# THE GEOMORPHOLOGY OF THE BONNECHERE CAVES

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B.A. Research Paper

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# PREFACE

This paper deals with the specific problem of the formation of the Bonnechere Caves, and the more universal problem of scallop or flute formation. The Bonnechere Caves have been studied in two previous papers, which speculate on their formation, but no detailed field work has been done that deals with all the significant variables that affected their formation. The problem of scallop formation has remained unexplained in its entirety, and there have been no large bodies of data collected to analyse the effects of different variables on their development.

The purpose of this paper was to study these two problems through detailed field work and to arrive at some concrete conclusions concerning cave formation and scallop formation which could be substantiated by significant data. Because of the uniqueness of each cave system, it is very difficult to make any generalizations about all cave systems from the observations of one single system -- except those generalizations which border on intuition. However, a solution or partial solution for the scallop problem would have much wider applications because this feature is common to practically all caves and deals with the basic mechanics of flow. The purpose is not to explain the actual physics of scallop formation which the author is not equipped to do, but rather to discover correlations between the size of scallops and the variables involved in their formation, and then use the scallop size as an index of these variables. In this way the problem is a geographical one since the main concern is to apply correlations over space.

The author's background prevents detailed discussion of the many properties of variables involved in the development of caves. However, since the process of cave development is the primary issue, the role of each variable in the development of the caves is the main concern rather than the intrinsic nature of the variable itself. Only that degree of detail which leads to an understanding of the role of each variable in the whole framework is necessary in any geographical study.

I wish to thank Dr. D. C. Ford for his patient assistance during the writing of this paper. Thanks are also due to Mr. Tom Woodward, proprietor of the Bonnechere Caves, for his generosity in allowing me to freely use his caves and property during the period of field research.

# CHAPTER I

## INTRODUCTION

The Bonnechere Caves are situated at the Fourth Chute of the Bonnechere River approximately five and one half miles east of the town of Eganville in Renfrew County, Ontario. The caves are located in the Bonnechere outlier of Ordovician limestone which covers an area of about twenty square miles and extends fifteen miles in a narrow belt along the Bonnechere River from Mud Lake to Northcote Station. This area was exposed to Pleistocene glaciation and much of the bed-rock is obscured by drift and alluvium, but there are many good exposures of limestone in the area. This limestone is of the Mohawkian Series, and the exposure at the Fourth Chute consists of Chaumont Limestone, the topmost member of the Black River Group overlain by the basal beds of Rockland Limestone, Trenton Group. The lithology of the area will be discussed in detail later in the paper.

Clear evidence of the glacial action which took place in this area is the rock drumlin, (Fig. 1), which has been formed on the north side of the Fourth Chute. Further evidence of glaciation was the till on both sides of the river which was quite bouldery and contained granitic erratics.

The caves were developed in a terrace of rockland limestone which is bordered on the north by a normal fault. A scarp of pre Cambrian gneiss, created by this fault, rises 600 feet in one-quarter of a mile. This fault (The Douglas Fault) has an axis bearing of 319 degrees, running almost parallel to the river. On the other side of

# TOPOGRAPHY OF THE FOURTH CHUTE AREA, BONNECHERE RIVER
# RENFREW COUNTY, ONTARIO

Fig. 1

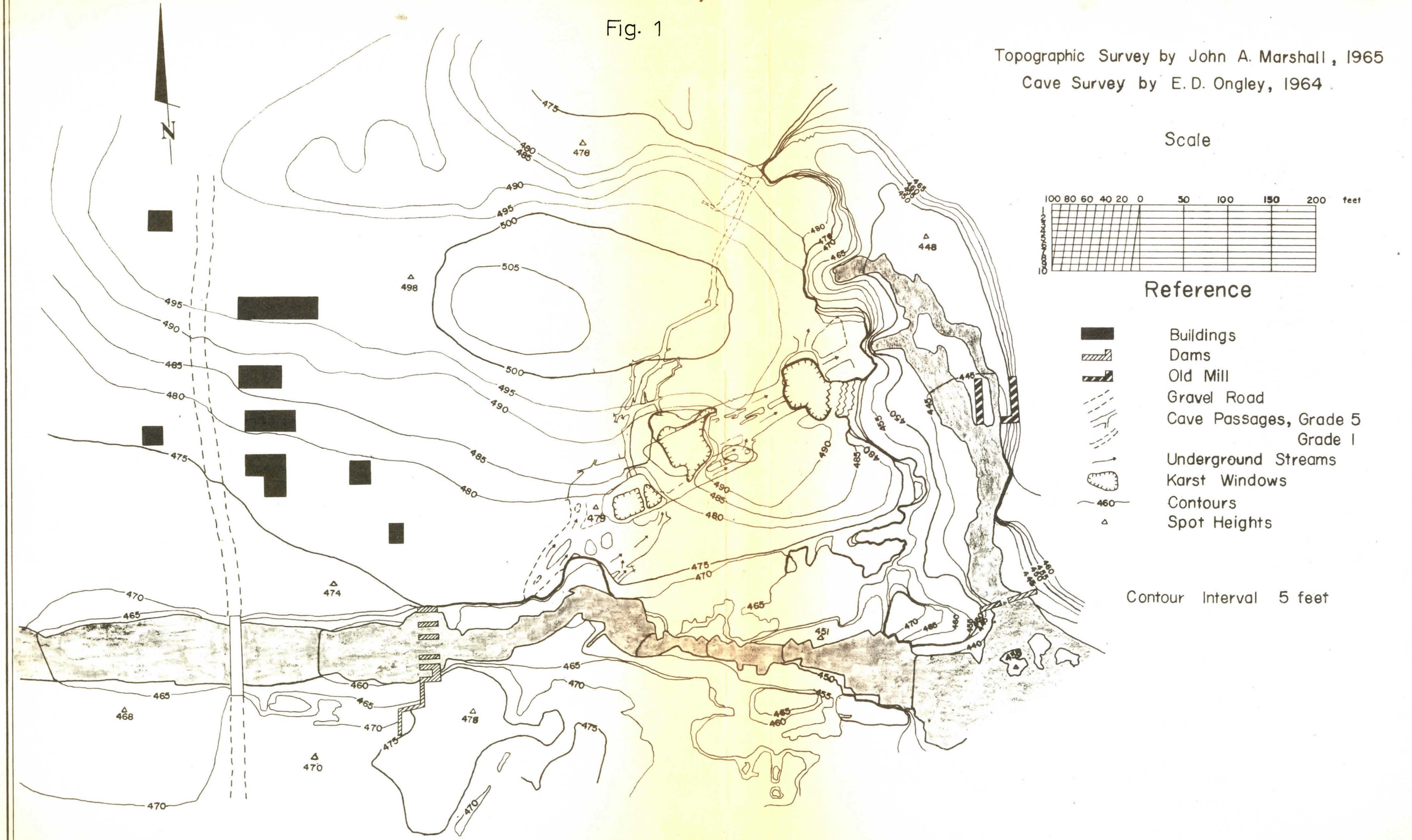

PLATE I: The Earliest Incision of the Bonnechere River: Note the Delicate Castellating

PLATE II: Looking East along the Fourth Chute the river about two miles from the gorge, there is another fault (The Packenham Fault) with an axis of 320 degrees.[1] The scarp here rises 100 feet in just over one-quarter of a mile. This leaves the cave area in a graben, bordered by these parallel faults.

At the Fourth Chute, the Bonnechere River has cut a sharply defined gorge into the Rockland terrace. Its depth varies from about one foot where the river is constricted above the bridge, to about seventy feet at the confluence of the tributary gorge. The Rockland bench terminates sharply in an erosional scarp, about 275 yards downstream from the bridge. A tributary gorge enters the Bonnechere River from the north running along the base of the scarp.

Previous Papers

Two previous papers have been written with detailed reference to the Bonnechere Caves. The first one, a note written in 1960 by D. C. Ford for the Canadian Geographer[2], was a short, essentially descriptive paper which outlined the form of the caves, the major controls in their formation, and related these to the general theories of cave formation. He asserts that the caves post date the last glaciation, since the earliest incision of the river is delicately castellated -- this could not have survived if over-ridden by ice (Plate I ) Ford relates the lithology of the Fourth Chute as described by G. M. Kay[3]

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[1] Kay, G. M.: Ottawa -- Bonnechere Graben and Lake Ontario Homochine.
Geol. Soc. Amer. Bull. 53, Jan. - June 1942, pp. 585 - 646.

[2] Ford, D. C.: The Bonnechere Caves, Renfrew County, Ontario: Canadian Geographer, J(3), 1961, pp. 22 - 25.

[3] Kay, G. Marshall: "Ottawa Bonnechere Graben and Lake Ontario Homoclime", Geol. Soc. Amer. Bull. 53, Jan. - June, 1942, pp. 588

and divides the chute into four levels, each controlled by a thick bed of massive limestone. He believes the caves were initiated when the river incised to the third level, exposing platy strata to lateral penetration by river water, and attributes their development to highly favourable conditions of chemical composition, lithology, and jointing. Ford asserts that the establishment of unobstructed circulation was due primarily to a complex grid of joints, and further development of the caves "can be attributed to boring by rapidly moving waters in a 'paraphreatic situation', i.e. one of intermittant flooding or not quite complete water fill". The development of many passages in the cave grid to an accessible size is attributed to waters filling the whole system under a small head-- 15 feet when the river was at bank-full stage. The occurrence of scallops throughout the system is further evidence of the dominance of solution. The great disparity of size between the two parts of the system is due to the outlet of the larger passage being lower than that of the smaller passage. The processes of decay are now becoming more dominant in the passages, with collapse occurring at the exits. In the larger system, Ford says that the calcite sandstones in the Rockland section are quite impermeable, and prevent percolation of surface water into the caves. This has restricted deposits to a few small stalactites and has prevented the development of any ponors or avens. He feels that the caves are an instructive example of many principles of limestone caverns in that they illustrate a full cycle of cavern erosion.

The second work that deals with the Bonnechere Caves in detail is an unpublished B.A. thesis presented to the University of Toronto in 1965 by E. D. Ongley, entitled, "A Study of Caves in Southern Ontario".

Mr. Ongley did a survey of the Bonnechere Caves in 1964, producing an accurate map of C.R.G. Grade 5 standard, i.e. done with a calibrated prismatic compass, clinometer, and steel tape, with bearings to the nearest degree. Some of the side passages were done to Grade 4 specifications, i.e. with a prismatic compass (error not known) graduated in single degrees, and a measuring tape. The lower sections of the commercial passage are done to Grade 1 specifications, i.e. a memory sketch.

In his discussion of the caves, Ongley echoes most of D. C. Ford's genetic conclusions but discusses them in more detail. He feels that jointing at the different levels has strongly controlled cave development at those levels, and cites the example of the lack of caves developing at the second level being the result of unfavourably aligned joints, observed at that level along the chute. He attributes cave passage crossectional shapes to the lithology, stating that the differential erosion of the limestone has controlled them in both sections of the cave.

Ongley, after conferring with D. C. Ford in the field, suggests that a phreatic "loop" situation existed in the commercial system, i.e. that the flow of water followed a Darcy flow net pattern. He discusses the theory of scallops and indicates on his map the direction of flow indicated by the scallops, in the Bonnechere system.

Both Ford and Ongley agree that the caves were developed under phreatic and paraphreatic conditions, and now are subject to considerable vadose attack. The only point of disagreement is the control of the shape of the commercial passage -- Ford believes boring by rapidly moving waters shaped the commercial passages primarily, while Ongley emphasises the role of lithology.

A Review of the Literature on Limestone Cave Formation:

A general review of the literature on caves is necessary in order to acquaint the reader with the general theories of cave formation. All modern theories of limestone cave formation acknowledge the importance of water action, either as a solvent or as a transporting agent for rock material with which to scour the beds of cave streams. The different theories lay varying emphasis on these processes, which are generally called chemical erosion or corrosion, and mechanical erosion or corrasion. Some author's claim that caves originate and are developed above the water-table (within the vadose zone); others consider that many originated below the water-table (in the phreatic zone), though opinions vary regarding the depth at which they form.

The predominant process in cave formation is chemical erosion or corrosion. The solution of limestone requires that the water have an acid charge, which it acquires in the free atmosphere and the soil atmosphere by dissolving carbon dioxide. Also the water picks up an acid charge by mixing with humic acids in the soil. The erodability of $CO_2$ is inversely proportional to temperature; but in tropical regions there is a much greater supply of humic acid to offset this. Solution is the essential starting process because corrasion can work only when an adequate passage is dissolved.

There are three main groups of theories of the origin of limestone caves. The first group of theories, the vadose theories, contend that the water percolation through the vadose zone, the zone above the water-table, will dissolve almost all the calcium carbonate it is able to hold in solution before it reaches the water table. As the water-table is lowered by rivers cutting into a limestone body, water is encouraged to percolate downwards, thus solutional activity will be greatest along openings favouring this movement, chiefly joints and steeply dipping bedding planes. As solution progresses, this movement will be speeded up, particularly near the surface where the solvent capacity of the ground water is greatest. Below the water-table, flow will be slower and more diffuse, and will be largely confined to the upper portion of the phreatic zone, where most of the water movement is thought to occur, towards the major streams.

When the tributary streams flow across exposed limestone, they will gradually lose water through vadose channels. These channels will become larger than those channels which depend solely upon surface supplies of water for their enlargement. Once a stream enters an underground passage it enlarges it chiefly by mechanical erosion, however, solution attack is not ended and sometimes it leads the stream to take short cuts, leaving dry passages to mark its old route. The mechanical erosion is controlled by the velocity and volume of water, and the debris available. Such erosion cannot cut below the water-table, and the streams try to become graded to it though most cave streams are far from achieving this.

When the water-table is reached, penetrable passages end and cave streams disappear into pools, narrow bedding planes, or masses of loose rock. Gradually more concentrated drainage routes will develop, at or just beneath the water table, which may be fed by one or more caves. As these slowly develop, excess water will be removed more easily and the water-table lowered slightly, permitting the development of a master cave containing a stream with a free air surface along much of its course.

Seepage is facilitated by the development of a large cave system, and sometimes this is reflected in the enlargement of roof joints which act as feeders to the main cave. These enlargements taper upwards and are known as "avens", and are presumed to result from the accelerated flow of water near its outlet on the cave roof, causing a greater amount of solution to occur than higher up in the joint. Sometimes the term "aven" is given to roof features which may later prove to be vertical tributaries of the cave system.

Major changes in the water-table level are not generally taken into account in vadose theories, but they are quite important. A lowering of the water-table would result in the draining of a zone of limestone, the joints of which were poorly developed by solutional enlargement. This would result in piracy of the master cave streams, and of some of the others as passages developed in the lower zone, and a return to diffused drainage until a second series of master caves became developed. Older levels would be left dry and possibly subject to encrustation by stalactite deposit or filling by rode falls. Accumulations of clay or gravel from old stream courses would be left high and dry.

The second group of theories concerns cave development below the water-table, in the phreatic zone. These theories were developed by those who hold that many caves originated, and to a large extent developed below the water-table, with only comparatively minor development after a major change of water level had occurred. In this two-cycle or phreatic theory of cave development Davis[4] considers that cave development would take place as soon as fresh water begins to push out the original salt water contained in the limestones; but active development would only occur during those periods when the limestones were near the surface and had water from it passing through them. If artesian flow exists in the limestone, water movement occurs at relatively great depths and cave development can take place under considerable overburden. Davis hypothesized very deep lines of water flow in a limestone body, which feed a surface river.

In the phreatic zone, water moves under the pressure of the 'head' of water, i.e. the height of the highest point of the water-table above the river level at the point of discharge. At any point this pressure is exerted equally in all directions, and so movement is not always towards a lower level, as in the vadose zone, but rather towards any direction where the pressure is lower. Passages opened up below the water-table are liable to form complicated three-dimensional networks rather than integrated systems at one level. Development would be by the solution of bounding walls, the coalescing of once separated passages, and by collapse, followed by solutional attack on the debris.

The existence of phreatic networks above the existing water-table is explained by the inaugeration of a new cycle of erosion at a lower level. Davis thought that for many passages, this would lead to the heavy deposition of calcium carbonate on their roofs, walls, and

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[4] Davis, W. M., 1930; Origin of Limestone Caverns; Bull. Geol. Soc. Am., XLI; pp. 475 - 628.

floors, and the accumulation of rock falls. Others would develop if a surface stream was captured and diverted into these channels, which would be modified to fit the new conditions of flow under the influence of gravity.

Further studies using deep water-borings have proved the existence of caves down to 200 feet below the water table. Also further studies on the potential of water to erode limestone at depth have proved that water acquires a stronger acid charge when seeping through soil because of the increased partial pressure of $CO_2$ in the soil atmosphere over the free atmosphere. Thus water is even more able to erode limestone if it must seep through an overburden of soil and it still retains much of this charge by the time it reaches the water table. From this evidence it is shown that certain assumptions made by the proponents of the vadose theories were wrong, and that conditions below the water table are often favourable for cave development.

A. C. Swinnerton (1932) suggested that the passages in the phreatic system closest to the water table would be enlarged much more quickly than those at depth because of the much shorter path of flow[5]. Greater circulation at this level would dissolve the limestone much more quickly -- thus the main passages would be developed just below the water table. This theory is a more realistic one than the "random" depth concept of Davis.

Rhoades and Sinacori attempt a compromise between the vadose

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[5]Swinnerton, A. C., 1932; Origin of Limestone Caverns; Bull. Geol. Soc. Am., XLIII; pp. 662-93

and phreatic theories[6]. They suggest that a trunk stream will develop a pattern of ground-water flow modified to fit the local structure. Near the points of discharge in the stream, the bigger joints would become enlarged, forming master conduits, which would draw water from the smaller openings. These would be extended away from the stream, along the water table and would act as effluents for the water flowing along deeper channels, causing the outlet of the phreatic flow network to be dislocated away from the stream also. In this theory, the phreatic flow network and solution would be dominant at first, but would gradually die out as the master effluents increased in length and size.

The acceptance of one theory of cave development is impossible because of the great number of different environments in which caves do develop. It is imperative to distinguish between cave origin and development in discussing the overall formation of caves because of the importance of any movement of the water-table during the overall process of formation. When caves are studied, modifications due to local geological and hydrological conditions must always be borne in mind.

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[6] Rhoades, R. and Sinacori, M. N., 1941; The Pattern of Ground-Water Flow and Solution; J. of Geol; XLIX; pp. 785-794.

# CHAPTER II

## FIELD METHODS

The methods used during the field research are presented here to enable the reader to better evaluate the date collected. The methods were:- plane tabling, lithological mapping, surficial material sampling and cave description.

The plane table survey was done in order to obtain a complete picture of the development of the Bonnechere Caves. The topographic features that caused or were caused by the cave development, as well as features that resulted from the same processes as those which developed the caves can be shown in detail on a large scale topographic map. Particularly important in this study are the relative elevations of these features which can be expressed precisely using a five foot contour interval.

The survey used a plane table, alidade and spirit level, with a steel tape being used to measure the base line. The reference elevation was the S.W. corner of the house on the west side of the road which is 475 feet above mean sea level according to the topographic sheet of the area (contour intersection). The third station and about fifteen others were found by triangulation while about seventy stations were plotted by resection. A total of approximately ninety stations were plotted, the height of each one found with the alidade.

The entire Fourth Chute area is mapped, with the north side of the gorge, which contains the caves, mapped more extensively than the south side.

The cave map survey by E. D. Ongley has a scale of one inch = to twenty feet or 1:240. This was reduced to the scale one inch equals seventy-five feet or 1:900 by means of a pantograph and corresponded very well to the cave entrance, cave exits and kaist windows on the topographic map, (Fig. 1).

The lithology exposed at the Fourth Chute was mapped using an engineer's, scale with every recognizable bed recorded. Each bed was measured, as accurately as possible, to the nearest inch. The beds were classified as being either massive or brashy: a massive bed was unbroken between the two bedding planes which confined it, while a brashy bed was broken into plates by cracking parallel to the bedding planes or interbeds of shale. The section arrived at corresponded quite closely to the more general section of G. M. Kaye, (Fig. 3), and will be illustrated later. The five foot difference between the total height of the section and the topographic height would be due mostly to error in the measurement of beds, caused by the weathering of the limestone on the exposed section. This could also be due in part to error of survey.

Surficial material was sampled to investigate former river levels in the area. Twenty-two sample stations were chosen, covering the area uniformly; so that any discontinuities of material could be located quite accurately. The presence or absence of granitic material was the main concern of the study, but particle sizes were recorded also in the event that this information would be useful.

A detailed reconnaissance of the caves was made in order to accurately map crossections, and put them into their lithological context. This would enable an accurate determination to be made of the effects of the various beds on the cave development. The deposits on the floor of the caves were also examined, in order to be able to determine processes at work in the cave development.

The source of light in the large caves was a large flashlight; but in the commercial caves, the electric lights installed there by Mr. Woodward were put at my disposal much of the time. This enabled a great deal of the work to be carried out with great facility and accuracy.

The methods used in the joint bearing measurement and scallop sampling will be discussed in Chapters VI and VII respectively. This is done because the methods used to sample these phenomena warrant detailed discussion in the relevant chapters.

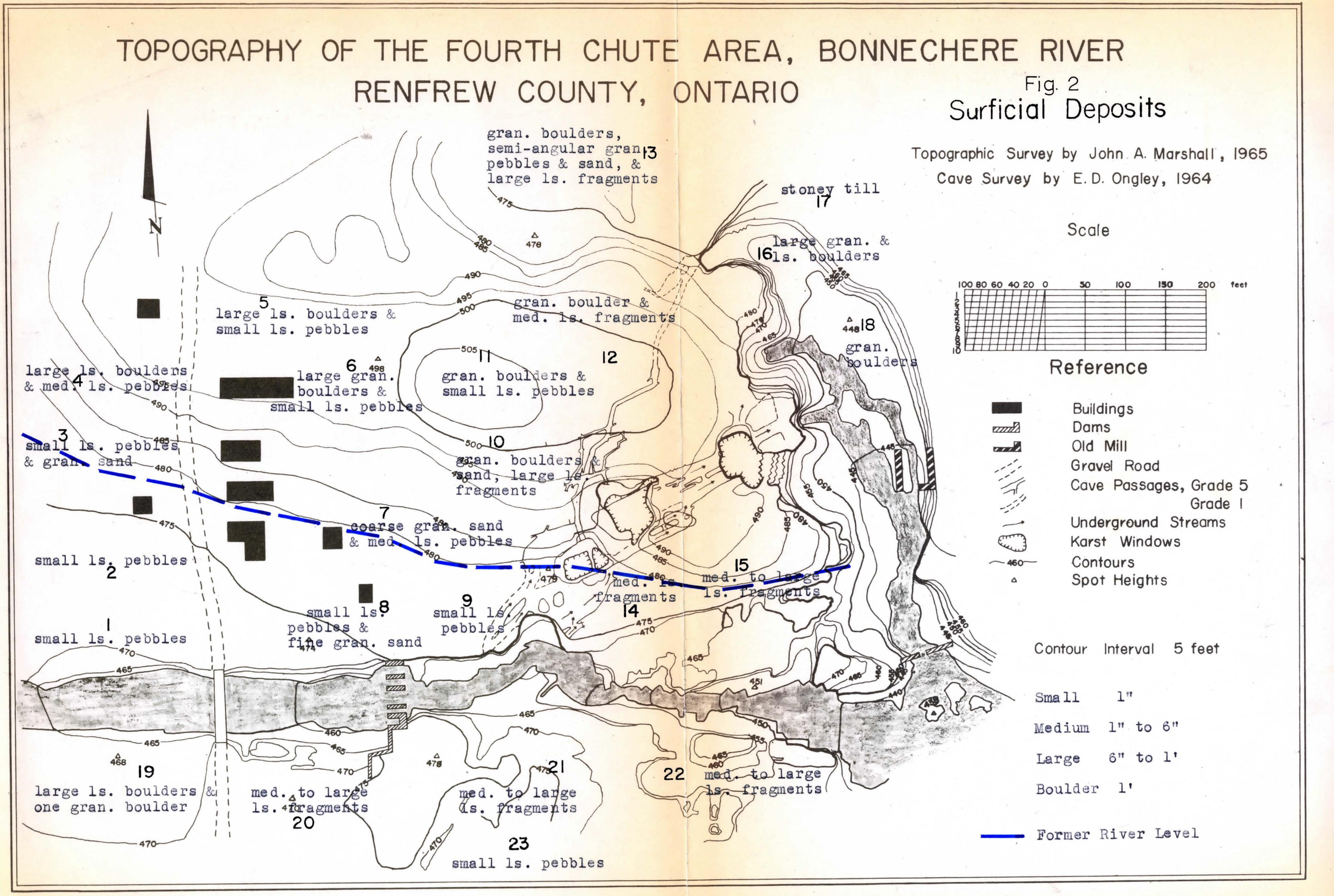
## CHAPTER III

## STUDY OF SURFICIAL MATERIAL

Determination of a former higher level of the Bonnechere River in post-Pleistocene times offers a partial explanation for certain topographic forms and establishes a maximum time limit for their existence. This area was glaciated in the Wisconsin glaciation, and both the present Bonnechere Caves and the collapsed caves at higher levels were developed after the withdrawal of the ice. Dr. D. C. Ford gives the fact that rock first incised by the river is delicately castellated as evidence of this maximum age, since ice action would have destroyed these features.[7] Any glacial deposits in the area would likely be of metamorphic origin since most material in the glacier would be derived from the Canadian Shield.

The method of determining a former level of the Bonnechere River at the Four Chute, involved an examination of surficial material in order to determine which areas were stream washed. Since there is till with metamorphics on both sides of the river, in areas to the East of the erosional scarp, the absence of metamorphic material would indicate stream erosion after the withdrawal of the ice from this area. Twenty-three sampling stations were chosen in order to best cover the area of the Fourth Chute: these are shown on the topographic map, Fig. 2. An abbreviated account of the observations is also shown on the map: the

[7]Ford, D.C.; The Bonnechere Caves; Renfrew County, Ontario: A Note, Canadian Geographer, Vol. 3, 1961; pp. 22-26.



TOPOGRAPHY OF THE FOURTH CHUTE AREA, BONNECHERE RIVER
RENFREW COUNTY, ONTARIO
Fig. 2
Surficial Deposits
Topographic Survey by John A. Marshall, 1965
Cave Survey by E. D. Ongley, 1964
Scale
100 80 60 40 20 0 50 100 150 200 feet
Reference
Buildings
Dams
Old Mill
Gravel Road
Cave Passages, Grade 5
Grade 1
Underground Streams
Karst Windows
Contours
Spot Heights
Contour Interval 5 feet
Small 1"
Medium 1" to 6"
Large 6" to 1'
Boulder 1'
Former River Level
N
1 small ls. pebbles
2 small ls. pebbles
3 small ls. pebbles & gran. sand
4 large ls. boulders & med. ls. pebbles
5 large ls. boulders & small ls. pebbles
6 large gran. boulders & small ls. pebbles
7 coarse gran. sand & med. ls. pebbles
8 small ls. pebbles & fine gran. sand
9 small ls. pebbles
10 gran. boulders & sand, large ls. fragments
11 gran. boulders & small ls. pebbles
12
13 gran. boulders, semi-angular gran. pebbles & sand, & large ls. fragments
14 med. to large ls. fragments
15 med. to large ls. fragments
16 large gran. & ls. boulders
17 stoney till
18 gran. boulders
19 large ls. boulders & one gran. boulder
20 med. to large ls. fragments
21 med. to large ls. fragments
22 med. to large ls. fragments
23 small ls. pebbles

actual field observations are shown in the appendix on pages 65 and 66. The categories of rock fragments used on the map are: small -- less than 1 inch; medium -- 1 inch to 6 inches; large -- 6 inches to 1 foot; and boulders -- greater than 1 foot.

The boundaries of stream washed areas can be complicated by the process of sheet flow which could move finer granitic material into areas that were stream washed -- thus the determination of a former higher stream level can become rather subjective.

The stream washed area on the north side of the Fourth Chute is marked approximately by the 480 foot contour on the topographic survey -- the hypothesized line is marked in blue on Fig. 2. The discontinuity of surficial material can be seen between stations 2 and 3, 7 and 8, and 9 and 10. This line also accounts for the lack of granitic material at stations 14 and 15. There was no apparent line of discontinuity on the south side of the river, within the bounds of the contour map.

The line of discontinuity of material on the north side of the gorge is also marked by a small terrace just below the 480 foot contour. There is a terrace approximately two feet in height on the south side of the chute, about one hundred yards back from the edge of the gorge. The surficial material between the gorge and the terrace here was completely of medium to large limestone fragments, indicating that stream washing occurred in this area.

From these results, it can be postulated that a post-Pleistocene river flowed across the limestone terrace here at a level of approximately 480 feet above present mean sea level. The rock drumlin on the north side of the Chute, under which the caves have been developed, prevented a wide extension of the flow on that side of the present gorge, but there was no such obstruction on the south side of the gorge, and the river extended back about 100 yards. That former river probably cascaded over the present erosional scarp in the form of a cataract, approximately 40 feet high. The present much narrower gorge is the result of a concentration of flow into a narrower zone by jointing and possibly a reduction in the water supply to the Bonnechere River.

It was not until the river was intrenched deeply into the limestone that the caves could be developed. In this way a possible chronology of the development of the Fourth Chute is forwarded, in order to better explain how the conditions evolved which resulted in the development of the caves

## CHAPTER IV

## THE LITHOLOGY OF THE FOURTH CHUTE

The rock section at the Fourth Chute of the Bonnechere River consists of part of the Mohawkian Series of Ordovician limestone; exposing about 40 to 45 feet of rock. The lower 37 feet consists of the Chaumont Formation the topmost member of the Black River Group; and above it, completing the top 8 feet of the section are the basal beds of the Rockland Formation which is the first member of the Trenton Group. The contact between the two is quite well marked, the Rockland being coarser textured than the Chaumont. This contact lies at about 467 feet above mean sea level.

The lithological section by G. M. Kay taken at Meath, altered slightly to fit this Fourth Chute description, is shown in Fig. 3. The rock section is divided into eight groups of beds, seven in the Chaumont Formation and one in the Rockland Formation. These are described on Fig. 3, and can be fitted to the more detailed description of thirty-five beds given in this paper, which is also shown on Fig. 3. This more detailed description consists of 23 beds in the Chaumont Formation and 12 in the Rockland Formation. Fig. 3 gives the thickness of the bed and its stratigraphic characteristics, i.e. whether it is massive or brashy. Kay describes his section in more exact geological terms. However, since the development of caves is so greatly controlled by the stratography of the limestone, here the distinction between massive and brashy beds is most critical.

# Rock Lithology at the Fourth Chute

Fig. 3

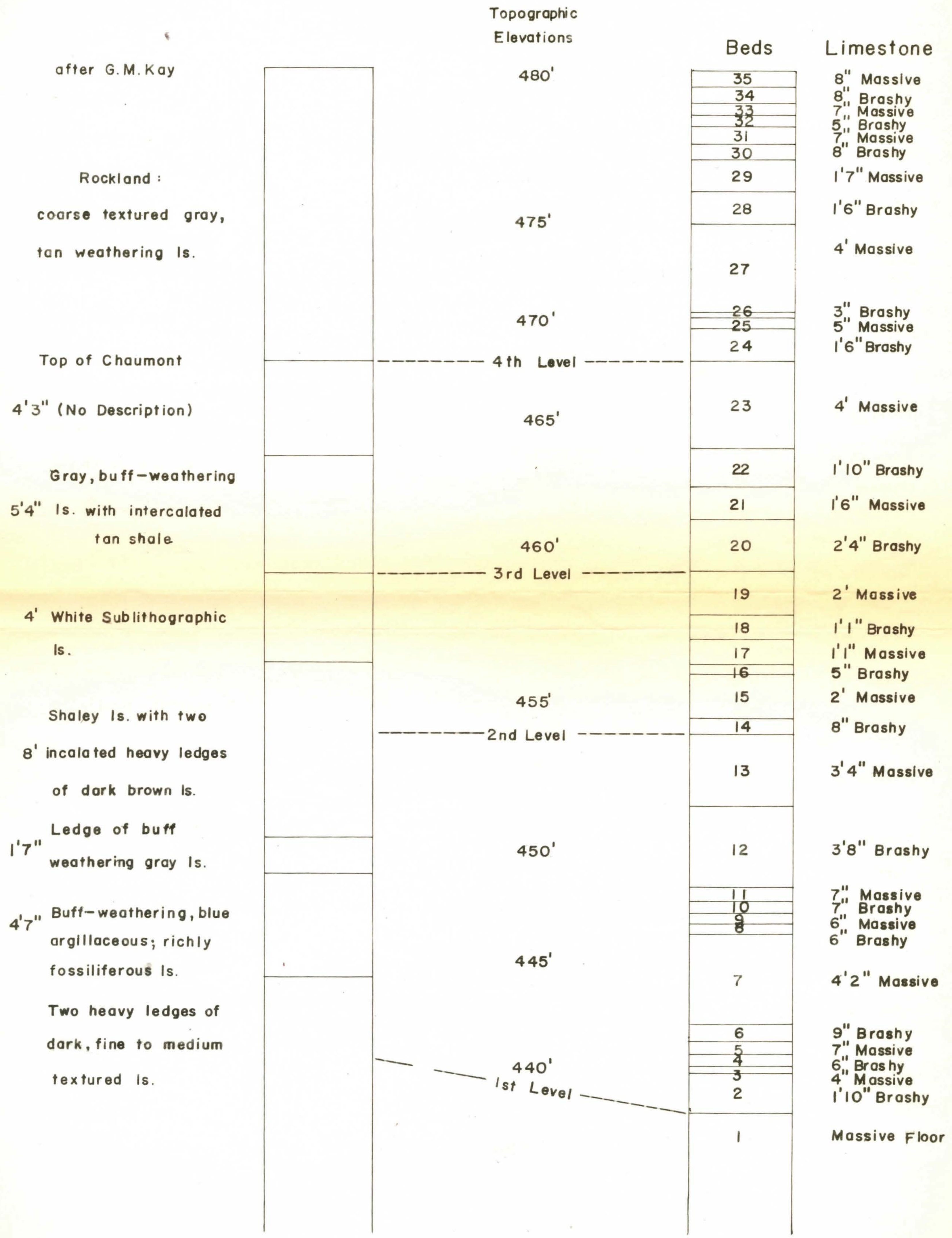


Fig. 4 Long Profile of the Fourth Chute, Bonnechere River

Vertical Exaggeration: 10×

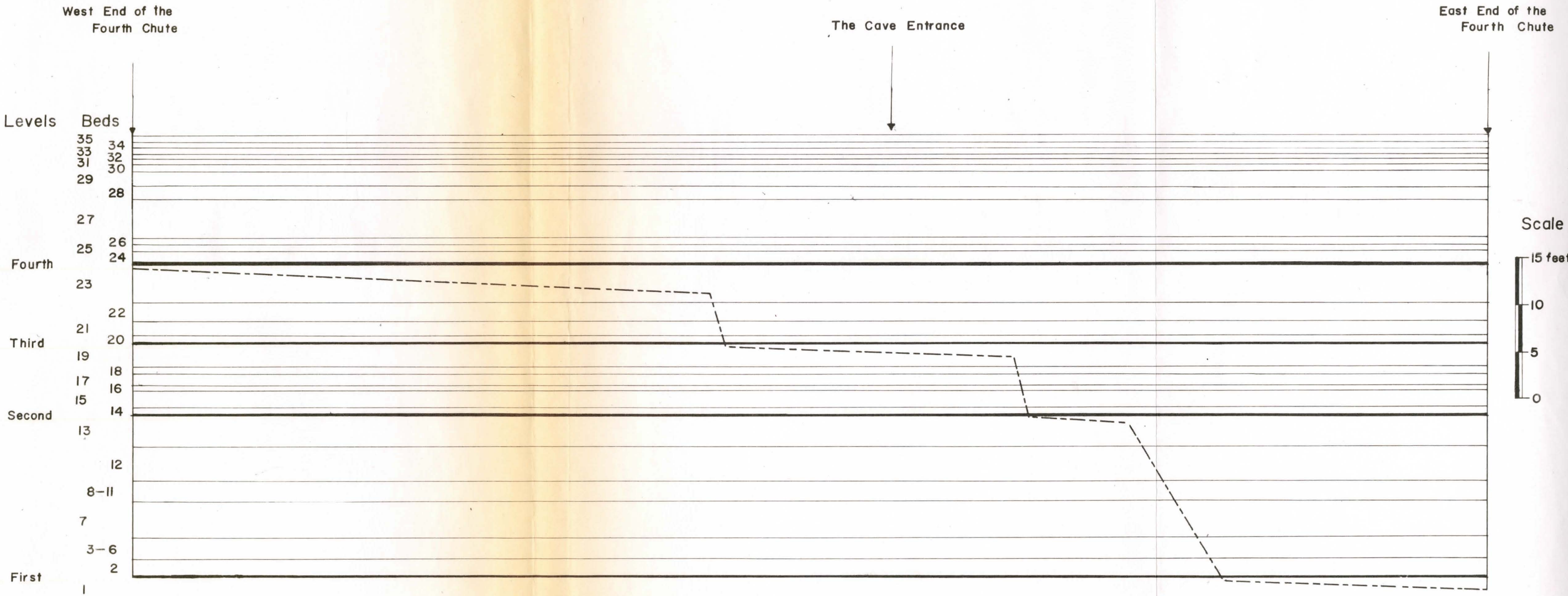


PLATE III(a): The Collapsed Caves on the South
Bank of the Fourth Chute

PLATE III(b): The Stone Arch in the Vicinity
of the Collapsed Caves

The bedding in limestone is an important factor in the development of caves. Brashy beds which contain many bedding planes and sometimes partings of softer rocks eg. shale, offer numerous opportunities for water to penetrate the limestone and concentrate corrosion and erosion at one level. When other conditions are favourable the development of caves is possible. Massive beds are thick strata of limestone unbroken by any bedding planes, thus resisting any concentrated attack by water. Due to this factor, caves are usually developed in brashy beds with the massive beds acting as ceiling and floor until they are truncated. Massive beds often act as cap rock in fluviatile erosion, creating chutes and cataracts.

Three of the four levels at Fourth Chute of the Bonnechere River described by Ford and Ongley are the direct result of cap rock erosion, where the occurence of four massive beds has created a series of rapids. The fourth is the floor of the lowest level of the chute (Plate II). These beds also have an important effect on the development of the caves: this will be discussed in a later section of this paper. The four levels are shown on the long profile of the chute, Fig. 4, in their lithological context.

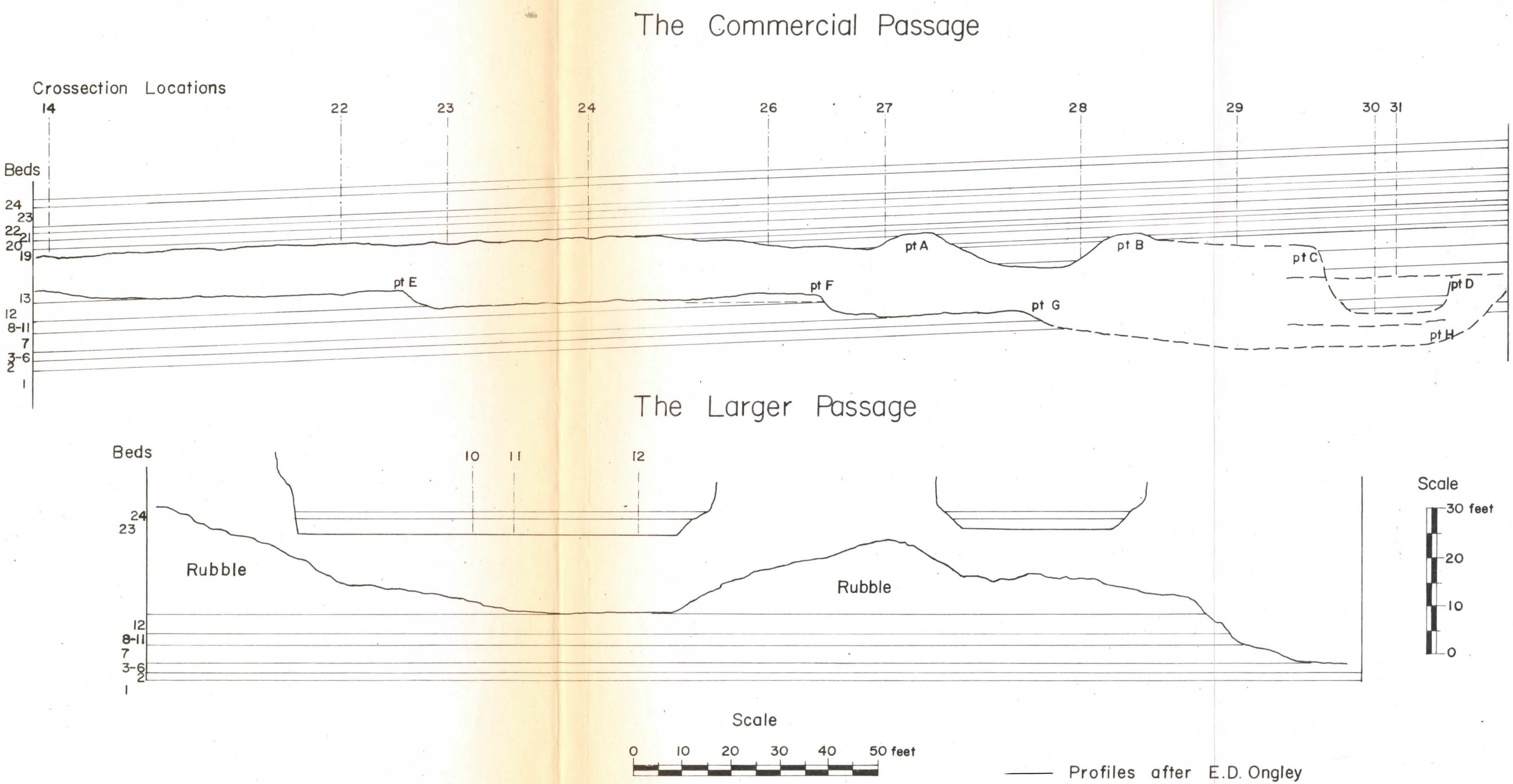
Bed no. 1 is a ledge of dark, fine to medium, textured limestone. It forms the floor of the lowest level of the chute and the lowest level of the tributary gorge, which lies at about 438 feet above mean sea level. The second level of the chute lies at approximately 450 feet above mean sea level and is formed on bed no. 13, a heavy ledge of dark brown limestone. Between these two massive beds are twelve beds of less resistent strata: eight of these are less than one foot thick and can be easily eroded. Two others of 3 feet 8 inches and 1 foot 10 inches thickness are brashy beds. One 4 foot 2 inch bed of massive buffweathering, blue fine textured, richly fossiliferous limestone is about 450 feet above mean sea level but apparently has not presented a significant barrier to erosion. This level has created ledges about 25 feet in width on both sides of the gorge by the collapsed caves (shown on Fig. 1 and Plate III).

The third level is on bed no. 19, two feet of white, sublithographic limestone. This limestone is relatively very resistant to erosion and has created a rather flat stretch in the chute of about 75 yards, from the dam to the constriction of the river at the end of the bend. Between the second and third levels there are 3 feet of shaley limestone and a heavy ledge of dark brown limestone which is 2 feet thick. This is at 455 feet above mean sea level and has not had an extensive effect on the chute, but it has created ledges on both sides of the river, especially at the south side of the river opposite the cave entrance, (Plate IV). The third level is perhaps the most important in the section because it acted as the floor of the initial passages of the Bonnechere Caves, and it still constitutes much of the floor of passages A, B, C, D, E, and F. A broad bench in the north side of the gorge has been caused by this bed which also acts as the floor of the collapsed caves on the south side of the river. The fourth level marks the top of the Chaumont Formation and has been created by bed no. 23, a massive limestone at 465 feet above mean sea level. This bed floors the chute above the dam, forms a large bench just east of the cave entrance, and is the upper surface of the limestone on the south side of the gorge east of the bend in the chute. It is also the base for some minor solution features between the dam and the bridge on the south side of the gorge. Between the third and fourth levels of the chute are about five and one half feet of limestone consisting of two beds of brashy limestone 2 feet 4 inches and 1 foot 10 inches, and a thin massive bed of 1 foot 6 inches. This level is very susceptible to penetration by water and it is here that the formation of the Bonnechere Caves began.

From evidence of stream washing that will be presented later, it is probable that the river flowed in a much wider channel immediately after the Pleistocene at a level of about 450 feet above mean sea level, i.e. at the fourth level. The river then fell over the erosional scarp then extending across the end of the present gorge. By means of cap rock erosion at the fourth, third and second levels the chute was eroded upstream with the greatest erosion at the second level since the first, third and fourth levels form long stretches of the chute. The second level has been eroded upstream more rapidly than the third and now the two are quite close together forming a vigourous waterfall of 15 feet just downstream from the cave entrance, (Plate II).

The narrow gorge in which the Bonnechere River flows at the Fourth Chute is due mainly to jointing in the limestone body which opened the rock to more rapid downward erosion by the river. The steepness of the gorge sides is due to the existence of the resistant levels of limestone, but the location of the gorge was due to factors other than lithology.

Fig. 5 CAVE PROFILES



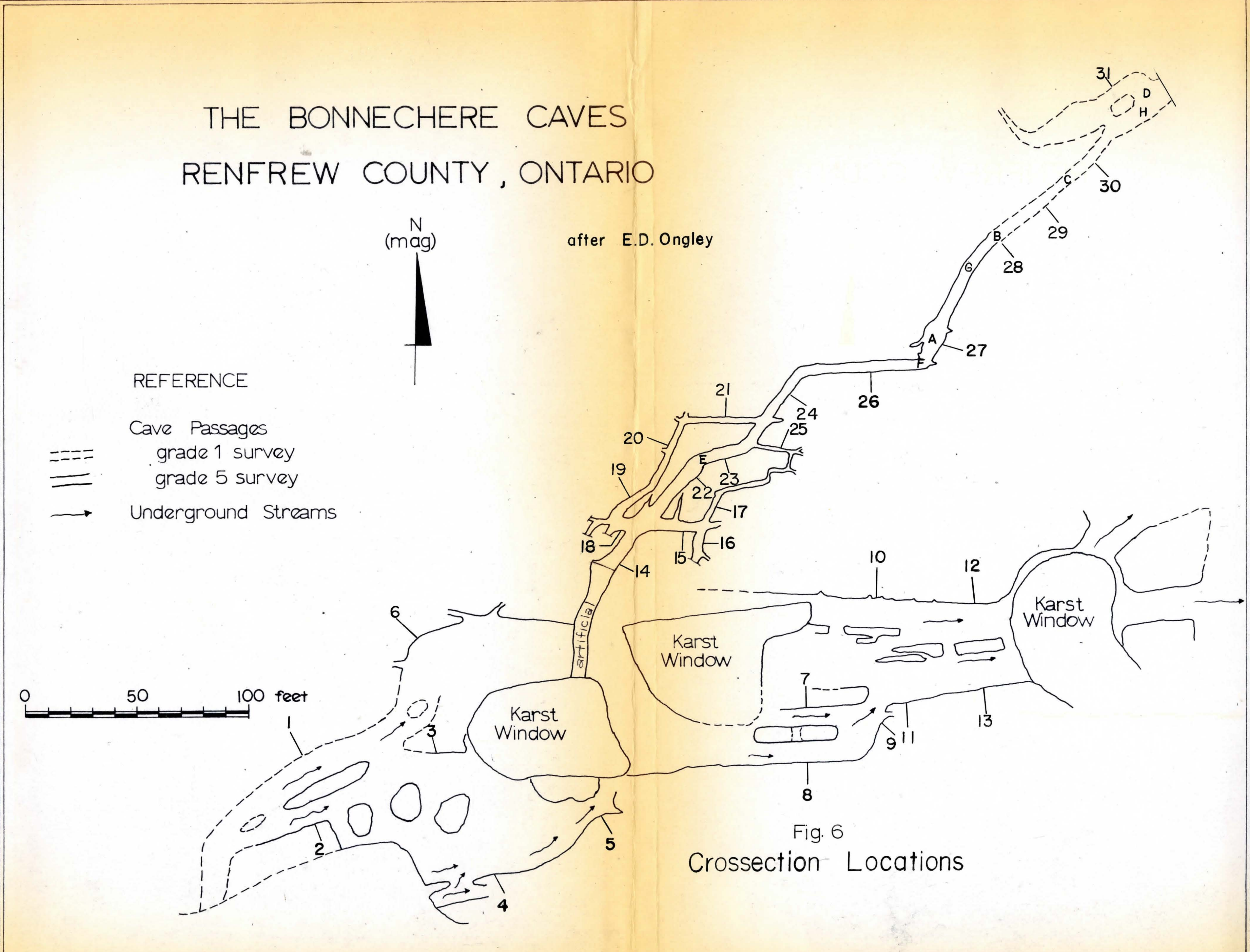


Fig. 6
Crossection Locations

Cave Crossections in the Larger Passage

in their Lithological Context

Fig. 7

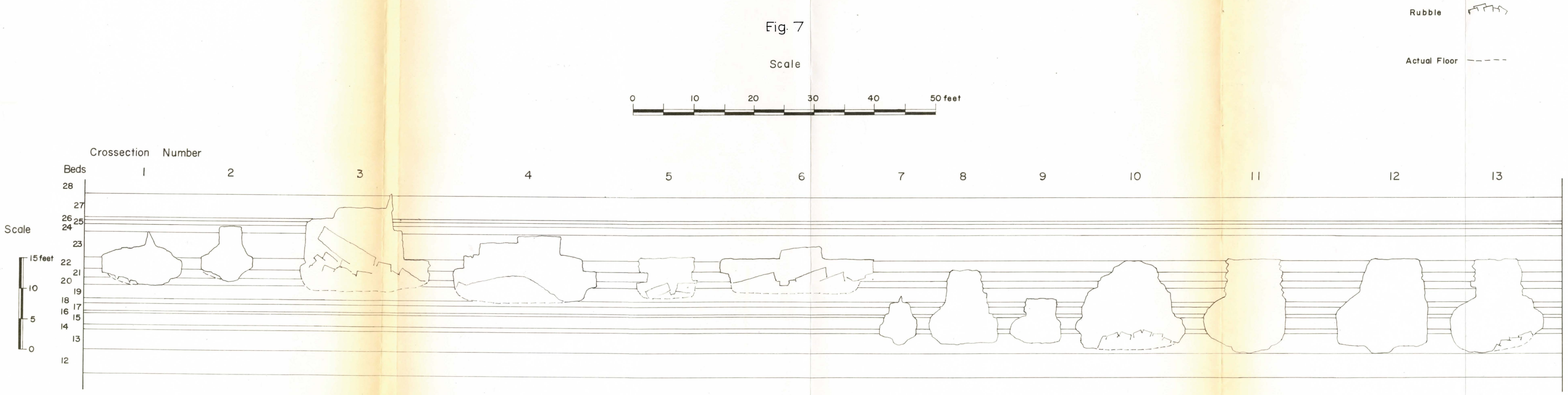
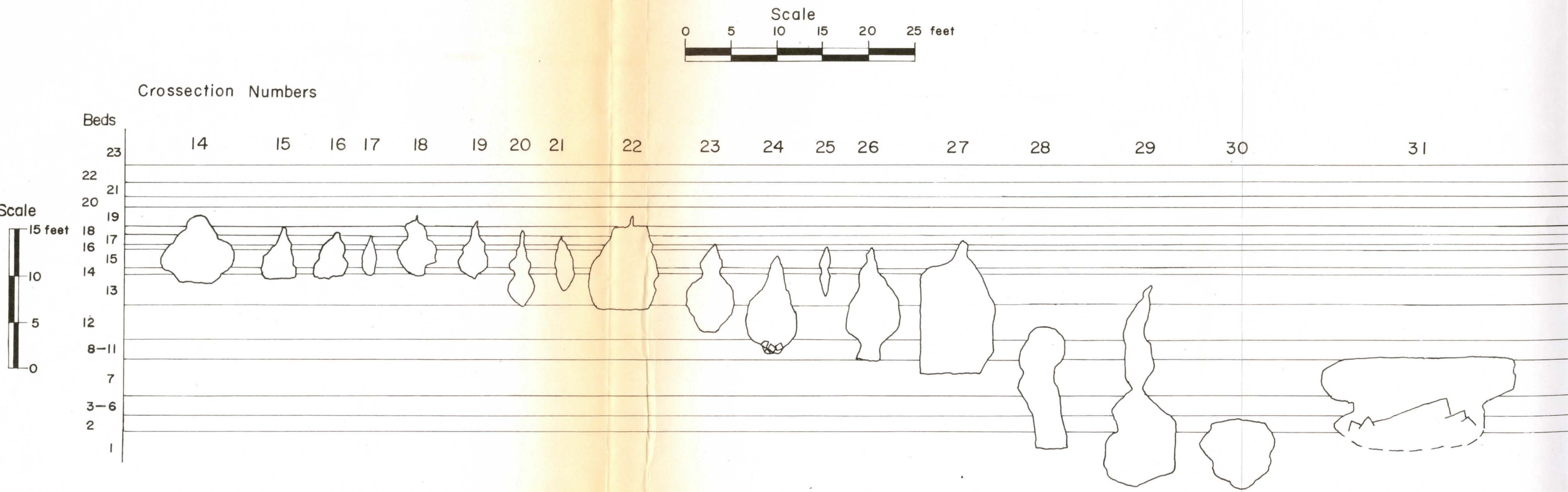


Fig. 8

# Cave Crossections in the Commercial Passages in their Lithological Context



CHAPTER V

THE CAVES AND LITHOLOGY

To best illustrate the effects the various beds have had on the form of the caves, the two profiles drawn by E. D. Ongley[8] and the passage crossections drawn by the author were superimposed accurately on diagrams of the lithological section, (Fig. 5). Since the floor of the caves is difficult to determine, because of rubble that lies on it (put there by Mr. Tom Woodward), a slight degree of freedom will be used in interpretating its true position. This difficulty was observed by Ongley in his discussion of the passage profiles. The remaining portion of the commercial passage that could not be mapped by Ongley, since it was flooded in 1964, has been sketched in by the author -- it can be considered only approximate. Reference will be made to cross-sections numbers and points marked in the caves by letters: these are shown on Fig. 5, Fig. 6, Fig. 7, and Fig. 8.

The commercial passage covers a vertical range of about twenty-two feet, with the roof of the cave remaining virtually horizontal, until it dips sharply in the lower section of the passage, (Fig. 5). The floor of the initial mapped part of the commercial passage and the outlet of the passage are almost exactly the same height, approximately 455' asl, but the passage floor reaches a maximum depth of 12 feet below this level in the lower section of the passage. The existence of this situation

[8] Ongley, E.D.; A Study of Caves in Southern Ontario, Unpublished B.A. Thesis; University of Toronto, 1965.

substantiates the speculation of Ford that a "phreatic loop" exists here, i.e. that water has been able to flow against gravity because an artesian condition existed.

The development of the commercial passage has occurred below bed no. 19 down to five feet below the surface of no. 1 bed. The roof of the passage is controlled by the undersurface of no. 19 bed for the upper 125 feet of the passage and then undulates considerably between the undersurface of no. 15 bed and the undersurface of no. 13 bed until it drops almost fifteen feet to the underside of no. 3 bed. These beds are of massive limestone and being relatively resistant to solution they create an upper barrier to rapid erosion. The undulations in the roof of the passage at points a and b occur at bends in the passage (see Fig. 6) and are interpreted as the result of increase in erosion caused by the turbulence which exists in such situations. The upper part of the passage is very narrow between points b and c, as seen from crossection no. 29, appearing to be an enlarged joint; and the sudden dropping of the cave ceiling at point c is due to the termination of this joint in beds 7 to 12. The roof drops down to the underside of bed no. 3, and then, at point d, rises to bed 9 where the passage opens up into a room at the exit of the passage. This room is the result of the confluence of the commercial passage and a larger vadosed passage (crossection no. 31) that seems to have developed at the exit, much in the manner which is described by Rhoades and Sinacori[9], (Plate IV). This adjacent passage seems to have been fed from a source independent of the main passage, but there seems

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[9] Rhoades and Sinacori, 1941, The Pattern of Ground-Water Flow and Solution; J. of Geology, XLIX, pp. 785-794.

PLATE IV: Collapse in the Passage at the Down-
stream End of the Commercial Cave

PLATE V: Crossection No. 28: Note the offset
to the left

PLATE VI: The Upper Part of Crossection
No. 29

PLATE VII: The Entrance of the Caves: Note
the ledge at the right, Created
by No. 21 bed

to be no obvious explanation where the source of this water existed.

The floor of the commercial passage can be divided into four distinct segments, which are created by four different massive beds. There is a distinct step between each of these segments, every one at a bend in the main passage. The sudden increase in turbulence that occurs at a bend in a passage would increase the rate of erosion at that point and thus could possibly lower the cave floor. More likely is the fact that a new master joint has been selected by the water flow, and this could truncate the massive bed which acted as the floor for the upper segment. The massive beds which create the floor for each segment of the commercial passage are: 1 - the beginning of the passage to point e -- bed 13, which has been truncated slightly near point e; 2 - from point e to point f -- bed no. 7, from point f to point g -- bed no. 7 has been eroded considerably but still acts as floor of this segment; from point g to h -- bed no. 1, which has been eroded deeply, probably due to jointing; from point h to the exit of the passage -- the floor rises to the surface of bed no. 1.

Ongley claims that lithology here controls the shape of the passages after erosion has started along the joints; but after an examination of the crossections in the commercial passage, it appears that Ford's interpretation: "the bulk of passage expansion to the present dimensions can be attributed to boring by rapidly moving waters in a 'paraphreatic' situation, i.e. one of intermittent flooding or not quite complete water fill"[10], is the correct one. Passage crossections no. 14 and no. 19 all show widening in the no. 15 bed which is a bed of massive

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[10] Ford, D.C.; The Bonnechere Caves; Renfrew County, Ontario: A Note; Canadian Geographer, Vol. 3, 1961, pp. 24

limestone: this seems to indicate the long existence of a moderately existing water level near the top of no. 15 bed, eroding just the lower parts of the passages. This assertion seems also to be valid for crossections no. 22 to no. 27; but in crossections no. 26 and no. 27 there is narrowing caused by no. 7 bed and no. 13 bed. The relatively unusual trench shape of no. 28 crossection seems to be caused by the almost full condition of the passage here along a very long joint, (Plate V) -- preventing any differential erosion other than the offset to the left caused by the bend which exists over the entire height of the passage. The lower widening of no. 29 passage indicates a predominant water level, (Plate VI). The pipe shape of no. 30 is typically phreatic, completely below water level. The adjacent passage, shown by no. 31 crossection shows considerable vadose collapse: this passage was probably controlled by the bedding plane below no. 7 bed, rather than by joints as the other passages are, with no. 7 bed collapsing on to the floor of the passage.

The vertical development of the large passage of the system seems almost completely controlled by lithology. The profile drawn by Ongley (Fig. B) shows only the lower reaches of the cave: here the roof is in no. 23 bed, the floor created by no. 13 bed, and the gorge floor formed by no. 1 bed. This passage is broken by three areas of collapse that have resulted in three karst windows. Bed no. 23 acted as the roof for water erosion of this passage; but subsequent collapse has occurred and the roof now is no. 24 and no. 25 bed in the upper parts of the passage (crossections no. 1 to no. 4). The upper section of this passage has no. 19 bed as its floor, a bed of massive sublithographic limestone. Corrasion has caused considerable lowering of the passage floor, but the initial penetration through no. 19 bed and no. 15 bed, down to no. 13 bed was due, no doubt to jointing. The lateral development in the larger passage is due to horizontal penetration of bedding planes in the less resistant brashy beds. In the upper section of this passage, the beds between the resistant no. 23 and no. 19 beds have been stripped away considerably -- see crossections 1 to 6. In the lower section of the passage, lateral development has occurred in the less resistant beds between bed no. 19 and bed no. 13. Much of the enlargement in the upper sections of these passages is due to collapse of the beds between no. 19 bed and no. 23 bed -- the rubble on the floor is evidence of this collapse. Bed no. 19 acts as the roof for portions of this passage (see crossections 7 and 9) and may have been the roof for much of this section before vadose collapse occurred.

The role of lithology is dominant in the vertical development of the passages; but the initial role of joints in creating unobstructed circulation (See Chapter VI) is also important. The lithology also has a dominant role in the horizontal development of the larger pasage; but hydrologic factors appear to exert more control on passage crossectional form in the commercial caves (See Chapter VI).

The initial penetration of water into the caves was facilitated by the bedding planes between no. 23 bed and no. 22 bed, and between no. 22 bed and no. 21 (Plate VII). The role of joints must not be overlooked, but this "sandwich" structure of a brashy bed, no. 22, between bed 23 and bed 21 is a classically ideal situation for cave initiation. The relatively wide development of the crossections (nos. 1 to 6) in the upper part of the larger passage, at the level of bed no. 22, indicates that erosion has occurred there longer than at any other level near the entrance of the caves.

# CHAPTER VI

## THE CAVES AND JOINTS

Limestone is usually traversed by joint fractures, the result of either tension or stress in the rock. Tension is caused by warping or folding. The joints in this case are in two sets, parallel and perpendicular to the strike of the fold. Tension jointing is usually restricted to individual beds in a lithology. Shear stresses are set up when lateral movement I.E. faulting occurs in the rock body. This condition causes jointing along the lines of shear and the joints thus caused intersect at approximately 60° and 120°. Jointing due to shear stress usually occurs throughout a rock body, not being restricted to individual beds. Jointing in both cases is most frequently perpendicular to the stratification plane, so that in cases of horizontal bedding the joints are at or near vertical.

In the case of the terrace of Rockland and Chaumont limestone in which the Bonnechere Caves have been developed, there is warping of the limestone[11], and also major faulting within a quarter mile of the caves, on both sides of the river. (Douglas Fault on the North, Packenham Fault on the South).[12] If warping had the greatest effect on the joing pattern,

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[11] Kay, G. M.; Ottawa - Bonnechere Graben and Lake Ontario Hanodine; Geol. Soc. Amer. 53; Jan. - June 1942; pp. 585-646.

[12] Ibid.

we would expect master joint sets at 90° of each other; aligned with one set on N. or N.N.E. bearings -- the direction of warping here.[13] If the shear stresses set up by faulting had the greatest effect, we would expect the master joint sets at 60° and 120° from the axis of the faulting, which is at approximately 319° and 320° -- measured from G. M. Kay's Map[14]. Thus if warping caused tension jointing, the master sets would be at about 0° to 10° and about 270° (90°) to 280°, whereas if shear stress jointing occurred we would expect master sets of joints at 20° and 80°.

The joints in the Rockland terrace of limestone were measured in exposed shelves of limestone along the Fourth Chute. The joints were measured by means of a prismatic compass and all bearings were expressed in the South to North direction along the axes of the joints -- thus all bearings occur in the 180° between 270° and 90°, through 0° (magnetic North). The bearings are shown in the approximated position on Fig. 9 and the list of joints for each of the eight measuring stations is on Table 1. The bearings are also shown on the rose diagram, Fig. 10(a), and the bearings in each sector are listed on Table 2.

From the joint bearing data shown on Fig. 10(a) and Table 2 we can see that the greatest number of joints occur in the 70 to 79° sector (20.3%), second greatest in the 60° to 69° and 20 to 29° sectors (11.9%), and third greatest in the 10° to 10° sector (10.2%). There is a concentration in the 270° to 299° sectors (5%, 5%, and 5%). This could be

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[13] *Ibid.*

[14] *Ibid.*

# TOPOGRAPHY OF THE FOURTH CHUTE AREA, BONNECHERE RIVER
# RENFREW COUNTY, ONTARIO

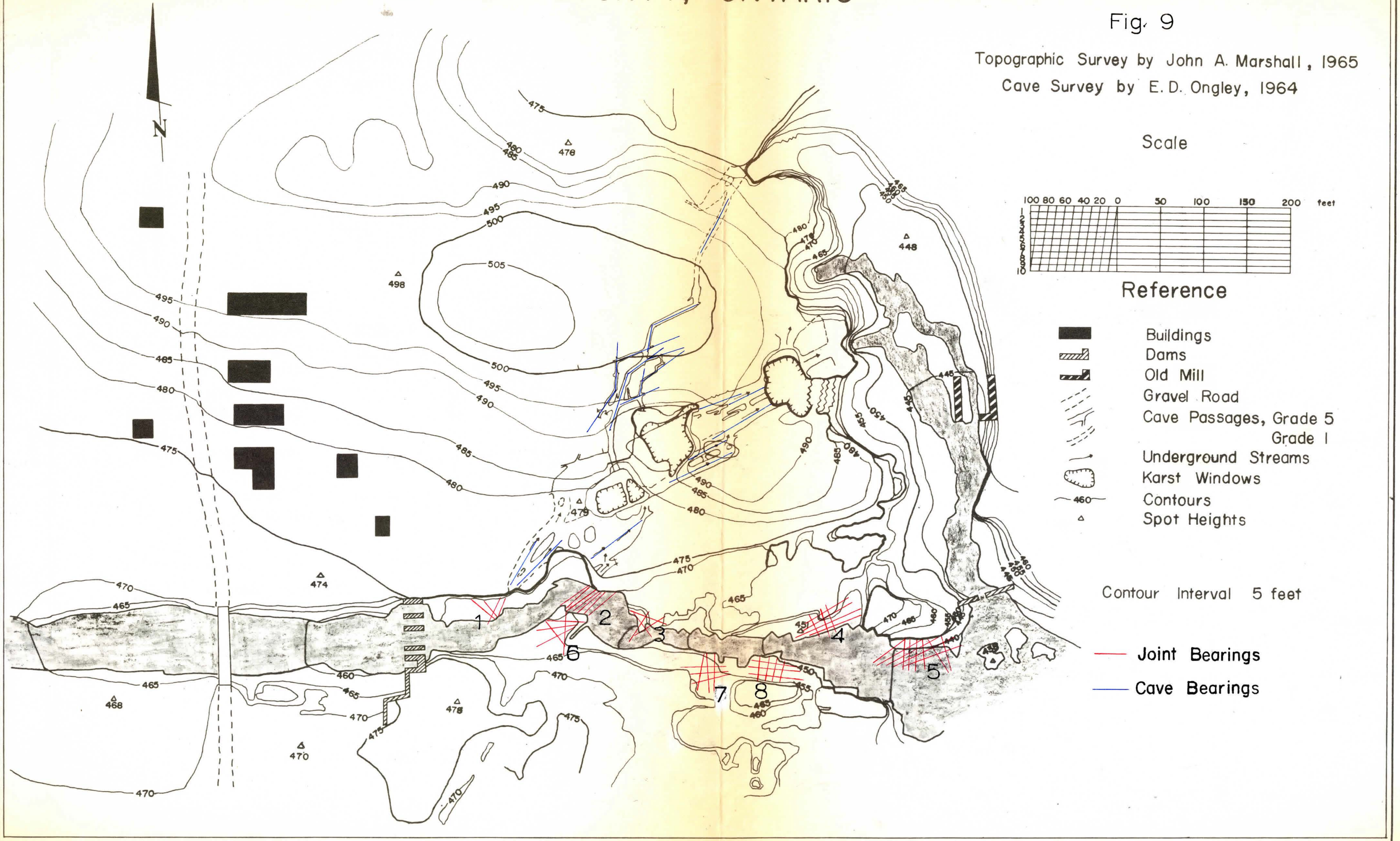

Fig. 10 (a)

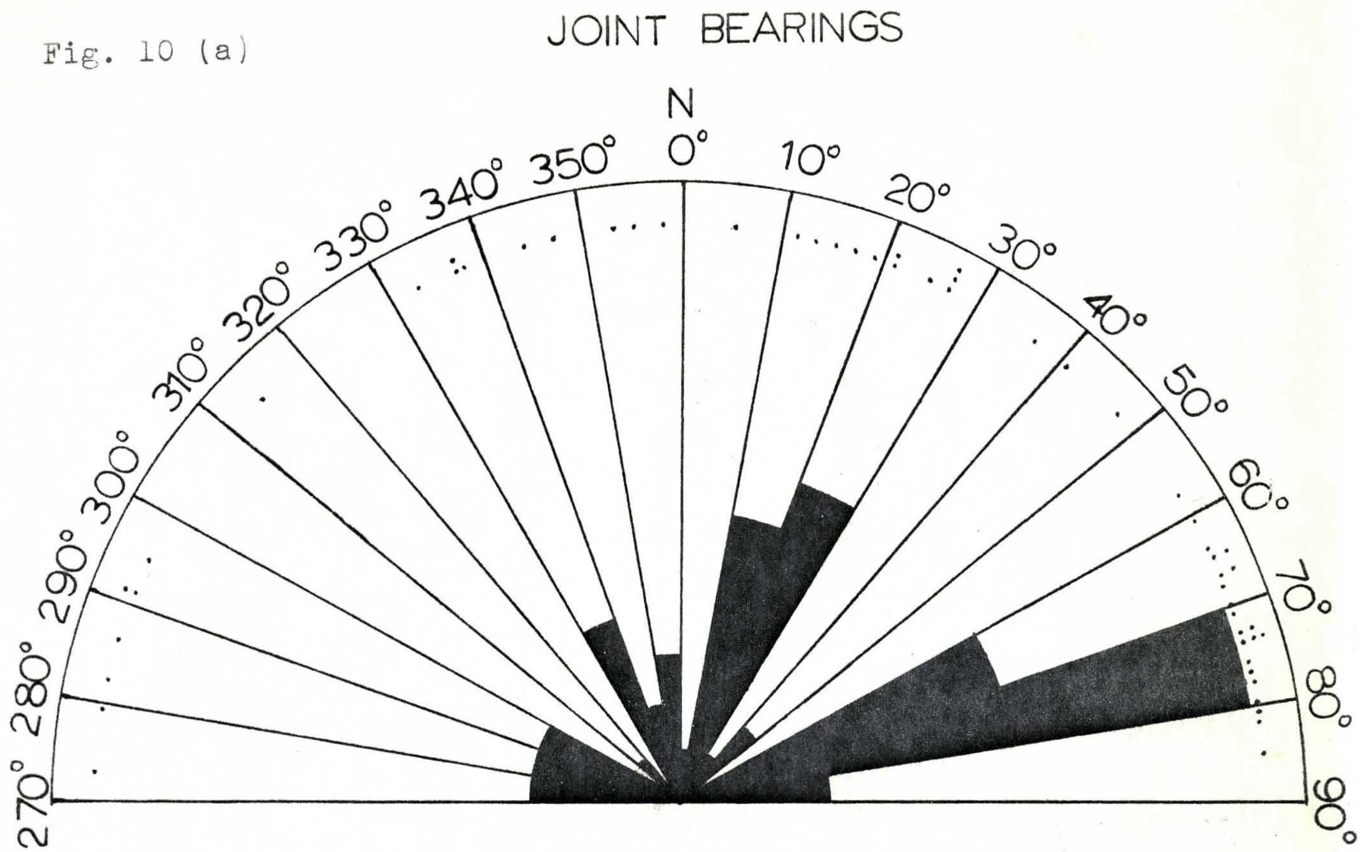


Fig. 10 (b)

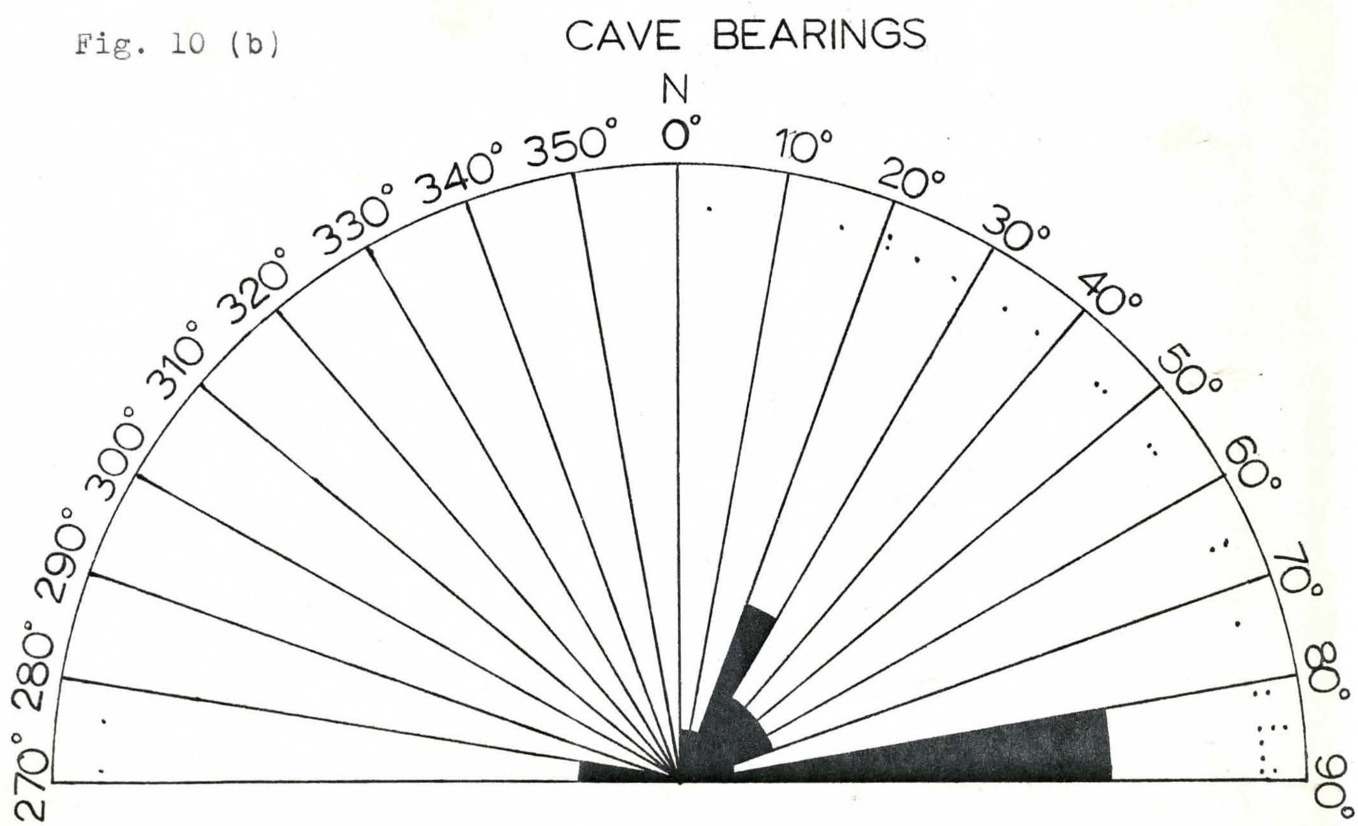

PLATE VIII: The Narrow Roof of a Passage in the Commercial Caves

PLATE IX: Karst Window No. 1, from the portion of the roof that has not collapsed interpreted as showing that shear stress jointing predominates because of the approximately 60° difference between the first two concentrations, 10° to 29° and 60° to 79°, with tension jointing being secondary as shown by the concentrations in 270° to 299° and 10° to 29°.

As can be seen from Fig. 9, shear stress jointing predominates by the entrance to the cave -- stations 1, 3, and 6 -- and also by the tributary gorge -- station 5. This is shown by the intersections of the joints at these stations; these are predominantly near 60° or 120°. At stations 4, 7, and 8 however, there are strong rectangular patterns of jointing. This could indicate that shear stress jointing predominates in the limestone near the entrance and exit of the caves, and tension jointing predominates in the limestone where the greatest proportion of the passages occur.

The joint bearings are shown in their lithological position on Table 3. This is also expressed in the histograms on Fig. 11 which show the number of bearing occurrences in each sector for each bed in which joints occur. Shear jointing predominates in beds 23 and 19, while tension jointing predominates in beds 15 and 13. Both types of jointing occur in bed 1, but shear jointing appears the more important. This distribution of jointing through the lithology is probably the explanation for the apparent areal diversity of the jointing, since the beds are exposed in shelves in different locations.

Jointing obviously has an effect on the cave passages in the commercial system, where most of the passages still retain narrow roofs and floors -- the appearance of an enlarged joint, (Plate VIII). This can be seen by examining the crossections of the commercial system. An obious test of the jointings' effect on cave development is a comparison between the joint bearings measured, and cave passage bearings measured from E. D. Ongley's map. These cave passage bearings are shown on Table 5, a rose diagram, Fig. 10(b), and on Table 6.

A superficial examination of the rose diagrams at once shows a similarity between the two distributions, especially in the 20° to 30° sector which is related to both shear and tension jointing. There is also a correlation between the 270° to 280° sectors. However, the strong concentrations in both distributions are proximate, but distinctly 10° apart. A partial explanation of this could be that the bulk of these 80° to 90° cave bearings occur in the lower section of the larger passage where the maximum effect of the water outlet is felt. It seems possible that the outlet may have been effected in such a position as to distort the passage alignments slightly to the South, since the water flow is attracted in this direction throughout the system. This occurs because of the proximity of the erosional scarp if the water flows in this direction. This, however, does not explain the lack of cave passages in the 70° to 80° sector in the commercial passage.

There does not appear to be any strong correlation between joint bearings and caves that occur at the same level. (Ongley speculated that there may be some correlation along these lines)[15]. The joint bearings in each bed and the corresponding cave bearings are plotted on the histograms on Figure . Because the data is very meagre when categorized, few concrete conclusions can be drawn. Nevertheless, no strong correlations

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[15]Ibid.

appear to exist, except perhaps in no. 15 bed: this correlation is probably the result of the overall correlation of joint and cave bearings in the entire limestone lithology. However, in the commercial passage, bends in the main passage at points E, F, and G correspond with a marked drop in the floor. This gives evidence of joints of different bearings controlling development at different levels; but yet no strong correlations can be made in the bearings of caves and joints.

There is a strong correlation between the joints and the collapsed cave passages on the south side of the river. The rectangular pattern of the joints there is strongly reflected in the former passages which intersect at right angles, (See Fig. 9).

The dearth of cave development in beds 3 to 11 could be due to the corresponding lack of joints in this section of the lithology. Only crossection no. 28 and crossection no. 31 have any significant development at this level: no. 28 crossection could have originated in bed 1 and in beds 8-12, and much of the development in crossection 31 at this level is due to collapse. This could be interpreted as indicating that initiation of the cave passages was strongly controlled by joints.

The bend in the Bonnechere River by the cave entrance, which directs water into the limestone terrace follows the predominant joints in that level of the limestone terrace. The river flows initially at 277° across the limestone, then is diverted northwards on a bearing of 79° for about 110 feet, then southwards for 100 feet on a bearing of 324°. These two arms of the bend approximately follow the two joint sets at stations 1, 2, and 7. The river then continues across the limestone on a bearing of 288°. This initial deflection of the river must be considered paramount in the creation of the caves, in that a great supply of water under a head is directed into planes of weakness in the limestone, i.e. joints and bedding planes. On this point, Ford states: "Certain authors consider hydrostatic pressure is essential if deep penetration (in this case at least 80 yards to the outlets) is to be made; otherwise the initial tiny tubes may be readily blocked by the precipitation of calcite from a saturated solution.[16] This implies the Bonnechere system began when the bed of the river was being cut down into the platy strata, the channelled water then supplying a head of about 15 feet at bankfull stage".[17]

The initial penetration occurred in the brashy beds sandwiched between beds 23 and 19, along favourably aligned joints. Penetration of the limestone to the outlets at the erosional scarp is due primarily to joints because the water must penetrate through the very resistant no. 19 bed and the other massive beds to reach the outlets, which occur on bed no. 13 (large passage) and bed no. 1 (commercial passage). The tilting of the limestone (25° from North to South) is a factor that can be overcome only by jointing, since the water would flow against gravity along bedding planes -- soon dissipating the head of water at the entrance. A flow of water through the limestone from the entrance to the erosional scarp was thus facilitated by a complex grid of joint lines which had been expanded to form tall passages, a few inches in width.[18]

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[16] Ford D.C.; The Bonnechere Caves, Renfrew County, Ontario: A Note; Canadian Geographer; Vol. 3, 1961, pp. 24

[17] Ibid., pp. 24

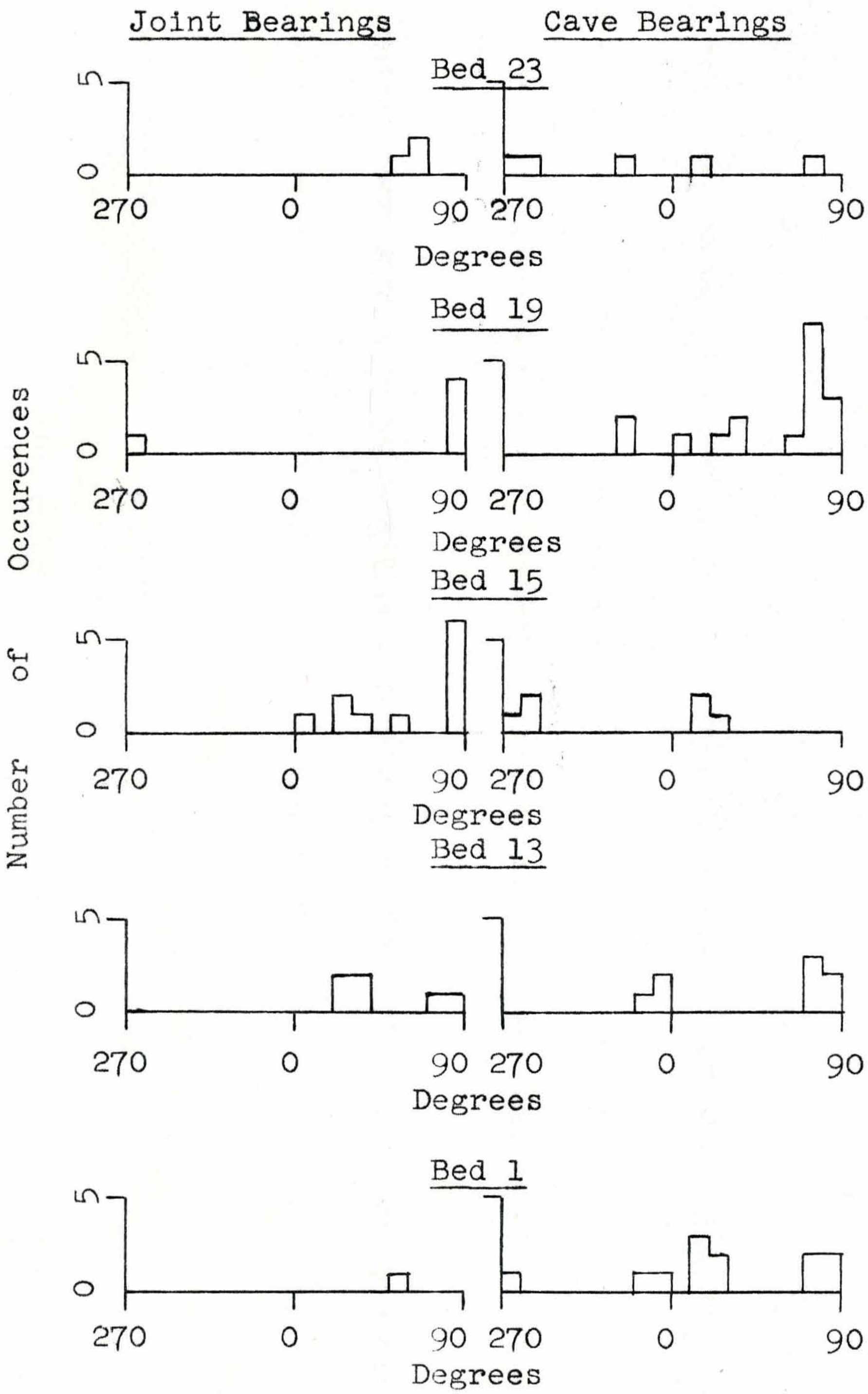
[18] Ibid., pp. 24

The larger passage was, no doubt, in existence longer than the commercial passage because its outlet is far closer to the entrance to the caves, thus a circulation could be established much sooner through the limestone. This is reflected in the greater width and height of this passage. Rather than a simple system of single joints, interconnected, this passage was formed by a grid of joints interconnected, with three main lines of flow resulting -- these are shown on Fig. 12. Unobstructed circulation was established through the present commercial caves at a later time, because of the greater distance to the outlet at the erosional scarp. The closer position of the outlet of the larger passage would direct more water through the larger passage; and also the "phreatic loop" (see Chapter VII) situation in the commercial passage would inhibit rapid circulation through that passage -- thus the larger passage would have been developed much more quickly. This is reflected in the much larger passage crossections that occur in the larger passage and also the much greater width of the passage as a whole

The larger passage is interpreted as the result of the coalescence of three smaller passages of roughly the same magnitude as that of the present commercial passage, (See Fig. 12). These resulted from the three main lines of flow mentioned earlier in this chapter. As these passages were enlarged, water flow accelerated and gradually the limestone separating the passages was eroded away where the flow from the river was hatched against it. (These areas are cross patched on Fig. 12.) This created a very wide passage in these sections (approximately 34 feet wide) with very little support remaining for the roof, which was ten feet thick (beds 23 to 35). This lack of support for such a relatively

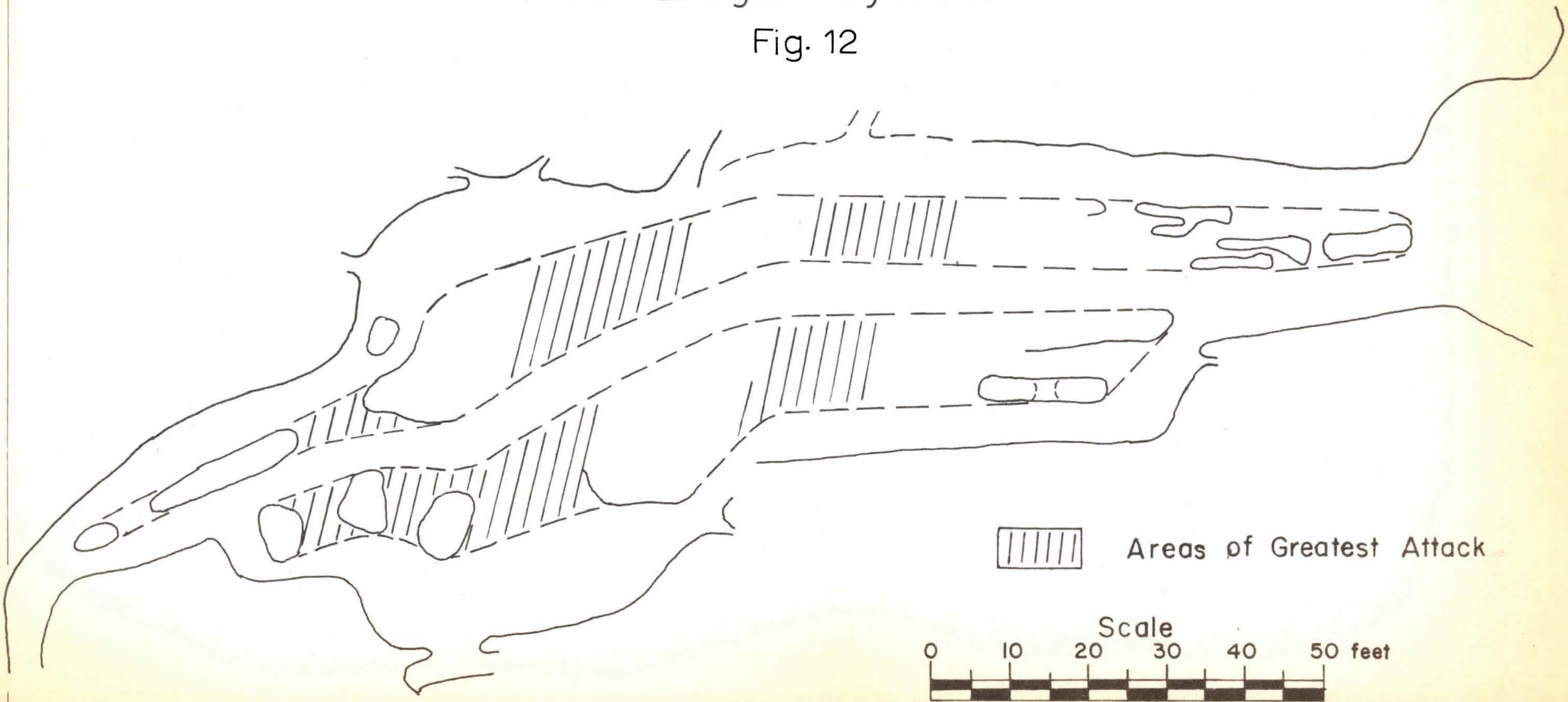
Fig. 11

HISTOGRAMS OF JOINT BEARINGS AND CAVE BEARINGS IN THE SAME BEDS



Hypothetical Former Cave Passages in the Larger System

Fig. 12



thin roof coupled with jointing in these upper beds resulted in collapse of the roof in these areas and created two karst windows (nos. 1 and 2 on Fig. 13). These have been observed closely in the field, and it appears that jointing along the edges marked in red on Fig. 13 caused collapse, with the central portion of each window remaining in position -- acting like hinges.

This central portion has collapsed, in karst window No. 2 but has remained fairly intact in karst window No. 1. The third karst window at the erosional scarp has been created by the difference of the passages near the erosional scarp. There is a confluence of the passages just east of the second karst window, into two main passages; but near the scarp they branch widely into three passages. The point of diffluence became quite wide (approximately 70 feet) and with a roof that was only ten feet thick, collapse occurred. Jointing along the perimeter of the window which is coloured red, facilitated the collapse. With the southern edge acting as the hinge (Fig. 13).

It is difficult to determine at what stage during the development of the larger passage that the commercial passage was initiated and developed most quickly. Perhaps the second karst window collapsed before the first one, and the resulting constriction of flow in the larger passage directed more water into the commercial system, (Plate XI). The commercial passage may also be almost uniformly contemporaneous with the larger passage since development occurred much more slowly there with a lesser water supply being directed through the passage. The establishment of a chronology here is a difficult task because of the many possible alternative situations that could have resulted in the same form being developed.

Fig. 13 Karst Windows

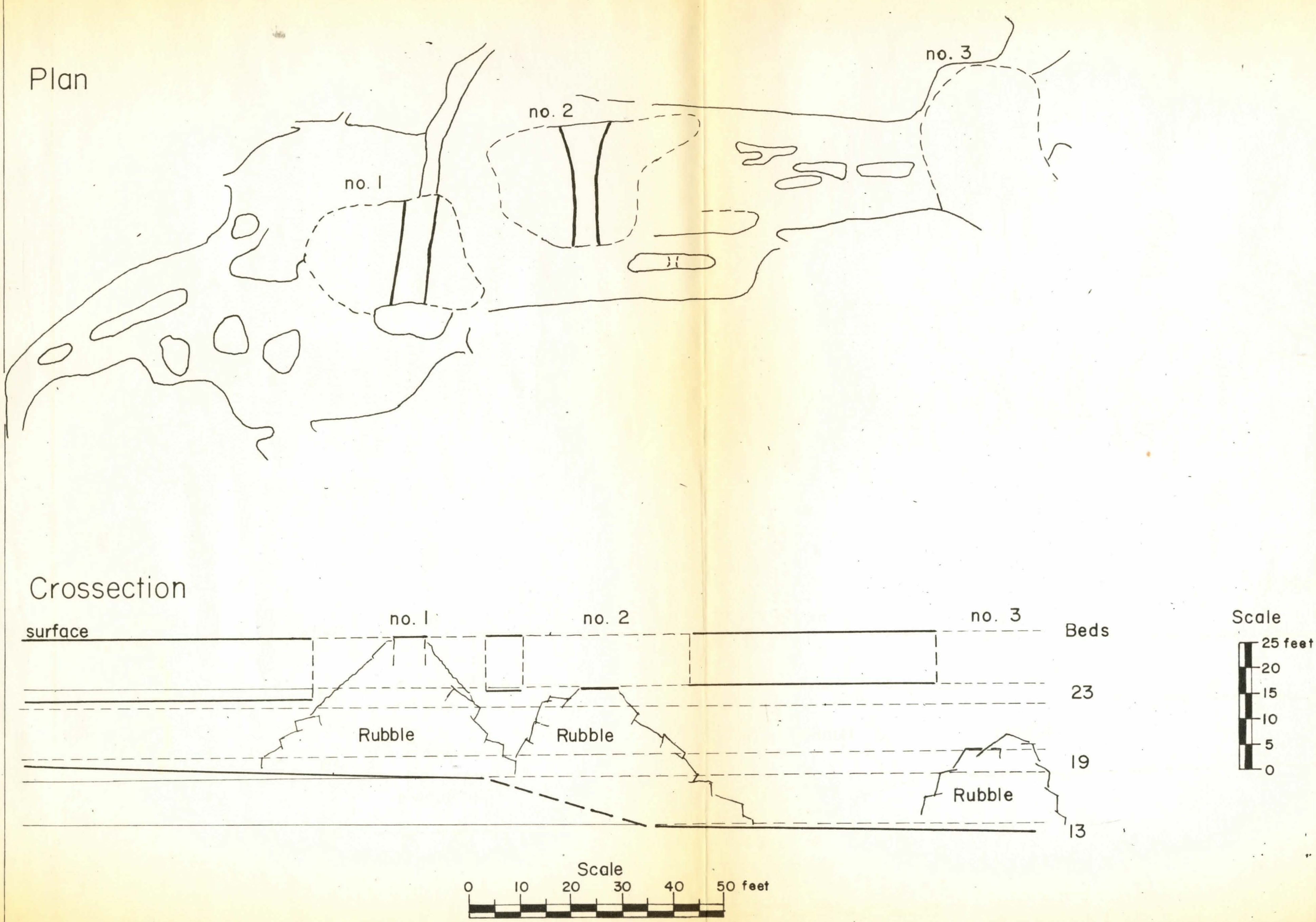


PLATE X: Karst Window No. 1, from inside the caves

PLATE XI: Collapse at Karst Window No. 2, from inside the caves

The control of jointing on the formation and deformation of the Bonnechere Caves has been thus clearly indicated from field data. However, the small size of the body of data has restricted the formulation of very strong postulates concerning the creation of the joints and their actual control on the cave formation.

TABLE NO. 1

JOINT BEARINGS

| Station | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|---|
| | 27° | 5° | 64° | 314° | 353° | 70° | 278° | 21° | 291° |
| | 37° | 58° | 71° | 48° | 355° | 344° | 288° | 11° | 294° |
| | 41° | 74° | 65° | 74° | 78° | 77° | 338° | 15° | 291° |
| | 333° | 68° | 67° | 337° | 347° | 76° | 78° | 282° | 25° |
| | 337° | 78° | 67° | | 74° | 13° | 17° | 286° | 27° |
| | | | 65° | | 80° | 85° | | 273° | 21° |
| | | | 61° | | 73° | | | | 27° |
| | | | | | 82° | | | | |

TABLE NO. 2

ROSE DIAGRAM FIGURES

JOINTS

| Sectors | Number of Bearings | Percentage of Total |
|---|---|---|
| 270° - 279° | 3 | 5% |
| 280° - 289° | 3 | 5% |
| 290° - 299° | 3 | 5% |
| 300° - 309° | 0 | 0 |
| 310° - 319° | 1 | 1.7% |
| 320° - 329° | 0 | 0 |
| 330° - 339° | 4 | 6.8° |
| 340° - 349° | 2 | 3.4% |
| 350° - 359° | 3 | 5% |
| 0° - 9° | 1 | 1.7% |
| 10° - 19° | 6 | 10.2% |
| 20° - 29° | 7 | 11.9° |
| 30° - 39° | 1 | 1.7% |
| 40° - 49° | 2 | 3.4% |
| 50° - 59° | 1 | 1.7% |
| 60° - 69° | 7 | 11.9% |
| 70° - 79° | 12 | 20.3% |
| 80° - 90° | 3 | 5% |

TABLE NO. 3

JOINT BEARINGS AND CAVE BEARINGS IN EACH BED

| Bed 23 Joints | Bed 19 Joints | Bed 15 Joints | Bed 13 Joints | Bed 1 Joints |
|---|---|---|---|---|
| 278° | 27° | 21° | 355° | 344° |
| 288° | 37° | 11° | 353° | 77° |
| 17° | 31° | 15° | 347° | 76° |
| 338° | 5° | 282° | 78° | 13° |
| 78° | 58° | 285° | 74° | 85° |
| | 74° | 273° | 80° | 358° |
| | 68° | | 73° | 19° |
| | 73° | | 82° | 17.5° |
| | 337° | | | 279° |
| | 333° | | | 20° |
| | 64° | | | 25° |
| | 71° | | | 81° |
| | 65° | | | |
| | 67° | | | |
| | 67° | | | |
| | 65° | | | |
| | 61° | | | |

TABLE NO. 4

| Caves | Caves | Caves | Caves | Caves |
|---|---|---|---|---|
| 67° | 271° | 271° | 74° | 58° |
| 57° | 86° | 276° | 32° | |
| 66° | 81° | 89° | 85° | |
| | 85° | 34° | 38° | |
| | 85° | 3° | 24° | |
| | | 86° | 21° | |
| | | 28° | | |
| | | 54° | | |
| | | 85° | | |
| | | 81° | | |
| | | 85° | | |
| | | 24° | | |
| | | 90° | | |

TABLE NO. 5

CAVE BEARINGS

| Larger Passage | Commercial Passage |
|---|---|
| 57° | 34° |
| 66° | 3° |
| 88° | 89° |
| 67° | 54° |
| 16° | 24° |
| 85° | 90° |
| 85° | 58° |
| 271° | 74° |
| 81° | 32° |
| 86° | 28° |
| 81° | 88° |
| | 276° |
| | 85° |
| | 21° |
| | 58° |

TABLE NO. 6

ROSE DIAGRAM FIGURES

CAVES

| Sectors | Number of Bearings | Percentage of Total |
| --- | --- | --- |
| 270°-279° | 2 | 7.1% |
| 280°-289° | 0 | 0% |
| 290°-299° | 0 | 0% |
| 300°-309° | 0 | 0% |
| 310°-319° | 0 | 0% |
| 320°-329° | 0 | 0% |
| 330°-339° | 0 | 0% |
| 340°-349° | 0 | 0% |
| 350°-359° | 0 | 0% |
| 0%-9° | 1 | 3.5% |
| 10°-19° | 1 | 3.5% |
| 20°-29° | 4 | 14.2% |
| 30°-39° | 2 | 7.1% |
| 40°-49° | 2 | 7.1% |
| 50°-59° | 2 | 7.1% |
| 60°-69° | 2 | 7.1% |
| 70°-79° | 1 | 3.5% |
| 80°-89° | 9 | 32.1% |

## CHAPTER VIII

## SCALLOPS

### Introduction

Scallops or flutes are shallow, oval depressions that form patterns on the walls of caves; these are best shown by means of a sketch (Fig. 14). Many scallops are assymetric along their main axis, having a steeper upstream face, thus direction of formative flow can be determined in a passage abandoned by the former stream. The steeper face is on the upstream side of the scallop (Fig. 14).

The concensus of thought on scallops, expressed in a few qualitative papers, is that scallops are formed by solution of rock, usually limestone, by the action of turbulent water. The eddies or vortices in turbulent flow result in the solution of the limestone into the oval, saucer-shaped depressions. Bretz claims that turbulence depends on the velocity of flow in the channel and the roughness of the channel's sides,[19] therefore these factors probably also control the size of scallops the most. T. D. Ford (1964), from some qualitative observations, contended that flow markings (including scallops) are caused by high velocity, highly turbulent, sand-loaded water.[20] He observed a cave floor covered with sand and gravel and postulated that turbulent

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[19] Bretz, J. Harlen, 1942; Vadose and Phreatic Features of Limestone Caverns; J. of Geology, L; pp. 675-811

[20] Ford, T. D.; Flow Markings; C.R.G. of Grt. Britain Newsletter; Number 90/91, June 1964, pp. 11-12.

flow would have carried the sand in load, and corraded the cave walls. However, he believes that solution is dominant in slow water flow and that there must be a correlation between the potential of the flow to carry material in load--thus the velocity of the flow--and the size of the scallops. He also asserts the importance of differences in rock texture on scallop formation.

J. Eyre (1964) observed one small section of a cave wall in a location of former turbulent flow, and concluded from flow marks that strong current produced areas of small scalloping and slower current produced medium sized cockling.[21] R. E. Davies (1963) hypothesizes, after a conversation with a noted expert on laminar and turbulent flow, that vortices are caused to start by some local discontinuity in the rock and first form tiny scallops.[22] These scallops grow largwr as the vortex, of constant size, eroded further into the limestone; thus larger scallops are older and smaller scallops younger. E. A. Glennie[23] (1963) contends that during times of flood, flow is very fast in cave passages and very small scallops develop. Decreased turbulence leads to an increase in the size and regularity of the scallops. Finally, he believes, that if the water flows in a laminar fashion, having a much lower velocity, the scallops will enlarge and coalesce.

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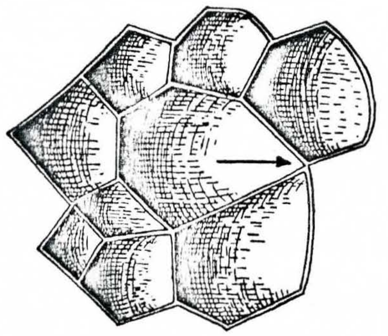
[21] Eyre, J.; Flow Markings in South-East Passage, Gaping Gill; C.R.G. of Grt. Britain Newsletter; number 90191, June 1964, pp. 14.

[22] Davies, R. E.; Flow Markings (1); C.R.G. of Grt. Britain Newsletter; number 87; March 1963; pp. 8-9.

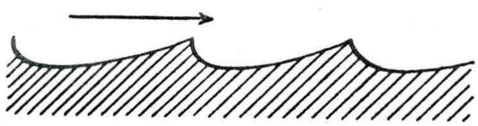
[23] Glennie, E.A.; Flow Markings (2); C.R.G. of Grt. Britain Newsletter; number 81, March 1963; pp. 9.

Fig. 14 THE FORM OF SCALLOPS

( The arrows indicate the downstream direction of former water flow )



(a) The plan of a group of scallops: note the elongation downstream



(b) The crossection of a group of scallops: note the assymetry

after G.T.Warwick

Thus the most popular speculations are that scallop size varies inversely with velocity of water in cave passages; and that the texture of the rock controls the amount of turbulence along the cave wall, and scallop size. Thus this study of scallops was aimed at substantiating or refuting the hypotheses that scallop size varies inversely with water velocity, and that rock texture controls the size of scallops.

Dr. D. C. Ford told the author that he had rarely seen better sets of scallops than in the Bonnechere cave system, and that this would be an excellent site for detailed examination of this phenomenon. Since a large sample of scallop measurements had never been collected or quantitatively analysed, a major purpose of the entire research was, therefore, a scalop investigation. Because the author has a very limited background in the mechanics of flow, it is very difficult to arrive at any genetic conclusions, thus correlations between scallop size and other factors will be related, with a comment on the possible implications of each correlation.

Since the passages in which scallops are measured are relatively free of water, the velocities of the water which created the scallops must be ascertained from some index of these former velocities. Many complicating factors prevent any exact calculation of the velocity in any portion of the cave. Chezy's Equation for calculating the velocity of water flow in channel requires: the crossectional area of the channel, the wetted perimeter of the channel -- from these is derived the hydraulic radius, and the gradient of the channel. Because of the paraphreatic[24] situation which existed in the caves, with its water level oscillation,

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[24] Ford, D.C.; The Bonnechere Caves, Renfrew County, Ontario. A Note; Canadian Geographer, Vol. 3, 1961; pp. 22-25

it is very difficult to determine the water level at which the scallops were formed -- thus the exact crossectional area of the channel and its wetted perimeter cannot be ascertained. As a relative index of velocity the author simply took the complete crossectional area at each station since the shape of the passages measured were roughly the same -- greater height than width -- thus the hydraulic radii were proportional to the crossectional area.

The degrees of roughness on the channel walls are a function of the type of limestone. The main categories of massive and brashy limestone are the two obvious subdivisions of limestone; but using G. M. Kay's description of the section at the Fourth Chute[25] it was possible to subdivide the massive limestone into four categories. By using these different subdivisions it is possible to associate the differences in scallop sizes, occuring in the various rocks, to their texture. Textures were evaluated subjectively in the field.

In order to obtain a sample of scallop sizes which represent a significant range of passage crossections and lithology, the scallop sampling stations had to be systematically located. Twenty-eight stations were selected and at each station five scallops were measured from each bed that was exposed. Both the greatest length and greatest width of each scallop were measured to check for changes in the shape of the scallop. The stations are marked on Fig. 15. Measurements at each station are tabulated in the appendix. 371 scallops were measured.

The horizontal and vertical measurements are plotted separately

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[25] Kay, G. M.; Ottawa - Bonnechere Graben and Lake Ontario Homodine; Geol. Soc. Amer. Bull. 53, Jan. - June 1942; pp. 585-646.

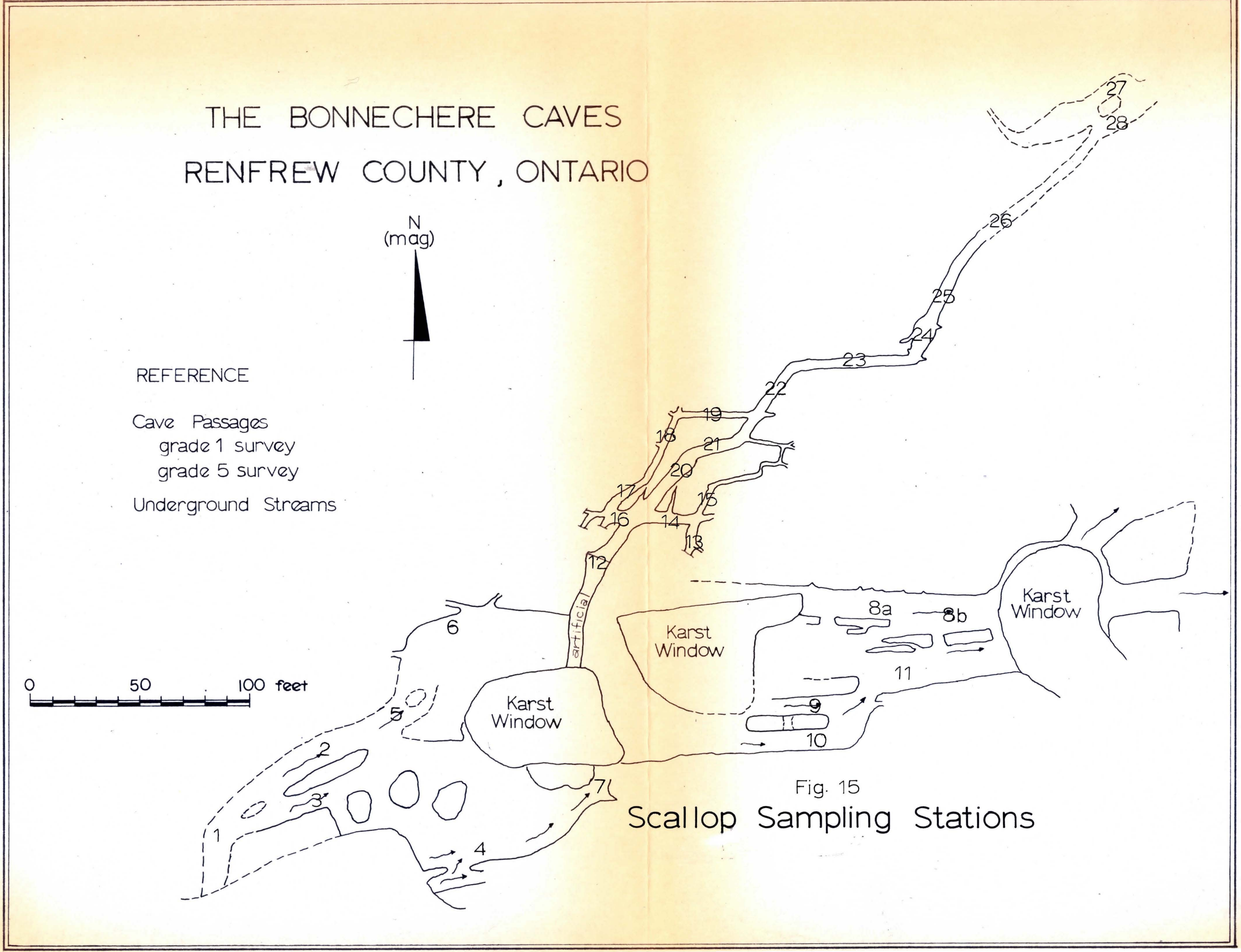



Fig. 15
Scallop Sampling Stations

on histograms, Figs. 16 and 17.

Both populations are quite normally distributed--showing slight positive skewness. At once the elongated shape of scallops in plan is realized in the .2 difference between the horizontal and vertical means. The closest approximation of the variance ($\hat{\sigma}^2$) of each population is relatively small (0.2209 and 0.2666). This could be interpreted as illustrating a relatively small range in water flow velocities in these caves or a small range of rock texture.

To find if the elongation of the scallops changed under different conditions, three samples of scallops from passages of different crossectional area and also three samples from different beds were examined. Scatter plots were constructed for each of the six samples (Fig. 18 and Fig. 19).

A mean regression line was drawn through each scatter plot by eye. These regression lines were examined visually (superimposing them on one another) and conclusions were drawn from their relationships.

Scallops were examined from the following three ranges of passage crossectional area: 10 to 15 sq. ft.; 30 to 40 sq. ft; and 161 to 177 sq. ft. The results, as can be seen from Fig. 18 have the regression lines steepening in slope gradually from the group 10 to 15 sq. ft. to the group 161 to 177 sq. ft. This indicates that the vertical axis of the scallop increases directly with crossectional area and thus with water velocity. Scallops in smaller passages would be expected to be more assymetrical in plan than those in larger passages. This would lead to the conclusion that the eddies in turbulent flow become less elongated with an increase in velocity.

Fig. 16 HISTOGRAM FOR SCALLOP VERTICAL MEASUREMENTS

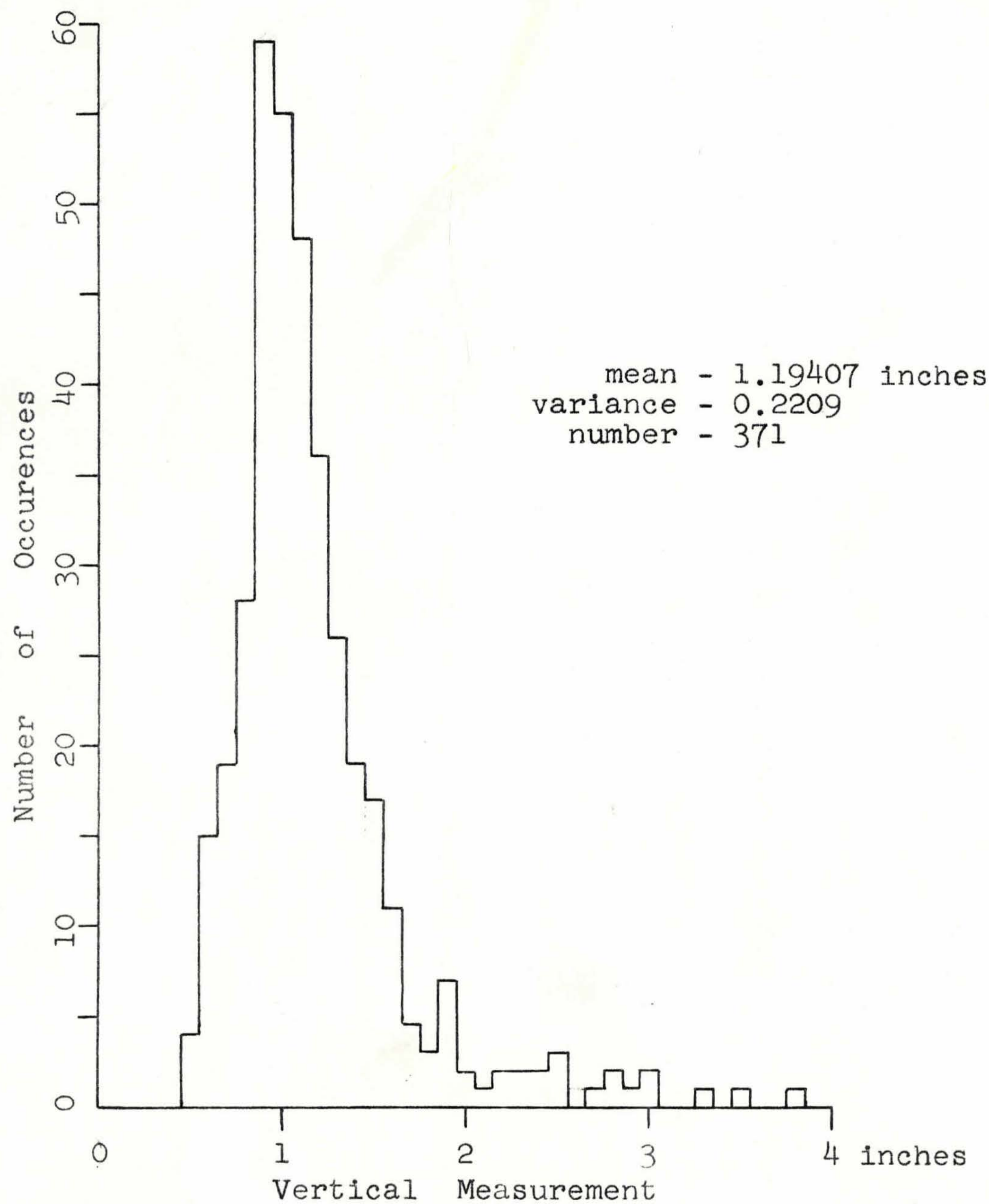


Fig. 17: HISTOGRAM FOR SCALLOP HORIZONTAL MEASUREMENTS

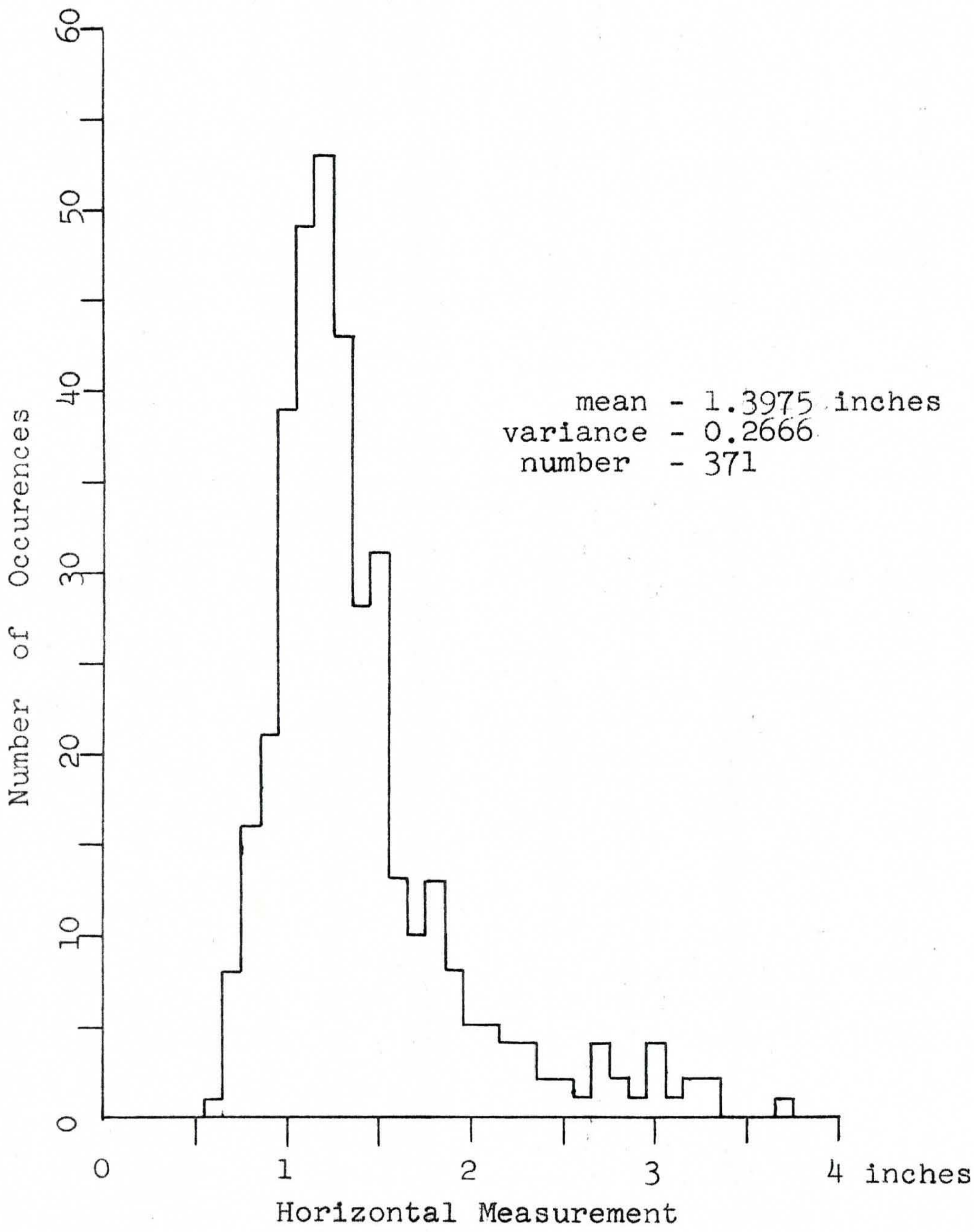
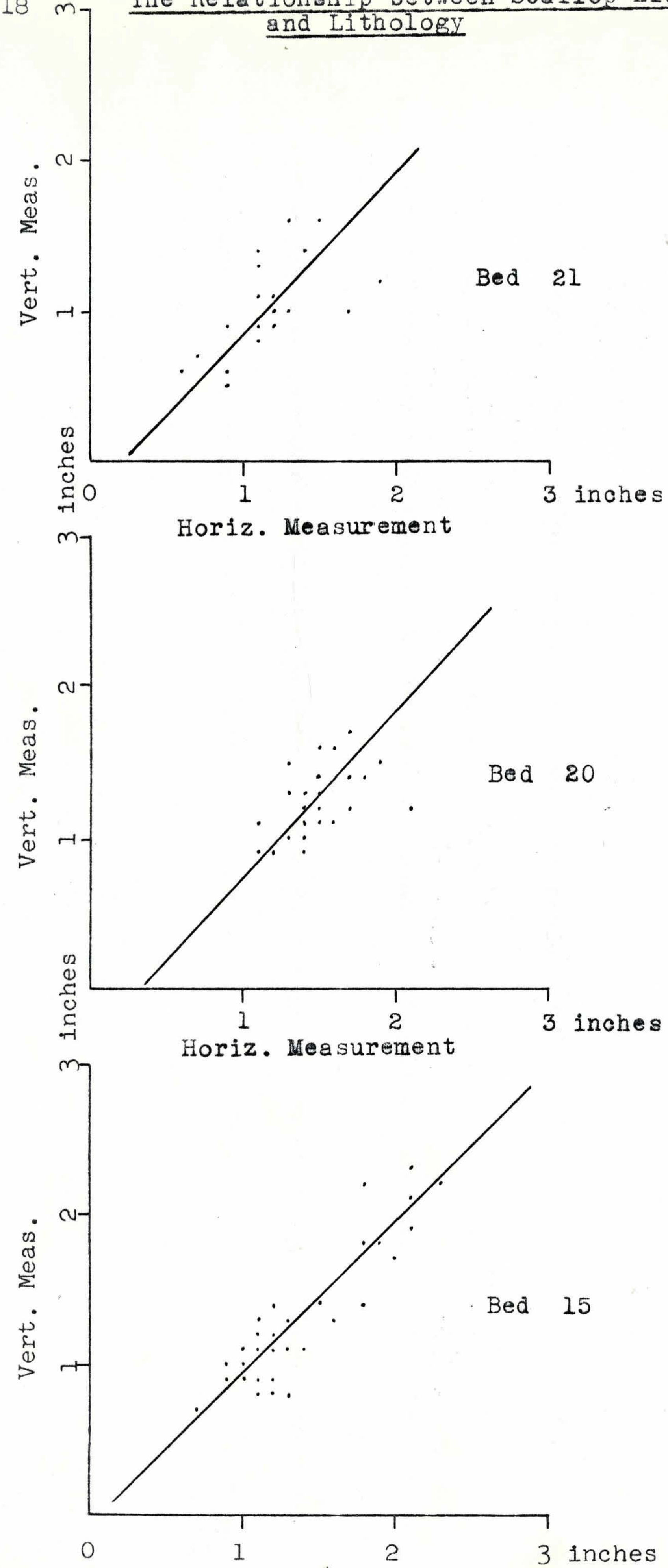


Fig. 18 The Relationship between Scallop Elongation and Lithology



To determine whether or not the texture of limestone would affect the elongation of the scallop plan, samples of scallops from three different beds were taken. The three beds with their lithological characteristics are: Bed 15 -- dark brown massive limestone; Bed 20 -- brashy, gray, buff-weathering limestone; and Bed 21 -- massive, gray, buff-weathering limestone. The three regression lines for these beds were almost identical in slope; thus it could be interpreted that the assymetry of the scallop plan does not change with rock texture.

Since scallops are developed by eddies in the turbulent flow in a cave passage, the horizontal measurement of the scallops will most reflect any differences in water flow, velocity in the caves, since eddy size varies with water velocity. Since eddy development also depends on the roughness of the cave walls, the horizontal measurement of the scallop will reflect also changes in roughness. Thus in the following examination of scallops, correlating their sizes with differences in lithology and crossectional area, only the horizontal measurement of the scallops will be considered.

In order to determine whether or not scallop size varies with the texture of limestone the scallops that occurred in limestones of different texture were examined. The first obvious subdivision is between massive and brashy limestone; therefore the scallops that occurred in massive and brashy limestone were plotted on histograms (Fig. 20). A two-tailed t test was applied to these two populations and a t value of 2.67 was calculated. This gave a significant level of .995, which indicates that the populations are significantly different. The mean

Fig. 19 <u>The Relation between Scallop Elongation and Passage Crossectional Area</u>

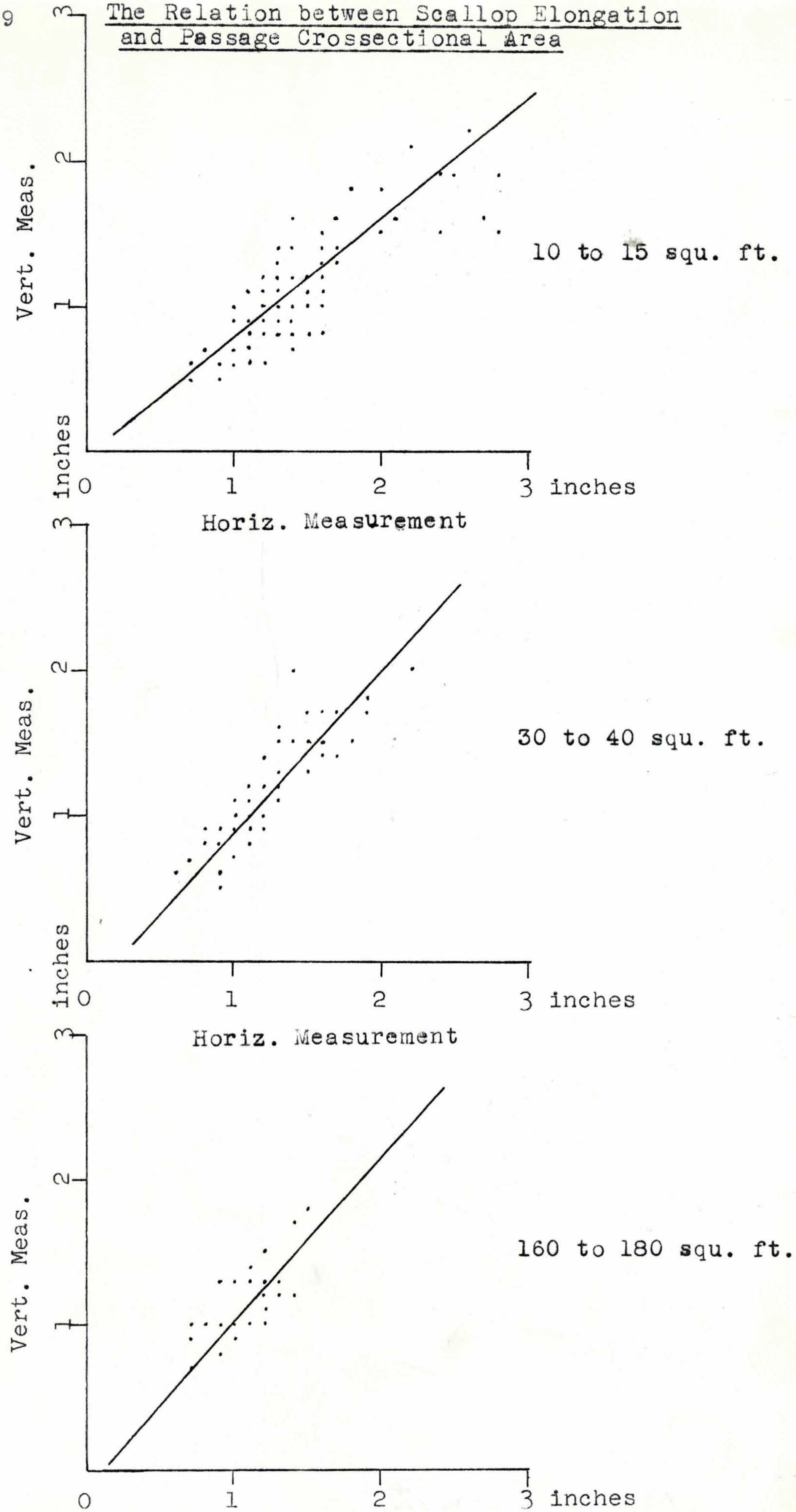
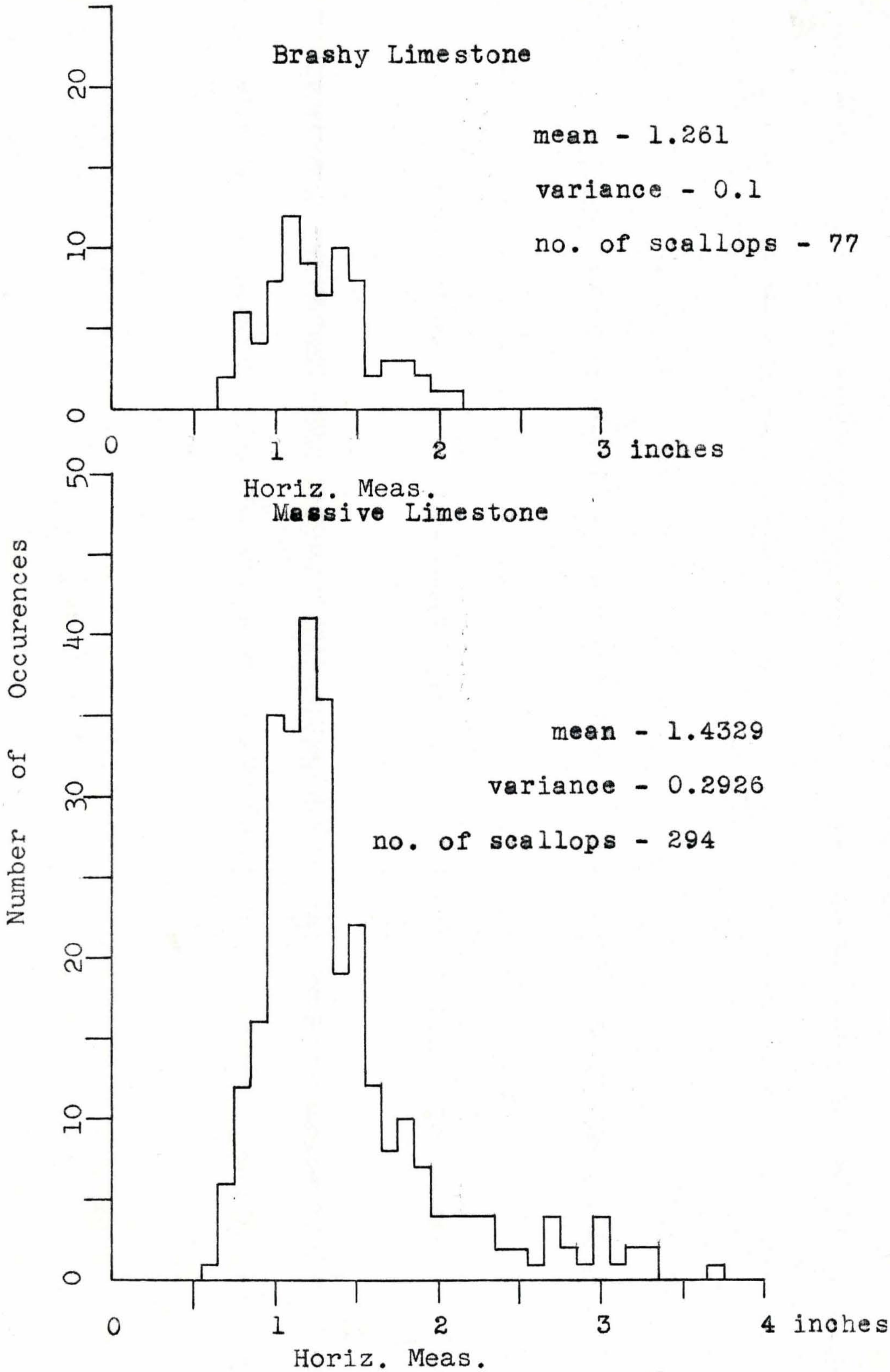


Fig. 20: HISTOGRAMS OF SCALLOPS IN MASSIVE AND BRASHY LIMESTONE



of the massive limestone scallop is .1719 of an inch greater than the mean of brashy limestone: this indicates that the rougher textured brashy limestone -- broken by bedding planes -- causes smaller scallops to be formed. It could be interpreted from this that the rougher the rock, the greater the turbulence in the flow along the wall surface -- and the smaller the eddies.

To further test this interpretation, the massive beds were subdivided into four types. The scallops in each type are plotted separately on histograms (Fig. 21). The means and closest approximations of the variances were calculated for each of the histograms and two-tailed "t" tests were used between the four populations. The results are:

TABLE NO. 7

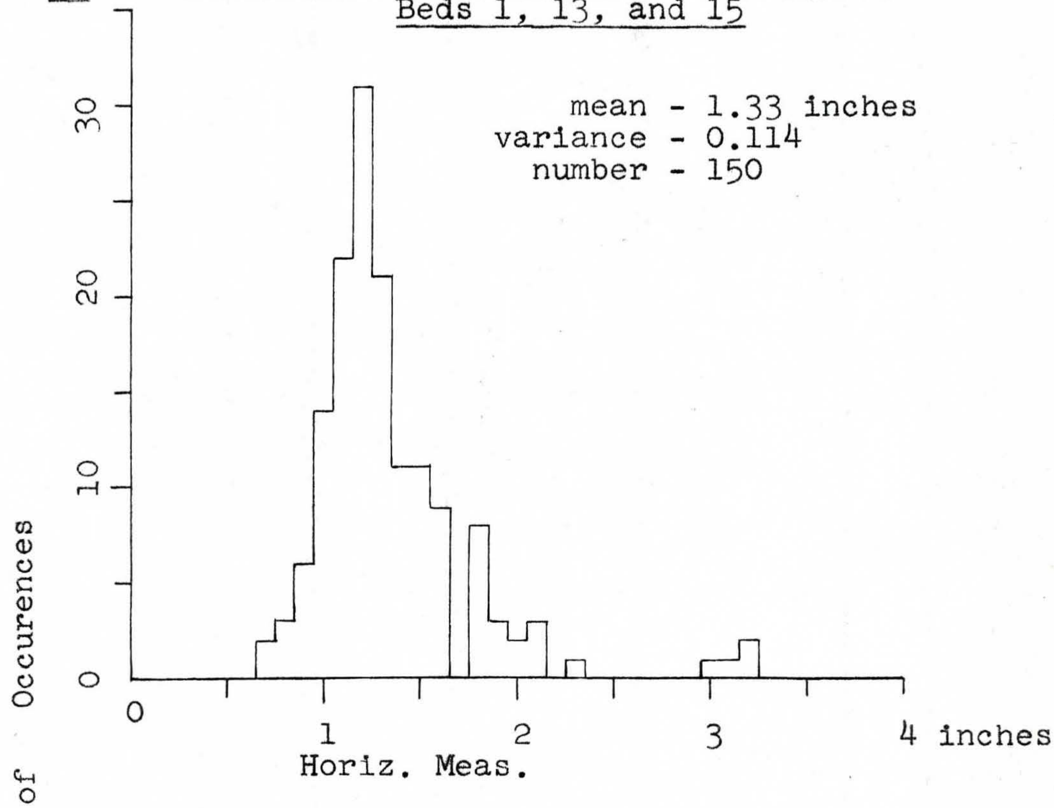
| Populations | t value | degrees of freddom | Level of Significance |
|---|---|---|---|
| 1 vs 2 | 4.09 | 203 | .999 |
| 1 vs 3 | .434 | 190 | less than .8 (off the t scale) |
| 1 vs 4 | 2.24 | 168 | .975 |
| 2 vs 3 | 3.608 | 95 | .999 |
| 2 vs 4 | 4.8 | 73 | .999 |
| 3 vs 4 | 2.22 | 60 | .975 |

The populations that were not significantly different are in limestone of medium texture. All the other combinations of populations differ significantly. Particularly notable is the occurrence of the lowest mean in the population of scallops in the coarsest limestone, no. 4, and the highest mean in the scallops which occur in the finest textured limestone,

HISTOGRAMS OF HORIZONTAL SCALLOP MEASUREMENTS IN FOUR

Fig. 21 DIFFERENT KINDS OF MASSIVE LIMESTONE ( 2 PAGES )

1. Dark Brown Limestone : Medium Texture
Beds 1, 13, and 15




2. White, Sublithographic Limestone : Fine Texture Beds 17 and 19

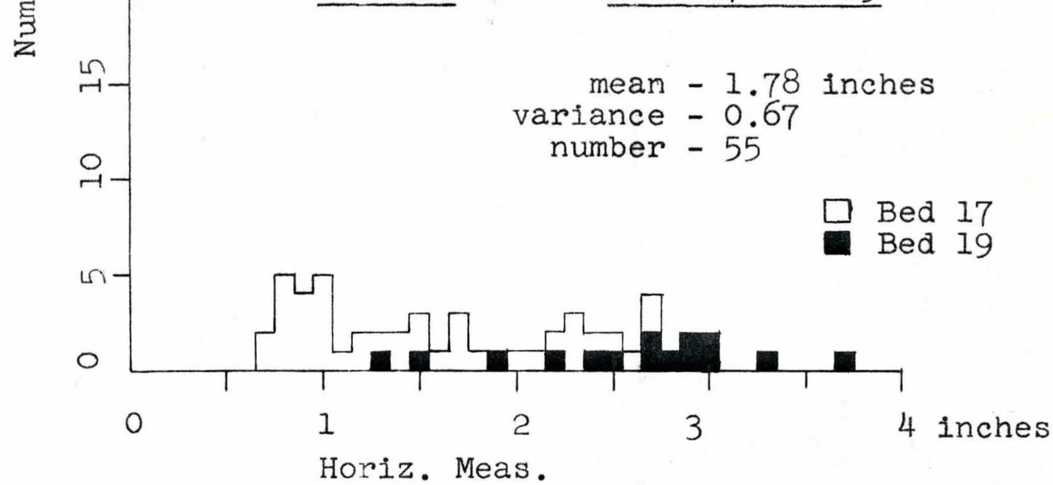


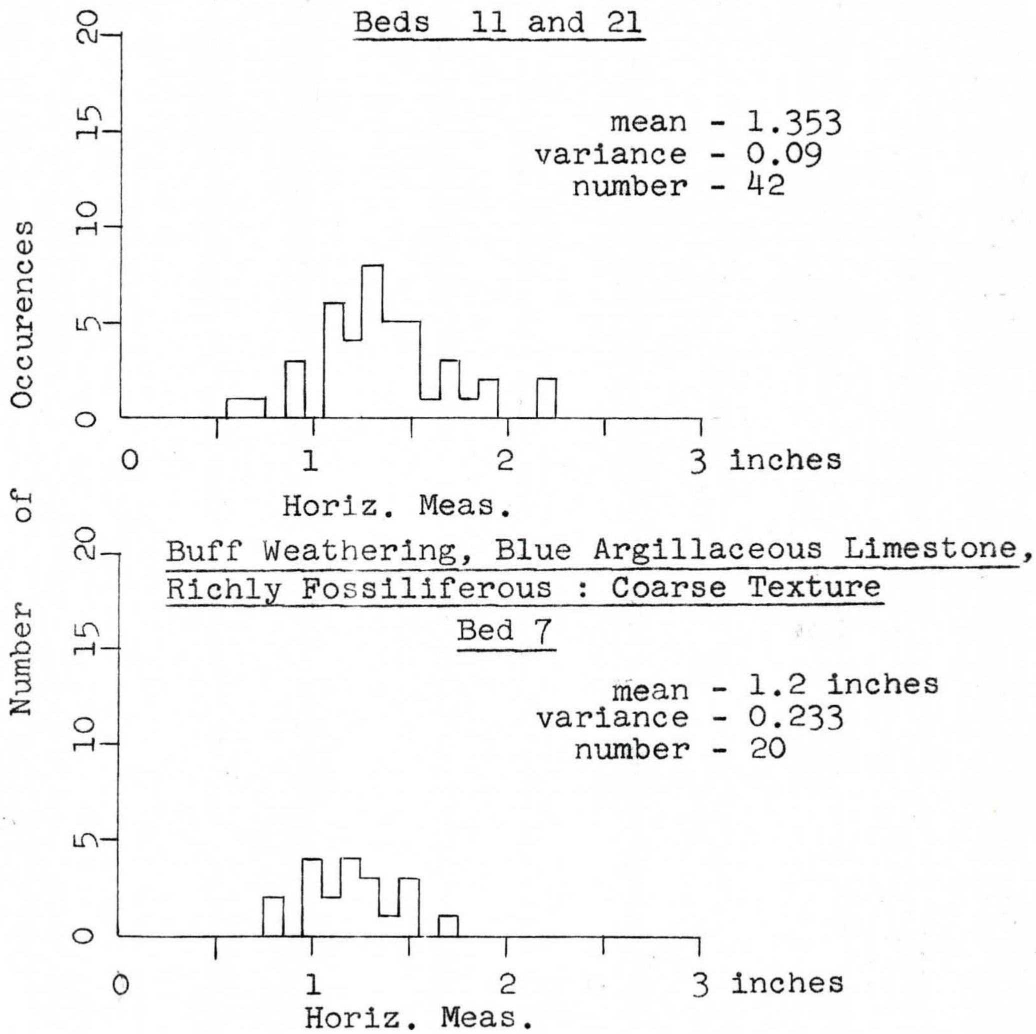
Fig. 21 (cont'd)

3. <u>Buff Weathering, Gray Limestone : Medium Texture</u>

<u>Beds 11 and 21</u>

4. <u>Buff Weathering, Blue Argillaceous Limestone, Richly Fossiliferous : Coarse Texture</u>

<u>Bed 7</u>



no. 2. It can be interpreted from this that roughness of the limestone cave passage walls has a strong effect on scallop size -- it becomes larger as the texture of the wall becomes finer. This substantiates the contrast of massive and brashy limestones. The only drawback in this procedure is the very high variance in the no. 2 limestone, due to the differences between no. 19 bed and no. 17 bed. No. 19 bed has very large scallop sizes and when observed in the field seemed to be the finest textured bed in the whole section. Kay's groupings are quite generalized, and there may be a significant difference in texture between the two beds in his group of white sublithographic limestone.

These findings concerning scallop size and passage wall roughness give a larger role to rock texture than was expected.[26] Consistent significant correlations between texture and scallop size lead to the conclusion that the degree turbulent flow varies directly with coarseness, and the size of eddy created varies inversely with coarseness.

In filled passages of similar gradient it is presumed that the bigger the passage, the faster the flow. Because the role of texture in the creation of scallops has been clearly shown, the role of water velocity would seem to be best shown if only those scallops which occur in one massive limestone type are considered. As the dark brown limestone, no. 1, contains the greatest number of scallop measurements of the massive types, it population of scallop measurements was subdivided into four ranges of crossectional area. These are as follows: 1, 5 square ft; 2, 11½ to 17½ square feet; 3, 30 to 54 square feet; and 4, 162 to 176½ square feet. The scallop measurements in each group were plotted on four histograms, and the means and closest approximations of the variances of each are noted on the appropriate histograms, (Fig. 22). Two-tailed "t" tests were applied to the various combinations of the populations, and these are shown on Table No. 8

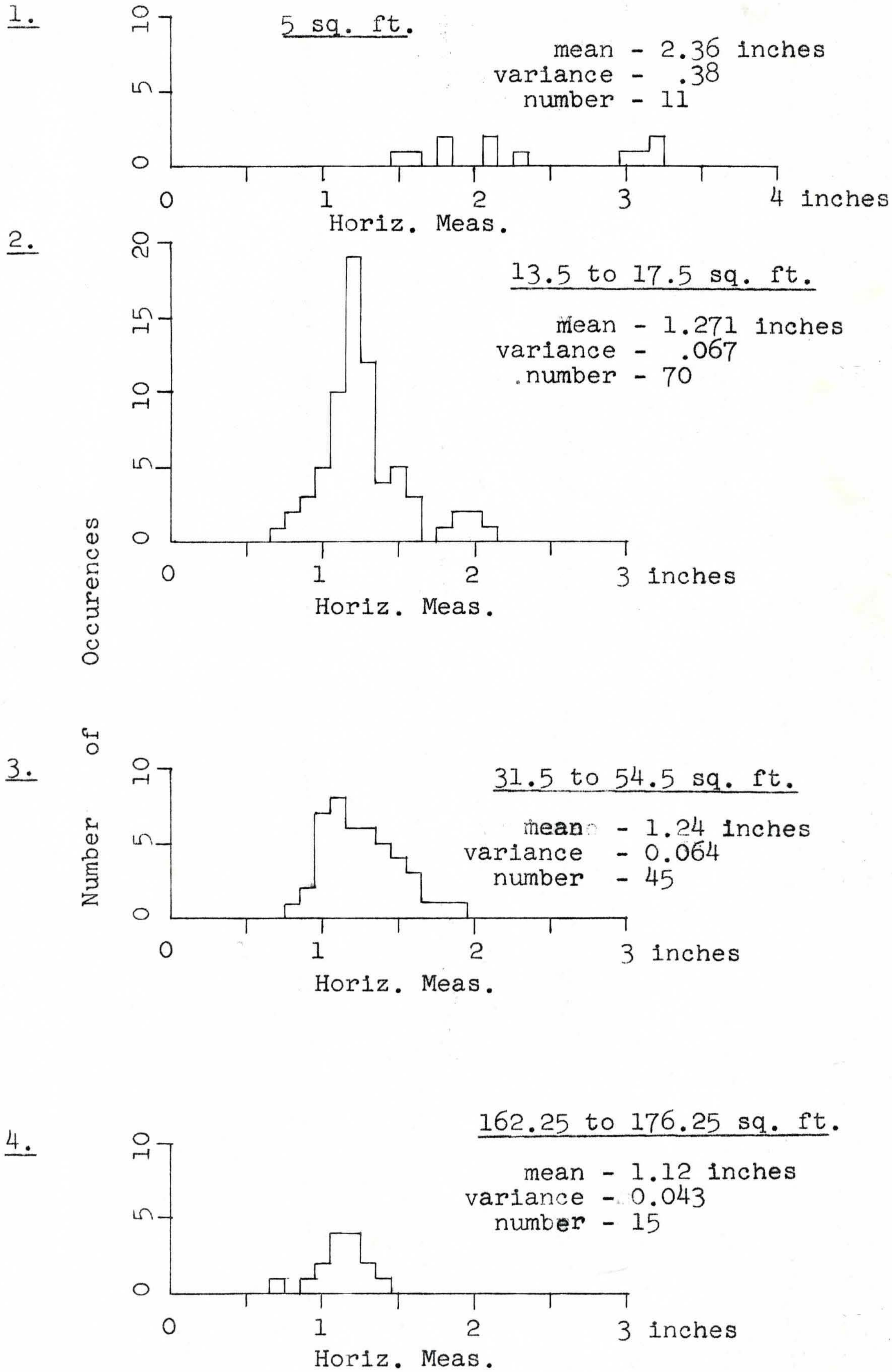
TABLE NO. 8

| Populations | t value | degrees of freedom | Level of Significance |
|---|---|---|---|
| 1 vs 2 | 5.74 | 78 | .999 |
| 1 vs 3 | 5.63 | 54 | .999 |
| 1 vs 4 | 6.2 | 24 | .999 |
| 2 vs 3 | .625 | 113 | less than .8 (off the t scale) |
| 2 vs 4 | 2.78 | 84 | .995 |
| 3 vs 4 | 2.07 | 58 | .975 |

As can be seen from Table 8 , only the means between populations 2 and 3 are not significantly different. The differences between the other means have very high levels of significance -- .975 to .999. There is a strong correlation between the means of scallop size for the populations, and the range of crossectional area which they represent. Mean scallop size varies inversely with crossectional area: the highest mean is in the group of 5 square feet crossectional areas, and the smallest mean occurs in the population of the 162¼ to 179½ range of crossectional areas. The other two means also follow this pattern; but the difference between them is not significant.

It can be concluded that scallop sizes probably vary inversely with water velocity. This would lead to the postulation that the eddies which occur along the wall of a cave passage become smaller as the velocity

Fig. 22: HISTOGRAMS OF HORIZONTAL SCALLOP MEASUREMENTS IN BEDS 15 & 13 FOR DIFFERENT RANGES OF CROSSECTIONAL AREA



of flow increases. However, because of the limitations of crossectional area as an index of flow velocity, the firmest conclusions cannot be drawn.

The results of this study of scallops substantiates many of the hypotheses forwarded by the authors mentioned earlier in the chapter. The important roles of water velocity (Bretz) and rock texture (T.D.Ford) are shown clearly by the correlations arrived at in this study. Also the relationship between water velocity and scallop size, i.e. scallop size varies inversely with water velocity (Eyre and Glennie) has been reinforced from the findings here. The strong control of time as hypothesized by Davies cannot be tested; but in view of the strong correlations found between scallop size and factors other than time, the role of time may be considered minor.

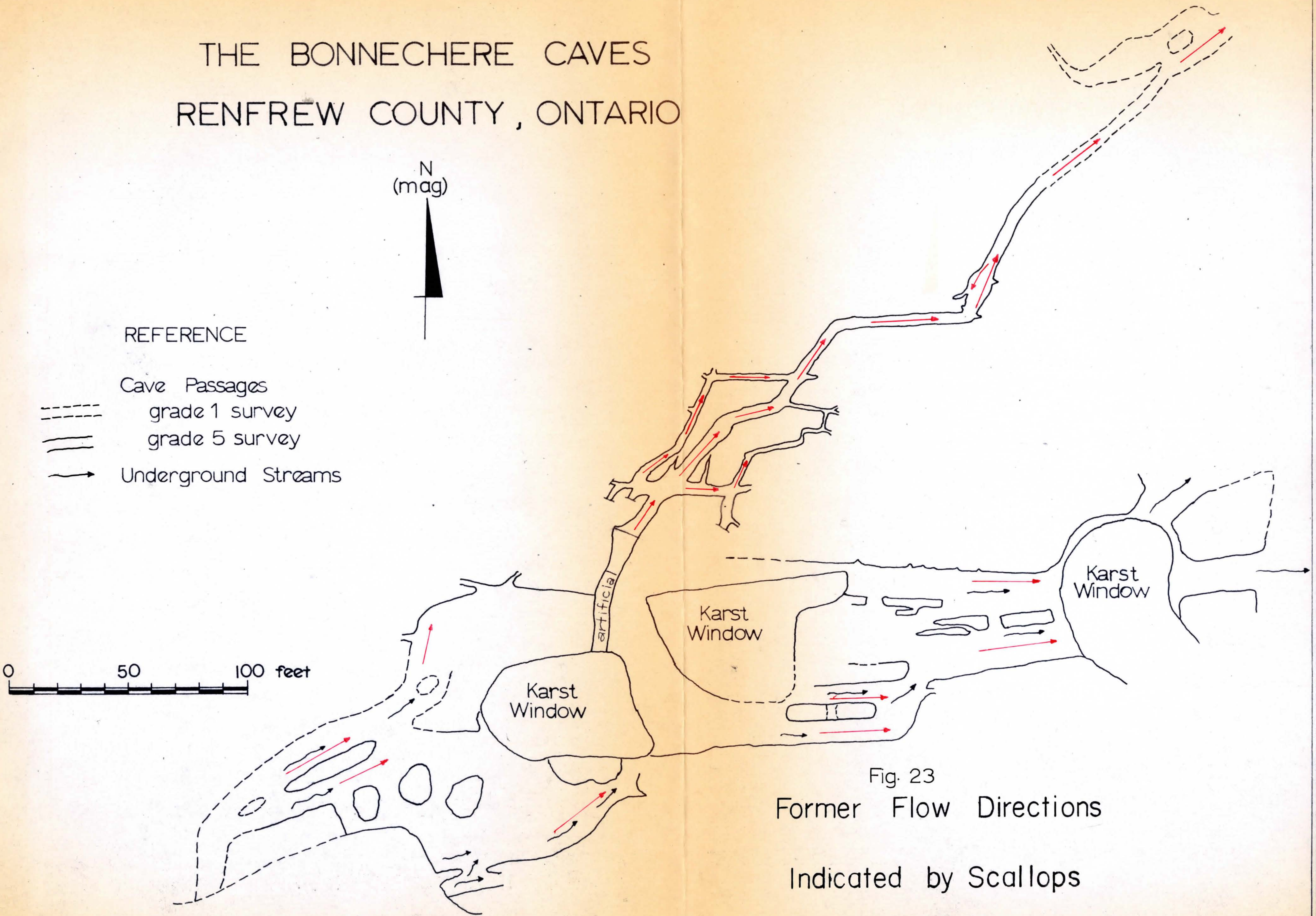



Fig. 23
Former Flow Directions
Indicated by Scallops

## CHAPTER VIII

## CONCLUSION

The Bonnechere Caves have been discussed in detail with reference to each chapter to a specific variable which controlled their formation. Specific conclusions have been stated at the end of each chapter, and this general conclusion serves to summarize the findings in this page.

The strong control of lithology on the four levels of the Fourth Chute of the Bonnechere River has been clearly shown, confirming the observations of Ford[26] which were illustrated by Ongley[27]. The lithological control on the profiles of the caves and the crossectional shapes of the larger passage has been shown, but the strong control of lithology on the crossections of the commercial passage, as stated by Ongley, has been refuted--confirming the ideas of Ford of boring by Waters in a paraphreatic situation shaping the passages.

The jointing in the limestone terrace of the Fourth Chute has been discussed in relation to tectonic movements in the immediate area, showing that both tension and shear jointing have occurred. The control of jointing on the caves has been demonstrated, substantiating the observations of Ford and Ongley. However, the idea of strong joint control on cave formation at different levels, as ventured by Ongley does not seem to show strongly in the data collected by the author.

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[26] Ford, D.C.; The Bonnechere Caves, Renfrew County, Ontario: A Note; <u>Canadian Geographer</u>, Vol. 3, 1961; pp. 23.

[27] Ongley, E.D.; <u>A Study of Caves in Southern Ontario</u>; Unpublished B.A. Thesis, University of Toronto; 1965.

The findings of the investigation of scallops in the Bonnechere Caves is undoubtedly the most significant section of this paper. The statistical expression of the scallop measurements as controlled by certain variables has made some strong indications as to the nature of their formation. This empirical study has been given some quantitative substantiation to the purely qualitative observations of T. D. Ford and E. A. Glennie. The study of scallops under more ideal conditions, i.e. where the variables are more constant, could lead to the establishment of scallops as an index of the water velocity in a cave at the time of its development.

The two cycle theory of cave development of W. M. Davis fits the Bonnechere Caves very well in that formation was primarily phreatic, with the river at a higher level than at present. The downcutting of the river resulted in a gradual drainage of the larger passage, leaving only a small stream flowing in it, with the resulting prolific vadose collapse and small stalactite formation. The commercial caves were still primarily phreatic when they were pumped out by Mr. Tom Woodward.

The relatively small vertical range of the caves substantiates the Summerton theory of cave formation. The commercial caves exhibit a phreatic "loop", indicating that water flowed below the water table, but the largest development was near the water table, since the vertical range of the commercial passage is only about 20 feet. The existence of a passage showing vadose collapse, at the downstream end of the commercial passage illustrates the development hypothesized by Rhoades and Sinacori.

This illustration of three of the theories of cave formation in the Bonnechere Caves is an example of the tremendous complexity of the process of cave formation. Every cave is unique in its genesis and formation, since the variables that cause and control cave formation can vary considerably in their intrinsic nature and relative role in formation from cave to cave. Any hypothesis attempting to explain the formation of caves in detail, can only hope to be able to incorporate a fraction of the caves that exist.

# APPENDIX I

## FIELD OBSERVATIONS OF SURFICIAL MATERIAL

Stations:

1. - very angular limestone fragments; 1/2" to 1" in size (some granitic sand here; but it was washed down from material used in the construction of the gravel road).

2. - angular limestone fragments; 1/4" to 1" in size.

3. - angular limestone fragments; from very fine to 3" in size.
   - fine granitic sand.

4. - limestone boulders about 3' in size; very angular 3" to 6" limestone fragments, about.

5. - limestone boulders about 3' in size, very angular 3" to 6" limestone fragments, about.

6. - a cluster of 3' - 4' granite boulders, and some about 1'
   - 4" to 6" angular limestone fragments.

7. - coarse granitic sand and 4" angular limestone fragments
   - this sand disappears towards the river.

8. - 4" angular limestone fragments; find granitic sand on the parking lot surface - could be washed or blown off upper surface or road.

9. - 1" angular limestone fragments.

10. - 6" to 1' angular limestone fragments, grantic boulders 1 in diameter, granitic sand.

11. - odd 1' granitic boulder; very angular 1" limestone fragments, angular granitic stones, about 1" in diameter

12. - one very large granitic boulder; some 4" limestone fragments.

13. - granitic boulders, 1' in size; very coarse granitic sand, 1" subangular and angular granitic stones.

16. - some very large granitic boulders, about 4' x 3' and some smaller ones 1' or 2' in diameter; limestone fragments of about 6".

17. - coarse, bouldery till exposed in the road cut here.

18. - granitic boulders, 4' x 3' and about 1' on limestone floor; very large limestone slabs on the west side of the tributary gorge.

19. - large limestone boulders; and one granitic boulder on bare limestone.

20. - 1" to 5" angular limestone fragments, and one granitic boulder.

21. - small slabs of limestone, 1' - 2', and 1" limestone fragments.

22. - 1" limestone fragments, very angular

23. - 1" limestone fragments scattered over a field of bare limestones.

APPENDIX II

SCALLOP MEASUREMENTS

| Station | Crossectional Area sq. feet | Bed No. | Horizontal Meas. (inches) | Vertical Meas. (inches) |
|---|---|---|---|---|
| 1 | | 21 | 1.3 | 1.6 |
| | | | 1.4 | 1.4 |
| | | | 1.1 | 1.4 |
| | | | 1.1 | 1.3 |
| | | | 1.1 | 1.1 |
| | | | 1.1 | 1.3 |
| | | | 1.9 | 1.2 |
| | | | 1.7 | 1.0 |
| | | | 1.7 | 1.0 |
| | | | 1.1 | 0.8 |
| | | | 1.1 | 0.9 |
| | | | 1.5 | 1.6 |
| 2 | 71 | 20 | 1.5 | 1.4 |
| | | | 1.5 | 1.6 |
| | | | 1.4 | 1.2 |
| | | | 1.6 | 1.6 |
| | | | 1.3 | 1.3 |
| | | | 1.4 | 1.1 |
| | | | 1.5 | 1.3 |
| | | | 1.1 | 1.5 |
| | | | 1.7 | 1.7 |
| | | 23 | 0.9 | 1.0 |
| | | | 1.0 | 0.9 |
| | | | 1.1 | 1.1 |
| | | | .07 | .06 |
| | | | 1.0 | 1.0 |
| | | | 1.3 | 1.1 |
| | | | 1.9 | 0.9 |
| | | | 1.2 | 1.2 |
| | | | 1.3 | 0.9 |
| | | | 1.6 | 1.3 |
| 3 | 49½ | 20 | 1.7 | 1.2 |
| | | | 2.1 | 1.2 |
| | | | 1.4 | 0.9 |
| | | | 1.8 | 1.4 |
| | | | 1.9 | 1.5 |

| Station | Crossectional Area sq. feet | Bed No. | Horizontal Meas. (inches) | Vertical Meas. (inches) |
|---|---|---|---|---|
| 4 | 107½ | 23 | 1.0 | 1.1 |
| | | | 0.8 | 0.8 |
| | | | 1.1 | 0.9 |
| | | | 1.0 | 0.8 |
| | | | 1.0 | 0.7 |
| | | | 1.0 | 0.9 |
| | | | 1.1 | 1.0 |
| | | | 1.1 | 0.7 |
| | | | 1.1 | 0.9 |
| | | | 1.1 | 1.0 |
| | | 19 | 3.0 | 2.9 |
| | | | 3.7 | 3.5 |
| | | | 2.4 | 2.4 |
| | | | 2.8 | 2.4 |
| | | | 3.3 | 3.3 |
| 5 | | 23 | 1.2 | 0.9 |
| | | | 1.2 | 1.1 |
| | | | 0.8 | 0.8 |
| | | | 0.9 | 0.8 |
| | | | 0.9 | 0.9 |
| | | 20 | 1.4 | 0.9 |
| | | | 1.5 | 1.2 |
| | | | 1.1 | 1.1 |
| | | | 1.6 | 1.1 |
| | | | 1.5 | 1.3 |
| 6 | | 23 | 3.3 | 3.8 |
| | | | 2.0 | 1.5 |
| | | | 3.0 | 2.8 |
| 7 | 59½ | 19 | 2.5 | 2.8 |
| | | | 2.8 | 2.5 |
| | | | 2.7 | 2.3 |
| | | | 3.0 | 3.0 |
| | | | 2.7 | 1.9 |
| 8(a) | 176½ | 17 | 0.8 | 1.0 |
| | | | 0.8 | 1.2 |
| | | | 1.2 | 0.9 |
| | | | 1.0 | 1.1 |
| | | | 0.9 | 1.1 |
| | | 15 | 0.7 | 0.7 |
| | | | 0.9 | 1.0 |
| | | | 1.1 | 0.9 |
| | | | 1.0 | 0.8 |
| | | | 1.2 | 1.0 |

| Station | Crossectional Area sq. feet | Bed No. | Horizontal Meas. (inches) | Vertical Meas. (inches) |
|---|---|---|---|---|
| 8(b) | 175 | 17 | 0.7 | 0.9 |
| | | | 0.7 | 1.0 |
| | | | 0.9 | 0.7 |
| | | | 0.9 | 1.2 |
| | | | 0.8 | 0.9 |
| | | 15 | 1.2 | 1.2 |
| | | | 1.4 | 1.1 |
| | | | 1.1 | 1.3 |
| | | | 1.3 | 1.2 |
| | | | 1.2 | 0.9 |
| 9 | 31¼ | 21 | 0.9 | 0.5 |
| | | | 0.9 | 0.6 |
| | | | 0.6 | 0.6 |
| | | | 0.7 | 0.7 |
| | | | 0.9 | 0.9 |
| | | 20 | 1.4 | 1.1 |
| | | | 1.1 | 0.9 |
| | | | 1.2 | 0.9 |
| | | | 1.4 | 1.0 |
| | | | 1.1 | 0.9 |
| 10 | 107½ | 21 | 1.2 | 0.9 |
| | | | 1.3 | 1.0 |
| | | | 1.2 | 1.1 |
| | | | 1.2 | 1.0 |
| | | | 1.3 | 1.1 |
| | | 20 | 1.3 | 1.5 |
| | | | 1.2 | 0.9 |
| | | | 1.3 | 1.0 |
| | | | 1.4 | 1.3 |
| | | | 1.7 | 1.4 |
| | | | 1.2 | 0.9 |
| | | | 1.3 | 1.0 |
| 11 | 162¼ | 17 | 1.0 | 1.2 |
| | | | 1.2 | 1.4 |
| | | | 1.5 | 1.7 |
| | | | 1.4 | 1.6 |
| | | | 1.1 | 1.3 |
| | | 15 | 1.2 | 1.2 |
| | | | 1.2 | 1.1 |
| | | | 1.3 | 1.1 |
| | | | 1.0 | 0.9 |
| | | | 1.1 | 1.2 |

| Station | Crossectional Area sq. feet | Bed No. | Horizontal Meas. (inches) | Vertical Meas. (inches) |
|---|---|---|---|---|
| 12 | 38¾ | 19 | 1.3 | 1.6 |
| | | | 1.5 | 1.5 |
| | | | 2.9 | 2.5 |
| | | | 2.2 | 1.8 |
| | | | 1.9 | 1.5 |
| | | 17 | 1.0 | 0.7 |
| | | | 0.8 | 0.8 |
| | | | 0.9 | 0.8 |
| | | | 0.8 | 0.8 |
| | | | 1.0 | 0.7 |
| | | 15 | 1.0 | 1.0 |
| | | | 1.0 | 1.0 |
| | | | 1.0 | 1.0 |
| | | | 0.9 | 0.9 |
| | | | 1.2 | 1.4 |
| | | 13 | 1.1 | 0.9 |
| | | | 1.5 | 1.1 |
| | | | 1.3 | 1.1 |
| | | | 1.1 | 1.0 |
| | | | 1.6 | 1.5 |
| 13 | 13½ | 15 | 1.3 | 1.6 |
| | | | 1.0 | 1.1 |
| | | | 1.1 | 1.1 |
| | | | 1.1 | 1.2 |
| | | | 1.1 | 1.0 |
| | | 15 | 1.8 | 1.4 |
| | | | 2.0 | 1.6 |
| | | | 1.9 | 1.8 |
| | | | 1.5 | 1.4 |
| | | | 2.1 | 2.1 |
| 14 | 13½ | 17 | 2.3 | 1.5 |
| | | | 2.5 | 2.2 |
| | | | 1.5 | 1.2 |
| | | | 1.8 | 1.2 |
| | | | 2.3 | 1.9 |
| | | 16 | 1.2 | 0.9 |
| | | | 1.0 | 0.9 |
| | | | 0.9 | 0.5 |
| | | | 1.0 | 0.8 |
| | | 15 | 1.1 | 0.9 |
| | | | 1.3 | 0.8 |
| | | | 1.1 | 0.8 |
| | | | 1.2 | 0.8 |
| | | | 1.2 | 0.9 |

| Station | Crossectional Area sq. feet | Bed No. | Horizontal Meas. (inches) | Vertical Meas. (inches) |
|---|---|---|---|---|
| 15 | 5 | 15 | 1.8 | 2.2 |
| | | | 2.1 | 1.9 |
| | | | 1.8 | 1.8 |
| | | | 1.5 | 1.4 |
| | | | 2.3 | 2.2 |
| | | | 2.1 | 2.3 |
| 15 | | 15 | 3.0 | 2.7 |
| | | | 3.1 | 1.9 |
| | | | 3.2 | 3.0 |
| | | | 3.2 | 2.5 |
| | | | 1.6 | 1.5 |
| 16 | | 17 | 2.2 | 1.5 |
| | | | 1.7 | 1.5 |
| | | | 1.7 | 1.4 |
| | | | 2.0 | 1.7 |
| | | | 2.1 | 1.7 |
| | 17½ | 16 | 1.5 | 0.8 |
| | | | 1.1 | 0.8 |
| | | | 1.3 | 1.0 |
| | | | 1.3 | 1.1 |
| | | | 2.0 | 1.4 |
| | | 15 | 1.3 | 1.1 |
| | | | 1.5 | 1.3 |
| | | | 1.2 | 1.0 |
| | | | 1.3 | 1.2 |
| | | | 1.0 | 0.9 |
| | | | 1.1 | 1.1 |
| | | | 0.8 | 0.6 |
| | | | 0.8 | 0.7 |
| | | | 0.9 | 0.8 |
| | | | 0.7 | 0.6 |
| | | 13 | 2.0 | 2.0 |
| | | | 1.2 | 1.1 |
| | | | 1.3 | 1.3 |
| | | | 1.5 | 1.4 |
| | | | 1.3 | 1.1 |
| 17 | 11¼ | 17 | 2.4 | 1.9 |
| | | | 2.7 | 1.9 |
| | | | 2.7 | 1.5 |
| | | | 1.7 | 1.8 |
| | | | 2.6 | 1.7 |

| Station | Crossectional Area sq. feet | Bed No. | Horizontal Meas. (inches) | Vertical Meas. (inches) |
|---|---|---|---|---|
| 17 | | 16 | 1.5 | 0.8 |
| | | | 1.4 | 0.8 |
| | | | 0.8 | 0.7 |
| | | | 1.3 | 0.9 |
| | | | 1.8 | 0.9 |
| | 11¼ | 15 | 1.5 | 1.1 |
| | | | 1.3 | 1.0 |
| | | | 1.9 | 1.5 |
| | | | 1.0 | 0.7 |
| | | | 1.2 | 1.0 |
| | | 15 | 1.6 | 1.4 |
| | | | 1.5 | 1.3 |
| | | | 1.2 | 1.1 |
| | | | 1.0 | 0.9 |
| | | | 0.9 | 1.0 |
| 18 | 12¾ | 16 | 1.0 | 0.6 |
| | | | 0.8 | 0.7 |
| | | | 0.9 | 0.6 |
| | | | 1.2 | 1.0 |
| | | | 1.4 | 1.2 |
| | | 15 | 1.2 | 0.9 |
| | | | 1.2 | 1.1 |
| | | | 1.1 | 0.9 |
| | | | 1.2 | 0.9 |
| | | | 1.1 | 0.8 |
| | | 15 | 1.3 | 1.4 |
| | | | 1.0 | 1.1 |
| | | | 1.2 | 1.1 |
| | | | 0.9 | 0.9 |
| | | | 1.2 | 0.9 |
| | | 14 | 0.7 | 0.6 |
| | | | 0.8 | 0.7 |
| | | | 0.7 | 0.5 |
| | | | 1.1 | 0.6 |
| | | | 1.5 | 1.0 |
| | | | 1.6 | 1.6 |
| | | | 1.3 | 1.0 |
| | | | 1.3 | 0.7 |
| | | | 1.2 | 1.2 |
| | | | 1.2 | 0.9 |
| 19 | 14 | 15 | 1.1 | 0.9 |
| | | | 1.4 | 1.2 |
| | | | 1.2 | 1.0 |
| | | | 1.1 | 1.0 |
| | | | 1.4 | 1.1 |

| Station | Crossectional Area sq. feet | Bed No. | Horizontal Meas. (inches) | Vertical Meas. (inches) |
|---|---|---|---|---|
| 19 | 14 | 14 | 0.9 | 0.6 |
| | | | 1.0 | 0.7 |
| | | | 1.1 | 0.8 |
| | | | 1.1 | 0.8 |
| | | | 1.0 | 0.9 |
| | | 13 | 1.2 | 1.3 |
| | | | 1.4 | 1.1 |
| | | | 1.4 | 1.0 |
| | | | 1.6 | 1.3 |
| | | | 1.2 | 0.9 |
| | | 13 | 1.3 | 1.0 |
| | | | 1.2 | 1.4 |
| | | | 1.2 | 1.3 |
| | | | 1.3 | 1.2 |
| | | | 1.2 | 0.8 |
| 20 | 54½ | 17 | 2.3 | 1.3 |
| | | | 1.0 | 0.7 |
| | | | 1.3 | 1.1 |
| | | | 1.6 | 1.3 |
| | | | 1.4 | 0.9 |
| | | 16 | 0.9 | 0.7 |
| | | | 1.0 | 0.9 |
| | | | 1.1 | 0.9 |
| | | | 0.8 | 0.6 |
| | | | 1.2 | 0.9 |
| | | 15 | 1.0 | 1.0 |
| | | | 0.9 | 0.7 |
| | | | 1.2 | 1.1 |
| | | | 1.4 | 1.2 |
| | | | 1.1 | 1.0 |
| | | 14 | 1.1 | 0.7 |
| | | | 1.1 | 1.1 |
| | | | 1.0 | 0.6 |
| | | | 1.2 | 1.0 |
| | | | 0.8 | 0.6 |
| | | 13 | 1.4 | 1.4 |
| | | | 1.2 | 1.0 |
| | | | 1.0 | 0.8 |
| | | | 1.3 | 1.0 |
| | | | 0.8 | 0.6 |
| | | 13 | 1.2 | 1.0 |
| | | | 1.0 | 1.0 |
| | | | 1.3 | 1.0 |
| | | | 1.1 | 1.0 |
| | | | 1.1 | 0.8 |

| Station | Crossectional Area sq. feet | Bed No. | Horizontal Meas. (inches) | Vertical Meas. (inches) |
|---|---|---|---|---|
| 21 | 30 | 15 | 1.3 | 1.1 |
| | | | 1.1 | 1.1 |
| | | | 1.0 | 1.1 |
| | | | 1.1 | 1.0 |
| | | | 1.1 | 1.2 |
| | 30 | 14 | 1.2 | 0.9 |
| | | | 1.2 | 0.9 |
| | | | 1.0 | 0.9 |
| | | | 1.1 | 0.8 |
| | | | 0.8 | 0.9 |
| | | 13 | 1.8 | 1.3 |
| | | | 1.5 | 1.1 |
| | | | 1.6 | 1.2 |
| | | | 1.2 | 1.0 |
| | | | 1.3 | 1.5 |
| 22 | 31½ | 13 | 1.6 | 1.3 |
| | | | 1.4 | 1.1 |
| | | | 1.2 | 1.2 |
| | | | 1.4 | 1.3 |
| | | | 1.5 | 1.1 |
| | | 11 | 1.7 | 1.5 |
| | | | 1.4 | 0.8 |
| | | | 1.9 | 1.6 |
| | | | 1.3 | 0.9 |
| | | | 1.4 | 1.0 |
| 23 | 38¼ | 13 | 1.3 | 1.0 |
| | | | 1.5 | 1.3 |
| | | | 1.9 | 1.6 |
| | | | 1.7 | 1.2 |
| | | | 1.4 | 1.3 |
| | | 11 | 1.3 | 1.3 |
| | | | 2.2 | 2.3 |
| | | | 2.2 | 1.5 |
| | | | 1.8 | 1.5 |
| 24 | 93 | 11 | 1.4 | 1.2 |
| | | | 1.5 | 1.3 |
| | | | 1.5 | 1.2 |
| | | | 1.3 | 1.0 |
| | | | 1.6 | 1.2 |
| | | 11 | 1.3 | 1.1 |
| | | | 1.4 | 1.2 |
| | | | 1.3 | 1.3 |
| | | | 1.5 | 1.0 |
| | | | 1.2 | 1.2 |

| Station | Crossectional Area sq. feet | Bed No. | Horizontal Meas. (inches) | Vertical Meas. (inches) |
|---|---|---|---|---|
| 24 | 93 | 7 | 1.0 | 1.0 |
| | | | 1.0 | 1.1 |
| | | | 1.5 | 1.2 |
| | | | 1.7 | 1.1 |
| | | | 1.4 | 1.2 |
| 25 | 49½ | 7 | 1.2 | 0.9 |
| | | | 1.2 | 0.9 |
| | | | 1.3 | 0.9 |
| | | | 1.3 | 1.1 |
| | | | 1.5 | 1.1 |
| 26 | 84 | 1 | 1.6 | 1.0 |
| | | | 1.8 | 1.4 |
| | | | 1.6 | 1.2 |
| | | | 1.5 | 1.0 |
| | | | 1.8 | 0.9 |
| 27 | 72½ | 7 | 1.5 | 1.1 |
| | | | 1.3 | 1.0 |
| | | | 1.1 | 1.0 |
| | | | 1.2 | 1.1 |
| | | | 1.0 | 0.8 |
| 28 | 46 | 1 | 1.2 | 0.9 |
| | | | 1.8 | 1.3 |
| | | | 1.3 | 0.9 |
| | | | 1.0 | 0.7 |
| | | | 1.4 | 1.0 |
| | | 7 | 1.2 | 1.0 |
| | | | 0.8 | 0.6 |
| | | | 0.8 | 0.5 |
| | | | 1.0 | 0.8 |
| | | | 1.1 | 0.9 |

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