statement giving the next station number in brackets prompts the user what the next station number will be, assuming a numerical progression of one, but will not apply, and should be ignored, if the leapfrog method is used. If a vertical pitch is encountered (i.e. inclination of 90^{o}), then the bearing should be entered as zero, and the value for pitch height given for distance, and the clinometer as 90, + or - according to direction.

If N for finish of data entry is pressed, the printer will list the data for all the stations, followed by the values for the direct horizontal distance and bearing between the start and finish points of the set of data entered. The display will then show:

FOR SECTION, ENTER BEARING

When a bearing is entered, data to draw a section on that bearing (projected section) is printed. By following the prompts, as many sections of varying bearings can be produced, thus allowing a simplified form of polar analysis.

If a closed loop survey has been achieved, the closure point should ideally have the same ordinates as the start of the loop. The error can be distributed by taking the difference in the values for grid east and grid north and depth, at the closure point, and dividing them by the number of survey stations in the loop.

The values are given by the computer and may be used by re-running the program using the values in the appropriate correction factors (either the whole of the data could be re-processed, or the loop portion only. Note that the user will have to check the "polarity" of the values, i.e. whether positive or negative, by reference to the difference between the start and finish ordinates.

Finally, it should be noted that where possible, "gates" are incorporated, so that if a key is pressed in error, the program will not abort, just repeat the previous prompt, e.g. line 1080 refers to the request to enter F or R, if a letter other than these is entered, the program returns to line 1060 to repeat the prompt. A sample of print out is given in Appendix I to illustrate the presentation of data.

CONCLUSIONS

To expand the program further would require extra memory beyond that possessed by the machines at which it is aimed. It should be noted that, if a good closed loop is achieved, then the values for the straight line horizontal distance and bearing from end to end can be in error, but this will usually be obvious. Also note that when entering the title, the maximum number of characters allowed, including punctuation and spaces, is 96.

It is recommended to check the program for errors arising in transcription by first using it on data known to be accurate, and previously calculated and drawn. Appendix 2 is an example of a simple test that can be applied as it effectively plots a square. To use this, enter the four sets of data shown in the example, if all is well the final ordinates East North and Altitude will be the same as those initially entered.

Appendix 1 lists the program, while Appendix 3 gives an example of the full print out, using the same data as in Appendix 2 but with errors, then the same data re-processed to show the effect of using the error correction values.

Finally, if a computer other than a Hewlett Packard HP85 is used it is recommended that the user types in the program with reference to Appendix 4 and the machines instruction manual to accommodate any differences in syntax as they arise.

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```
10 REM ************************
20 REM **** PROGRAM 'BCRA'   ***
30 REM **** S.REID  1983     ***
40 REM ************************
50 OPTION BASE 1
60 DIM B(153)
70 DIM H(153)
80 DIM L(153)
90 DIM T(153)
100 DIM D(153)
110 DIM E(153)
120 DIM G(153)
130 DIM V(153)
140 DIM K(153)
150 DIM A(153)
160 DIM O(153)
170 DIM U(153)
180 DIM M(2,153)
190 FOR N=1 TO 153
200 L(N)=0
210 B(N)=0
220 O(N)=0
230 E(N)=0
240 U(N)=0
250 H(N)=0
260 NEXT N
270 DIM X$[96]
280 T,K,N,Q,S,P=0
290 DEG
300 DISP "NOTE THAT THE MAX.No.O
    FSURVEY STATIONS ACCEPTABLE
    TO THIS PROGRAMME IS 150"
310 DISP
320 DISP
330 DISP "ENTER GRID AS 5 DIGIT
    No.BOTH EAST&NORTH i.e.NNNNN
       RESOLUTION = 10cm"
340 DISP
350 DISP
360 DISP
370 DISP
380 DISP "ENTER SURVEY TITLE (DO
    NOT USE COMMAS)"
390 INPUT X$
400 PRINT X$
410 PRINT
420 PRINT
430 PRINT
440 PRINT
450 CLEAR
460 DISP @ DISP
470 PRINT
480 CLEAR
490 DISP @ DISP
500 DISP "ENTER COMPASS CORRECTI
    ON VALUE"
510 INPUT C
520 PRINT
530 PRINT "COMPASS CORRECTION VA
    LUE ";C
540 PRINT
550 CLEAR
560 DISP @ DISP
570 DISP "ENTER CLINO. CORRECTIO
    N VALUE"
580 INPUT J
590 PRINT "CLINO.CORRECTION VALU
    E ";J
600 PRINT
610 CLEAR
620 DISP @ DISP
630 DISP "ENTER START ORDINATE E
    AST"
640 INPUT E
650 PRINT "START ORDINATE EAST "
    ;E
660 PRINT
670 CLEAR
680 DISP @ DISP
690 DISP "ENTER START ORDINATE N
    ORTH"
700 INPUT G
710 PRINT "START ORDINATE NORTH
    ";G
720 M(1,1)=E
730 M(2,1)=G
740 PRINT
750 CLEAR
760 DISP @ DISP
770 DISP "ENTER START ALTITUDE"
780 INPUT U0
790 PRINT "START ALTITUDE ";U0
800 PRINT
810 CLEAR
820 DISP @ DISP
830 DISP "ENTER GRID EAST CORREC
    TION VALUE"
840 INPUT E2
850 PRINT "GRID EAST CORRECTION
    VALUE";E2
860 CLEAR @ PRINT
870 DISP @ DISP
880 DISP "ENTER GRID NORTH CORRE
    CTION VALUE"
890 INPUT G2
900 PRINT "GRID NORTH CORRECTION
     VALUE";G2
910 PRINT @ CLEAR
920 DISP @ DISP
930 DISP "ENTER DEPTH CORRECTION
     VALUE"
940 INPUT V2
950 PRINT "DEPTH CORRECTION VALU
    E";V2
960 PRINT
970 PRINT
980 U=U0
990 CLEAR
1000 DISP @ DISP
1010 DISP "NOW BEGIN TO ENTER ST
     ATION DATA"
1020 DISP @ DISP
1030 N=1
1040 DISP "STATION No. ?"
1050 INPUT L
1060 DISP "DIRECTION F/R ?"
1070 INPUT F$
1080 IF F$#"F" AND F$#"R" THEN 1
     060
1090 IF F$="F" THEN Z=0
1100 IF F$="R" THEN Z=1
1110 DISP "DISTANCE ?"
1120 INPUT D
1130 DISP "BEARING ?"
1140 INPUT B
1150 IF B=0 THEN Z5=10
1160 IF B>0 THEN Z5=5
1170 DISP "CLINO. ?"
1180 INPUT A
1190 B=C+B
1200 IF Z>0 THEN B=180+B
1210 IF B>360 THEN B=B-360
1220 A=A+J
1230 H=COS(A)*D
1240 IF Z>0 THEN A=-A
1250 V=SIN(A)*D
1260 V=V+V2
1270 W=SIN(B)*H
1280 E=W+E
1290 E=E+E2
1300 X=COS(B)*H
1310 G=X+G
1320 G=G+G2
1330 U=V+U
1340 T=V+T
1350 K=D+K
1360 IF Z5=10 THEN K=K-D
1370 IF Z>0 THEN L=L-1
1380 B(N)=B @ H(N)=H @ T(N)=T @
     L(N)=L @ D(N)=D @ U(N)=U
1390 E(N)=E @ G(N)=G @ V(N)=V @
     A(N)=A @ K(N)=K
1400 N=N+1
1410 M(1,N)=E
1420 M(2,N)=G
1430 GOTO 1650
1440 FOR N=1 TO 153
1450 IF L(N)=0 THEN 2100
1460 PRINT "STATION No.   ";L(N)
1470 PRINT
1480 PRINT
1490 PRINT USING "8A,XXXXXXX,DDD
     DD.D," ; "ORD.EAST";E(N)
1500 PRINT USING "9A,XXXXXX,DDDD
     D.D," ; "ORD.NORTH";G(N)
1510 PRINT USING "7A,XXXXXX,DDZ.
     DD" ; "HOR.CH. ";H(N)
1520 PRINT USING "8A,XXXXX,DDZ.D
     D" ; "VERT.CH. ";V(N)
1530 PRINT USING "8A,XXXX,DDDZ.D
     D," ; "ALTITUDE";U(N)
1540 PRINT USING "6A,XXXXXX,DDDZ
     .DD," ; "LENGTH";K(N)
1550 PRINT USING "5A,XXXXXXX,DD
     Z.DD," ; "DEPTH";T(N)
1560 PRINT
1570 PRINT "Distance       ";D(N)
1580 PRINT "Bearing        ";B(N)
1590 PRINT "Clino.         ";A(N)
1600 PRINT
1610 PRINT
1620 NEXT N
1630 CLEAR
1640 DISP @ DISP
1650 DISP "MORE DATA 'Y' OR 'N'
     ?"
1660 DISP
1670 DISP "          (Next Stati
     on No)";L+1
1680 INPUT Y$
1690 IF Y$#"Y" AND Y$#"N" THEN 1
     630
1700 IF Y$#"Y" THEN M(1,N+1)=-1
1710 IF Y$#"Y" THEN B(N+1)=INF
1720 IF Y$#"Y" THEN O(N+1)=INF
1730 IF Y$#"Y" THEN H(N+1)=INF
1740 IF Y$#"Y" THEN Q0=M(1,N) @
     Q1=M(2,N)
1750 IF Y$="N" THEN 1440
1760 GOTO 1040
1770 REM **********************
1780 REM ****   SECTION    ****
1790 REM ***   ON REQUEST  ****
1800 REM **********************
1810 PRINT @ PRINT @ PRINT
1820 DISP "FOR SECTION,ENTER BEA
     RING"
1830 INPUT R
1840 PRINT
1850 PRINT "SECTION REQUESTED ON
      BEARING ";R
1860 PRINT
1870 PRINT
1880 N=0
1890 N=N+1
1900 IF L(N)=0 THEN 2010
1910 O=H(N)*COS(B(N)-R)
1920 O(N)=O
1930 PRINT USING "10A,XX,DDZ," ;
      "STATION No ";L(N)
1940 PRINT
1950 PRINT USING "11A,X,DDDZ.DD,
     " ; "SECTION HOR ";O
1960 PRINT USING "8A,XXXX,DDDZ.D
     D," ; "ALTITUDE ",T(N)
1970 PRINT
1980 PRINT
1990 GOTO 1890
2000 GOTO 2010
2010 DISP "FINISHED!.IS ANOTHER
      SECTION REQUIRED?,IF SO,KE
     Y IN 'Y'.IF NOT,KEY IN 'N'
     "
```

```
2020 INPUT Z$
2030 IF Z$#"Y" AND Z$#"N" THEN 2
     010
2040 IF Z$="Y" THEN 1820
2050 IF Z$="N" THEN 1630
2060 PRINT @ PRINT @ PRINT @ PRI
     NT
2070 REM *********************
2080 REM ****    DIRECT    ****
2090 REM *********************
2100 S=0
2110 B=0
2120 P=0
2130 N=0
2140 N=N+1
2150 FOR N=1 TO 153
2160 IF B(N)=INF THEN 2210
2170 IF B(N)-C=0 THEN GOTO 2200
2180 S=S+H(N)*COS(B(N))
2190 P=P+H(N)*SIN(B(N))
2200 NEXT N
2210 O1=ATN2(P,S)
2220 I=SQR(S*S+P*P)
2230 IF O1<0 THEN O1=O1 MOD 360
2240 PRINT @ PRINT @ PRINT @ PRI
     NT
2250 PRINT "DIRECT BEARING @ DIS
     TANCE FROM ENTRANCE TO END
     ="
2260 PRINT
2270 PRINT USING "18A,XXXX,DDZ.D
     D," ; "BEARING (Degrees)=";
     O1
2280 PRINT USING "18A,XXX,DDDZ.D
     D," ; "DISTANCE (Metres)=";
     I
2290 PRINT @ PRINT
2300 PRINT @ PRINT @ PRINT @ PRI
     NT @ PRINT @ PRINT @ PRINT
     @ PRINT
2310 X0,Y0=INF
2320 X1,Y1=0
2330 GOTO 2340
2340 REM ***********************
2350 REM ***   CORR.FACTORS   ***
2360 REM ***********************
2370 IF L(1)>1 THEN 2410
2380 H6=(M(1,1)-E(N-2))/L(N-2)
2390 H7=(M(2,1)-G(N-2))/L(N-2)
2400 H8=(U0-U(N-2))/L(N-2)
2410 H6=(M(1,1)-E(N-2))/(L(N-2)-
     L(1)+1)
2420 H7=(M(2,1)-G(N-2))/(L(N-2)-
     L(1)+1)
2430 H8=(U0-U(N-2))/(L(N-2)-L(1)
     +1)
2440 PRINT "VALUES FOR CLOSED LO
     OP CORRECTION"
2450 PRINT
2460 PRINT "CORRECTION FACTOR EA
     ST  =";H6
2470 PRINT "CORRECTION FACTOR NO
     RTH =";H7
2480 PRINT "CORRECTION FACTOR DE
     PTH =";H8
2490 PRINT
2500 PRINT "NOTE:check 'polarity
     ' of values"
2510 GOTO 1770
2520 END
```

APPENDIX 2 EXAMPLE OF SIMPLE PROGRAM TEST

```
EXAMPLE OF PROGRAM TEST.

COMPASS CORRECTION VALUE  0

CLINO.CORRECTION VALUE  0

START ORDINATE EAST  10000

START ORDINATE NORTH  10000

START ALTITUDE  100

GRID EAST CORRECTION VALUE 0

GRID NORTH CORRECTION VALUE 0

DEPTH CORRECTION VALUE 0

STATION No.   1

ORD.EAST          10000.0
ORD.NORTH         10018.8
HOR.CH.           18.79
VERT.CH.           6.84
ALTITUDE         106.84
LENGTH            20.00
DEPTH              6.84

Distance          20
Bearing           .00001
Clino.            20

STATION No.   2

ORD.EAST          10018.8
ORD.NORTH         10018.8
HOR.CH.           18.79
VERT.CH.          -6.84
ALTITUDE         100.00
LENGTH            40.00
DEPTH              0.00

Distance          20
Bearing           90
Clino.           -20

STATION No.   3

ORD.EAST          10018.8
ORD.NORTH         10000.0
HOR.CH.           18.79
VERT.CH.           6.84
ALTITUDE         106.84
LENGTH            60.00
DEPTH              6.84

Distance          20
Bearing           180
Clino.            20

STATION No.   4

ORD.EAST          10000.0
ORD.NORTH         10000.0
HOR.CH            18.79
VERT.CH           -6.84
ALTITUDE         100.00
LENGTH            80.00
DEPTH              0.00

Distance          20
Bearing           270
Clino.           -20

DIRECT BEARING @ DISTANCE FROM E
NTRANCE TO END =

BEARING (Degrees)=      90.00
DISTANCE (Metres)=       0.00

VALUES FOR CLOSED LOOP CORRECTIO
N

CORRECTION FACTOR EAST  =
-.000000825
CORRECTION FACTOR NORTH =
 .000000005
CORRECTION FACTOR DEPTH = 0
```

APPENDIX 3 EXAMPLE OF USING ERROR CORRECTION VALUES

```
TEST-CLOSED LOOP WITH ERROR.

COMPASS CORRECTION VALUE  0

CLINO.CORRECTION VALUE  0

START ORDINATE EAST  10000

START ORDINATE NORTH  10000

START ALTITUDE  100

GRID EAST CORRECTION VALUE 0

GRID NORTH CORRECTION VALUE 0

DEPTH CORRECTION VALUE 0

STATION No.   1

ORD.EAST        10000.0
ORD.NORTH       10017.1
HOR.CH.         17.12
VERT.CH.         5.56
ALTITUDE       105.56
LENGTH          18.00
DEPTH            5.56

Distance         18
Bearing          .00001
Clino.           18

STATION No.   2

ORD.EAST        10018.8
ORD.NORTH       10017.8
HOR.CH.         18.79
VERT.CH.        -6.84
ALTITUDE        98.72
LENGTH          38.00
DEPTH           -1.28

Distance         20
Bearing          88
Clino.          -20
```

```
STATION No    3

ORD.EAST        10015.6
ORD.NORTH        9999.7
HOR.CH          18.35
VERT.CH.         4.92
ALTITUDE       103.64
LENGTH          57.00
DEPTH            3.64

Distance         19
Bearing          190
Clino.           15

STATION No.   4

ORD.EAST         9998.1
ORD.NORTH        9996.6
HOR.CH.         17.74
VERT.CH.        -6.81
ALTITUDE        96.83
LENGTH          76.00
DEPTH           -3.17

Distance         19
Bearing          260
Clino.          -21

DIRECT BEARING @ DISTANCE FROM E
NTRANCE TO END =

BEARING (Degrees)=      209.00
DISTANCE (Metres)=        3.86

VALUES FOR CLOSED LOOP CORRECTIO
N

CORRECTION FACTOR EAST  =
 .4682587
CORRECTION FACTOR NORTH =
 .8447591425
CORRECTION FACTOR DEPTH =
 .7923815381
```

APPENDIX 3 continued

```
CLOSED LOOP WITH ERROR CRRECTION

COMPASS CORRECTION VALUE  0

CLINO.CORRECTION VALUE  0

START ORDINATE EAST  10000

START ORDINATE NORTH  10000

START ALTITUDE  100

GRID EAST CORRECTION VALUE
 .4682587

GRID NORTH CORRECTION VALUE
 .844759

DEPTH CORRECTION VALUE .792381

STATION No.   1

ORD.EAST        10000.5
ORD.NORTH       10018.0
HOR.CH.         17.12
VERT.CH.         6.35
ALTITUDE       106.35
LENGTH          18.00
DEPTH            6.35

Distance         18
Bearing          .00001
Clino.           18

STATION No.   2

ORD.EAST        10019.7
ORD.NORTH       10019.5
HOR.CH.         18.79
VERT.CH.        -6.05
ALTITUDE       100.31
LENGTH          38.00
DEPTH            0.31

Distance         20
Bearing          88
Clino.          -20
```

```
STATION No.   3

ORD.EAST        10017.0
ORD.NORTH       10002.2
HOR.CH.         18.35
VERT.CH.         5.71
ALTITUDE       106.02
LENGTH          57.00
DEPTH            6.02

Distance         19
Bearing          190
Clino.           15

STATION No.   4

ORD.EAST        10000.0
ORD.NORTH       10000.0
HOR.CH.         17.74
VERT.CH.        -6.02
ALTITUDE       100.00
LENGTH          76.00
DEPTH           -0.00

Distance         19
Bearing          260
Clino.          -21

DIRECT BEARING @ DISTANCE FROM E
NTRANCE TO END =

BEARING (Degrees)=      209.00
DISTANCE (Metres)=        3.86

VALUES FOR CLOSED LOOP CORRECTIO
N

CORRECTION FACTOR EAST  = 0
CORRECTION FACTOR NORTH =
 .00000014
CORRECTION FACTOR DEPTH =
 .0000005381
```

APPENDIX 4

Unfortunately the B.A.S.I.C. language used by computers is not exactly the same in each make. Differences in syntax exist which are commonly minor, the major variations being the commands to the printer. For the latter not much guidance can be given, except to consult the relevant manual. The following comments should anticipate most syntax variables, but are particularly relevant to Sinclair machines.

OPTION BASE 1 (line 50)	Hewlett Packard machines assume that all array subscripts begin at one unless specified otherwise by an OPTION BASE statement. I believe this statement is unique to Hewlett Packard machines and can be deleted for all other machines.
RUN	This is the command to initiate the program, other machines may have a key labelled EXECUTE ,or ENTER
LET	Most machines require a mathematical statement to be prefixed LET. Thus lines such as 1250 to 1350 inclusive etc. are prefixed LET, e.g. 1280 LET E = W + E.
REM (lines 10, 20, 30 etc)	Lines prefixed REM are not executed, they are in the program listing for user information and are not essential for the program to work. ! symbol has the same function.
PRINT (lines 960, 970 etc.)	PRINT means advance the printer paper by one line. Equivalents may be LPRINT or SCROLL
PRINT "----"	Means print whatever is between the inverted commas. Equivalent is LPRINT
DISP (line 300 etc.)	Means place a gap one line deep on the screen, equivalent can be PRINT. Also means display on the screen whatever is between inverted commas, e.g. PRINT "----".
CLEAR (line 550 etc.)	Means erase whatever is on the screen. Equivalent often SCLEAR. N.B. on some machines CLEAR means erase all values so far entered. Another equivalent is CLS
$\neq$ (line 1080 etc.)	Means NOT, which is an alternative.
@	Means AND, which is an alternative.
PRINT USING (line 1490 etc.)	A printer formating statement associated with Hewlett Packard machines (or those with Enhanced BASIC). It allocates spaces for the legends and the number of digits before and after the decimal point. A simple alternative could be: 1490 PRINT "ORD.EAST "; E(N) This will give a large number of digits after the decimal point, but the irrelevant ones can be ignored.
Line 10 etc.	The hatched symbol is a graphic character used to enhance a title, it is not essential. See also REM.
END (line 2520)	Some machines have to be told the end of a program, can be omitted on some.
GOTO	Some machines use G. (include the full stop).
DEG (line 290)	Most computers work in radians unless told otherwise by the DEG statement, if this facility is not available the conversion must be done subsequent to entering a degree value, e.g. add line 1165 B = B/·2957 add line 1185 A = A/·2957

APPENDIX 5

If a printer is not available, the version of the program given below will display the results on the screen, otherwise it is identical in operation to the main program. When all the survey data is entered and "N" is keyed in, the values for the first station will be displayed, and will remain on the screen while the user copies them. Using the CONTINUE key (or equivalent) will display the next set of values. By using the CONTINUE key as prompted, all the values given by the main program are accessible.

APPENDIX 5. for use without printer

```
 10 REM **************************
 20 REM **** PROGRAM 'BCRA'   ***
 30 REM **** S.REID  1983     ***
 40 REM **************************
 50 OPTION BASE 1
 60 DIM B(153)
 70 DIM H(153)
 80 DIM L(153)
 90 DIM T(153)
100 DIM D(153)
110 DIM E(153)
120 DIM G(153)
130 DIM V(153)
140 DIM K(153)
150 DIM A(153)
160 DIM O(153)
170 DIM U(153)
180 DIM M(2,153)
190 FOR N=1 TO 153
200 L(N)=0
210 B(N)=0
220 O(N)=0
230 E(N)=0
240 U(N)=0
250 H(N)=0
260 NEXT N
280 T,K,N,Q,S,P=0
290 DEG
300 DISP "NOTE THAT THE MAX.No.O
    FSURVEY STATIONS ACCEPTABLE
    TO THIS PROGRAMME IS 150"
310 DISP
320 DISP
330 DISP "ENTER GRID AS 5 DIGIT
    No.BOTH EAST&NORTH i.e.NNNNN
       RESOLUTION = 10cm"
460 DISP @ DISP
490 DISP @ DISP
```

```
500 DISP "ENTER COMPASS CORRECTI
    ON VALUE"
510 INPUT C
550 CLEAR
560 DISP @ DISP
570 DISP "ENTER CLINO. CORRECTIO
    N VALUE"
580 INPUT J
610 CLEAR
620 DISP @ DISP
630 DISP "ENTER START ORDINATE E
    AST"
640 INPUT E
670 CLEAR
680 DISP @ DISP
690 DISP "ENTER START ORDINATE N
    ORTH"
700 INPUT G
720 M(1,1)=E
730 M(2,1)=G
750 CLEAR
760 DISP @ DISP
770 DISP "ENTER START ALTITUDE"
780 INPUT U0
810 CLEAR
820 DISP @ DISP
830 DISP "ENTER GRID EAST CORREC
    TION VALUE"
840 INPUT E2
860 CLEAR
870 DISP @ DISP
880 DISP "ENTER GRID NORTH CORRE
    CTION VALUE"
890 INPUT G2
910 CLEAR
920 DISP @ DISP
930 DISP "ENTER DEPTH CORRECTION
     VALUE"
940 INPUT V2
980 U=U0
990 CLEAR
1000 DISP @ DISP
1010 DISP "NOW BEGIN TO ENTER ST
     ATION DATA"
1020 DISP @ DISP
1030 N=1
1040 DISP "STATION No. ?"
1050 INPUT L
1060 DISP "DIRECTION F/R ?"
1070 INPUT F$
1080 IF F$#"F" AND F$#"R" THEN 1
     060
1090 IF F$="F" THEN Z=0
1100 IF F$="R" THEN Z=1
1110 DISP "DISTANCE ?"
1120 INPUT D
1130 DISP "BEARING ?"
1140 INPUT B
1150 IF B=0 THEN Z5=10
1160 IF B>0 THEN Z5=5
1170 DISP "CLINO. ?"
1180 INPUT A
1190 B=C+B
1200 IF Z>0 THEN B=180+B
1210 IF B>360 THEN B=B-360
1220 A=A+J
1230 H=COS(A)*D
1240 IF Z>0 THEN A=-A
1250 V=SIN(A)*D
1260 V=V+V2
1270 W=SIN(B)*H
1280 E=W+E
1290 E=E+E2
1300 X=COS(B)*H
1310 G=X+G
1320 G=G+G2
1330 U=V+U
1340 T=V+T
1350 K=D+K
1360 IF Z5=10 THEN K=K-D
1370 IF Z>0 THEN L=L-1
1380 B(N)=B @ H(N)=H @ T(N)=T @
     L(N)=L @ D(N)=D @ U(N)=U
1390 E(N)=E @ G(N)=G @ V(N)=V @
     A(N)=A @ K(N)=K
1400 N=N+1
1410 M(1,N)=E
1420 M(2,N)=G
1430 GOTO 1650
1440 FOR N=1 TO 153
1450 IF L(N)=0 THEN 2100
1460 DISP "STATION No.   ";L(N)
1470 DISP
1490 DISP USING "8A,XXXXXXX,DDDD
     D.D," ; "ORD.EAST";E(N)
1500 DISP USING "9A,XXXXXX,DDDDD
     .D," , "ORD.NORTH";G(N)
1510 DISP USING "7A,XXXXXX,DDZ D
     D" ; "HOR.CH.  ";H(N)
1520 DISP USING "8A,XXXXX,DDZ.DD
     " ; "VERT.CH.  ";V(N)
1530 DISP USING "8A,XXXX,DDDZ.DD
     ," ; "ALTITUDE";U(N)
1540 DISP USING "6A,XXXXXX,DDDZ.
     DD," ; "LENGTH";K(N)
1550 DISP USING "5A,XXXXXXXX,DDZ
     .DD," ; "DEPTH";T(N)
1570 DISP "Distance        ";D(N)
1580 DISP "Bearing         ";B(N)
1590 DISP "Clino.          ";A(N)
1595 DISP
1596 DISP " press CONT to contin
     ue"
1610 PAUSE
1620 NEXT N
1630 CLEAR
1640 DISP @ DISP
1650 DISP "MORE DATA 'Y' OR 'N'
     ?"
1660 DISP
1670 DISP "            (Next Stati
     on No)";L+1
```



```
1680 INPUT Y$
1690 IF Y$#"Y" AND Y$#"N" THEN 1
     630
1700 IF Y$#"Y" THEN M(1,N+1)=-1
1710 IF Y$#"Y" THEN B(N+1)=INF
1720 IF Y$#"Y" THEN O(N+1)=INF
1730 IF Y$#"Y" THEN H(N+1)=INF
1740 IF Y$#"Y" THEN Q0=M(1,N) @
     Q1=M(2,N)
1750 IF Y$="N" THEN 1440
1760 GOTO 1040
1770 REM ********************
1780 REM ****  SECTION     ****
1790 REM ***  ON REQUEST   ****
1800 REM ********************
1810 CLEAR @ DISP
1820 DISP "FOR SECTION,ENTER BEA
     RING"
1830 INPUT R
1880 N=0
1890 N=N+1
1900 IF L(N)=0 THEN 2010
1910 O=H(N)*COS(B(N)-R)
1920 O(N)=O
1925 CLEAR @ DISP @ DISP
1930 DISP USING "10A,XX,DDZ," ;
     "STATION No ";L(N)
1940 DISP
1950 DISP USING "11A,X,DDDZ.DD,"
     ; "SECTION HOR ";O
1960 DISP USING "8A,XXXX,DDDZ.DD
     ," ; "ALTITUDE ";T(N)
1963 DISP @ DISP
1964 DISP " press CONT to contin
     ue"
1965 PAUSE
1990 GOTO 1890
2000 GOTO 2010
2010 DISP "FINISHED!.IS ANOTHER
      SECTION REQUIRED?,IF SO,KE
     Y IN  'Y'.IF NOT,KEY IN 'N'
     "
2020 INPUT Z$
2030 IF Z$#"Y" AND Z$#"N" THEN 2
     010
2040 IF Z$="Y" THEN 1820
2050 IF Z$="N" THEN 1630
2060 PRINT @ PRINT @ PRINT @ PRI
     NT
2070 REM ********************
2080 REM ****   DIRECT     ****
2090 REM ********************
2100 S=0
2110 B=0
2120 P=0
2130 N=0
2140 N=N+1
2150 FOR N=1 TO 153
2160 IF B(N)=INF THEN 2210
2170 IF B(N)-C=0 THEN GOTO 2200
2180 S=S+H(N)*COS(B(N))
2190 P=P+H(N)*SIN(B(N))
2200 NEXT N
2210 O1=ATN2(P,S)
2220 I=SQR(S*S+P*P)
2230 IF O1<0 THEN O1=O1 MOD 360
2245 CLEAR @ DISP @ DISP
2250 DISP "DIRECT BEARING @ DIST
     ANCE FROM ENTRANCE TO END =
     "
2260 DISP
2270 DISP USING "18A,XXXX,DDZ.DD
     ," ; "BEARING (Degrees)=";O
     1
2280 DISP USING "18A,XXX,DDDZ.DD
     ," ; "DISTANCE (Metres)=";I
2282 DISP @ DISP
2283 DISP " press CONT to contin
     ue"
2285 PAUSE
2310 X0,Y0=INF
2320 X1,Y1=0
2330 GOTO 2340
2340 REM *********************
2350 REM ***   CORR.FACTORS  ***
2360 REM *********************
2370 IF L(1)>1 THEN 2410
2380 H6=(M(1,1)-E(N-2))/L(N-2)
2390 H7=(M(2,1)-G(N-2))/L(N-2)
2400 H8=(U0-U(N-2))/L(N-2)
2410 H6=(M(1,1)-E(N-2))/(L(N-2)-
     L(1)+1)
2420 H7=(M(2,1)-G(N-2))/(L(N-2)-
     L(1)+1)
2430 H8=(U0-U(N-2))/(L(N-2)-L(1)
     +1)
2435 CLEAR @ DISP @ DISP
2440 DISP "VALUES FOR CLOSED LOO
     P CORRECTION"
2450 DISP
2460 DISP "CORRECTION FACTOR EAS
     T  =";H6
2470 DISP "CORRECTION FACTOR NOR
     TH =";H7
2480 DISP "CORRECTION FACTOR DEP
     TH =",H8
2490 DISP
2500 DISP "NOTE:check 'polarity'
      of values"
2502 DISP
2503 DISP " press CONT to contin
     ue"
2505 PAUSE
2510 GOTO 1770
2520 END
```

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THE ANGLO-CANADIAN ROCKY MOUNTAINS SPELEOLOGICAL EXPEDITION, 1983

Compiled by D. J. Lowe

ABSTRACT

During August and September 1983 a team of ten British speleologists joined ex-patriate and Canadian cavers in a study of previously unexplored outcrops of the Lower Cambrian Mural Formation around the Mount Robson Syncline of British Columbia and Alberta. Three weeks of fieldwork led to the discovery, exploration and survey of ten significant new caves and many shorter ones, the longest in excess of 1.2 km. Observations of geology and geomorphology have produced an improved appreciation of the potential for cave development in the Mural Formation and a revision of the mapped limits of limestone outcrops in the areas studied. Wide-ranging reconnaissance of areas not studied in detail has allowed speculation on future potential for cave exploration in the Mount Robson area.

TEAM MEMBERS: (* denotes members active throughout the Expedition)

British	Expatriate and Canadian
Dave (Deej) Lowe, Joint Leader *	Chas Yonge, Joint Leader *
Norman Flux*	Steve Worthington
Linda Gough*	Chris Pugsley
Anne Gough*	Pam Burns
Janet Miller*	Pam Pugsley
Neil Anderson*	Eric Von Vorkampff
Pat Langdon*	Marg. Saul
Charlotte Roberts*	Ian McKenzie
Torfine Bruce*	Rick Blak
Richard Acton	(and Tama Pugsley)

Tama Pugsley, at three years old, was the youngest member of the Expedition, the remainder ranging in age from early twenties to mid thirties. Organisation and responsibility was somewhat flexible; Janet Miller had overall responsibility for finances, Charlotte Roberts was Medical Officer. In the field all team members were involved in surface reconnaissance work, underground exploration and survey, whilst Deej Lowe, Chas Yonge and Steve Worthington had main responsibility for observing the geology and geomorphology.

INTRODUCTION

The idea for a small team of Cave Projects Group members to visit the Canadian Rockies in 1983 was suggested by Chas Yonge in late 1982. Out of an original plan to join Canadian explorations in the Prince George area grew a more grandiose plan to reconnoitre karst areas centred on the Arctomys Valley (north-west of Jasper) and Job Pass (south-east of Jasper) (Fig. 1). Interest was greater than anticipated and the British team, originally comprising six members, was expanded to ten when it was realised that most of the Canadians would only be available for parts of the project. Much of the background research prior to the Expedition was carried out by Chas Yonge in Canada and D. J. Lowe in England, whilst all matters concerning sponsorship and equipment were dealt with by the British team.

Research suggested that the outcrop of the Lower Cambrian Mural (Limestone) Formation around the Mount Robson Synclinorium (Figs. 2 and 3) offered great potential for cave development, with numerous streams running off high altitude impermeable rocks and an impressive vertical range between the "Alpine" karst and the valley bottom resurgences. Surprisingly, since it contains Arctomys Cave (Thompson, 1976), the deepest cave in Anglo-North America, the Mural outcrop had received only scant attention in comparison to more extensive karst areas elsewhere. When it was also discovered that a recent logging trail penetrated the Small Creek Valley, close to the western culmination of the Synclinorium (Figs. 3 and 4), it was decided to concentrate the efforts of the Expedition on the more easily accessible parts of the Mural Limestone outcrop, west of Small Creek, around Arctomys Cave and south-east of the Arctomys area (Figs. 3 and 18). Ease of access is used advisedly and in this context is purely relative.

The British team flew to either Vancouver or Edmonton in mid-August and assembled in Jasper on Monday, August 15th. Transport from Edmonton and into the mountains was provided by a hired General Motors Corporation "van" with an enormous engine, automatic transmission and power steering, augmented at times by the cars and truck of Chris Pugsley, Pam Burns and Ian McKenzie.

GENERAL EXPEDITION DETAILS

Leaving Jasper by mid-day on 15th August 1983, the Yellowhead Highway (Route 16) was followed northwestwards along the southerly limb of the Mount Robson Synclinorium, pausing en route to admire Mount Robson itself. Turning north from the highway a good logging road was followed along the valley of Small Creek (a sizeable river), with spectacular views of

LOCATION OF ACRMSE 1983

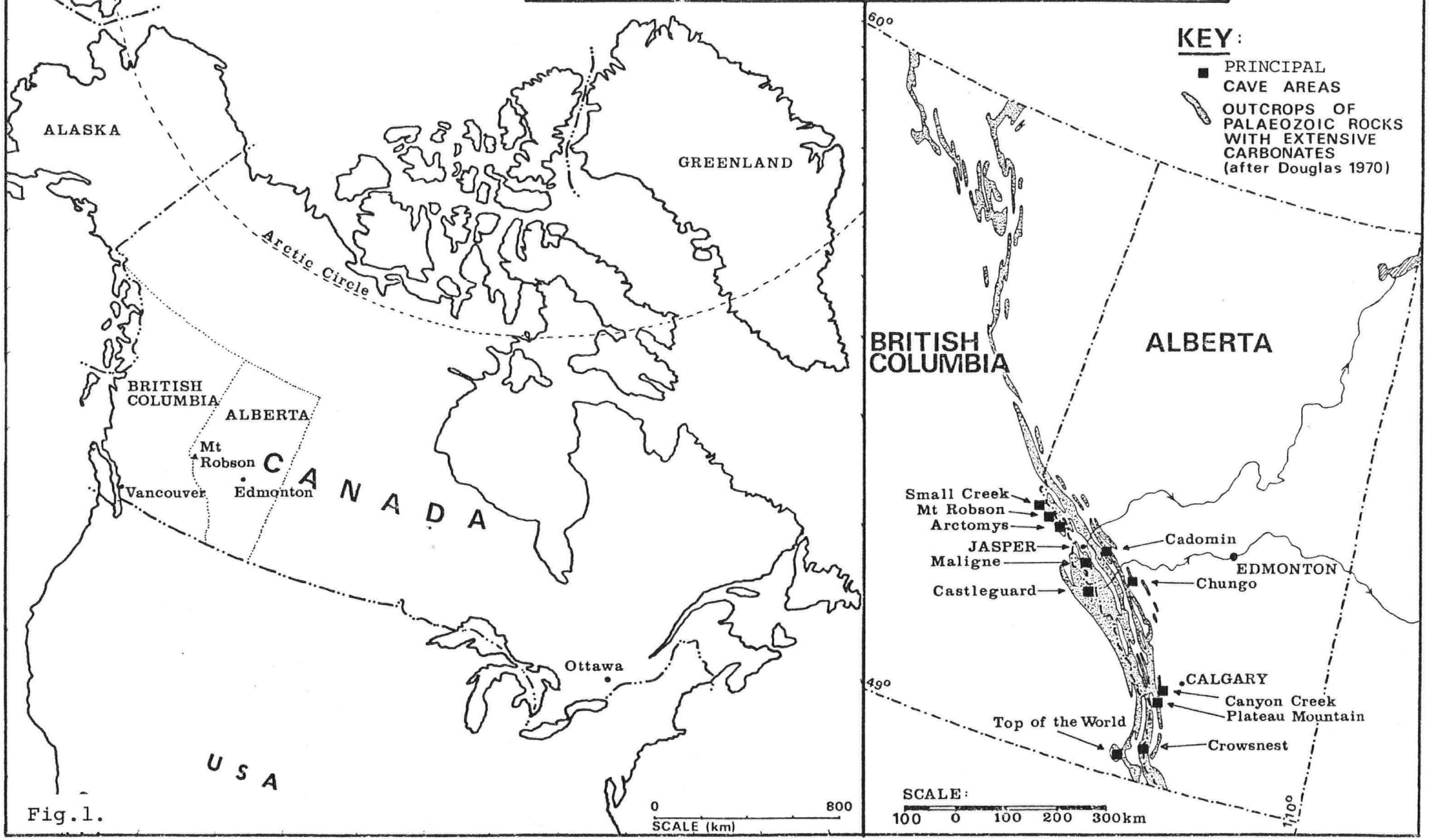


Fig.1.

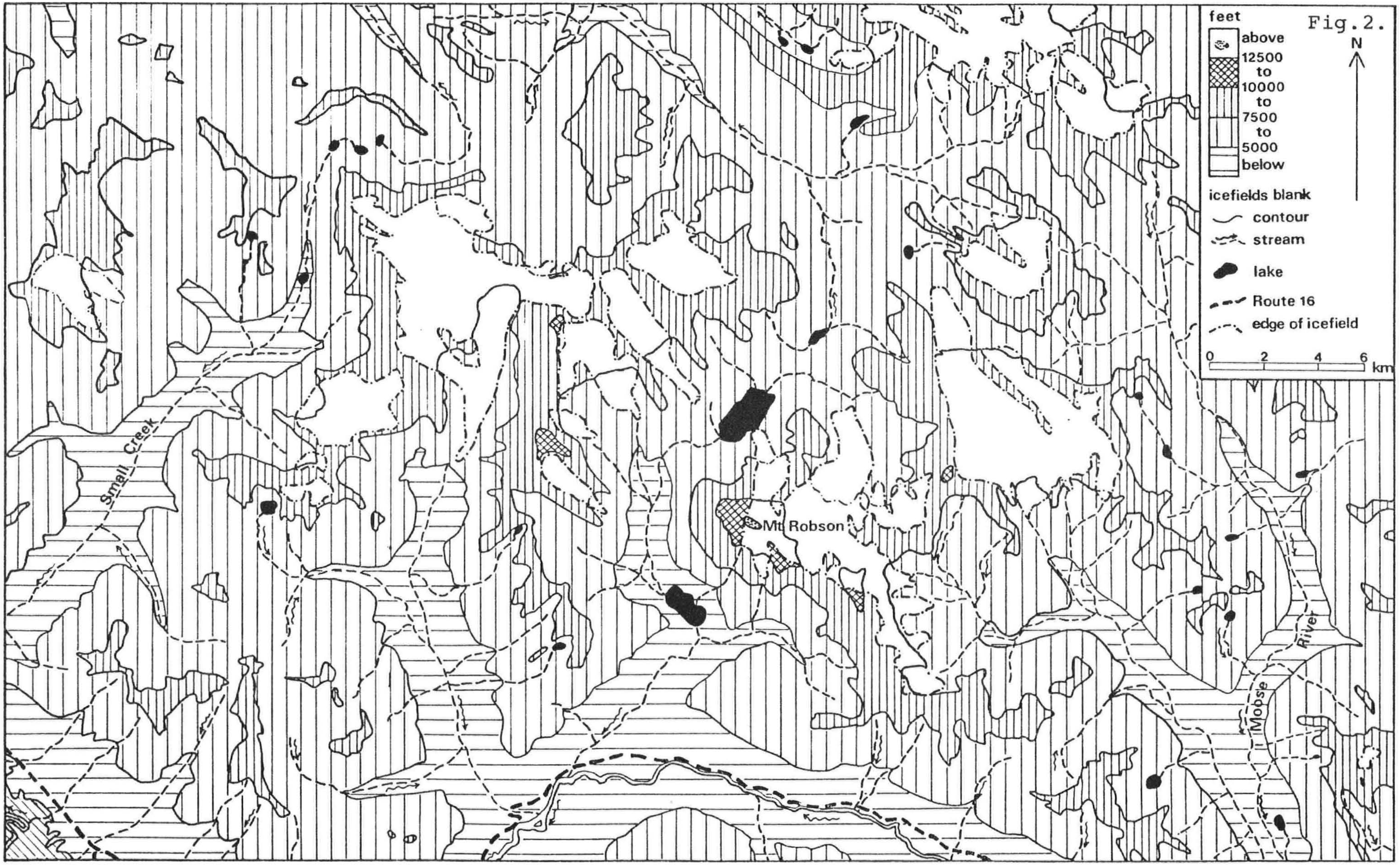


Figure 2 - Relief and drainage of the Mount Robson area

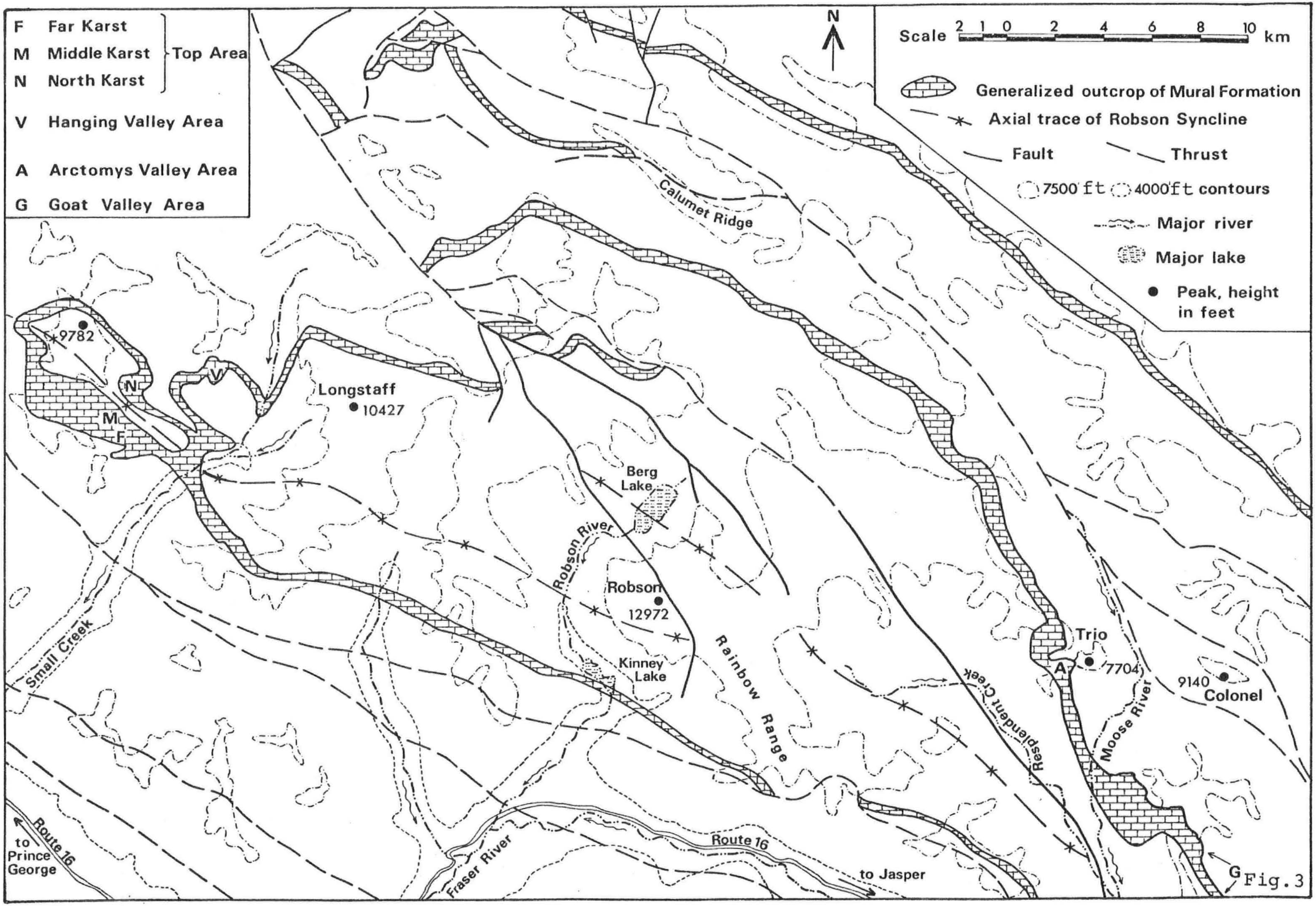


Fig.3. Generalized outcrop of the Mural Formation, major faults and thrusts in the Mt.Robson area.

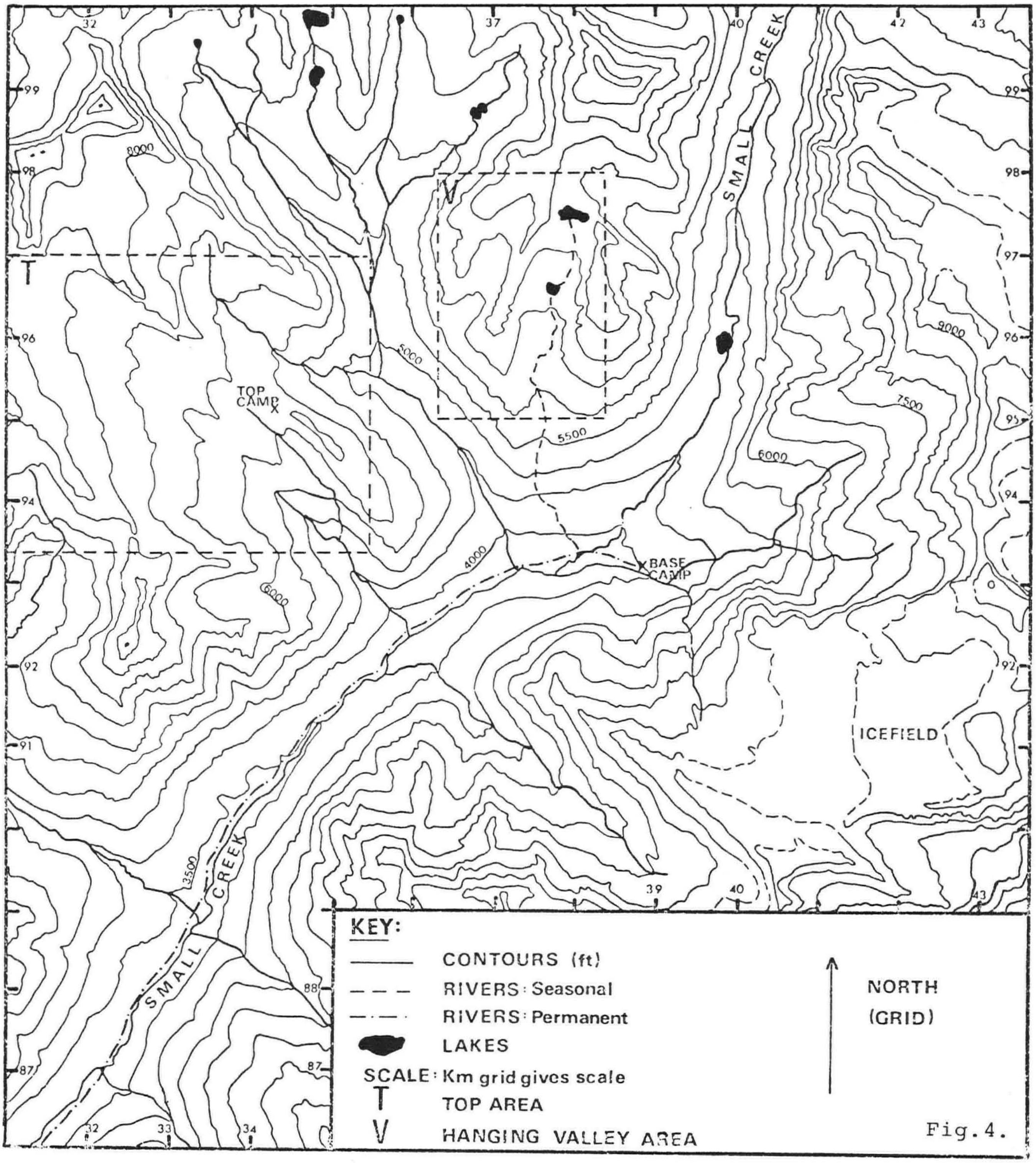


Fig.4. Topography of the Small Creek area.

the Mural Limestone and beds above and below dipping steeply northwards towards the major axis of the Synclinorium. Examination of a tributary of glacial meltwater joining from the west gave the first close up of the Mural Limestone. Base camp was established at an altitude of about 1220 m (4000 feet) at the head of the logging road, where both water and ready-cut firewood were in plentiful supply. Whilst camp was being set up a rapid local reconnaissance revealed interesting exposures of limestone and a significant, though overgrown, resurgence to the northwest of the camp.

Tuesday, 16th August, saw the team split into four reconnaissance groups, Chas, Chris and Torfine worked west of Base and, despite the presence of large icefields not marked on the 1:50000 maps, located a very promising area (Top Area, see later) with several open caves. Janet, Linda, Anne and Charlotte examined an area slightly farther northeast where a large closed depression was shown on the topographic map. Though numerous promising sites were located, all were choked by rock debris. From a ridge above the depression they looked down into the next valley where streams from several small lakes appeared to sink (Hanging Valley, see later). Norman's team followed Small Creek northwards from Base, hoping to intersect the Mural on the northern limb of the Synclinorium. No significant sites were located however. The final group, Deej, Neil and Pat, was similarly unsuccessful in following the tributary to the east of Small Creek, where no significant karst was located. At the end of the day it was agreed that the first two areas were worth further exploration, the emphasis being on the first. It was also realised that "bushwacking" with a full pack up to the Alpine meadows would be no easy undertaking.

THE TOP AREA EXPLORATIONS

During a period of about ten days, intense activity took place from the Top Camp, situated at a break in the synclinal ridge between the North and Middle karsts. The more obvious karst meadows and pavements were rapidly reconnoitred and open holes explored and surveyed where necessary.

In the Far Karst the F1 Resurgence Cave (Figs 5 and 9), a very large rising with a peak afternoon flow in excess of 1 cumec, was found to sump after about 80 m of big passage. Dry passage beyond led to a very unstable fault-controlled rift which might provide a sump by-pass, but not for the faint-hearted. Also in the Far Karst Fiddler's Cave (F2) was explored (Figs 5 and 8) and a second, lower, entrance discovered from inside. Above the Resurgence a sink, Grot'ole (Figs 5 and 10) was excavated and after further underground digging was pushed to a point where airspace became minimal and wet-suits desirable. A number of minor sites were looked at during the reconnaissance of the Far Karst, including Bomb Pot (Fig. 11), where much energy was expended trying to pass a huge boulder (the bomb) before an alternative way in was found.

The Middle Karst is less extensive and its twin risings (Fig. 5) were found to be impenetrable. Exploration of Porcupine Cave (Figs 5 and 7) commenced from the M2 entrance, from which the easier M3 entrance was located. Subsequently M1 was also found to join the system. Excitement ran high when the sound of a roaring stream was heard from a high tube in the main cave and a climb gave access to a sub-parallel active system. Sadly the streamway was found to sump upstream, whilst downstream a short sump was by-passed, only to lead to another, terminal, sump. Porcupine Cave proved to be the longest and deepest system explored during the Expedition. Also in the Middle Karst many choked holes were checked out, but little open passage was found. M4 (Fig. 11) was one such minor discovery.

Ranging more widely the icefield to the west was crossed and Mural carbonate outcrops discovered close to the watershed between the Small Creek and Horsey Creek catchments. Several small sinks were located at altitudes up to 8300 feet but all holes were either too tight or choked. Back on the surface of the icefield a number of surface streams sank down moulins into the glacier. An abandoned moulin was found and eventually descended on a very early morning trip (to avoid snow melt) but the trip had to be aborted when the water from an active moulin close by was intersected at the top of an estimated 14 m pit. The Moulin (Figs 5 and 11) provided a very entertaining trip, a return exploration really requiring crampons, ice tools and colder weather.

The North Karst (Fig. 5) received slightly less attention and no long systems were located. At the south-east limit of the area a number of small caves were found in the Mural cliffs (CP1-CP5, Fig. 5) but were not pushed. Elsewhere in the area a number of choked sinks and impressive shafts were found and a number of digs took place, all to no avail. To the north-west of the area were a number of small choked sinks and the nearby Quadruple Pot (Fig. 11) which had four entrances but again was choked. Most holes in this area draughted strongly and a more concerted effort is required before it is abandoned.

The weather during the stay at Top Camp was generally good, with clear skies. Some nights good displays of Northern Lights were visible, and one night a moonbow. On any future visit a camp by the clear water stream on the near edge of the North Karst might be slightly more convenient.

THE HANGING VALLEY EXPLORATIONS

A team of three commenced the examination of the Hanging Valley. The first cave located was Lower Lake Sink Cave (Figs 12 and 15) where the small entrance was enlarged by boulder removal and hammering. During the first exploration the end was not reached, though the streamway became dismal and a sump seemed imminent. At the top of the valley the huge entrance to Upper Lake Sink Cave was located on the second day and the cave explored and surveyed as far as a constriction in the streamway. On the same day the entrances of L3, L5, L6 and L7 were located (Fig. 12) and the first part of L7 (Fossil Cave) was explored. On the final day of this short reconnaissance Fossil Cave was explored to several indefinite ends. The team then returned to Base Camp, eventually to ascend to the Top Area.

After the Top Area explorations a strong team returned to the Hanging Valley. In Lower Lake Sink Cave the expected sump was soon reached, probably lying on a fault, and the survey completed. Fossil Cave was surveyed (Fig. 16) and a number of small extensions found. Close to the Upper Lake Sink the previously located L5 (Fig. 17) was explored and pushed through three chokes to a final choke now known to be close to the end of Upper Lake Sink Cave. The misfortune of one of the explorers led to L5 being renamed Slippery Disc Cave. Despite the slipped disc the explorers moved on to the Upper Lake Sink Cave and found a by-pass to the stream constriction, turning back when they reached a pitch. Late that night another team descended, bottomed the pitch and found that the cave ended in a rather paradoxical sump after 30 m. Two teams descended the cave the following morning to push the loose ends and complete the survey (Fig. 14).

Elsewhere others had been busy and a number of promising sites were located, and a number of areas written off. Potential remains good in the Hanging Valley and the depression to the west (Fig. 12) since the whole of the exposed karst is very complex and could not be examined in minute detail. A second sink below the Lower Lake might also be worth excavation.

ARCTOMYS CAVE

Many of the team were keen to descend Arctomys Cave, in the Mount Robson Provincial Park, at 522 m deep the deepest cave in Anglo-North America. It is reached by an easy walk in (compared to the Small Creek area) of about 25 km from Route 16 (Fig.18). Whilst the explorations at Small Creek were being concluded a team of six spent two full days at Arctomys. The party split into two and while one group did a 'tourist trip' to the bottom of the cave the others extended the upstream section by surveying a fair amount of previously unrecorded passage. Next day the groups' roles were reversed.

The tourist trip was extremely enjoyable even though the Endless Climb virtually finished off some of the team. Variety was the key to the quality of the trip, with some fine formations, extensive roomy walking stream passages, tricky climbs, wet and dry pitches and even some archaeology to look at. Upstream was quite a contrast as the passages were almost dry. The leads off the main route were generally large and the overall length of the system must have been extended considerably by the passages surveyed. When the surveys are plotted and tied to the existing main line survey there is also a chance that the overall vertical range of Artomys Cave will be increased. A number of leads remain to be explored and mapped and potential for extension must still exist. Additionally the areas north of Arctomys Valley, partly seen during the Long Reconnaissance (see below) need detailed examination.

MID EXPEDITION

Following the Arctomys Cave trip outlined above and the Small Creek explorations the Expedition team returned to Jasper to regroup and reprovision before beginning the second period of reconnaissance.

THE LONG (MOUNT ROBSON) RECONNAISSANCE

Four members of the Expedition team spent a week investigating the Mural Formation around Mount Robson, in areas unexplored before this reconnaissance (Fig. 22). The terrain was a pleasant surprise after strenuous climbs through thick bush in the Small Creek area. The start of the trail from Route 16 was relatively flat with no dead trees or Devil's Club to negotiate. The first day's walk to intersect the Mural outcrop led past Kinney Lake, through the Valley of the 1000 Waterfalls and past Berg Lake where a glacier from Mount Robson meets the water. Camp was set up next to Calumet Creek just below the Mural Limestone.

Next day the ridge was reached from the creek and a limestone dry valley meeting shale on one side was explored. The area looked promising but only three small caves with signs of animal habitation were found. The Canadians had warned about the 1st of September and the rapid onset of winter which follows, but they had not quite been taken at their word. After about three hours of walking along the Mural the weather changed dramatically; clouds came down and the heavens opened, prompting a rapid retreat into the valley.

It was still raining next morning. Plans of trying to follow a route round the glacier ahead were abandoned and the Moose Trail was rejoined. Again progress was rapid and leaving the trail at the junction of Moose River and Steppe Creek a route was followed back towards the Coleman Glacier. Camp was set up in a clearing close to the treeline and near here the first (and last) bear was seen - fortunately it was retreating!

To the north of this area and back on the Mural Limestone a large rising was located the following day, but the area around appeared barren of holes. Lower down was a series of sinks and resurgences plus two caves, which both quickly choked. This area warrants a more thorough survey than could be carried out in the time available. From Steppe Creek a ridge behind camp was climbed, still following the limestone. Over the top a number of well-developed joints were located, but with no associated passage. It now began to snow, dictating a rapid dash to the treeline, camp, firewood, food and water. After a very rough night the group split into two, and while two of the party headed out by way of Arctomys and the Moose Trail the other two finished the reconnaissance above camp. A huge sink area and two large resurgences were found, but with time running out there was little chance for detailed examination.

The hasty retreat from the Mount Robson area was hampered by driving rain, snow and low temperatures, but the sight of a porcupine climbing a tree and the first view of a moose helped to brighten things up.

This was a rapid lightweight reconnaissance survey and it was felt that more time and effort should be spent in this area in the future, as potential is great and wide scope exists for original and worthwhile exploration.

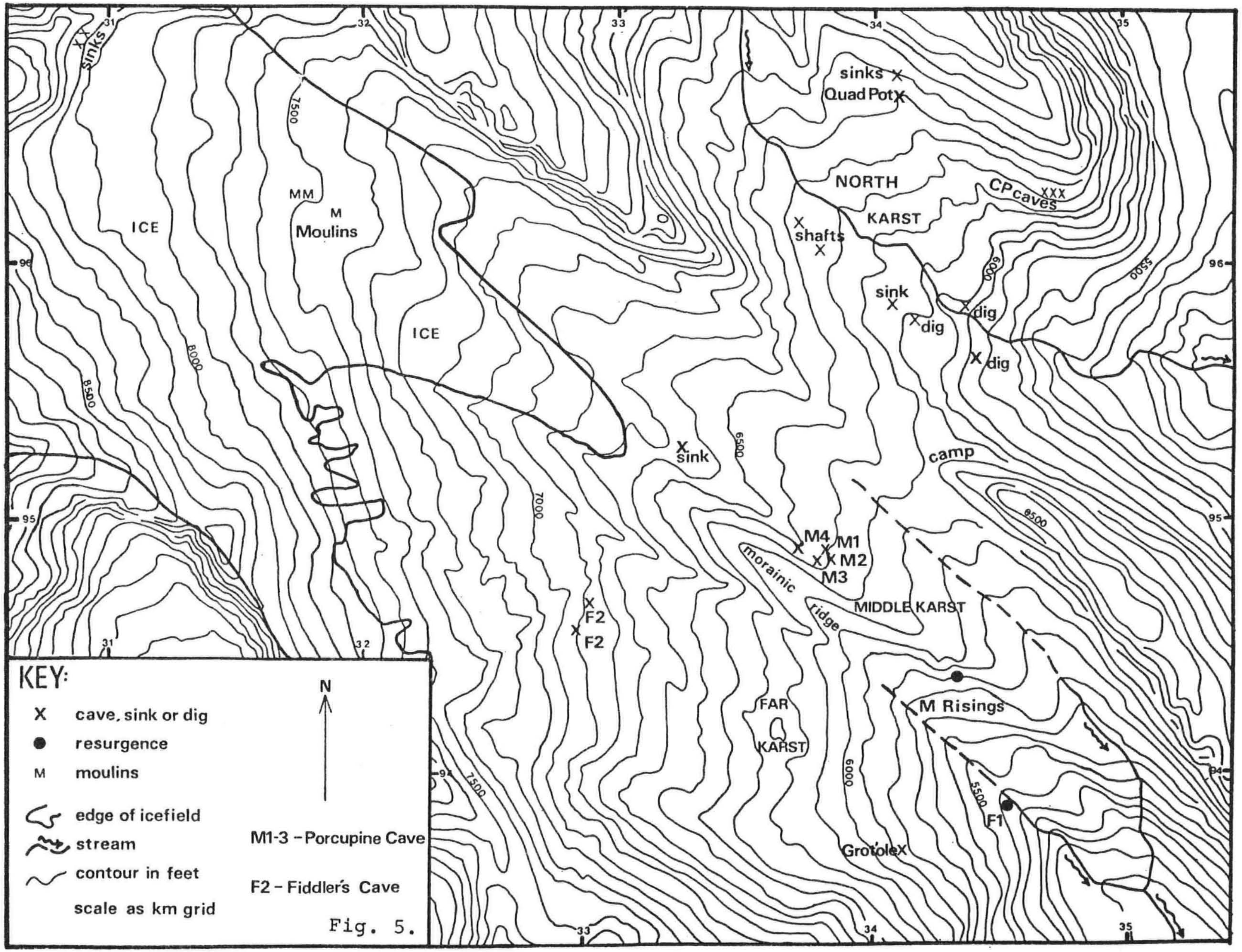


Fig. 5.

Figure 5 - Topography and cave locations, Top Area, Small Creek

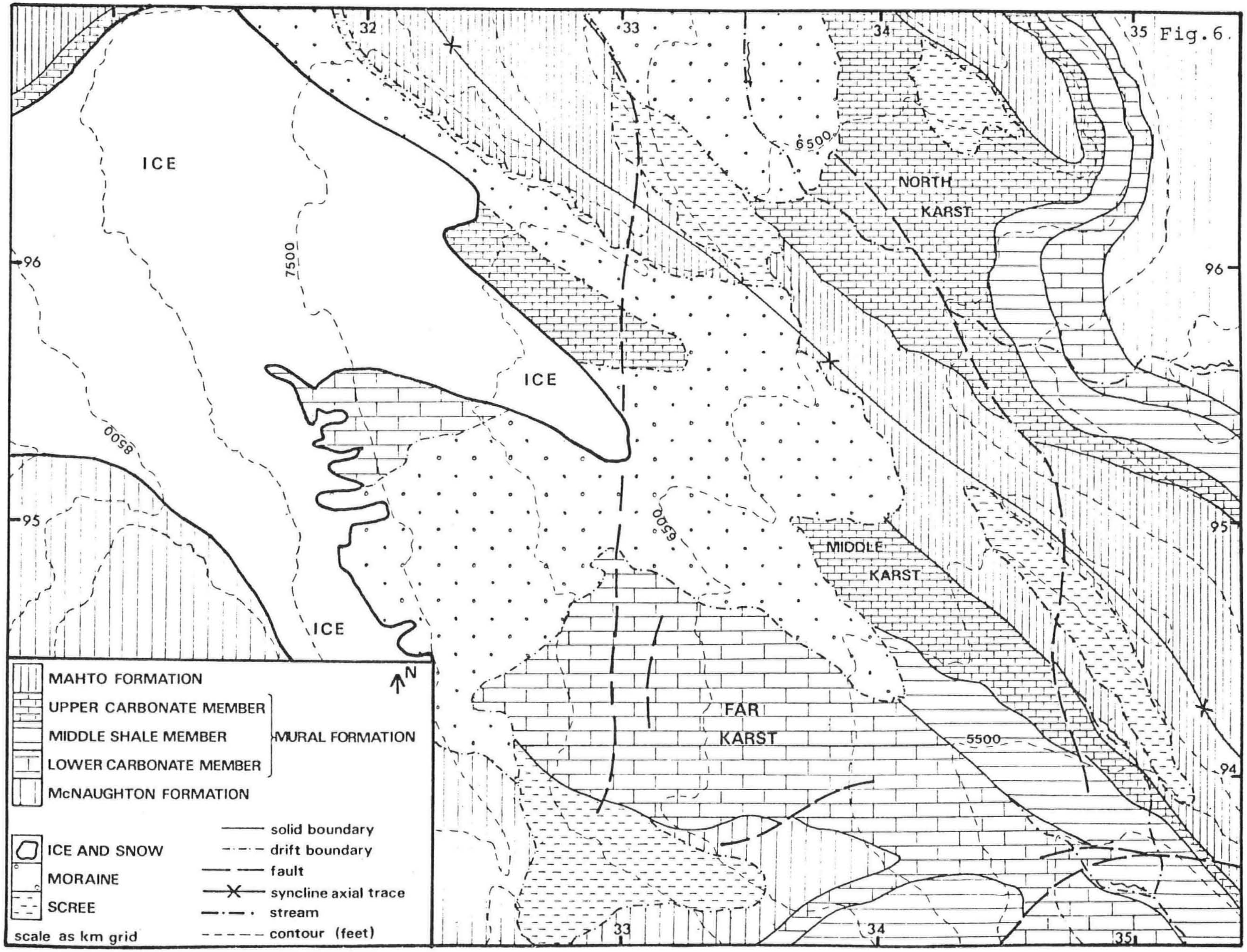


Figure 6 - Geology of the Top Area, Small Creek

GOAT VALLEY

While a party of four continued exploring and surveying in the Arctomys Cave upper series, the two remaining Expedition members struggled across the ridge of the Endless Mountain into an un-named valley southeast of Arctomys later named Goat Valley after its inhabitants.(Fig.21). Here they found

In Goat Valley they found an extensive karst with several sinks, all of which choked at or close to their entrances. A small hole was found in a strike depression which seemed to lead to a big drop, so realising that they had neither the equipment nor the manpower to explore this and the rest of the valley the pair trekked across to Arctomys Cave and co-opted the team there. The return to Goat Valley was somewhat harrowing, but by noon the next day all six had completed the journey. By now the weather was breaking, with heavy rain, icy winds and eventually snow. A number of holes were looked at with no significant results and the open hole was found to lead to an icy shaft. Next day the shaft was bottomed and found to be effectively blocked by ice at a depth of 43 m. A howling draught blew out over the ice and chippings fell an estimated 10 m below, but no further progress was possible. The hole, which was beautifully decorated with ice flows and ice flowers, was named Calvados (Un Trou Normande) in honour of its discoverer.

In the face of worsening weather a retreat was now made to Jasper, passing en route a number of very promising sites including one very large sink, with a somewhat smaller rising about 200 m farther down the valley. After the Expedition Norman Flux made a solo return to this area. One very promising site from valley level seemed to be a huge abandoned resurgence in a cliff face high above, but this turned out to be 'The Biggest Frost Pocket In The World'. On the other hand the major sink referred to above, which probably swallows 2 to 3 cumecs, was found to be open and not to be resurging lower down the valley. Without backup and suitable equipment it was unthinkable to explore the hole, Thor's Mouth, which must await a return. No geological map of this area has been located, but projection from the Goat Valley would suggest that the river sinks into the Lower Carbonate Member of the Mural Formation.

THE END OF THE EXPEDITION

The Goat Valley team were first back in Jasper, soon followed by the Long Reconnaissance team. A day was spent in Jasper sorting out the debris of the trip, cleaning up and shopping, before the whole of the British team headed south to Calgary by the Icefields Parkway. The Columbia Icefield was something of an anticlimax after the unspoiled glaciers farther north. One night was spent in Calgary before the majority of the team flew back to England, leaving Anne and Linda Gough and Norman Flux to continue touring and exploring.

MAJOR EXPEDITION DISCOVERIES

<u>Far Karst</u>			
	Fiddler's Cave (F2)	Length 384 m	Depth 58 m
	F1 Resurgence Cave	Length 220 m	Vertical Range 30 m
	Grot'ole	Length 300 m	
	Bomb Pot	Length 40 m	
<u>Middle Karst</u>			
	Porcupine Cave (M1/2/3)	Length 1200 m+	Depth 88 m
	M4	Length 60 m	
<u>North Karst</u>			
	Quadruple Pot	Length 60 m	Depth 10 m
plus the Moulin, length 50 m and depth 40 m (end not reached)			
<u>Hanging Valley</u>			
	Lower Lake Sink Cave (L1)	Length 190 m	Depth 47 m
	Fossil Cave (L7)	Length 245 m	Depth 62 m
	Upper Lake Sink Cave (L4)	Length 330 m	Depth 71 m
	Slippery Disc Cave (L5)	Length 150 m	Depth 50 m
<u>Goat Valley</u>			
	Calvados		Depth 45 m
	Un-named Cave	Length 75 m	

CAVE DESCRIPTIONS

PORCUPINE CAVE (M1, M2, M3)
Middle Karst, Top Area, Small Creek (Figs 5 and 7)
Grid Reference (M1) LJ83819486   Altitude: 6300 feet

The M1/2/3 complex comprises two independent streamway systems, the older one along the base of the limestone with much of its floor of shale. All four entrances drop into this abandoned system which probably takes water in spring. The second, newer, system is active, with a large stream of glacial meltwater.

Easiest way into system is M3, a small hole in the cliff face on the limestone-shale boundary, which was originally dug from inside. Short crawl drops quickly into mainly walking size passage. Climbs down and over boulders lead to breakdown chamber where M2 entrance drops in. Walking passage over boulders leads to T-junction with main passage where Latecomer's Entrance also joins. Downdip way on continues as high joint-controlled

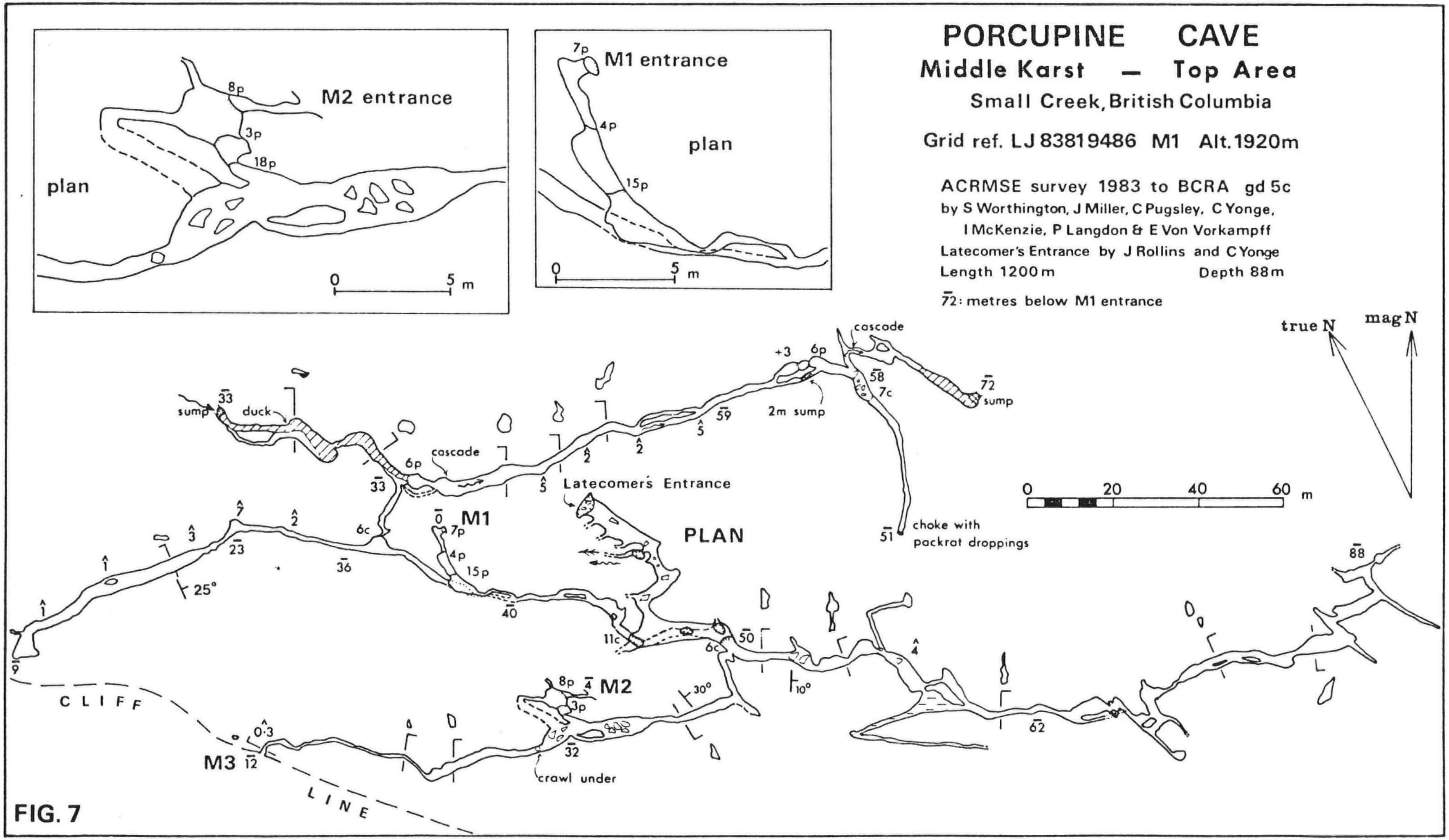

PORCUPINE CAVE
Middle Karst — Top Area
Small Creek, British Columbia
Grid ref. LJ 83819486 M1 Alt. 1920m
ACRMSE survey 1983 to BCRA gd 5c
by S Worthington, J Miller, C Pugsley, C Yonge,
I McKenzie, P Langdon & E Von Vorkampff
Latecomer's Entrance by J Rollins and C Yonge
Length 1200 m
Depth 88m
72: metres below M1 entrance
M2 entrance
plan
8p
3p
18p
0
5 m
M1 entrance
7p
4p
15p
plan
PLAN
true N
mag N
0
20
40
60
m
sump
duck
cascade
6p
Latecomer's Entrance
M1
M2
M3
2m sump
choke with
packrat droppings
crawl under
CLIFF
LINE
25°
30°
10°

FIG. 7

rift with slippery shale floor. Numerous side passages become tight or end in breakdown. Main way terminates in small breakdown chamber with abundant thixotropic mud. Updip from the junction the rift is narrower and crawl under blocks can be avoided by oxbow on right. M1 entrance drops in from above and sound of rushing water can soon be heard from hole high on right. Continuing, a short climb and bend lead to area of bedding development, ending in breakdown, close to the surface cliff.

The M1 entrance is a surface shaft in the meadows, which drops via three short pitches into a tight rift passage breaking out into the roof of the main abandoned passage upstream of the junction. The M2 entrance is at base of small cliff in meadows where short crawl leads to 8 m pitch, closely followed by short pitch and climb down into the M3 entrance passage. Traversing over first pitch leads to alternative drop to same point (not descended) Since the Expedition another surface connection, Latecomer's Entrance, has been found, which starts in the meadows below M1 and leads to a climb down into the abandoned streamway by the M3 junction.

Upstream from where M1 joins the old streamway short climb up rift with squeeze at top followed by flat out slide down leads to small balcony at side of impressive waterfall. Upstream from balcony traverse above stream until wade and duck lead to upstream sump. Downstream pitch rigged to side of waterfall. Traversing over cascades leads eventually to sump which can be bypassed by climb up rift and 6 m pitch. Streamway crosses rift (which chokes to right) before further cascade leads to terminal sump.

FIDDLER'S CAVE (F2)
Far Karst, Top Area, Small Creek (Figs 5 and 8)
Grid Reference: LJ 32829447 Altitude: 6900 feet

Climb down entrance shaft and into a small passage in the southern corner. Follow narrow winding rift, descending where possible, down a short climb and over collapsed blocks. A narrow slot, passable for some, connects to the bottom of a climbable pitch otherwise reached by traversing over the slot. From foot of pitch small passage leads north, but rapidly chokes.

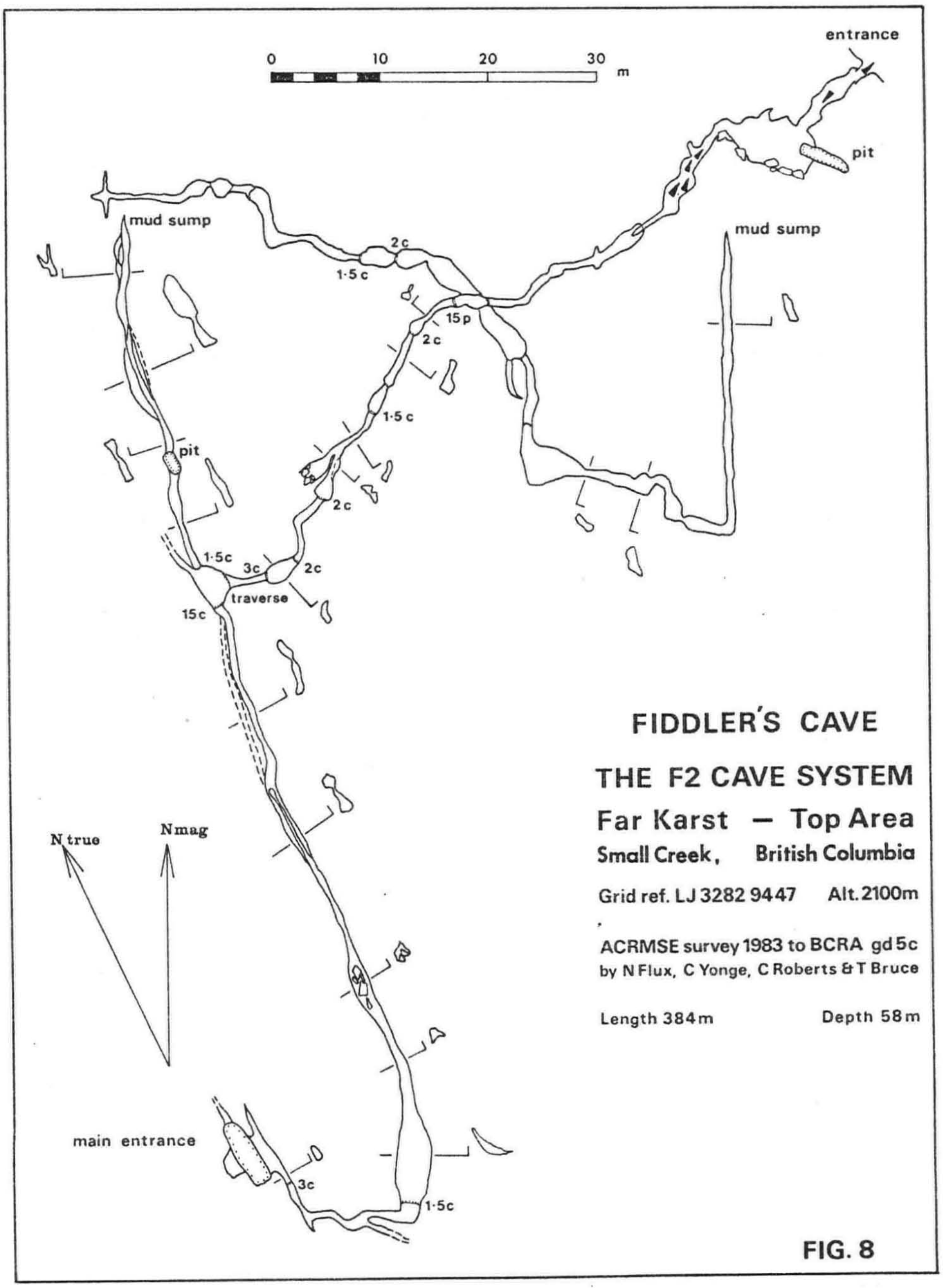


FIG. 8

Above this another passage continues for about 30 m, roomy in places, but ending in a mud sump. Back at the pitch it is possible to traverse over into another passage, leading down a series of short climbs to the head of a 15 m pitch. Traversing over the pitch leads to passage continuation dropping to an area of fractured rock. Climb up this leads to low wide chamber with a crawl to a second entrance in a small depression. Descending pitch enters chamber 15 m by 2 m. Upstream are small climbs and pools before passage ends in cross rift choked by silt close to the mud sump reached below first pitch. Downstream leads to straight passage on the strike, which also ends in a mud sump.

Potential: 1350 feet to F1 Resurgence Cave, or 2900 feet to Small Creek Valley.

F1 RESURGENCE CAVE
Far Karst, Top Area, Small Creek (Figs 5 and 9)
Grid Reference: LJ 84249411 Altitude: 5550 feet

Large entrance in short side valley to main gorge below Far Karst with strong stream emerging. Huge passage (10 m x 8 m) winds forward with roof gradually lowering. Walk under partial boulder choke to reach upstream sump in right wall. Dry passage continues updip, becoming low and narrow before cross passage is reached. To right passage enlarges and leads to breakdown chamber with stream below. To left of chamber steep boulder slopes lead into large, nasty unstable fault rift, not pushed to conclusion.

Potential: the rising must transmit drainage from most, if not all of the Far Karst, the limits of the total catchment not yet known.

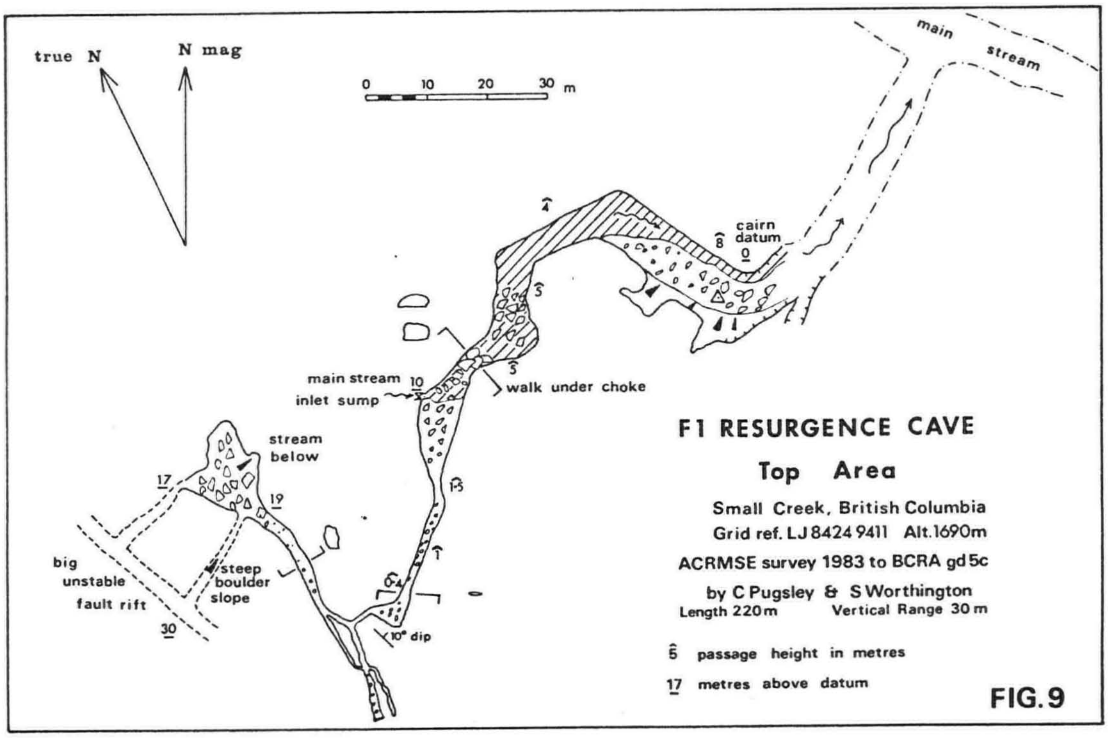
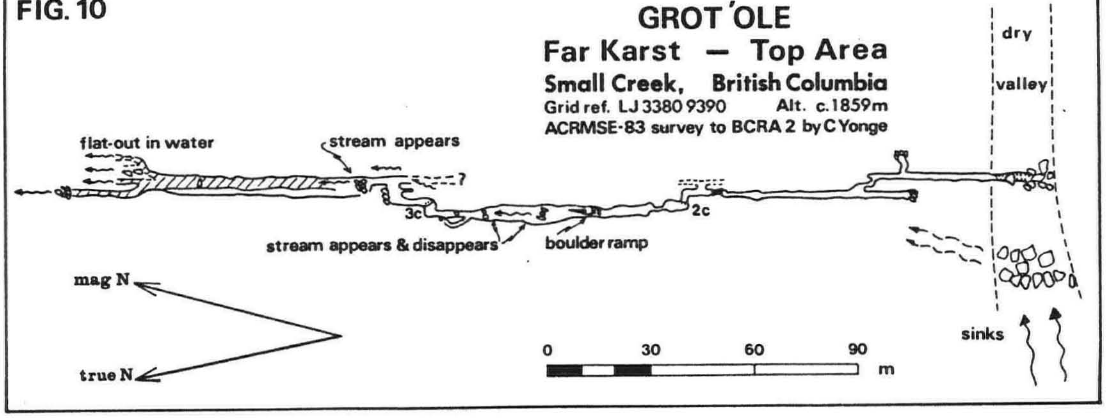


FIG. 9

FIG. 10


OTHER SITES

Top Area, Small Creek (Fig. 5)

GROT'OLE, an excavated sink in the Far Karst (Fig. 10), consists of about 300 m of generally unpleasant passage. Further progress may be possible in low-airspace streamways in lower water conditions, or if wet-suits were available. BOMB POT in the Far Karst and M4 in the Middle Karst (Fig. 11) are both short and choked, though possible digging sites. THE MOULIN, in the icefield above Top Area, was never bottomed due to high water and the lack of a suitable anchor point for an estimated 14 m pitch. Pitches above were rigged from beams or in one case around a small oxbow, and a further beam or ice screws would be needed for the next drop. Whether the drainage through the Moulin system eventually sinks into limestone at the sole of the glacier is a question that must await a fuller exploration.

QUADRUPLE POT (Fig. 11) was the longest cave explored in the North Karst, amounting to about 60 m in all entered by four climbable shafts. There are a number of small sinks close by and this, the highest part of the North Karst, must be an area of great potential. To the south-eastern corner of the North Karst the Mural Upper Carbonate Member forms a cliff where several short caves were found (Fig. 5). CP1 is an abandoned resurgence, now serving as an animal shelter, which leads after 10 m to a choked lower water level; a tube above is loosely blocked by boulders, which could be easily cleared. CP2 is a 3 m x 2 m passage, blocked after 10 m, with a small stream below a block floor. CP3 comprises an upward sloping tube and has not been pushed to a definite end. All these three have strong draughts, certainly worth another visit. CP4 runs parallel to the cliff with windows to daylight in the roof. CP5 is a rift passage on a strong joint, with no noticeable draught.

Elsewhere in the North Karst there are many active and abandoned sinks and shafts, some with very strong draughts. A number of these are marked on Fig. 5, but many more must exist, and the way into a large system could lie open somewhere among the chaos of coniferous scrub and limestone pavement.

LOWER LAKE SINK CAVE (L1)
Hanging Valley Area, Small Creek (Figs 12 and 15)
Grid Reference: LJ 37699837 Altitude: 6500 feet

To the south of Lower Lake stream passes through small pond and into well-marked gully in outcrop of Upper Carbonate Member of Mural Limestone, sinking after a few metres. Entrance is tight and awkward (enlarged by hammering), dropping into constricted streamway. Follow stream through crawl for about 5 m until sharp bend leads into larger passage. Streamway follows dip down steep rock ramp leading to 2 m climb into a chamber where another stream joins. Passage continues to descend steeply, becoming rifty and tighter. Much of stream seems to sump, probably on a fault. This lower section is probably totally sumped in wet conditions.

Back at surface shaft just above sink is choked, with sound of water in main cave audible through boulders. Following the outcrop to the west a low opening in the "crag" (L2) gives access to a steeply descending bedding passage which becomes low and unpleasant after about 10 m but probably joins the main cave.

Potential: About 2500 feet to Small Creek Valley

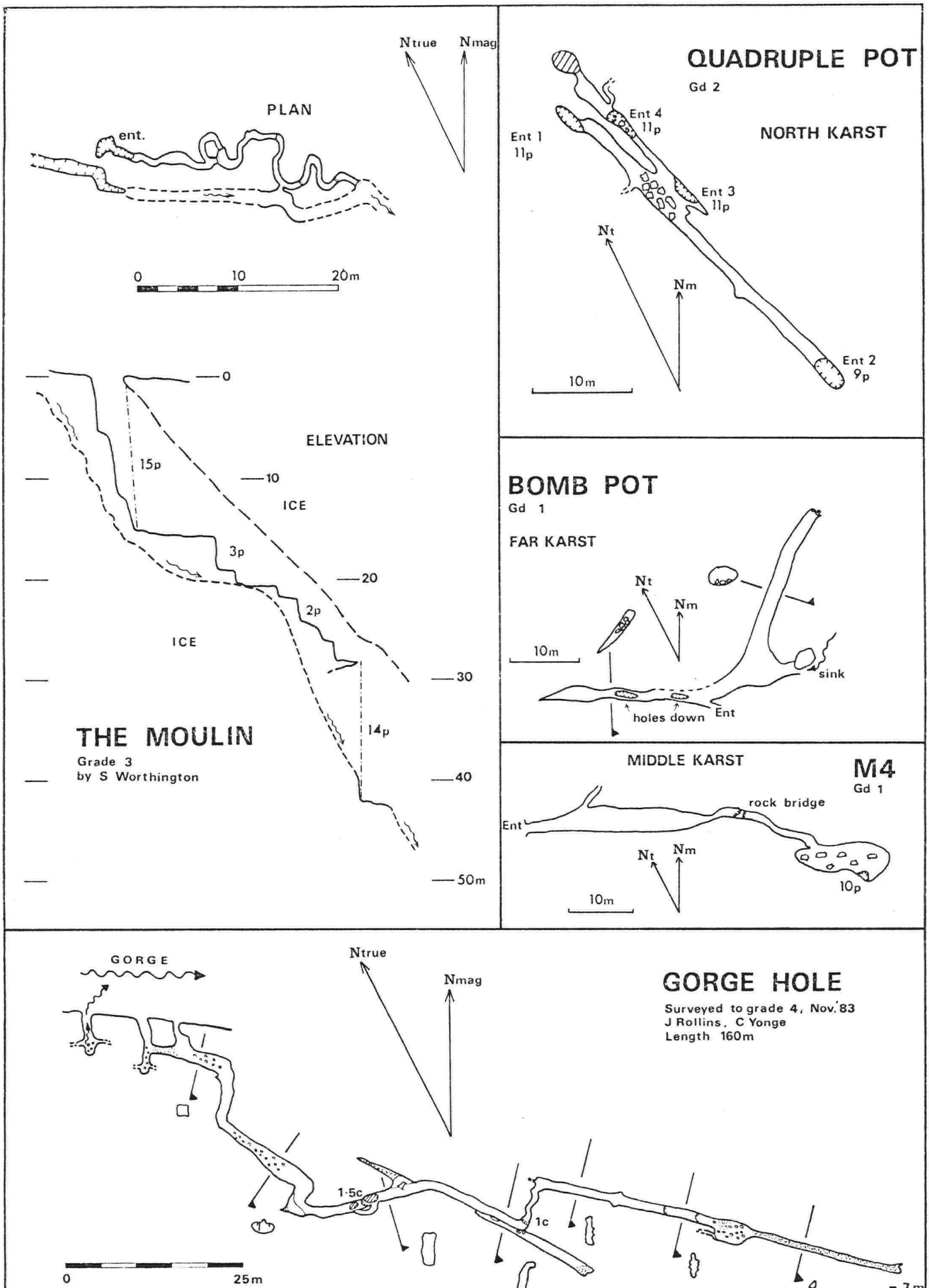
UPPER LAKE SINK CAVE (L4)
Hanging Valley Area, Small Creek (Figs 12 and 14)
Grid Reference: LJ 3787 9722 Altitude: 7175 feet

Massive entrance gully formed by breakdown of thinly-bedded soft limestone where stream from the Upper Lake encounters the basal part of the Mural Lower Carbonate Member. Several routes through huge boulders unite in a large passage with steep boulder slope following dip downwards. The stream is soon met and minor inlets join at several points, but the stream passage soon becomes too tight. Passage on left just inside entrance is a rifty oxbow rejoining the streamway just before the tight section. To the left of the constriction a scramble over boulders followed by a crawl over a huge slab (Grand Piano) gives access to a squeeze leading back to the streamway. For a short distance the passage passes through orange-coloured limestone before the canyon narrows and easier progress is made by traversing along obvious ledges. Rift widens to form chamber with dry abandoned routes leading off to left. All these choke but stream is audible in one. Streamway continues to 7 m pitch, with unstable boulder ledge at top, dropping into circular chamber. Streamway continues as high rift until becoming tight and "sumpy" after about 30 m.

Potential: About 3175 feet to Small Creek Valley.

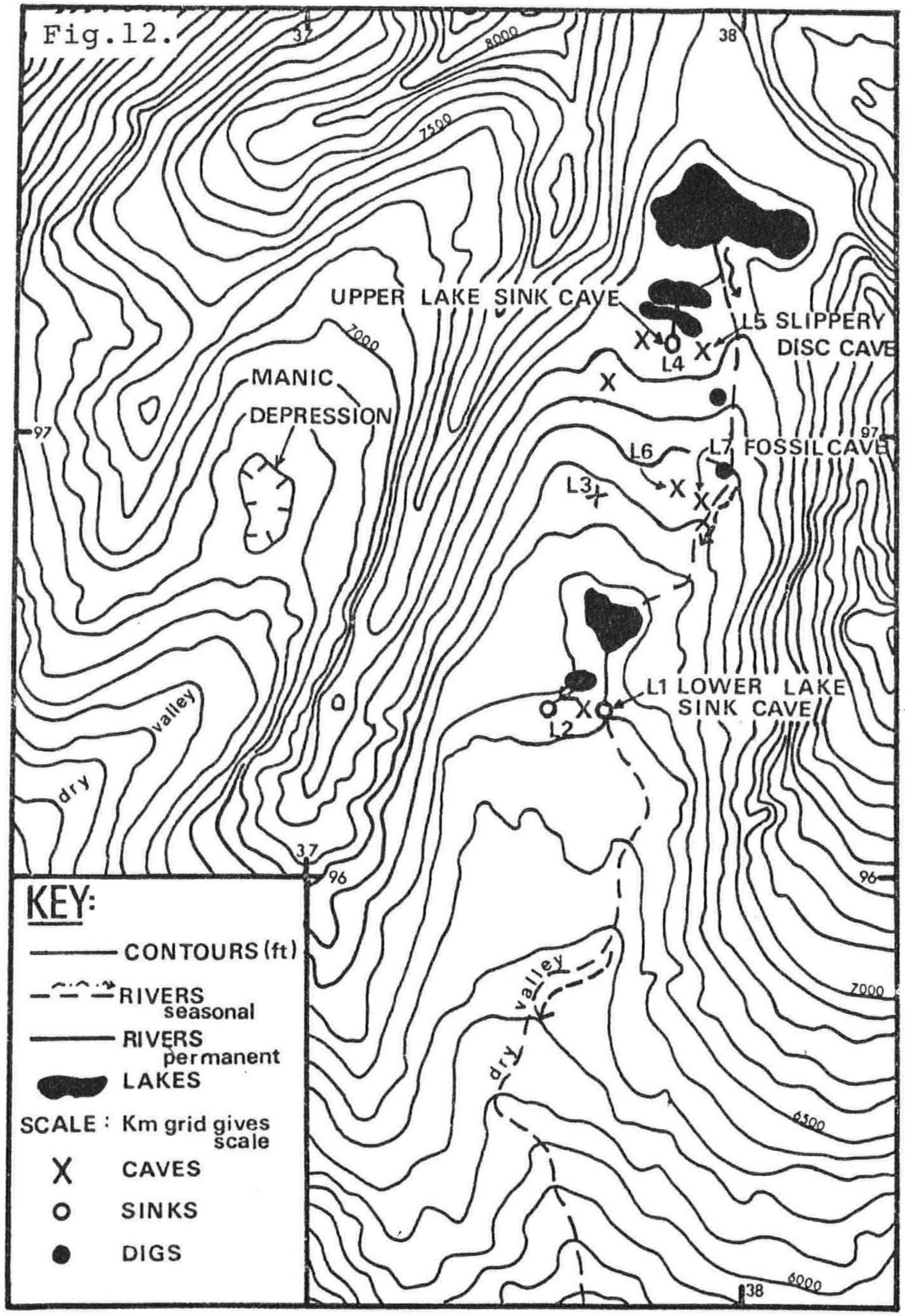
FOSSIL CAVE (L7)
Hanging Valley Area, Small Creek (Figs. 12 and 16)
Grid Reference: LJ 37919687 Altitude: 6850 feet

Small but distinctive entrance in highly fossiliferous pale Mural Limestone. Ice and snow slope descends at 30 degrees into chamber with choked floor. Up to left over boulders leads to short descending traverse to head of short pitch/climb into chamber. Bedding plane by-passes climb and leads to far side of chamber. Main passage continues large and dry with blocked tubes at various points. Several holes in floor blocked by boulders until traverse over obvious open rift. Chimney down at end of rift leads to narrow continuation and short climb down into mud floored chamber (where there was a small pool on the first exploration) and end of passage is tight and choked rift. Below chimney climb intricate



PLAN
ent.
Ntrue
Nmag
0
10
20m
ELEVATION
0
10
20
30
40
50m
15p
3p
2p
14p
ICE
ICE
THE MOULIN
Grade 3
by S Worthington
QUADRUPLE POT
Gd 2
NORTH KARST
Ent 1
11p
Ent 4
11p
Ent 3
11p
Ent 2
9p
Nt
Nm
10m
BOMB POT
Gd 1
FAR KARST
Nt
Nm
10m
sink
holes down
Ent
MIDDLE KARST
M4
Gd 1
rock bridge
Ent
Nt
Nm
10m
10p
GORGE
Ntrue
Nmag
GORGE HOLE
Surveyed to grade 4, Nov.'83
J Rollins, C Yonge
Length 160m
1·5c
1c
0
25m
- 7m

Fig.11.



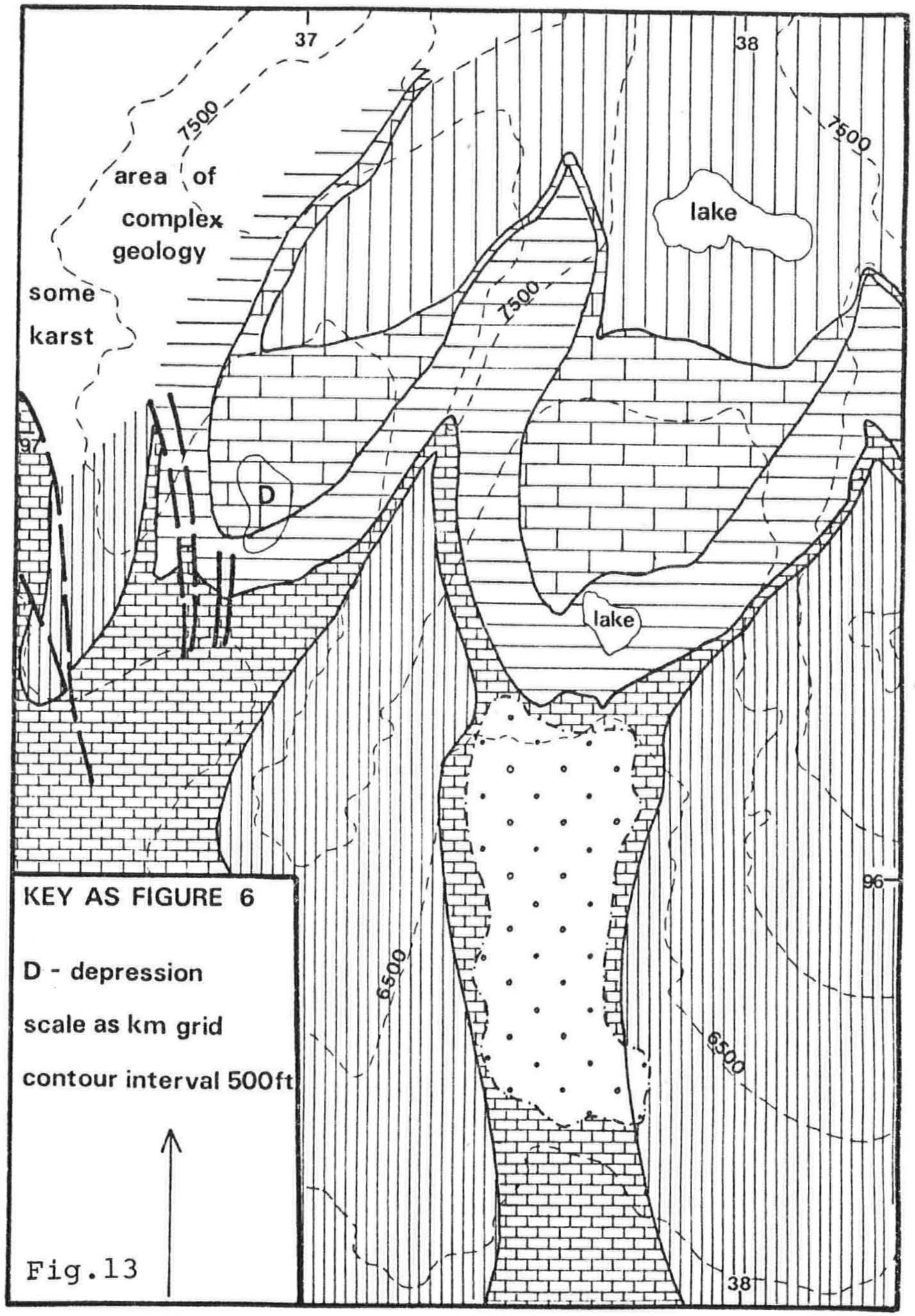
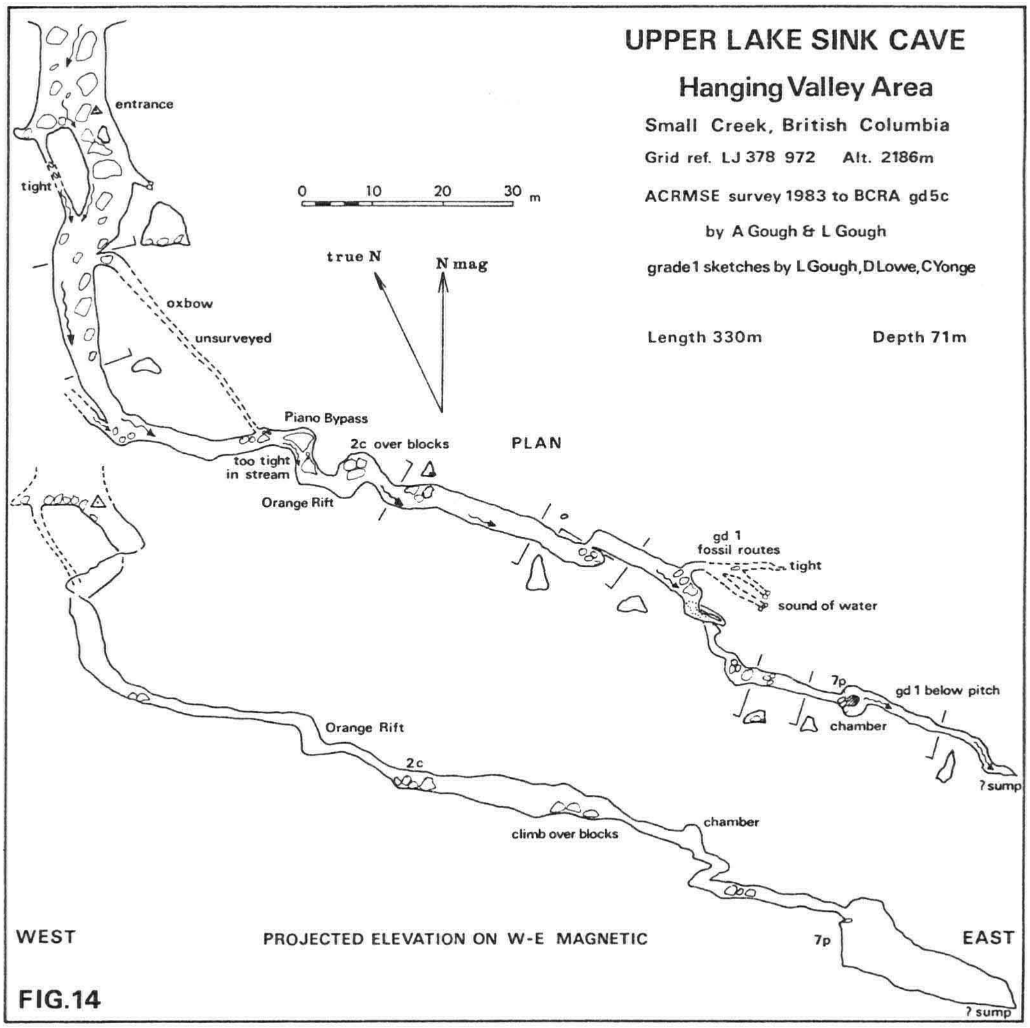
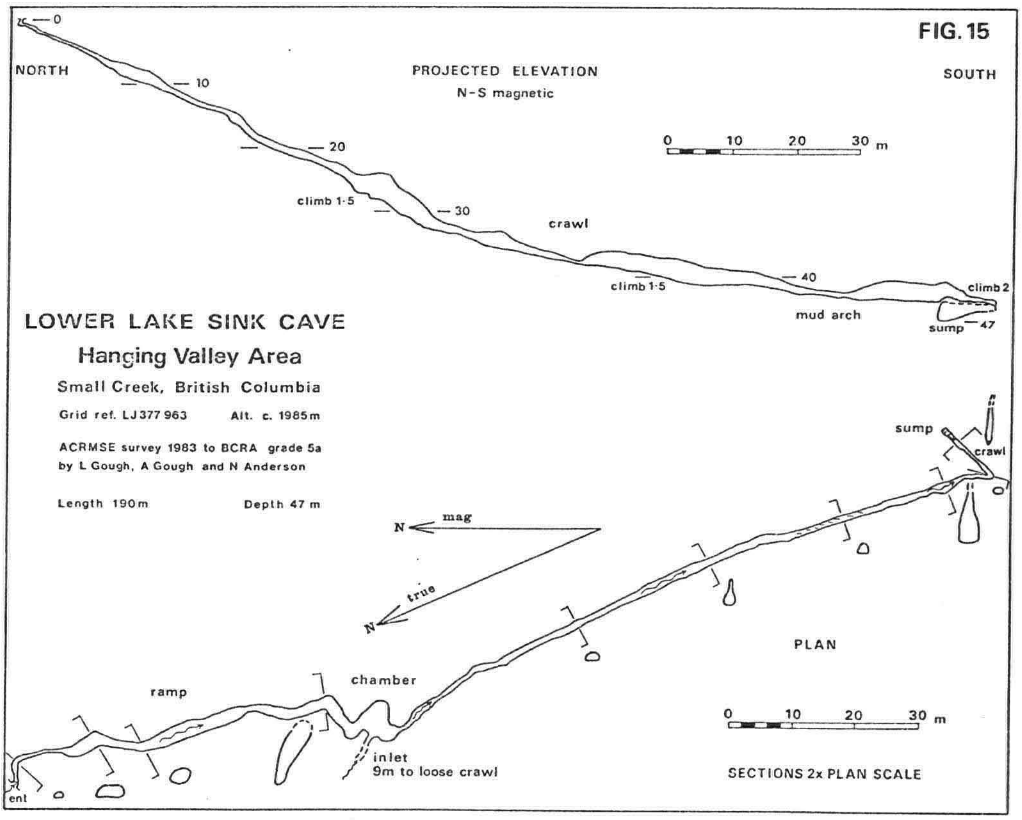


Figure 12 - Topography and cave locations, Hanging Valley Area,

Figure 13 - Geology of the Hanging Valley Area, Small Creek


UPPER LAKE SINK CAVE
Hanging Valley Area
Small Creek, British Columbia
Grid ref. LJ 378 972 Alt. 2186m
ACRMSE survey 1983 to BCRA gd5c
by A Gough & L Gough
grade1 sketches by L Gough, D Lowe, C Yonge
Length 330m
Depth 71m
0 10 20 30 m
true N
N mag
entrance
tight
oxbow
unsurveyed
Piano Bypass
too tight in stream
2c over blocks
Orange Rift
PLAN
gd 1 fossil routes
tight
sound of water
7p
gd 1 below pitch
chamber
?sump
Orange Rift
2c
climb over blocks
chamber
WEST
PROJECTED ELEVATION ON W-E MAGNETIC
7p
EAST
?sump
FIG.14


NORTH
PROJECTED ELEVATION
N-S magnetic
SOUTH
0
10
20
30
40
0 10 20 30 m
climb 1·5
crawl
climb 1·5
mud arch
climb 2
sump 47
LOWER LAKE SINK CAVE
Hanging Valley Area
Small Creek, British Columbia
Grid ref. LJ377963 Alt. c. 1985m
ACRMSE survey 1983 to BCRA grade 5a
by L Gough, A Gough and N Anderson
Length 190m
Depth 47 m
N mag
N true
sump
crawl
PLAN
ramp
chamber
inlet
9m to loose crawl
ent
0 10 20 30 m
SECTIONS 2x PLAN SCALE
FIG. 15

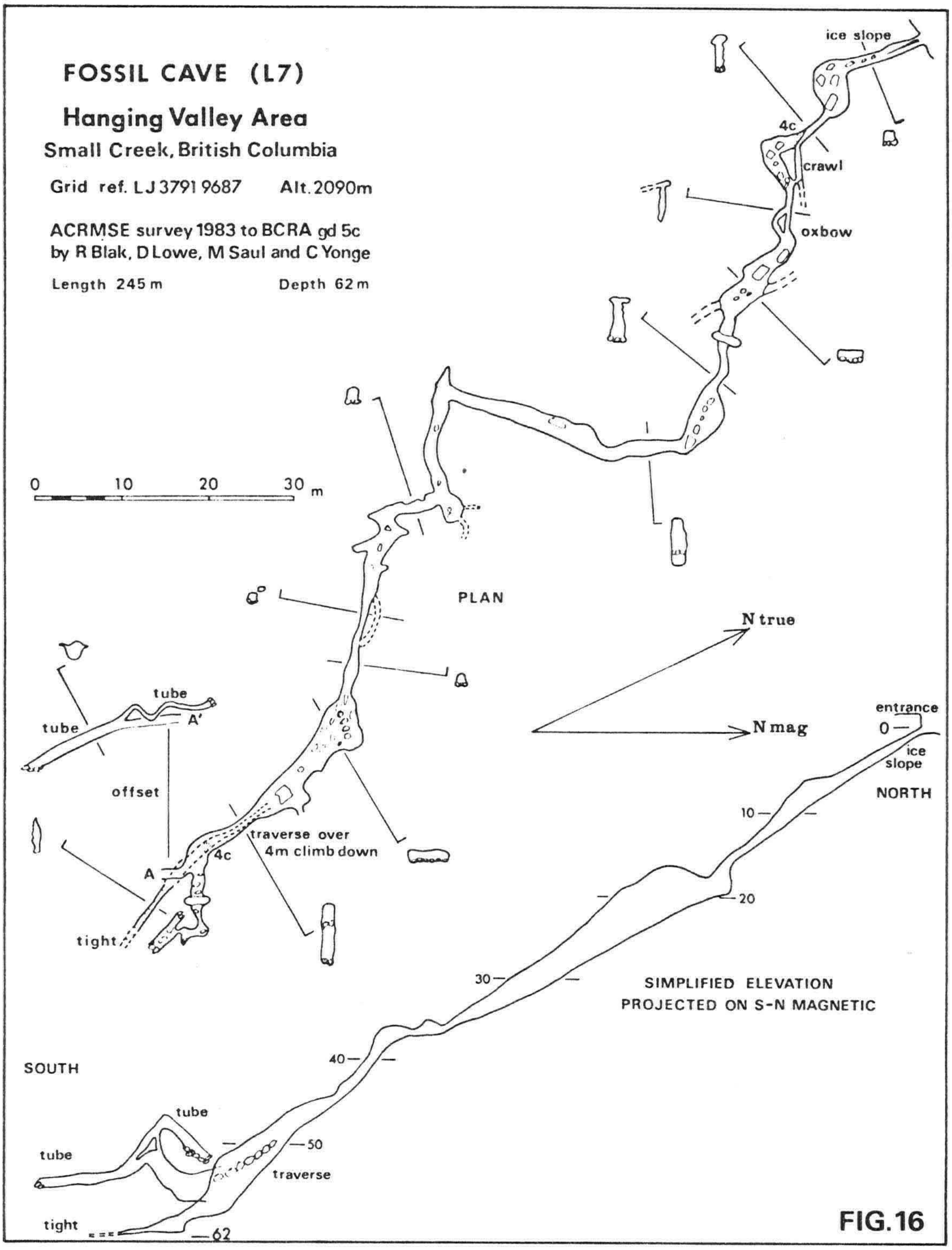

FOSSIL CAVE (L7)
Hanging Valley Area
Small Creek, British Columbia
Grid ref. LJ 3791 9687 Alt. 2090m
ACRMSE survey 1983 to BCRA gd 5c
by R Blak, D Lowe, M Saul and C Yonge
Length 245 m Depth 62 m
ice slope
4c
crawl
oxbow
0 10 20 30 m
PLAN
N true
N mag
tube
tube
A'
offset
A
traverse over
4m climb down
4c
tight
entrance
0
ice slope
NORTH
10
20
30
SIMPLIFIED ELEVATION
PROJECTED ON S-N MAGNETIC
40
SOUTH
tube
tube
50
traverse
tight
62

FIG.16

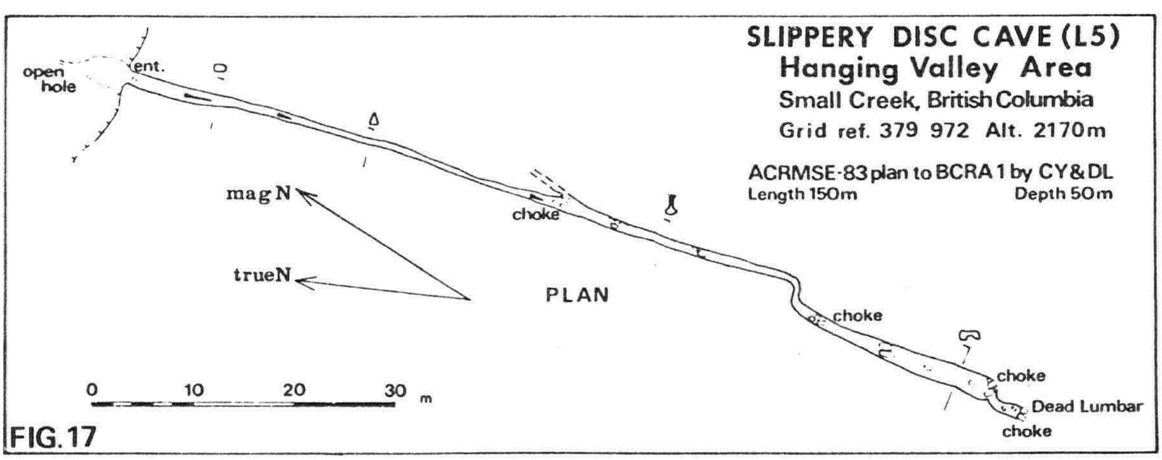

SLIPPERY DISC CAVE (L5)
Hanging Valley Area
Small Creek, British Columbia
Grid ref. 379 972 Alt. 2170m
ACRMSE-83 plan to BCRA 1 by CY&DL
Length 150m Depth 50m
open hole
ent.
mag N
true N
choke
PLAN
choke
choke
Dead Lumbar
choke
0 10 20 30 m

FIG. 17

route leads back to chaotic and highly dangerous boulder area below main passage. Back up climb main passage leads to climb up into impressive phreatic tube boring ahead down dip, only to end where fill reaches roof after a few metres. Tributary tube bores upwards to end in a choke. At the end of main passage low bouldery crawl over choked holes in floor ends in solid choke, but excavated squeeze on right gives access to large rift passage choked in both directions.

Potential: About 2850 feet to Small Creek Valley.

SLIPPERY DISC CAVE (L5)
Hanging Valley Area, Small Creek (Figs. 12 and 17)
Grid Reference: LJ 37919720 Altitude: 7175 feet

Obvious open fissure in lower Mural Limestone buttress to east of Upper Lake Sink. Scramble down open hole and under rock arch to straight passage (over large fallen slab) following 25 degree dip downwards. Roof eventually lowers and passage was originally blocked by boulders. Excavated rightward and leftward wriggles lead back into straight passage. After two more excavated chokes, both passed by low squeezes on left, passage eventually widens to "chamber" with choked floor and another excavated choke above to right. Climb up into large rift which soon ends in another choke (Dead Lumbar) - as yet undug. Though this cave was not surveyed (due to intervention of a slipped disc), its estimated length, measured geological dip and bearings taken along the main line, suggest that its end is close to the end of Upper Lake Sink Cave.

Potential: As for Upper Lake Sink Cave.

OTHER SITES
Hanging Valley area, Small Creek (Fig. 12)

Numerous potential digs were located during reconnaissance, both underground and on the surface. Two particularly promising ones just west of the dry valley below the Upper Lake are shown on the map. West of Lower Lake Sink Cave another minor stream sinks into a choked hole with signs of animal habitation, suggesting space fairly close beyond the boulders. Breakthrough here must provide hope of a bypass to the sump in Lower Lake Sink Cave, since no inlet to account for this sink was met in the cave.

Between the lakes many shorter holes were examined in the Lower Carbonate Member. L3 was a very large bouldery entrance probably choked in the floor. A window gave access to a parallel rift, which should have been a pitch, but was also choked. L6 was a phreatic rift cave of no great length in the highly karstic slopes north of Fossil Cave. No definitive end was reached but potential was probably limited. A number of rifts penetrate the scarp of the Lower Carbonate, one to the western end giving a choked cave about 35 feet (10 m) long. Many other sites await detailed examination.

GEOLOGY

GENERAL In contrast to many expedition areas the geology of this part of the Rocky Mountains is fairly well, though patchily, documented. Before the Expedition, copies of two geological maps were acquired, one (47-1963) at 1:126720 scale covering the eastern half of the area (including Arctomys Valley), the other (1499A) at 1:250000 scale covering the whole of the Mural Limestone outcrop of the Robson Synclinorium, except for its south-eastern extremity towards Moose River. The Mural outcrop was transferred to 1:50000 scale topographic maps for reference in the field, but as expected, when looked at in detail, the generalised lines of the 1:250000 sheet fell short of reality on the ground.

A good general background to the broad geology is provided by Campbell et al (1972), Fritz and Mountjoy (1975), Mountjoy (1961, 1971) and Pugh (1974).

In the field the geology was continually observed, but little mapping was attempted due to the scale and lack of topographic detail on the available maps. With the benefit of the field observations the detailed maps (Figs. 6, 13 and 20) were constructed from aerial photographs. The cover obtained was not perfect and Goat Valley was not included, so the maps are considered provisional. The geology of Goat Valley (included on Fig. 21) is based on published geological maps with minor modification to give a general impression of the tripartite nature of the Mural Formation. On Fig. 3 the outcrop of the Mural Formation around the Robson Synclinorium is again based on published maps, though in the west the lines have been modified to fit broadly with field observations and depict a sweeping generalisation, not necessarily in total accord with the detailed area maps.

As shown in Fig. 3 the outcrop of the Lower Cambrian Mural (Limestone) Formation more or less encircles the Mount Robson massif, and though locally shifted by thrusting and faulting it forms a useful and distinctive marker horizon. In broad terms the formation comprises two major carbonate units separated by vaguely calcareous argillaceous beds, some of which exhibit varying degrees of metamorphic foliation. The precise sequence varies from area to area but in general the majority of the lower part of the unit is a massive pinkish-white fossiliferous limestone, and it is this lithology that makes the Mural Limestone so distinctive, especially where it forms karstic dip slopes.

The geological map reveals the Mount Robson area to be a major syncline with its axis trending approximately north-west - south-east. The effects of faulting and thrusting have modified the simple synclinal structure somewhat, whilst locally minor folds are superimposed upon the major structure. The presence of minor anticlines and synclines within the major structure means that strictly it should be described as the Mount Robson Synclinorium. North-eastwards from the Synclinorium the Mural and associated beds are repeated several times in a number of thrust slices.

Though locally variable, the approximate geological sequence in the Mount Robson area is as follows:

Middle Cambrian and younger beds

Lower Cambrian	Hota Formation		(84m)
	Mahto Formation	Gog Group	(459m)
	Mural Formation		(245m)
	McNaughton Formation		
Pre-Cambrian	Upper Middle Lower	Miette Group	Very thick

At its type area (Fritz and Mountjoy 1975) the Mural Formation is about 245 m in thickness; thicknesses in areas studied are somewhat greater than this. The Mural Formation generally comprises at least three distinct divisions. At the current scale of Canadian Geological Survey mapping these sub-divisions are unformalised and the Formation is shown undivided but for the purpose of this report the terminology below is used:

Mural Formation	Upper Carbonate Member Middle Shale Member Lower Carbonate Member

The beds underlying the Mural Formation are fairly distinctive in all the areas studied, comprising massive blocky-weathering ortho-quartzites. Typically these rocks form boulder fields which support a flourishing lichen flora; the outcrop, even at a distance, is a distinctive pale green. Additionally the small lakes impounded on the quartzite have an abundant "algal" growth whilst lakes on the carbonate-rich beds stratigraphically above are notably sterile. Whether this pronounced difference is a reflection of variation in pH or of the nature of the dissolved minerals in the lake waters is not known. The base of these quartzites, the lowest part of the Gog Group, was not seen in any of the areas studied.

Above the Mural Formation a mixed sequence of quartzite, siltstone and shale, with one significant band of limestone, 10 m thick, in the lower part, comprises the Mahto Formation.

According to Mountjoy (1962) the thickness of the carbonate sequence in the Gog Group (= Mural Formation) increases to the south-west in the Mount Robson district. Hence the Small Creek area seemed the logical place to begin the Expedition.

Drift deposits comprising scree, moraine (in various morphological forms) and alluvium are locally common. Elsewhere above the tree line bare rock surfaces or thin impoverished soils are standard; thicker organic-rich soils occur in the forested areas.

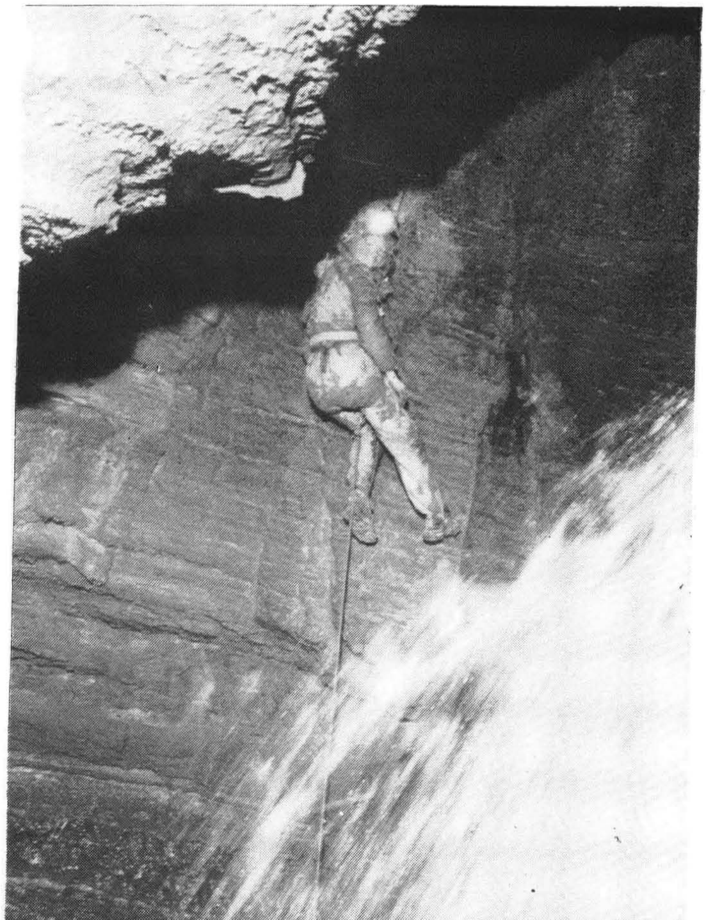
DETAILS - Top Area: The axial trace of the main Robson Syncline (Figs 3 and 6) passes from northwest to southeast through the Top Area. Beds making up the Far and Middle karsts dip generally eastwards at up to 40 degrees (locally variable), the North Karst dipping more gently towards the southwest. All dips on the flanks of the Syncline tend towards the horizontal as the axial trace is approached, but still with a southeasterly plunge component. To the northwest the two sets of Mural beds close to plunge southeast and the dips on both flanks of the syncline increase towards this closure. Much detail is obscured by ice, scree and moraine, so that precise relationships are conjectural.

Field observations and study of aerial photographs suggest that the Far Karst represents the outcrop of the Lower Carbonate Member, much of the exposure being a series of overlapping karst dip slopes. A number of minor faults cut the outcrop,usually with only minimal displacement. Towards the southwest of the area a thin veneer of Middle Shale Member is preserved on top of a crudely triangular area bounded by limestone cliffs, one at least of which is a fault scarp, the others probably erosional features. Northeastwards the Lower Carbonate passes beneath the Middle Shale, which forms the limit of the Far Karst.

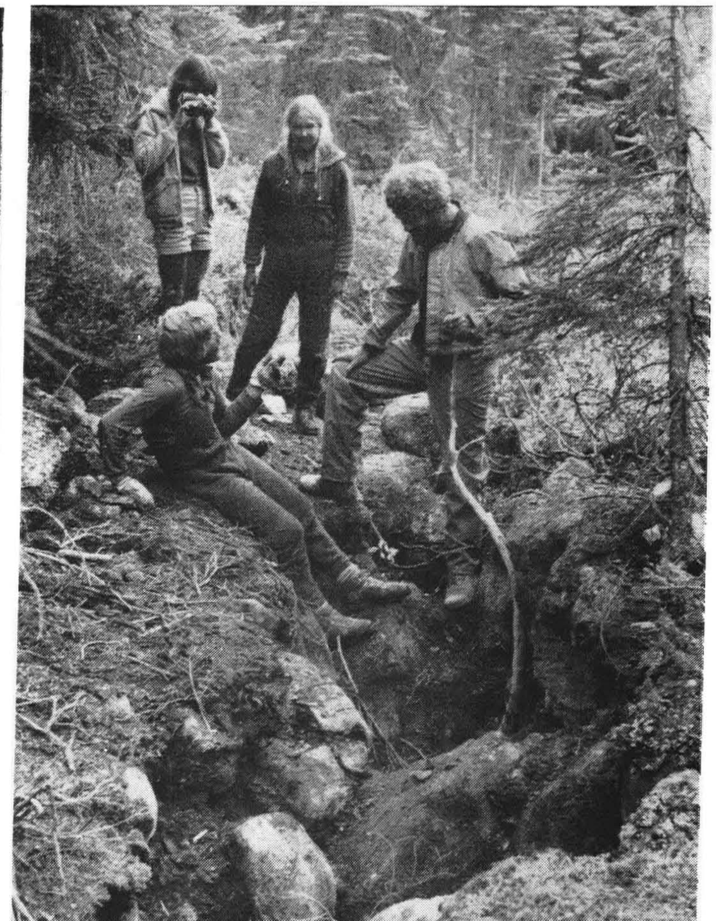
The Middle Karst is probably formed entirely within the Upper Carbonate Member, which dips southeastwards more gently than the Lower Carbonate. Again much of the outcrop comprises bedding slopes which eventually pass beneath the rocks of the Mahto Formation which form the central spine of the Top Area. Northwestwards of the main part of the Middle Karst smaller areas of glaciated pavement are exposed, whilst still further to the northwest a crag of the Upper Carbonate Member is exposed close to a col overlooking Horsey Creek. A number of small blocked sink were found in this area.

Exposure is less good in the North Karst, where a poor soil cover is present over much of the area, supporting a straggling coniferous vegetation, but all evidence suggests that the gently-dipping karst is the upper surface of the Upper Carbonate Member. The outcrop of the Lower Carbonate forms no significant karst in this locality, being present only as steep crags, or shrouded by scree.

1. The Hanging Valley looking down the dip-slope of the Mural Lower Carbonate towards Lower Lake (photo: A.K.Gough).



2. The Waterfall Pitch in Porcupine Cave (Photo: N.Anderson)



3. Discussing digging tactics, North Karst (photo: L.K.Gough)

The moraines below the main ice-sheet are magnificently formed and very fresh, elongate and sharp-crested, suggesting that they are relatively youthful features. They are, however, complex and multi-ridged and abut against less well-defined morainic material to the southwest, clearly reflecting a multiphase development. Above the North Karst is another impressive morainic suite, this one seeming less fresh than that mentioned above, but fresher than the moraine in the Hanging Valley area to the east.

HANGING VALLEY AREA: Exposure of the Mural Formation is generally good in this area (Figs. 3 and 13), though locally-extensive scree fans and ground moraine are present. The solid beds dip generally southwards, though the dip is variable in both direction and amount. The following sequence is exposed:

Manto Formation		quartzite, siltstone and shale
	Upper Carbonate Member	limestone
Mural Formation	Middle Shale Member	phyllitic shale
	Lower Carbonate Member	limestone/dolostone
McNaughton Formation		mainly quartzite, some thin conglomerate bands

The quartzite of the McNaughton Formation forms a wide outcrop at the top of the valley where there are extensive lichen-covered block-fields. Thin conglomeratic bands occur rarely, marking the base of sedimentary cycles and cross-bedding is locally well shown.

Fragmental Olenellid trilobites occur at some horizons and the trace fossils *Skolithus* and *Cruziana semiplicata* are common. The main upper lake lies on the quartzite and drains, via two smaller lakes in strike guided hollows, to Upper Lake Sink Cave.

At its base the Upper Carbonate Member comprises fairly soft arenaceous limestone and dolostone with thin interbands of calcareous siltstone, passing upwards into purer, more massive pale coloured carbonates which form the distinctive karstified dip slopes in the upper part of the Hanging Valley and the valley above the Manic Depression to the west, locally taking on a pinkish hue and with a rich fauna including Archaeocyathids (very common), primitive Echinodermata (common) and ?Olenellid trilobite fragments (rare). Various karren forms are well developed on the dip slopes, including rillenkarren, rinnenkarren, kluftkarren, meanderkarren and trittkarren. Kamenitza hollows are also common.

The Middle Shale Member is poorly exposed, but where seen consists of dark shales and siltstones, locally exhibiting a phyllite grade foliation. Very rarely occurring Olenellids in the shales are distorted, reflecting the compression of the rock mass during tectonism.

Exposure of the Upper Carbonate Member in the valley floor is poor, only the basal contact and a few metres of rock being visible in the vicinity of Lower Lake Sink Cave. In the valley sides however it is clearly seen, particularly to the east, where it forms a sheer cliff. The unit is mainly pale-coloured massive limestone, locally darker and possibly dolomitic. The overlying Mahto Formation is exposed only in the sides of the valleys and was not examined.

A number of minor faults cross the Hanging Valley area, generally of small throw but of appreciable length. A number of them appear to pass into tectonic master joints with no indication of displacement. The exposed dip slopes of the Lower Carbonate Member show numerous strong joints, particularly on a northwest - southeast alignment, which roughly parallels the predominant fault trend.

As mentioned above extensive block-fields exist on the quartzites. Both sides of the Hanging Valley and the valley sides above the Manic Depression are fringed by extensive scree slopes, locally weakly cemented. Thin poorly-sorted alluvium is present around the Lower Lake and this passes obscurely into the scree slopes above and a broad moraine below. The Hanging Valley moraine is morphologically less fresh than moraines in the Top Area, implying that this area has been free of significant glaciation in recent times. Between the Lower Lake and the hanging drop to Small Creek this ground moraine is present right across the valley. Its southern limit exhibits features suggestive of a terminal moraine and it is assumed that the whole moraine deposit represents the decay product of a minor cwm glacier.

ARCTOMYS AREA: Arctomys Valley is a classic example of a strike-controlled valley, running more or less north - south, with the solid sequence dipping westwards at about 35 degrees. A very great thickness of McNaughton Formation quartzites form the eastern part of the area, though much of the outcrop is obscured by scree (figs.19 & 20).

Both the Lower and Upper carbonates are present in the floor of the western arm of the valley and the ridge between here and Artomys Lake (Fig. 20), the total thickness being somewhat less than that seen to the west of the Syncline. Similarly the Middle Shale Member is relatively thin, more of a shaly parting than a significant bed, and even this appears to thin southwards, though detailed exposure is lost in the steep forested slopes above the Moose River.

Siltstones of the overlying Mahto Formation form an impressive cliff to the west of Arctomys, with good exposure of a 10 m carbonate band about 100 m above the top of the Mural Formation. Over the ridge to the west the steep slope down towards Resplendent Creek consists of overlapping steeply-dipping slabs of Mahto siltstone and quartzite.

Scree deposits are ubiquitous on the steep valley sides, only the more well-defined spreads being delimited on the detailed geological map. The area below Arctomys Lake probably comprises mixed alluvium and ground moraine, though no fresh glacial landforms were noted.

As in the Hanging Valley the Mural dip slopes are strongly karstified and kamenitza and karren forms are common. Deep kluft karren are guided by strong master joints which parallel a number of southward throwing minor faults.

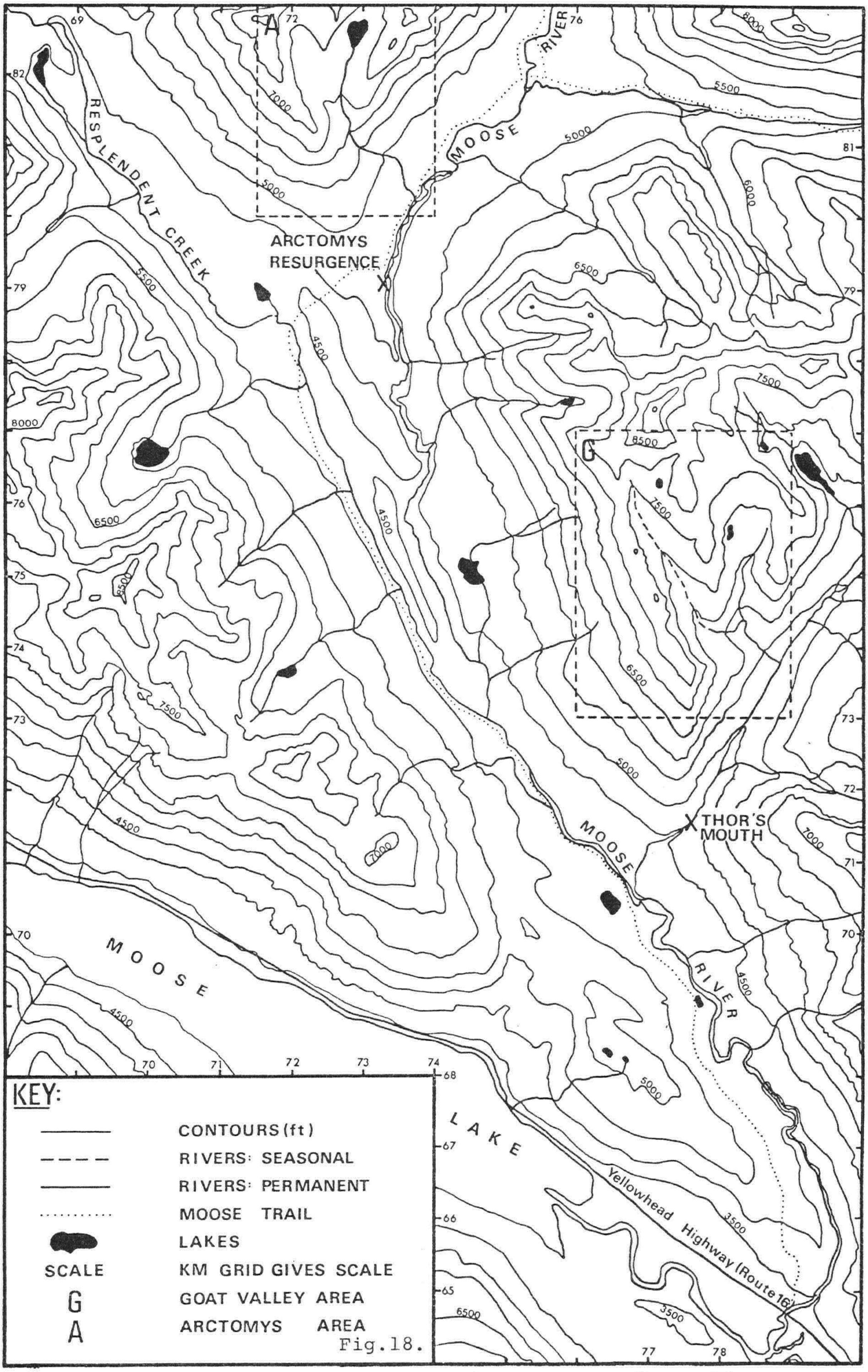


Figure 18 - Topography of the Resplendent Creek - Moose River area

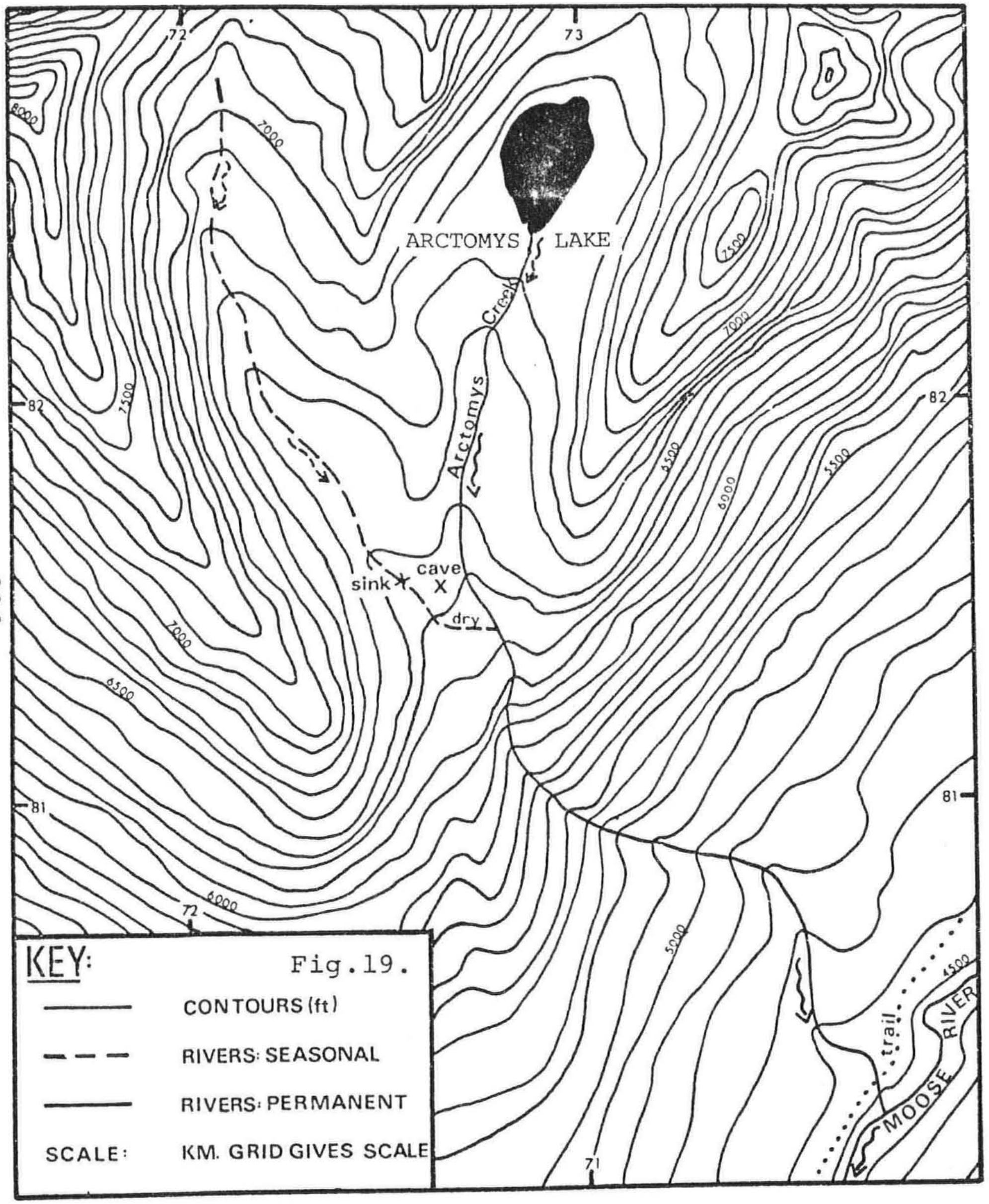


Figure 19 - Topography of the Arctomys Valley

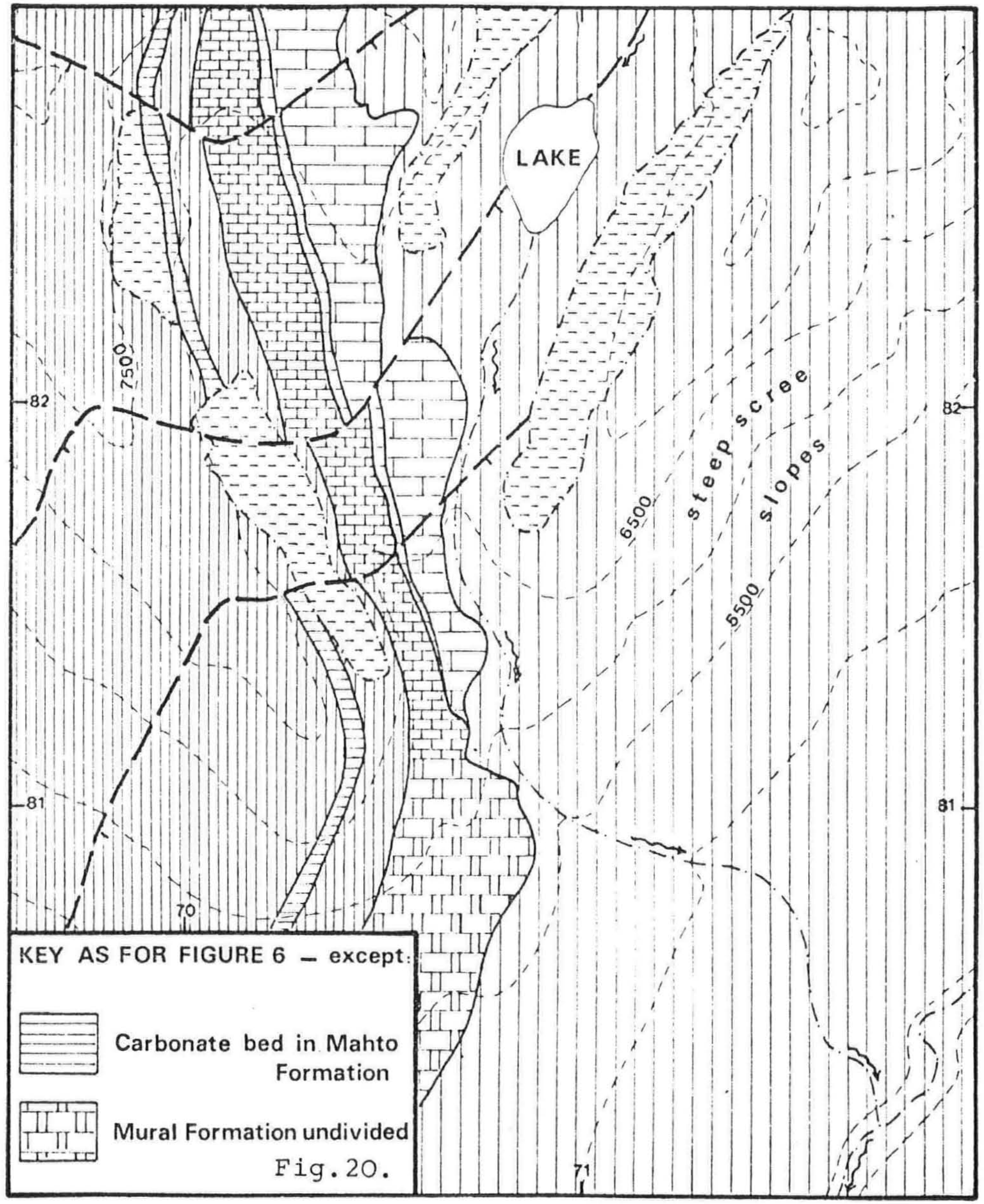


Figure 20 - Geology of the Arctomys Valley

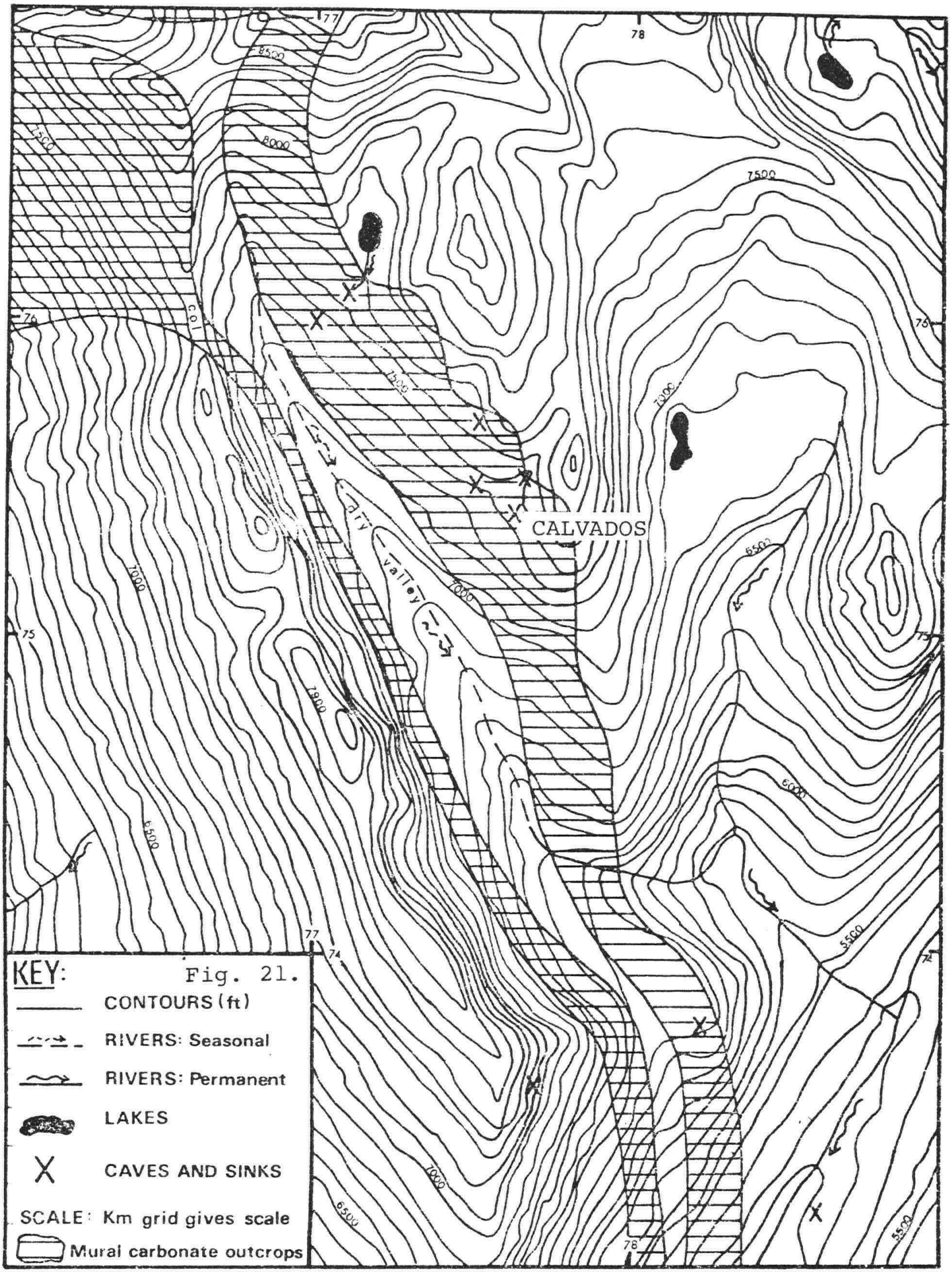


Figure 21 - Topography and Mural Formation outcrops, Goat Valley

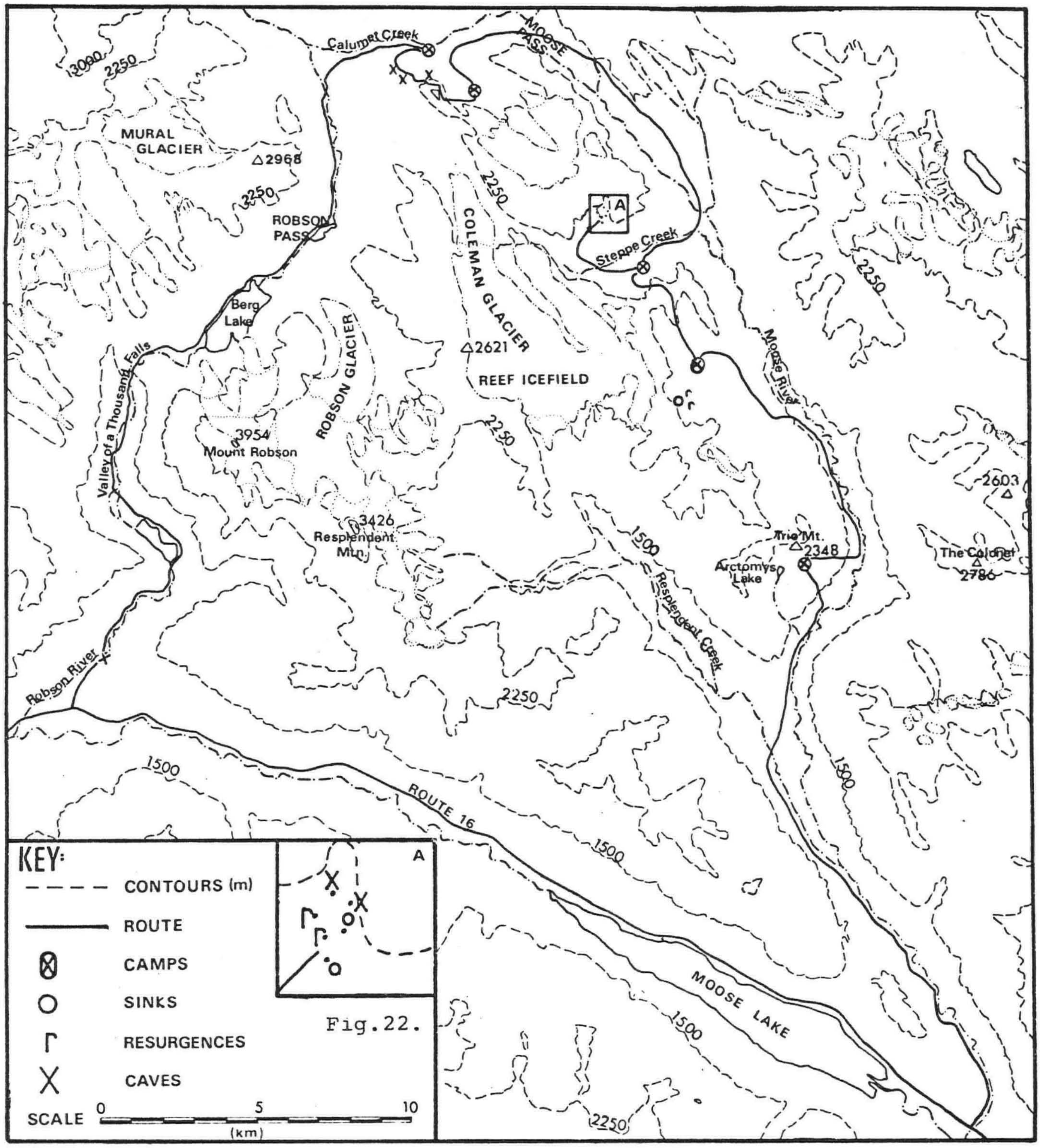


Figure 22 - Route map of the Long (Mount Robson) Reconnaissance

GOAT VALLEY: Broadly speaking the geology of Goat Valley (Fig.21) resembles that of the Arctomys area. The valley is again strike-controlled and again the dip is to the west at angles of between 25 and 40 degrees. Northwest of the valley the Upper Carbonate Member forms extensive dip slopes dropping towards Moose River but the outcrop climbs southwards to cross into Goat Valley, where it is present as a crag in the steep western wall. Southwards the Upper Carbonate drops towards the valley floor and crosses the lower limit of the valley close to its hanging culmination. The Lower Carbonate Member forms stepped dip slopes on the eastern side of the valley, where several streams flow from a rugged area of McNaughton quartzite and sink immediately into the limestone. Overlying the Lower Carbonate Member along this outcrop is a bed of massive quartzite at the base of the Middle Shale Member; this being followed by a more typical phyllitic shale, siltstone sequence with sporadic thin quartzite bands.

Drift deposits in the Goat Valley seem to be typical of the area in general, with steep scree slopes to the west. Hummocky moraines occur towards the southern culmination of the valley, exhibiting a general morphology which suggests that they are not very fresh.

General Comments: Study of the Lower Cambrian sequence was very informative and proved that the Mural Formation in particular is far more interesting than published maps would imply. Particularly striking was the very close resemblance of all the Gog Group formations to the Lower Cambrian - Ordovician sequence, including the Durness Limestone, of northwest Scotland - rock units can be matched in detail from the base of the McNaughton Formation up to the top of the Mural Formation. Above the Mural a continuous Cambrian sequence exists, whilst in Scotland it is generally accepted that a major unconformity is present within the Durness Limestone.

Whilst it might be argued that glacial conditions still exist in the Rocky Mountains it is generally agreed that the last major ice advance, the Late-Wisconsin, ended about 10000 years ago. Since then remnant ice sheets of oscillating extent have persisted in the Rockies, and undoubtedly there have been advances and retreats in more recent times. The present situation seems to be one of gentle retreat and the moraines of the Top Area present a very fresh morphology, indicative of the relatively late start of this phase. The more subdued morainic landforms of the other areas studied are taken to indicate that retreat here was earlier, though probably much more recent than the end - Wisconsin retreat.

SPELEOGENESIS

Following the reasoning of Ford (1974) karst development (including cave formation) should be appreciably less above the tree line, where glacial meltwater is only weakly aggressive. During the Expedition very little karst was located in the bush, partly due to the difficulties in tracing the outcrops of the Mural carbonates into the forest and partly because effort was concentrated on the more open areas above the trees. There was abundant evidence however of karst development up to the highest outcrops of Mural located, at an altitude of about 8300 feet (2500 m). At this level several minor sinks were found, one being a shaft 3 m x 2 m and 10 m deep. At the foot of this shaft only a minute fissure continued. The conclusion that must be reached is that at these altitudes only immature underground drainage routes exist, produced by weakly aggressive meltwater, and that any larger manifestations, such as the shaft mentioned above, are a function of proximity to the surface and fresh solvent water. The importance of other processes, such as frost shattering, is locally great at these higher altitudes - for instance the entrance of Upper Lake Sink Cave in the Hanging Valley is grossly over-enlarged.

Whilst the end of the Late Wisconsin glacial advance is generally accepted as being about 10000 years ago and lowland Canada has probably been largely ice-free since then, the higher parts of the Rockies have supported ice fields right up to the present, their size fluctuating in response to climatic variation. Minor local readvances are known to have occurred as recently as the last century. The ice fields are currently in retreat, though the retreat process is very slow. It seems likely therefore that much of the karst area examined during the Expedition, particularly in the Top Area, has only relatively recently been exposed from below the ice. Evidence for this is quite strong: the freshness of the morainic landforms in the Top Area, neoglacial pavements with sharp striae still intact and unweathered and the presence of sub-glacial calcite still preserved on exposed rock surfaces. Whether cave formation can occur beneath an ice sheet, where melting occurs at the sole or where surface drainage penetrates the ice, is another interesting question, which might at least be partially answered if the Moulin system above the Top Area karst can be followed down to the sub-glacial rock surface.

On balance it seems that a large part of the cave passage found by the Expedition is pre-Late Wisconsin in age, since it appears impossible for such large systems to have formed from scratch in such a short time in the post-Wisconsin regime at these altitudes. As a corollary to this assumption it must also be assumed that the caves were once far more extensive and may have been blocked or simply scraped away by ice. Examples of truncated older systems are many, the lower entrance of Fiddler's Cave and the M3 (Rathole) entrance to Porcupine Cave for instance. Another possibility is that the risings for the Far and Middle karst areas result from the glacial overdeepening of the valley between the two areas intersecting once deeper drainage routes. Possibly the gorge below F1 Resurgence Cave was an original underground route, unroofed by ice. Gorge Hole, explored by the Canadians since the Expedition, is part of a large abandoned system which leads away from the surface valley down dip, and may be a remnant of one of these older underground drainage routes.

On a more specific level the abandoned main route in Porcupine Cave, now blocked 'upstream' by glacial debris, is obviously very old, presumably pre-Late Wisconsin. The current active route is much more recent and immature with numerous cascades and an upstream sump ponded by a rock barrier. The connection between the two distinct parts of the system is a high-level phreatic tube, probably punched through from the new to the old system prior to the former beginning to develop its present vadose morphology. The older part of the cave presents a well-graded profile closely following the dip of the underlying impermeable beds. Both the M1 and M2 entrances (and the more recently discovered Latecomer's Entrance) are probably younger drainage routes which were active in turn as the surface stream opened new sinks in the obscure valley above, all probably being active in high flood, but all now effectively abandoned.

In the Hanging Valley the two known active systems exhibit markedly vadose features, though these are still at a fairly immature stage. Above the active routes phreatic remnants are locally preserved, though breakdown has removed much valuable evidence. In Fossil Cave, between the two active systems, a much larger amount of unmodified phreatic passage is preserved, having been left high and dry by vadose downcutting. All these phreatic remnants are blocked by silt; similar silt blockages were noted in the Top Area.

Much more information is required before any firm conclusions are made, but the following history of development is offered as a working model.

1. Pre-Late Wisconsin (this very loose term could include any time between pre-Pleistocene glaciation and the commencement of the Late Wisconsin Advance). Formation of deep phreatic drainage routes. In order that a hydraulic gradient and viable sink-rising systems could be set up it seems likely that a proto-Small Creek Valley must have existed and therefore an interglacial date is preferred for the commencement of this phase. (In the cases of the Arctomys and Goat Valley areas a proto-Moose River Valley system is required).

2. Late Wisconsin: Advancing ice removed much bedrock, deroofed many phreatic passages and possibly scraped away entire drainage systems. Concurrently some of the holes exposed must have been plugged by ground moraine, though not necessarily to any great depth.

3. Post-Late Wisconsin: As retreat began surface drainage must have increased dramatically with debris-laden streams flowing down surface valleys. Any open holes would be rapidly invaded and rapid vadose downcutting would ensue if drainage was unimpeded. Where old underground conduits were blocked by moraine or where outlets were moraine- or ice-dammed, ponding up would lead to further blockage by silt deposits. If an alternative drainage route was initiated the silt-filled tubes would be left abandoned at high level. At the same time minor phreatic enlargement of surface fissures probably began across the entire area of glacially scoured pavement revealed by the retreat. Eventually a second underground drainage system would develop and in some cases pirate surface drainage to form immature vadose cave passages. In turn some of these probably intersected fragments of the older system - as in Porcupine Cave - and in some cases might have commenced removal of clastic fill.

4. Present situation: Fragments of the old system passages are still extant and in some cases partly or completely active. The passages of the new system are still generally immature with perched sumps, nick points and unmodified phreatic tubes still present locally. The large vadose canyons cut below the old phreatic tubes (as in Fossil Cave) by debris-rich streams are now generally abandoned or fed by underfit streams, except at the time of the annual spring thaw.

The above is a necessarily simplistic view of the history of cave formation in the areas explored by the Expedition. Several conclusions can be drawn: a large amount of old cave has been removed by glacial action, many old passages have been blocked by moraine or silt and a proportion of currently active sinks will lead only to very immature cave systems which may not be explorable to their intersection with the main underground drainage routes, which may in turn be the reinvaded parts of the older system. It also follows that even on ridges or valley sides fragments of the older system may remain and have escaped both removal and debris blockage. Elsewhere in the Rockies major systems exist with their entrances preserved on ridges - Yorkshire Pot being one example. Additionally, reverting to the findings of Ford (1974) it would seem that if caves could be explored to a point where they pick up surface drainage from the coniferous forests there should be a chance of increased passage size due to both the increased aggressiveness of the forest drainage and the possibility of mixture corrosion conditions being established.

HYDROLOGY

Only very large creeks crossed the full width of the Mural Limestone outcrop at the time of the Expedition, though during the spring thaw more surface streams exist. Where the dip of the Mural Limestone is steep the underground drainage tends to follow the most favourable hydraulic gradient down dip, though not exclusively, since a number of sidestepping strike or even up-dip tube passages were noted. In the Top Area resurgences were located to account for the known underground drainage of both the Far and Middle karsts. Possibly in Pre-Wisconsin times the drainage was deeper and continuous beneath the present day surface drainage routes, perhaps to resurge at a much lower level. The North Karst illustrates the bygone situation in the other two areas. Here again a major surface stream crosses the limestone outcrop but has not cut down to the impermeable rocks below. The bed of this stream must be well-armoured since no sinks were located. Minor streams do sink in the area, however, and since no resurgences were located it is assumed that the sinking water continues to flow down dip to a resurgence by the logging trail in Small Creek.

Again, in the Hanging Valley area, the sinking streams flow down dip and here too the underlying impermeables do not come to crop in the slopes below the lip of the valley. No local resurgence is recognized ; the ultimate destination of the underground drainage could be the logging trail resurgence mentioned above, or possibly a somewhat smaller rising near Small Creek, to the west of Base Camp.

The Arctomys and Goat Valley areas exhibit very similar geological conditions and their underground drainage is probably comparable. Water sinking in the Arctomys Valley is known to flow diagonally by alternate dip- and strike-guided passages eventually to sump at a depth of 522 m before resurging by the Moose River at approximately the same altitude as the cave sump. The major sinks in Goat Valley are into the Lower Carbonate Member of the Mural Limestone which forms a karst dip slope on the east flank of the valley. Along much of the valley's length the Upper Carbonate Member is present in the cliff forming the steep western valley side, but this outcrop steadily descends to cross the valley close to its hanging culmination to the southeast. Here a number of minor streams sink into choked holes. By analogy with the Arctomys area it seems most likely that the Goat Valley water follows the dip of the Mural Limestone to resurge by the major stream (a tributary of the Moose River) in the valley below the end of Goat Valley.

The drainage routes described above, are (with the single exception of the Arctomys system) speculative and await confirmation by water tracing techniques. Volumetric estimates on various resurgences were made and it is uncertain, for instance, whether the Far Karst Resurgence (F1) and Middle Karst Resurgence account for all the water sinking in their respective areas, or whether a deeper drainage system exists which might drop to the level of Small Creek.

The following estimates were made for various sites:

F1 Resurgence	0.5 cumec rising to 1.0 cumec
M area resurgence	0.3 to 0.5 cumec (sum of both risings)
Stream in Porcupine Cave (M1/2/3)	0.1 to 0.3 cumec
Upper Lake Sink Cave	less than 0.1 cumec
Lower Lake Sink Cave	less than 0.1 cumec
Resurgence west of Base Camp	complex flows from "scree" perhaps 0.2 to 0.3 cumecs in all

Resurgence by Small Creek logging trail about 0.3 cumec

The temperature of the water emerging from the F1 resurgence was measured as $2^{o}C$; no variation due to the afternoon influx of glacial meltwater is recorded. This lack of meltwater influence could indicate long sumped sections between unknown sinks below the Top Area icefield and the upstream sump in the Resurgence Cave. On balance, however, long sumps in such steeply dipping beds seem unlikely, though where drainage is via immature recent routes, as in the active part of Porcupine Cave, it is possible to envisage a backing up of excess meltwater flow which is beyond the capacity of the drainage conduit. In Porcupine Cave the active upstream sump is held back by a rock barrier, which would support the idea of an immature passage, since below the sump the cave drops dramatically.

Hopefully it will be possible to trace the underground drainage routes in 1984, the only problem being that possibly further resurgences exist in the dense bush above Small Creek.

CONCLUSIONS

The area covered by the Expedition, with the exception of the Arctomys Valley, was previously unexplored by speleologists, despite its close proximity to Jasper, Edmonton and Calgary. In terms of the amount of new cave discovered and surveyed and of new insights into the geology of the Mount Robson Synclinorium, the Expedition was an undoubted success. Several areas of proven speleological potential are now known to exist, any of which are quite feasibly accessible to local Canadian cavers for weekend exploration. Activity has already started, in the wake of the Expedition, by local cavers and three Expedition members who remained in Canada, and has led to the reconnaissance of the areas between Goat Valley and the Moose River and the discovery of Gorge Hole and the Latecomer's Entrance to Porcupine Cave. No doubt further discoveries will be made. In 1984 a second Expedition will take place; in addition to following up the leads explored in 1983 and attempting to substantiate postulated drainage routes, the very promising areas located during the long reconnaissance will probably be fully explored.

ACKNOWLEDGMENTS

In addition to the sponsors listed below the Expedition would like to express gratitude to those Canadians who were so hospitable during and after the Expedition, particularly Ian McKenzie. Appreciation is also due to Paul Hatherley and Pete Robertson for their invaluable assistance in producing some of the illustrations for this report and feed-back to sponsors, and to the BCRA for providing the opportunity for early publication.

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This report is based on the findings, observations and reports of the members of the 1983 Anglo-Canadian Rocky Mountains Speleological Expedition, collated by D.J. Lowe, who also contributed the geological section, and Charlotte Roberts.

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APPENDIX 1: SURVEYING AND MAPS

The more important caves explored were surveyed to BCRA Grade 5, with detail varying between (a) and (c), depending upon the surveyor. Three sets of Suunto instruments were used, two of which were kindly donated by Suunto Oy of Finland. Distance measurement was by 30 m Fibron tape, two tapes being loaned by Rabone Chesterman Ltd. Some surveys were plotted in the field after co-ordinates were derived using a calculator. Calculator malfunction in mid-Expedition meant that some surveys, produced in Jasper and Calgary at the end of the trip were plotted by more traditional methods using steel rule and protractor.

Certain caves were not surveyed to Grade 5 for various reasons, though Grade 3 and 2 are claimed where compass bearings were taken, geological dip measured and distances estimated in body lengths or paces. Elsewhere shorter caves or abortive leads in the remoter parts of caves were sketched and only Grade 1 is claimed for them.

The location of cave entrances on the topographic base maps was often problematical. The National Topographic System 1:50,000 sheets were generally very useful, but in several respects they were found to be wanting:

1. Generally slopes were evenly contoured and gave no indication of crags or cliffs, even if they were very high. Only in extreme cases, where the contours could not be 'squeezed in' was an impression of verticality obtained.

2. Many streams were marked which probably only exist in the spring thaw. Elsewhere existing surface streams were not marked! The option exists to distinguish seasonal streams and in the area studied this option could be used more frequently.

3. Major icefields west of Small Creek were omitted from the topo maps. No obvious reason can be found for this since icefields of this size must be permanent features - and much smaller icefields are shown elsewhere.

4. A number of minor lakes are omitted (especially in the Hanging Valley and Arctomys areas). Again these lakes appear to be permanent and in some areas larger than the detail limits of the map. Smaller lakes are shown in other areas.

5. A number of major landmarks, especially prominent mountains are un-named and give no indication of height. This makes the location of caves by compass resection a bit 'hit and miss' and led to complex or cumbersome nomenclature.

APPENDIX 2: FOOD

Because of baggage restrictions very little food was shipped from England - only tea bags, coffee bags, preserves, fudge and other sweets. All other provisions were bought in Canada, either at Edmonton or Jasper. Suitable dehydrated meals (of the Batchelors type) were unobtainable locally. For main meals protein was supplied by various pulses augmented by small quantities of canned meat or fish and by cheese. Carbohydrate took the form of pasta, rice, potatoes (fresh and dehydrated) and flour. Abundant supplies of herbs and spices helped to make the diet more variable, as did various fresh fruits and vegetables, eggs (fresh and dried) and other small tasty 'treats'. An immense 'job lot' of powdered chicken noodle soup formed the basis of many recipes - a variety of soups would have been welcome. Breakfasts were planned to consist of our own mix of muesli, with dried milk and sugar, often made into porridge, but this was varied on occasions by the production of scrambled (intentionally or unintentionally) eggs, bread and pancakes. Midday snacks centred on our own mix of GORP, which was very popular with most people, with a ration of fudge, high glucose sweets, licorice and glucose tablets.

Brews were frequent, especially as the weather deteriorated towards the end of the Expedition. Tea bags were plentiful and of several exotic blends as well as 'normal'. Coffee bags were very popular, but supplies failed to last out the Expedition. The local price of coffee was so staggeringly high that coffee disappeared from the menu. All team members carried a water bottle, particularly when 'bush-wacking'. Above the tree line water was fairly plentiful, but often of dubious quality, being heavily loaded with glacial rock flour. Whenever possible non-glacial water was used.

Certain quantities of mundane and exotic liquors appeared from time to time and helped to celebrate such events as Steve Worthington's birthday. The necessity for carrying vast amounts of more basic foodstuffs, however, meant that serious drinking only happened off the mountain.

Back in civilisation people's 'on mountain' cravings for food could be appeased, often to excess, with blow-outs at various restaurants and at the Atha B. Burgers, pizzas, salads and shakes could be ordered by phone and delivered free. Huge fresh fruit ice creams and copious quantities of beer or fruit juice were also consumed.

Most team members were satisfied (if not exactly delighted) by the diet. Considering the raw material available, cooking was inventive and surprisingly varied. As noted above flour was carried up to the high camps and with the addition of baking powder it proved to be versatile; techniques of baking on stone slabs were soon developed. Whilst nobody suffered anything approaching malnutrition, it was felt that more vitamins should have been included in the diet, either in fresh fruit or as supplementary tablets - and most people would have liked more fudge.

APPENDIX 3: MEDICAL

Considering the rugged nature of the terrain and the frequent treks through deadfall-ridden bush and across raging rivers there were surprisingly few minor injuries. Common problems were cuts and grazes (from the rock, broken glass, falling down scree slopes or bush-bashing), blisters and splinters. Traversing on steep scree and along moraines was hard on ankles and knees - several members suffered from painful knees and some from metatarsalgia. The latter, a foot strain induced in this case by traversing, was a very painful condition; on resting, the foot swelled and the pain increased. Rest and strapping brought some relief.

Stomach complaints were few , though in one or two cases rather severe. The problem was local to certain areas and seems to have been related to drinking glacial meltwater rather than to diet.

The seriousness of one complaint was not recognised as such until later. A supposed strained back muscle, brought about by over-enthusiastic digging and pushing, which debilitated one member for two days, was kept under control by strong analgesics (Paramol 118), and eventually the pain passed away. Since returning to England the problem has been diagnosed as a classic slipped disc.

Medical supplies were plentiful and covered most eventualities. The ability for self help was essential, particularly since no Cave Rescue Service exists in Canada.

APPENDIX 4: WILDLIFE

Before leaving England there was a general feeling of apprehension, verging on paranoia in some people, about the possible dangers of encountering wild animals, particularly grizzly bears. To some extent these fears were fulfilled by press reports of a camper being killed and eaten by a deranged grizzly in the States. Once in Canada we heard the good news and the bad news - Chas Yonge had not encountered a grizzly since he moved to Canada- until the previous week when he had been charged by a full grown female who was protecting her cubs. On this occasion she veered off and the family made off at tremendous speed. Still it was something to think about, not to mention brown bears, wolves, several varieties of wild cat and wolverines. In the event Chas saw a brown bear on the road, Chris Pugsley saw two brown bears while walking out of the Top Area and the long recce party also saw a brown bear making off. No grizzlies were seen, though bear signs in the bush were common - footprints, droppings, stripped blueberry groves and savaged trees. The noise of big animals making off was commonly heard. Generally all recommended precautions were taken so as not to attract bears into the vicinity of camps and apparently the precautions worked!

Mountain goats or Dall sheep were fairly common, especially in Goat Valley, and seemed able to manoeuvre at high speed on the most unlikely looking slopes. The hair-raising descent route into Goat Valley was a sheep track along a tiny scree-covered ledge with a frightening drop below, but even this was tame by goat standards. A number of moose were also seen.

Smaller mammals were abundant, though generally somewhat shy. Apart from eating rubber motor components, porcupines were seen eating trees - even climbing them to reach the tasty bits. One reconnaissance team found a beaver pond, complete with beavers, up Small Creek. Marmots, pikas and pack rats were the most common small mammals, however, and were always around, even if not visible. The marmots in particular made their presence felt by whistling at each other; very confusing until we realised that the whistling was not of human origin. Steve Worthington had lost his watch to pack rats on a previous trip, so we were generally careful with small and easily 'liftable' articles. At Arctomys Cave an enamel mug was removed, probably by marmots, but it was later relocated.

APPENDIX 5: FINANCES

INCOME	
Grants	£800.00
Personal contributions	£5559.91
Miscellaneous from equipment sales	£249.56
Total to date	£6609.47
Contributions owed	£177.00
Total income	£6786.47
Less expenditure	£6321.70
Balance	£464.77
Owed to team members	£254.00
Residue for report and contingencies	£210.77

EXPENDITURE	
Travel (U.K.)	£52.50
Air fares (inc. tax)	£4280.00
Vehicle hire	£352.00
Tolls, etc.	£6.11
Petrol	£109.17
Repairs	£123.37
Rope	£201.00
Tents	£83.10
Other gear	£209.53
Food and drink	£489.48
Insurance	£315.00
Administration	£99.14
Loss on exchange rates and bank charges	.53
Total expenditure	£6321.70

CAVE SICENCE

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THE CAVES OF LECK FELL

by Tony Waltham and Paul Hatherley

ABSTRACT

The caves of Leck Fell, essentially the Lost Johns-Gavel Pot system and others directly associated, contain over 10km of mapped passages. A new compilation survey has been drawn and additional contributions to the understanding of the geomorphology are summarized.

Leck Fell spreads across the western slopes of Gragareth hill on the western margin of the Yorkshire Dales karst, though it falls entirely in the county of Lancashire. Its surface is a remarkably uninspiring drift-covered bench sloping gently through the upper beds of the Great Scar Limestone. Beneath it lies an integrated system of very fine caves where dendritic branches converge on a flooded tube draining towards Leck Beck Head. It is at the heart of the Three Counties Caves (Waltham & Brook, 1983). An unexplored gap northwards separates the Leck Fell cave system from Pippikin Hole and the Ease Gill System, while another southwards separates the system from the Notts-Ireby caves. Although breakthroughs may not come easily, the prospects for future exploration are still spectacular.

EXPLORATION

Explorations of the Death's Head shaft and parts of Short Drop Cave date back to the last century, but the big event on Leck Fell was the discovery of the Lost Johns Master Cave by the Yorkshire Ramblers Club in 1928. By 1950, most of Lost Johns, Short Drop, Death's Head and Rumbling Hole had been explored. The discovery of Long Drop Cave in 1965 preceded a burst of activity, when the Lyle Cavern High Levels were found in Lost Johns Cavern in 1969, Gavel Pot was opened the following year and Big Meanie was discovered in 1971.

Since then there have been minor discoveries in every part of the Leck caves except Rumbling Hole. The most important have been the linking of Lost Pot to Lost Johns in 1982, and, over a number of years, the dives in the Gavel Pot sumps; though the divers have found only minimal airspace, they have revealed considerable lengths of underwater passage and made the connection to Lost Johns.

Unfortunately nearly all the known passages have now been explored to rather conclusive ends and there are almost no obvious leads which can offer great hope without unspecified amounts of effort. The promised land lies to the west where both high and low level routes downstream of Notts Pot await discovery. The west end of the Lyle Cavern High Levels offers great potential in its own right, besides having the chance of meeting a Notts route, but it is sealed by a very solid, well-calcited choke. The upstream sump in Gavel is guarded by a fiercely deep phreatic lift, which is unfortunate as open streamway must lie beyond as indicated by the difference of 36 m between the levels of the Notts and Gavel sumps. Downstream the Gavel sump has also started to go deep after 600 m; the point reached by divers is less than 300 m from the point reached in the tributary Pippikin Pot sump and a connection would not only be a fine feat but would put the combined system back in the world's top ten for length.

Other exploration potential tends to the esoteric. The downstream fossil continuations in Gavel Pot await discovery after considerable excavation and somewhere there is a downstream passage from Lyle Cavern that has not yet been found (Waltham, 1974, p.292). Major digging could also open the Gavel to Big Meanie link and clear the choke between Death's Head and Lost Johns, but such effort could probably be better spent elsewhere. Blasting would be needed to connect Rumbling to Lost Johns through a narrow flooded rift, and choice engineering could lower Leck Beck Head enough to turn the Lost Johns to Gavel link from a sump to a canal - but ethics also come into these problems.

THE NEW SURVEY

A completely new edition of the Leck Fell survey, published with this paper, has been drawn by Paul Hatherley. It is a compilation of many originals, based on the first Leck Fell survey by Tony Waltham from 1970, but extensively modified, corrected and updated.

The 1970 survey was also a compilation, based on mapping mainly by cavers from London and Leeds Universities and the Happy Wanderers Caving Club. It suffered, particularly in Lost Johns, by having very long traverses unchecked by closure and some significant errors were recognised soon after it was published. The vertical errors, which placed the Lost Johns sump below Leck Beck Head and the Gavel sump above, were remedied by new levelling by London University cavers (Bowser, 1973). These revealed a new entrance height for Gavel Pot and important errors in short sections of the Lost Johns entrance series. When corrected all the sump elevations tied in to acceptable limits. A much smaller horizontal error in the great length of the Lost Johns Master Cave was only corrected when the sump survey closed the loop to Gavel Pot.

All these corrections have been incorporated in the new survey, but it does remain a compilation; therefore, whilst it aims to be useful and practical, it does not claim absolute accuracy. Also added in are surveys of all the post-1970 explorations, taken mainly from published sources. Due acknowledgement is therefore recorded to the Gritstone, Craven, Northern Pennine and Burnley Caving clubs, London and Manchester universities and Cave Projects Group, and also to the Cave Diving Group for their unpublished sump surveys.

HYDROLOGY

Most of the hydrology is clear from the survey as all the stream routes are nearly completely explored. The longer links between Notts, Gavel, Lost Johns and Leck Beck Head have all been proven by dye tracing: dye transmission is slow downstream through the flooded passage to Leck Beck Head, but dye took only 5 hours from Notts to Gavel under low flow conditions (Bowser, 1973). This suggests a considerable length of fast-draining vadose passage upstream of Gavel, while a pulse test with instantaneous response has shown the downstream passage to Leck Beck Head to be a single phreatic loop.

The Gavel - Lost Johns sump lies at the regional water table, as dictated by resurgence level. In contrast, the Rumbling Hole and Sink Chamber (Lost Johns) sumps are perched, both where the drainage cuts through cross joints. Also perched is the Short Drop sump - more than 10 m above its outlet into Gavel Pot; this is rather unusual but not unreasonable in view of the amount of debris choking up the Gavel entrance hole. Dye has also shown the Rough Pot water to return to the Lost Johns entrance passage, so the title of the aven below Last Pitch is now a misnomer.

Simultaneous flow measurements have shown the Leck caves (not including Pippikin) to contribute just under 15% of the water to Leck Beck Head, with another 8% coming through the Gavel sump from Notts; these figures are in keeping with the relative sizes of the catchment areas (Bowser, 1973). Under very dry conditions the total Lost Johns flow is under 8 litres/second, while the Gavel stream is under 3 litres/second. In keeping with any cavernous aquifer, the hydrographs are, however, liable to many sharp peaks with rapid response to rainfall. A flow estimated at 300 litres/second has been experienced at Groundsheet Junction, more than 50 times base flow, and this is nowhere near a maximum.

GEOMORPHOLOGY

The existing assessment of the Leck Fell cave geomorphology (Waltham, 1974) still broadly applies, as discoveries since than have largely been as anticipated. The caves still show a remarkable correlation with the local details of geology, notably the Death's Head fault, the joints in the Lost Johns entrance series and the gentle syncline which controls the two vertically superimposed systems of convergent drainage in Short Drop and Lost Johns. Gently dipping bedding planes guide the long uninterrupted streamways.

The single bedding followed by the whole of the Lost Johns Master Cave downstream of Lyle Cavern has now also been traced into the phreas; it appears to guide most of the explored length of very shallow sump. The Gavel water descends to the same bedding via the joints of the Pot's last two pitches, but the Notts water ascends to the same bedding via the spectacular phreatic lift more than 40 m deep in the Gavel upstream sump.

A tight geological control can be seen on much of the route from Ireby Cavern to Leck Beck Head. In Ireby's Duke Street it follows the bedding and the dip into Sump 2, before rising on a joint to its emergence in Notts. Once through the complex of joints which control the perched sump at the bottom of Notts, the water can be expected to follow the bedding gently down the dip first in a canyon and then in the sump before its next phreatic lift in the Gavel sump. Further downstream it is again bedding-guided to depth and another phreatic lift, probably on a joint, must return it to resurgence level. The observed dip and the altitude loss suggest that there could be a kilometre or more of open canyon passage between Notts and Gavel - very comparable to the Lost Johns Master Cave. However, the great depth of the Gavel sump suggests that one bedding plane cannot be followed all the way, and somewhere the water must descend a joint (before ascending another on the phreatic lift). The position of this joint descent controls the length of air-filled passage that awaits exploration.

The older fossil caves of Leck Fell are not so completely explored, except upstream of Gavel. The Lyle Cavern High Levels still occupy the core of the unknown. Lost Pot is a massive feature and its recent exploration has revealed debris-filled rifts, extending to depths, of a size incompatible with the streamway down to the Master Cave at Lyle Cavern: it is therefore tempting to consider the possibility of Lost Pot being the source of the High Levels conduit. In Notts Pot the ancient choked outlets at the end of Adamson's Route are also well placed to feed to the Lyle Cavern High Levels even though they are about 40 m higher. However, they could equally well head off to the west and only further exploration can provide the evidence. Unfortunately, the south end of the High Levels will not easily yield the answer, but there is a lot of cave awaiting discovery in this area.

Stalagmite dating since 1974 has contributed some absolute figures to the chronological framework. Gascoyne (1983) found stalagmite from the Lost Johns Master Cave upstream of Groundsheet Junction to be 113,000 years old. This suggests a correlation of the Ipswichian interglacial with phase 3 (of Waltham, 1974), post-dated by little more than the rejuvenation of the lower end of the Master Cave and various re-routings in the Entrance Series. The limitations of cave dating, based on contained stalagmites, do of course mean that the phases could still be older.

Almost certainly, the mass of large phreatic tunnels at around the 280 m level must pre-date the Ipswichian, and by comparison with other Dales areas are most likely earlier than the Anglian glaciation. Unfortunately though, this cannot yet be substantiated with absolute dating, as these passages have so far yielded only young stalagmites. Gascoyne (1983) dated material from the Lyle Cavern High Levels to 125,000 years, but found only post-glacial stalagmite no older than 13,000 years from Glasfurd's Chamber in Gavel. More stalagmites from the Glasfurd's passages have been dated at up to 130,000 years old (Atkinson et al, 1978) but older material, probably more indicative of the caves' real age, has yet to be found.

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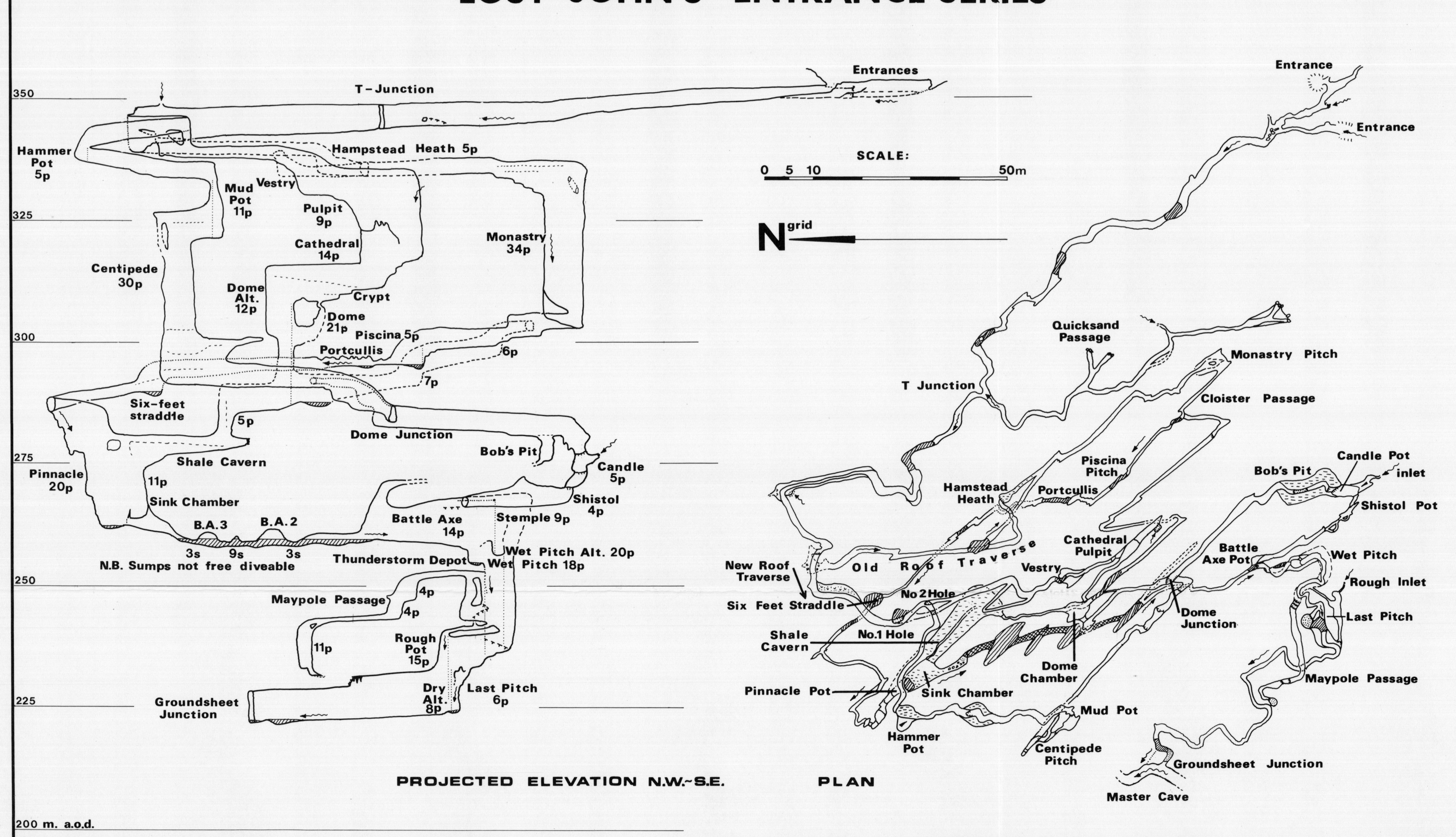
LOST JOHN'S ENTRANCE SERIES



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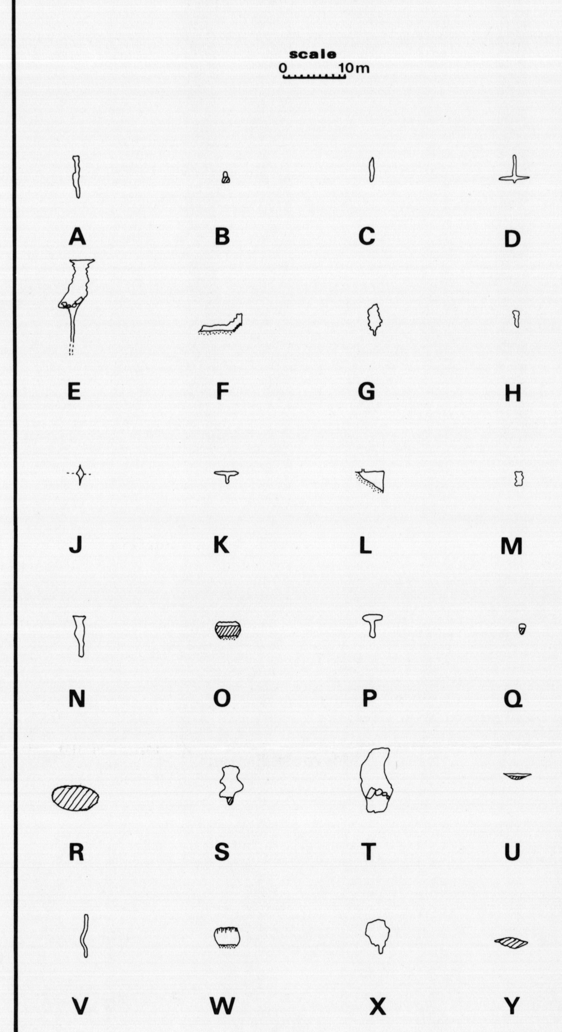

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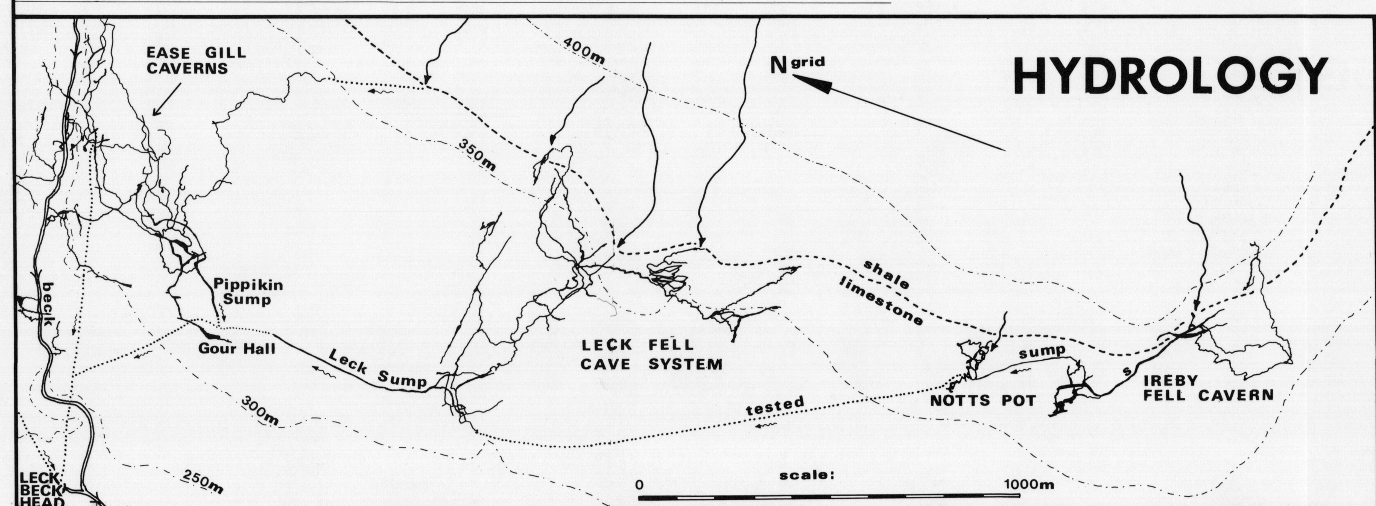

THE LECK FELL CAVE SYSTEMS

LECK FELL, LANCASHIRE, ENGLAND.

SCALE: 0 10 20 30 40 50 100 200m

N.G.R. LOST JOHN'S CAVE ENTRANCE:
SD 6708 7865

	Altitude (m)
LOST POT ENT.	360
LOST JOHN'S CAVE ENT.	354
L.J./GAVEL SUMP	213
LECK BECK HEAD	213
COAL HOLE ENT.	361

	Length (m)	Depth (m)
LOST JOHN'S/GAVEL POT/ SHORT DROP/LOST POT	9520	148 (dived to 186)
LONG DROP/DEATH'S HEAD/ BIG MEANIE	1020	91
RUMBLING HOLE AND CAVE	358	118

Drawn by Paul Hatherley, December 1983.

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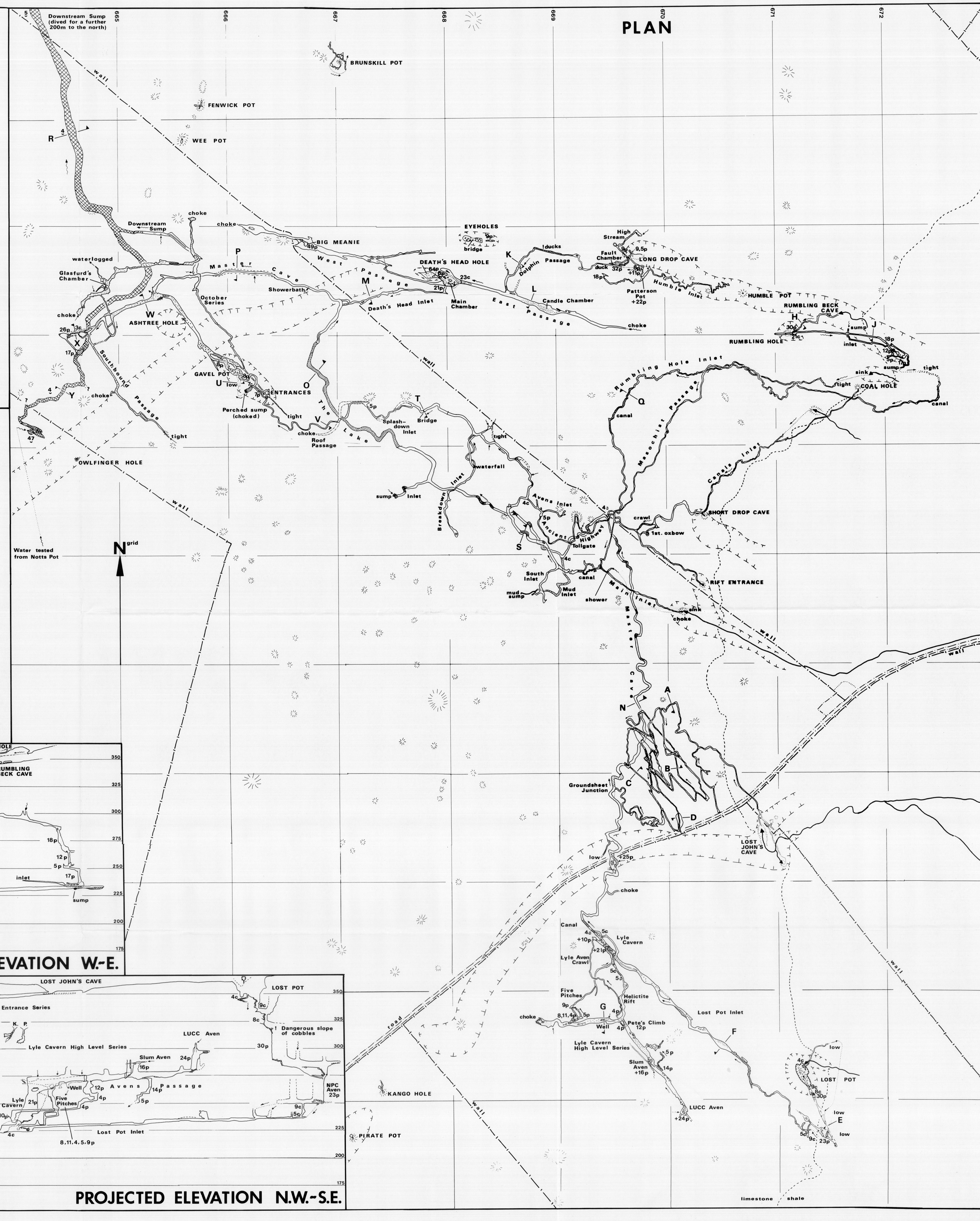
ORIGINAL SURVEYS BY:
LONDON UNIV. C.C., UNIV. LEEDS S.A., HAPPY WANDERERS C.P.C., CAVE DIVING GROUP, GRITSTONE C., NORTHERN C.C., CRAVEN P.C., MANCHESTER UNIV S.S., NORTHERN PENNINE C., BURNLEY C.C., CAVE PROJECTS GROUP, AND OTHERS.

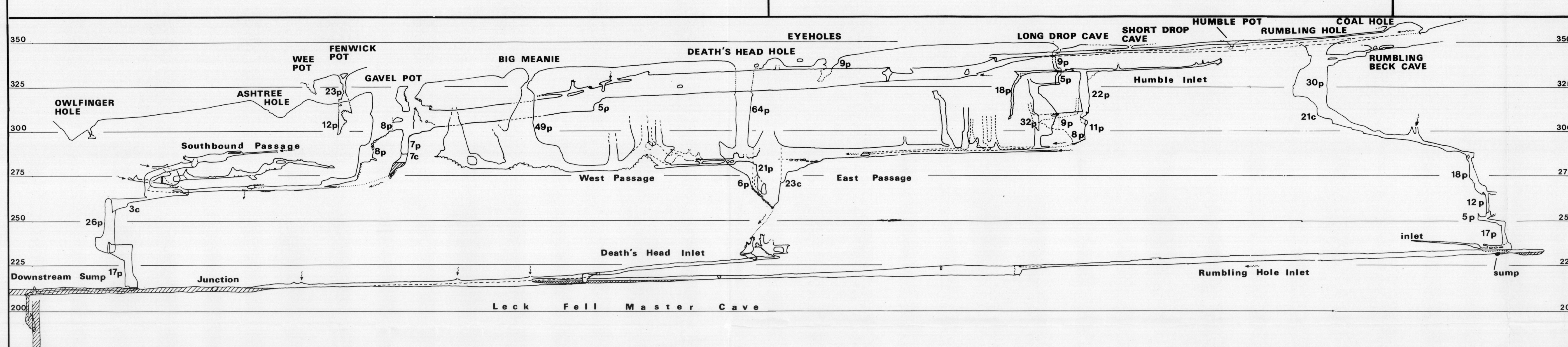
ALL DIMENSIONS IN METRES.
SURVEYED TO B.C.R.A. Gd. 4b/5b, EXCEPT SOME SIDE PASSAGES TO Gd. 3b.
SURFACE DETAIL FROM UNCONTROLLED AIR PHOTOGRAPHS AND 1:10560 O.S. MAPS.

p = pitch c = climb s = sump

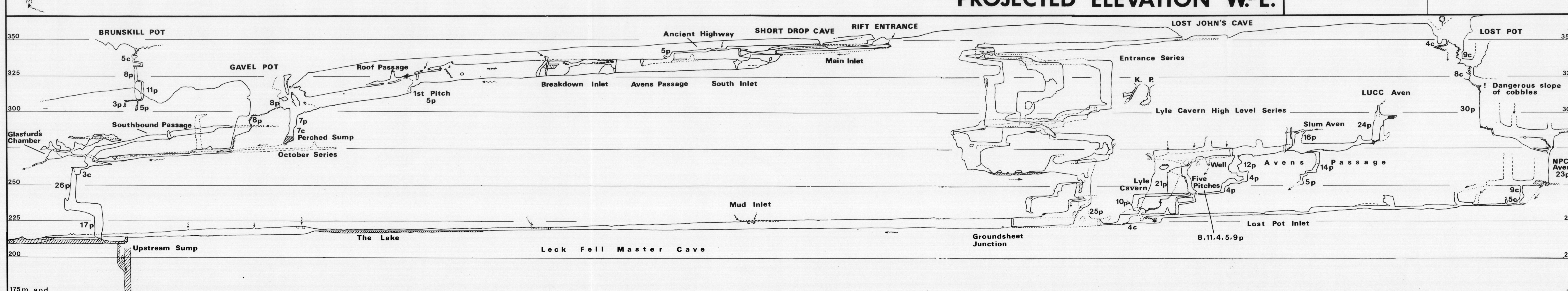
ACCESS TO THE CAVES OF LECK FELL BY C.N.C.C. PERMITS ONLY.

PLAN





PROJECTED ELEVATION W.-E.



PROJECTED ELEVATION N.W.-S.E.