KARST GEOMORPHOLOGY AT MOIRA RIVER, ONTARIO

By

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ABSTRACT

This is the first study of the karst features found at Moira River karst. This study intends to investigate a number of different karst features of the area rather than concentrating on one highly specific problem. Hopefully this will enable the reader to appreciate the wide diversity of karst able to form within a small area such as Moira karst.

The variation in karst features encountered at Moira River ranged from a relatively rare form of karst, called a draped karst, to dissolution patterns (scallops), found within a cave. The draped karst dominates much of the area and is formed by the preferential removal of thin, recessive limestone beds. The overlying, massive bedded unit remains and is "draped" over an underlying massive unit.

The river plays a dominant role in the formation of karst features at Moira Karst. It floods quite frequently as evidenced by the number of runoff channels found in the area. The caves at Moira River karst have developed as a short cut across a bend in the river and are fully inundated when the river reaches high flow rates. Karst development does not extend much beyond a range of 300 m from either bank of the river and is concentrated on the east side of the river.

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CHAPTER 1 INTRODUCTION

1.1 Location

Located in Central Ontario, Moira River extends 88.5 km (55 mi.) northward from the Bay of Quinte on Lake Ontario and has a drainage basin of 2745 km^2 (1060 square miles) (Sibul *et al*., 1974). A portion of the area along this river provides the study site for this research. The study site is situated approximately 20 km north of the river mouth, which is in the city of Belleville. Figure 1 is a location map of the research area. It is centered almost exactly between Belleville and Tweed, which is 18 km to the north.

The site is relatively small, with karst development restricted to a distance of 3 km along the Moira River. This area is contained within Hastings County and extends across the borders of two townships, Thurlow and Tyendinaga. The entire extent of the Moira karst can be encompassed within an area from Latitude 44° 18' 45" N. to 44° 20' 15" N. and Longitude 77° 18' 50" W. to 77° 20' 00" W. The Moira River karst is shown in Figure 2 and the karst development along the river is shown in Plate 1.

1.2 Climate

Temperature and precipitation are variable in the Moira River region as they are in most of south central Ontario. Since the Moira karst is centrally located between Belleville and Tweed, its climate is expected to resemble

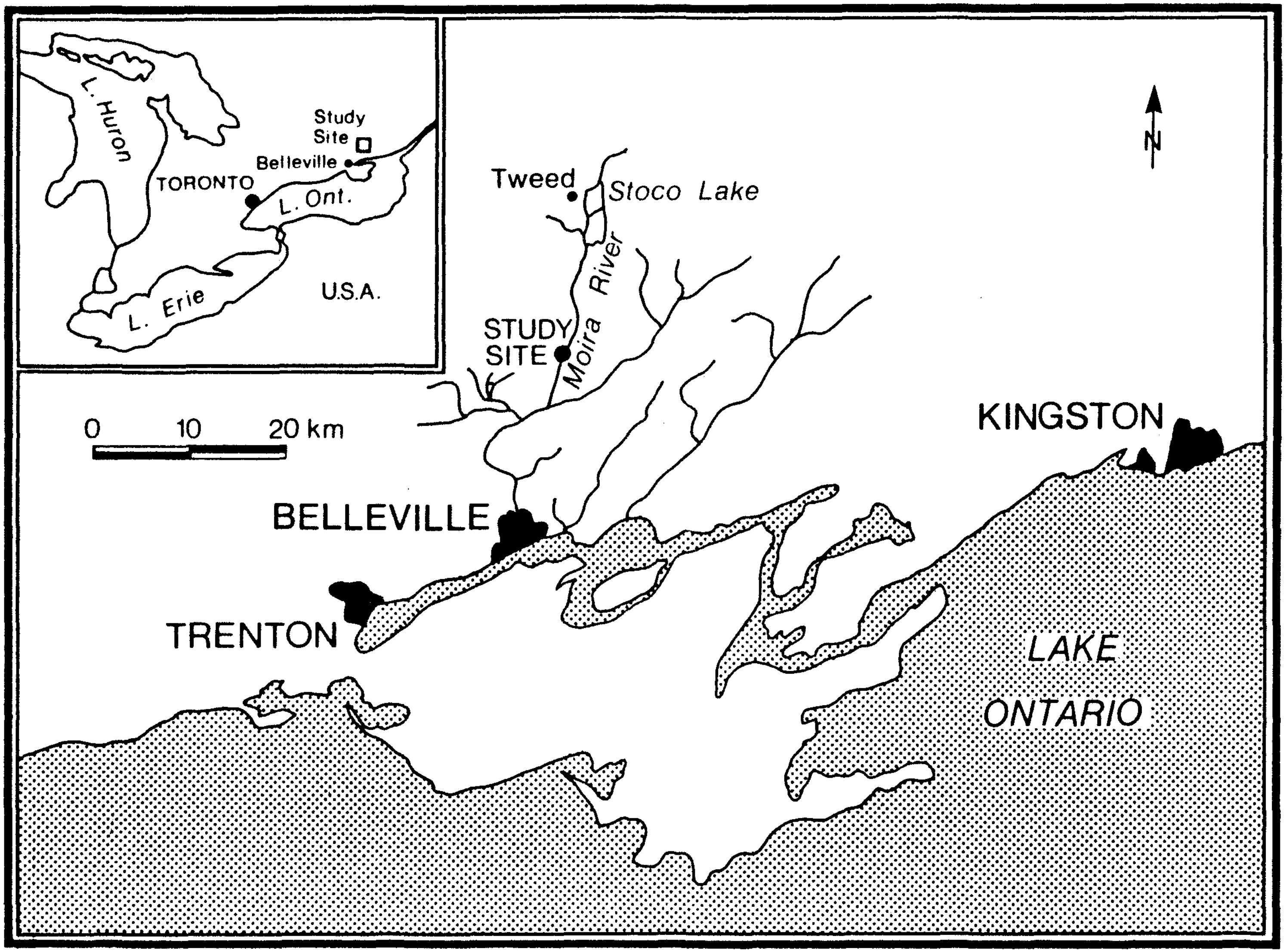

FIGURE 1. Study site location, Moira River, Ontario.

recorded values for those sites. Mean daily temperatures at Tweed range from -8.9° C in January to 20.3° C in July, with an annual mean daily temperature of 6.5° C. Belleville varies from -7.5° C to 21.1° C, with an annual mean of 7.4° C. Mean annual precipitation for Tweed is 889.6 mm and for Belleville 853.2 mm. Tweed records the highest mean annual snowfall of 193.8 cm. Snowcover is usually continuous for the entire winter but may be subjected to thaw at any time. Temperature and precipitation values were obtained from Environment Canada, Climate Normals 1951-1980.

1.3 Geologic Setting

The Moira karst is situated in the Southwestern Ontario Basin of the St. Lawrence Platform (Sanford, 1961; Douglas, 1970). In the Moira River area, the outcropping carbonate rocks are of late Middle Ordovician age and lie on Precambrian Crystalline rocks on the Algonquin Arch. The Precambrian rocks are part of the Canadian Shield and are exposed on the surface until south of Tweed where they are overlain by the Paleozoic limestones which thicken considerably southward. These late Middle Ordovician limestone strata consist of the Black River and Trenton Groups which reach an aggregate thickness of 220-275 m.

The Black River Group underlies the Trenton and is comprised of three formations. The Shadow Lake Formation is the lowest and is a transgressive unit which rests unconformably on Precambrian rocks. It consists of 6-10 m of red and green shale, siltstone, minor limestone and dolomite. The conformably overlying Gull River Formation comprises 25 m of grey, cream coloured lithographic limestone with interbedded pelletoidal limestone at its base and dolomite containing thin beds of bentonite in its upper part. The Coboconk Formation is the youngest unit and it ranges from 6 m at the Algonquin Arch to 30 m near southern Lake Huron. It consists of interbedded lithographic limestone, calcisiltite and calcarenite (Sanford, 1961; Douglas, 1970).

The Trenton Group also consists of three formations. The lowest is the Kirkfield Formation which contains interbedded finely crystalline shaly limestone, bioclastic limestone and calcarenite. It thickens southeastward from 18 m at Manitoulin Island to 73 m along the north shore of Lake Ontario. The Verulam Formation overlies the Kirkfield and is comprised of 25-43 m of coarse bioclastic limestone and calcarenite with shale interbeds. The Cobourg Formation is the uppermost unit of the group and ranges from 12-60 m of dark brown argillaceous and aphanitic limestone (Sanford, 1961; Douglas, 1970).

The coarse limestones of the Kirkfield and Verulam Formations are of shallow marine origin and are the dominant facies. The outcrop at Moira karst is at the contact between the two formations (Ford, 1986). A small 4 m escarpment located along the west bank of the river comprises the extent of the depth of exposed bedrock in the area. This escarpment makes it possible to observe recessive, thinly bedded, horizontal strata along with more massively bedded strata contained in the exposed limestone. This high frequency of bedding planes, coupled with dense jointing and very gentle, almost horizontal, southerly, dipping beds ($<1^{o}$) allow the development of karst in the Moira River study site.

1.4 Physiography

The physiography of the Moira River region is characterized by abundant overburden landform on the Paleozoic limestone (Sibul et al., 1974). Overburden on the limestone is comprised primarily of glacial till, lacustrine sand, silt and clay, eskers and drumlins. In many areas, the amount of glacial deposits are low and topography reflects the gentle southward dip ($<1^{o}$) of the underlying limestone (Sibul et al., 1974).

The Moira River karst site has examples of both large glacial landforms and thin glacial deposits. A large drumlin exists on the east side of the river, while on the west bank above the escarpment, glacial till is thin and limestone is exposed. The Dummer Moraine is located north of the study site and Chapman and Putnam (1984) suggest that the sandy till associated with this moraine is the main overburden type covering the landscape south of Tweed.

The Moira River has its headwaters in the rocky highlands of the Canadian Shield. The river flows into Stoco Lake at Tweed which is roughly the transition from Precambrian to Paleozoic rocks (Chapman and Putnam, 1984). From there it travels over limestone until it reaches the Bay of Quinte at Belleville. The mean discharge of the river measured at Foxboro is 29.8 m^3/s (1052 cfs) (Chapman and Putnam, 1984). The flow of the Moira River is extremely unreliable even though a large portion of its length is well forested and contains numerous lakes. Spring snowmelt is an important flooding factor on the river. Chapman and Putnam (1984) suggest that the limestone plains in the southern portion of the drainage basin may be responsible for the flash floods that do occur on the river.

1.5 Previous Studies in the Area

The only previous study conducted on the Moira karst was carried out in the spring of 1974 by Chris Harrison and Kirk MacGregor of the Toronto Caving Club. They produced preliminary maps and a short report on the area based on air photos and a limited reconnaissance survey. One map is a plan view of the entire Moira karst and illustrates the extent of the karstic development. The other map is a schematic diagram outlining the Moira cave system. The report deals mainly with the cave, exploration methods used in the cave, and stresses the need for cave conservation. Although of limited reliability, the preliminary map of the karst development produced by MacGregor provided an adequate base map of the area.

The other existing literature on the Moira River karst is a brief outline written by Ford (1986) within a text in preparation. In it, he describes some of the significant karst features seen at Moira karst. The work by MacGregor and Harrison (1974) and the outline by Ford (1986) are the extent of the literature written specifically about the karst development on Moira River.

1.6 Objectives

This is the first study of the karst along the Moira River that plans to look specifically at the development of the karst landforms. This study intends to investigate a number of different karst features of the area rather than concentrating on one highly specific problem. By doing this, a reasonably accurate and coherent report on the karst of the Moira River can be produced. Hopefully, it will enable the reader to appreciate the wide diversity of karst capable of being formed in a relatively small area such as the Moira karst. It may also inspire a more extensive study of the area once the reader is informed of the large variation of karst features present.

To enhance the understanding of the karst morphology located along the Moira River some problems encountered while studying the area will be analyzed. Upon investigation of the Moira karst, a major question arises as to whether or not it is accurate to say over a large area the thinly bedded limestone strata have been removed, leaving the thicker, more massive strata behind. It is possible to use the escarpment on the west side as a standard for the area. Then comparisons can be made with lower lying areas that appear to have retained their massive units while losing underlying, thinly bedded strata.

If this is true, the karst in these areas would be a relatively rare form called a draped karst. A draped karst is exemplified by thinking of a sandwich with the meat removed and the top slice of bread lying directly on the bottom slice (D.C. Ford, pers. comm.). By a process called interstratal solution (Quinlan, 1978), it would appear that the thin beds have been removed, thus lowering more massive overlying units onto more massive underlying units.

Generally, when limestone is divided into thick, massive beds and recessive, thinly bedded strata, the thin beds are expected to have a high shale content and thus be less soluble (D.C. Ford, pers. comm.). However, this does not appear to be the case in the draped karst areas where the massive beds remain and the thin beds seem more erodible and are removed. Thus, it is necessary to determine whether the purity of the different limestone units is a factor in the preferential removal of the thin beds or if some other process is responsible. A hypothesis can be developed that cites mechanical weakness as the dominant factor causing removal of thin beds, not solubility. This can be tested by comparing some simple physical properties (purity, porosity and rock hardness) between the existing draped strata and the more recessive, thin bedded strata.

An apparent limiting factor to the development of karst in the Moira River area is the amount of glacial till deposited on the surface. Thus, karst is restricted to areas with little or no glacial till on the surface and/or areas adjacent to the river where flooding has been important in the formation of karst. This would suggest that the karst development is post-glacial and that the till may be inhibiting the solution of the underlying limestone due to a high carbonate content. Since it is assumed that the karst has developed since the end of the most recent glaciation (app. 13,000 yrs. ago), it is possible to calculate erosion rates of the karst using the top of the escarpment as a base level.

In addition to the major draped karst feature at Moira River, a number of other karst features will be discussed. Many different sections of Moira karst support limestone pavement. It is particularly well developed on spring runoff channels as well as along the banks of the river. Pavement is also developing on top of the escarpment on the west side of the river in areas with little overburden. The literature (Sweeting, 1966, 1973; Williams, 1966; Trudgill, 1973) has established that glaciation is a dominant process that is at least partially responsible for the subsequent formation of pavement. The limestone pavement found at Moira River will be discussed.

Minor surface solution forms (karren) are also predominant in the area. One area in particular has shown extensive development of pits and pans on the limestone surface of an older, infrequently inundated runoff channel. The processes involved in the formation of karren forms will be analyzed in order to help enhance understanding of the morphology found at Moira karst.

Caves are also found at Moira River karst. They are narrow and have a joint-maze plan form. Within the caves, dissolution patterns (scallops) were found on the walls. Scallops have been well studied (Curl, 1974; Lauritzen, 1982), and they are useful for indicating past water flow directions. As well, equations have been developed which allow flow velocities and rates to be calculated within cave passages by using certain dimensional information about scallops and the conduit (Curl, 1974; Lauritzen, 1982). Dimensional measurements were taken in some cave passages to enable flow velocities and discharges in caves at Moira to be calculated. As well, the process behind the formation of scallops will be outlined.

Another karst feature found at Moira River was the anastomoses and pendants formed on the underside of limestone clints along the rivers edge. This was a rather unique feature since anastomoses and the resulting pendants are generally associated as solutional forms within caves. Anastomoses will be discussed and a hypothesis will be generated as to their formation along the rivers edge.

1.7 Methodology

1.71 Field Techniques

Field research at Moira River karst was conducted in late summer, during the last week of August, 1985 and encompassed a period of six days. Since this was the initial visit to the karst, the first two days were spent exploring the area. This reconnaissance survey served as a way of becoming familiar with the extent of karst development and with the karst features present at Moira. Dr. D.C. Ford accompanied my partner, John Niessen and myself on this field reconnaissance and was invaluable in suggesting what to study.

To establish the limit of karst development away from the river, four lines which transected the river were chosen to be surveyed (Fig. 2). A clinometer, staff and 30 m tape measure were used to conduct this survey which began at the start of the karst on one side of the river and terminated at the end of the karst on the opposite side of the river. The survey recorded changes in elevation over a measured distance by determining the deviation from the horizontal between the base point and the lead point, using the clinometer to find the horizontal. While surveying, it was possible to study the different karst features encountered. The dimensions of surface solutional forms (karren) were measured and a compass was used to determine the orientations of jointing patterns.

Rock samples were collected from different limestone units in the area for subsequent laboratory analysis of their purity, porosity and density. On lines 2 and 3, where the escarpment transected the survey, careful measurement of the bed thicknesses and descriptions of the units were made. A Schmidt hammer or sclerometer was used to test surface hardness of the limestone which is related to mechanical strength. Day and Goudie (1977) and Day (1980) explain the working principles behind the Schmidt hammer and assess the relative merits of using one in the field. It was found particularly useful at the escarpment where testing of the massive and recessive units with the Schmidt hammer helped determine significant differences in the mechanical strengths of the units.

A somewhat detailed study of an area that possessed well developed surface solutional forms called the "pit-pan-grike" area was conducted. One section of the area was mapped out in plan view to illustrate the distribution of the karren features. The dimensions of the pits, pans and grikes were measured, as was the slope of the bottom surface in the pans. Surface hardness testing using the Schmidt hammer was also performed on unaffected surfaces and surfaces which had karren development within the pit-pan-grike area. This was done in an attempt to establish if possible variations in rock hardness or mechanical strength were causing preferential development of solutional forms within the area.

Caves in the area were not mapped and were only entered a limited distance in order to measure scallop size. Dimensions at the cave passages housing the scallops were also recorded so that water velocity and discharge at the time of scallop formation could be calculated. Since water was moving in the cave passages, it made it possible to confirm that flow direction as indicated by the scallop shape was the same as that actually found in the cave. The anastomoses and pendants found along the river edge were photographed and some samples were collected for later analysis. A number of photographs of the karst features found at Moira River were taken to illustrate the karst.

1.72 Laboratory Analyses

Laboratory analyses consisted of testing collected limestone samples for purity, porosity and density. Density was found by weighing a rock sample to get mass and then finding the amount of volume displaced by the sample.

$$\text{Density } (g/cm^3) = \text{mass}(g)/\text{volume } (cm^3) \quad \ldots\ldots\ldots\ldots\ldots \quad 1$$

Porosity can be determined quite simply. A sample was oven dried, weighed and then immersed in water for several days. Upon removal from the water, the sample was re-weighed. The difference in weight found is a measure of the amount of interconnected pore space in the sample. Porosity is calculated as:

$$\%Porosity = \frac{\text{weight difference of samples (g)}}{\text{Dry weight of sample (g)}} \times 100 \quad \ldots\ldots 2$$

To measure the purity of a rock sample it is necessary to determine what percentage of the rock is non-soluble. A rock is weighed and then dissolved in hydrochloric acid. After waiting for at least 24 hours, the impurities which have not dissolved should be collected on a filter paper and weighed. The percentage amount of insoluble material can then be found by:

$$\frac{\text{weight of residue (g)}}{\text{weight of sample (g)}} \times 100 \quad \ldots\ldots 3$$

To determine the amount of soluble material or the purity of the sample, subtract by one.

CHAPTER 2 DRAPED KARST

A major karst feature seen at Moira River is the development of a draped karst (Plates 1 and 2) where thinly bedded strata have been preferentially removed, leaving more massive beds behind. This process is referred to as interstratal solution by Quinlan (1978). He discusses interstratal karst quite extensively and defines it as a type of karst that is covered and developed beneath pre-karst rock or sediment. The karst development is younger than its cover and is formed by the solution of soluble rock in the subsurface. Sweeting (1973 p. 298) has adopted the interstratal karst term, while Jennings (1985) uses the term subjacent karst.

The draped karst development at Moira River is somewhat different than that described by Quinlan (1978) in that river erosion is a factor. Most of the draped karst is found on the east side of the river in areas prone to flooding. The presence of an escarpment on the west side of the river (Plate 3) makes it possible to compare the two sides to determine if the massive blocks of the draped karst are similar to the massive beds within the escarpment. The escarpment was encountered on both Lines 2 and 3 and beds were measured and described. Figure 3 depicts the Line 2 escarpment and Figure 4 is a vertical profile of the scarp face at Line 3. Descriptions of the limestone units and the results of laboratory analyses are shown in Table 1.

Table 1 Laboratory Analyses Results on Samples

Location	Hardness (R)	Density (g/cm^3)	Porosity (%)	$CaCO_3$ (%)	Sample Description
Line 1					
1.east river bank blocks	48	2.58	0.3	95.53	massive fine grained,
2.east river bed	48	2.43	2.5	96.08	m.f.g., chert, stylolites
3.west bank runoff channel	25	2.31	1.7	94.52	m.f.g., smooth irreg. surface
4.east bank, west channel	32	2.49	1.2	91.29	m.f.g., "
5.west bank, west channel	30	2.36	0.9	94.06	m.f.g., "
Line 2					
1.Unit 1-scarp top	35	2.63	0.6	92.61	m.f.g., microfaults
2.Unit 2	27	2.65	1.0	91.32	recessive thin beds, f.g.
3.Unit 3	40	2.49	0.3	95.17	m.f.g., stylolites
4.Unit 4	-	2.62	0.5	94.11	recessive, f.m.g., calcite
5.Unit 5	45	2.71	0.4	94.70	m.f.g., microfaults
6.Base of Runoff channel	27	2.74	0.2	93.90	m.f.g., densely jointed
7.Is blocks	46	2.47	0.2	93.60	m.f.g., stylolites
8.riverbed	45	2.66	0.3	98.93	m.f.g., densely jointed
9.pit-pan-grike	30	2.70	0.3	95.27	m.f.g., stylolites
10.below pit-pan-grike	35	2.69	0.7	84.64	m.f.g., irreg. surf.
Line 3					
1.Unit 1 - scarp top	40	2.70	0.2	92.60	m.f.g., stylolites
2.Unit 2	28	2.33	0.1	96.49	recessive, f.g., fossiliferous
3.Unit 3	24	2.87	0.1	94.77	recessive, f.g., microcrack
4.Unit 4	-	2.54	0.7	96.87	most recessive, cellular structure
5.Unit 5	42	2.65	0.4	94.85	m.f.g.
6.Unit 6	40	2.55	0.8	85.85	recessive, f.g., microfaults
Line 4					
1.glacial scour	47	2.26	1.0	97.47	m.f.g., stylolites
2.cave	45	2.37	0.5	93.61	m.f.g.
Anastomosing Bed					
1.fine bed	-	2.65	0.6	87.76	m.f.g., stylolites
2.fossiliferous bed	-	2.56	0.4	91.33	m.f.g., fossiliferous

The massive bedded units found in the escarpment (Lines 2 and 3-Unit 5) appear to be the same massive units that comprise the draped karst. Limestone blocks of the draped karst were measured as being 1.50 m thick which compares quite well to the thickness of Unit 5 on both lines (1.37 m - 1.52 m). As well, the purity of the units (carbonate content) and porosity compare quite favourably. The purity of Unit 5 was found to be 94.7% to 94.9% $CaCO_3$ while the limestone blocks in the spring runoff channel that remain as draped karst tested at 93.6% $CaCO_3$. The difference in porosity was minor, with Unit 5 porosity at 0.40-0.44% and the blocks at 0.21%. These similarities in size and lithology would suggest that the massive units which constitute the draped karst are the same massive beds that are found in the escarpments on Lines 2 and 3.

It would appear that the dominant factor causing removal of the recessive, thin beds that once existed in draped karst areas is mechanical weakness and not solubility. This can be tested by comparing some simple physical properties like density, solubility, porosity and rock hardness using the escarpment as a base. Chemical analyses of samples (Table 1), reveals that there is no significant difference in the purity of limestone in the Moira River karst. All samples tested had $CaCO_3$ contents ranging from 85% to 98%. This is important because generally when a limestone is divided into massive and thin beds, the thin beds consist of more shale and are less soluble than the massive beds. If this was the case at Moira, it would be solid proof that the thin beds are being removed due to mechanical weakness because the massive beds would be expected to erode faster than the thin beds.

However, it is still possible to conclude that mechanical weakness is the dominant factor even though rock purities are similar. Testing of surface hardness with the Schmidt hammer, which is a measure of mechanical strength, reveals that the massive units are stronger than the recessive beds (Table 1). As well, visual examinations of the units reveals that the recessive beds are highly fractured with many bedding-planes and are mechanically weak. Therefore, the evidence makes it possible to suggest that the draped karst developed due to preferential removal of thin recessive beds that are mechanically weak. It can also be suggested that the river's erosive force was a contributing factor to this draped karst development. The Moira River is susceptible to flooding and water from the river may have helped erode out the thin beds, leaving the massive beds to drape down over other massive, underlying beds.

CHAPTER 3 RATE OF LIMESTONE EROSION AT MOIRA KARST

The rate of erosion of limestone at Moira River was calculated by the following method. By using the survey data compiled for the area on lines which transected the river, it was possible to derive elevations for the area using the river bed as zero elevation. A grid was placed over the karst map (Fig. 2) and x-and-y-coordinates were read at each point along with the elevation. Data was compiled in the computer and with the use of Surface II Graphics Systems TREND program (Sampson, 1984), the elevation data was interpolated between points and plotted as a contour map (Fig. 5). With a few additions to the computer program, the TREND package will produce a 3-Dimensional simulation of the area. This was done for Moira karst (Fig. 6). The depressed area represents the volume of limestone removed since karst processes began at the end of the last glaciation.

Figure 7 is the inverted 3-Dimensional map of Moira karst. The raised features on the inverted 3-D map (Fig. 7) represent the volume of limestone eroded assuming that the karst at Moira River is post-glacial and the surface was originally at the standard escarpment level seen today.

The size of the region outlined by the contours map (Fig. 5) is 1.785 km long and 625 m wide. This gives a total area for the map of 1.116 km^2. The total area which has experienced some lowering of base level (karst development) was calculated to be 0.330 km^2. The difference in elevation between the top of the escarpment and the river bottom was found to be 5 m. This indicates that up to 5 m of limestone has been eroded along the river channel since the time of the last glaciation (app. 13,000 yrs. ago). This suggests an average denudation rate of 385 mm/ka along the river bed. This compares favourably to estimated denudation rates found in the Canadian Rockies ranging from 100-1000 mm/ka (Ford *et al*., 1981). However, most areas at Moira River that have experienced karst development can be expected to have lower rates of limestone removal than those found at the river channel.

It can also be estimated by using the elevations on the contour map (Fig. 5) that the volume of limestone removed at Moira karst is 1.14×10^6 m^3. This translates into a total erosion rate of 265 $m^3/km^2/yr$ or 265 mm/ka for the limestone at Moira River. Usually this erosion rate is calculated using Corbel's Formula (Jennings, 1985).

Limestone denudation rate $(m^3/km^2/a) = 2.5\ Etn/1000$ 4

where E = runoff (in decimeters)
t = $CaCO_3$ concentration (mg/l)
1/n = fraction of catchment in limestone and limestone alluvium

Atkinson and Smith (1976) suggest that the highest erosion rates would generally be found in the humid tropics because of the high levels of rainfall. They report erosion rates for Jamaica between 70-100 $m^3/km^2/yr$ for mean annual runoff values of 1000-1300 mm. These erosion rates for

Jamaica are significantly less than the value calculated for Moira River which is 265 $m^3/km^2/yr$ for a mean annual runoff of 337 mm (Ministry of Natural Resources, 1986). This can be explained because the increased denudation rate at Moira River is caused by the erosive forces of the river.

The river has preferentially removed the thin, recessive beds at Moira River. This adds a mechanical erosion part to the erosion rate. This mechanical erosion is not considered in most limestone denudation rate calculations. Corbel's equation only considers the erosion of limestone caused by solution. Worthington (1984) suggests using an equation for calculating total erosion of limestone that considers both mechanical erosion and the carbonate content of the limestone. This may be a more appropriate means of calculating the total erosion rate of limestone.

CHAPTER 4 LIMESTONE PAVEMENTS AND KARREN FORMS

At Moira River karst it appears that the presence of glacial till on the surface has a limiting effect on karst development. This inhibition of solutional processes by the till is more pronounced with increased distance away from the river. The glacial till has been removed by flooding close to the river and exposes limestone which is open to attack. Where glacial till is not removed by the river, it protects the underlying limestone due to its high carbonate content. It has a high carbonate content with which to buffer penetrating water because of localized deposition of calcareous till. This till is comprised of limestone bedrock eroded from the surrounding area during the last glaciation. Many authors (Williams, 1966; Trudgill, 1972; Quinlan, 1978, Ford, 1983) contend that calcareous glacial till can protect the underlying limestone from solution. Williams (1966) and Pluhar and Ford (1970) found that there is almost no solution of bedrock beneath calcareous till in the Burren of Southwest Ireland and near the Niagara Escarpment, Ontario, respectively. Trudgill (1972) demonstrated that if the till cover was removed, subaerial weathering of the limestone would ensue.

The development of karst at Moira River appears to have begun since the recession of the last glaciation, Ford (1979) refers to this as postglacial karst forms. Glacial till is inhibiting solution of limestone over much of the region and karst is forming only near the river and where till cover is shallow. This concurs with the general environment agreed upon in the literature (Sweeting, 1966, 1973; Williams, 1966; Ford, 1983) for the development of limestone pavement. Glaciation of an area removes the earlier developed karst surface features. This leaves a freshly scoured surface open for subaerial weathering unless subsequently covered by glacial till. Because the glaciation will remove most of the karst as it erodes over the area, any surficial features which developed after the glaciation would be assumed postglacial in age.

Limestone pavement is defined by Williams (1966) as "a roughly horizontal exposure of limestone bedrock, the surface of which is approximately parallel to its bedding and is divided into a geometrical pattern of blocks by the intersections of widened fissures." Pavement at Moira is found on spring runoff channels (Plates 2 and 5), and adjacent to and in the river (Plates 1 and 4). It is also developing on top of the escarpment in areas with little overburden but is not well defined. Most grikes are small and filled with rubble. Cross-sectional representations of bare pavement and spring runoff channel pavement are shown in Figure 8.

The runoff channel grikes (solutionally widened joints) are generally narrow, ranging in width from 5-25 cm, with depths up to 20 cm. These grikes narrow with depth to resemble a v-shaped form (Fig. 8) and are often lodged with boulders transported by the river at flood stages. The runoff channel grikes basically follow an East-West orientation. Minor joint sets are oriented roughly perpendicular to the major sets, forming angles within a range of 70°-90°.

The pavement found in and along the river is dissected into well developed clints. Because of the direct contact with the river water, solutional processes have been able to widen the joints and cause the separation of limestone into distinct blocks much faster than on runoff channels which are only infrequently inundated. The cross-sectional profile of the bare pavement is depicted in Figure 8.

Solutional pits and pans are predominant on bare limestone surfaces near the river (Plate 6) and in abandoned runoff channels (Plates 7 and 8) at Moira karst. These pits and pans generally form best where surface dips are close to horizontal. Since most of the limestone surfaces at Moira are basically flat, there is little or no development of karren forms usually associated with sloped surfaces. Pits, pans and grikes are the main karren forms found at Moira River. Pans generally have a flat bottom and vertical sides and are deeper and larger than pits. Pits are usually round, while pans can vary from a round to a more oblong shape.

Pits ranged from 5-30 cm in diameter and were less than 10 cm deep. Jennings (1985) suggests that rainfall or leaf drip on bare rocks can produce small pitting. This can be attributed as the cause of some of the smaller pits seen along the banks of the river. Pits can be separated from one another by the original surface or may become so close as to have only sharp rims between them (Plate 7). Then the surface has a more irregular appearance. It seems likely that much of the solution in these pits is biochemical in nature. It is a result of the metabolism of blue-green algae (cyanobacteria), of both euendolithic and endolithic type (growing respectively in the top 0.2 mm and 3 mm layer of rock) (Dannin and Garby, 1983). These tiny organisms breathe out carbon dioxide at night which acidifies rainwater, wetting them and bringing them into activity (Dannin and Garby, 1983).

Solution pans or kamenitzas (Plate 8) are dish-shaped depressions, usually floored by a thin layer of silt, clay or algal remains. Pans at Moira ranged in size from 30-100 cm long, 20-80 cm wide and 5-30 cm deep. The pan bottoms were generally flat, with slopes never exceeding 5^{o}. The fine clasts on the flat bottom serve to protect the lowest parts from corrosion. The added Co_2 from organic matter increases the concentration of solution along the waterline around the sides, maintaining vertical or slightly undercut walls and a flat bottom (Jennings, 1985). Jennings (1985) suggests that continuous renewal of Co_2 and an absence of a protective seal around the pan make this the most favourable place for solution.

A large number of well developed pits, pans and grikes were found in an abandoned spring runoff channel (Fig. 2). Distributions of the karren forms found in one section of this "pit-pan-grike" area are illustrated in Figure 9 and Plate 8. A cross-sectional profile of the "pit-pan-grike" in Figure 8 shows how some of the pans have spilled into the grikes. This would suggest that the grikes developed first and as the pan developed it breached into the grike and forms a pan spillway (Fig. 8).

Surface hardness of the rock where karren formed was tested against unaffected surfaces in the "pit-pan-grike" region. This was done to determine if any significant differences in rock hardness were causing the preferential development of solution forms. The results indicate that this is not a factor in karren development as surface hardness values were the same for both unaffected areas and areas that had experienced solution.

CHAPTER 5 SOLUTIONAL FORMS (SCALLOPS) IN MOIRA CAVE

5.1 Introduction

The presence of scallops on the walls of caves at Moira River represent one of the diversified karst features found at Moira karst. The caves are located on the east side of the river and function as a short cut across a bend in the river. The caves are narrow and have a joint-maze plan form. They are developed mainly in a single massive bed approximately two meters thick. The passage forms are characteristic of joint widening by solution or possibly rock collapse (MacGregor and Harrison, 1974). Since the cave is a short cut for the river, it is prone to flooding during spring snow melt or extremely heavy rains and it is assumed that the scallops formed during these high discharge stages. When visited in late August, the water level was at approximately half the cave height and flow velocity was quite low as expected, taking into account the low summer discharge rates of the river.

Scallops have been known to form on the base of open stream channels, on boulders in the stream, and on the walls, ceilings and floors of cave passages (Goodchild and Ford, 1971). At Moira River, scallops were found on the walls of caves and in one isolated section of a spring runoff channel. The scallops formed on the cave walls are illustrated in Plate 9. Although little variation in scallop size is seen at a particular site, Goodchild and Ford (1971) have reported scallop lengths of 2 mm in caves in the Selkirk Mountains of British Columbia as compared to 2 m long scallops in Mammoth Cave in the Central Kentucky karst.

Through a number of field and laboratory studies, (Curl, 1966, 1974; Allen, 1971; Goodchild and Ford, 1971; Blumberg and Curl, 1974; Lauritzen, 1981, 1982) scallops have been analyzed quite extensively. Scallops have warranted this study because their asymmetrical longitudinal profile, with the steepest side always being on the lee side of the crest (Fig. 10), indicates the direction of water flow within a cave (Lauritzen, 1982). Curl (1974) and Blumberg and Curl (1974) also analyzed scallop patterns mathematically and were able to derive equations to predict flow velocity and rate within a cave based on scallop lengths. This makes it possible to deduce paleo-current direction and flow velocities in drained cave conduits.

5.2 Formation of Scallops

Goodchild and Ford (1971) state that "the flow of a viscous fluid over a modifiable bed can produce a variety of small scale relief patterns." They suggest, as does Lauritzen (1982), that current ripples on unconsolidated sediments are perhaps the best known examples. Scallops formed on limestone can be thought of as analogous to current ripples (Lauritzen, 1982). Scallops are thought to be individual forms defined by their ridges rather than their depressions and resemble a mosaic of inlaid scallop shells (Goodchild and Ford, 1971).

Curl (1974) suggests that the basic environment needed for the formation of scallops is the turbulent flow of a solvent over a soluble surface. In nature, this is most often seen when water dissolves limestone and sometimes with air "dissolving" ice (evaporation being analogous to the dissolution process) (Curl, 1974). In either case, because of surface irregularities, it is possible to create the flow situation shown in Fig. 10, from which Blumberg (1970) describes the following features.

> "At the crest of an irregularity (Point 1), the main flow separates, that is, it forms a "jet" above a region of slower recirculating flow. Within a short distance, this jet flow becomes strongly irregular and itself becomes turbulent (Point 2). Because the turbulence thereby produced causes mixing between the fluid in the lee eddy (Point 3) and the jet, fluid is entrained out of the lee eddy, causing the jet to turn toward the surface and reattach at Point 4. Some of the fluid then enters the lee eddy region and the rest flows onward along the surface."

In the vicinity of reattachment (Point 4), where the jet flow impinges most directly upon the surface, the rate of solution is the highest. One consequence of this is that the scallop patterns move downstream as they are dissolved further into the wall. Curl (1974) indicates that this phenomenon has occurred during all experimental simulations of scallop development. Figure 10 also illustrates the characteristic asymmetry of scallop profiles, from which flow directions can be established.

5.3 Calculating Flow Velocities and Rates in Cave Passages From Scallop Length

It has been established (Curl, 1966, 1974; Goodchild and Ford, 1971; Lauritzen, 1982) through calculations and experiments that a negative correlation exists between scallop wavelength and flow velocity close to the rock surface. This indicates that, the smaller the scallop wavelength is, the greater the velocity of water needed to form the dissolution patterns. Because of the possible presence of a number of small depressions that appear to be located at the intersections of the rims of the depressions Curl (1974) suggests the use of a 'Sauter-mean' on scallops. This will suppress the importance of the smaller features which are irrelevant to the rate of flow dependence (Lauritzen, 1982).

To use the Sauter-mean, a representative sample of scallop lengths in the same section of cave are needed. Scallop lengths are simply measured by using a ruler and determining length from crest to crest.

Sauter-mean of scallop lengths (L_{32}): (Lauritzen, 1982)

$$L_{32} = \frac{\Sigma L_i^3}{\Sigma L_i^2} \pm \frac{L_{32}\, e^{\sigma 32} - L_{32}}{L_{32} - (L_{32}/e^{\sigma 32})} \qquad \text{........ 5}$$

where:

$$\sigma_{32} = [13/n(n-1) \sum_{i=1}^{n} (\ln L_i - \overline{\ln L_i})^2]^{1/2} \quad \ldots\ldots\ldots\ldots \quad 6$$

σ_{32} is given approximately within 10-20 %, which is sufficient for this use. (Curl, pers. comm. to Lauritzen, 1982)

L_i is the longitudinal length of the individual scallops

n is the number of scallops in each sample

Once the Sauter-mean of scallop lengths for each sample set is calculated, the mean flow velocity ($\bar{u}$) can be found using an equation derived by Blumberg and Curl (1974):

$$\bar{u} = \frac{v}{L_{32}} Re^{*} [2.5(\ln(R_h/L_{32}) - 3/2) + B_L] \quad \ldots\ldots\ldots\ldots \quad 7$$

for a circular conduit, and

$$\bar{u} = \frac{v}{L_{32}} Re^{*}[2.5(\ln(R_h/L_{32}) - 1) + B_L] \quad \ldots\ldots\ldots\ldots \quad 8$$

for parallel walled passages

v is the kinematic viscosity of the liquid, which decreases with increasing temperature

L_{32} is the Sauter-mean of the scallop lengths

Re^{*} is the Reynold's number based on the friction velocity and L_{32} (a constant value of 2200 derived from flume experiments will be used)

R_h is the hydraulic radius of the conduit

$$R_h = A/P = \frac{\text{cross-sectional area}}{\text{wetted perimeter}} \quad \ldots .9$$

B_L is a fraction factor, found to be a constant of 9.4

Since the cave passages at Moira are joint widened and are closer in shape to a parallel walled passage (Fig.

11), that equation for calculating mean flow velocity ($\bar{u}$) was used. Once the flow velocity is determined, flow rates can be calculated by finding the cross-sectional area of the passage. This can be found by measuring the heights and widths of the various passages where scallop length samples were taken. Thus volumetric flow rate (Q) is determined by:

$$Q = A\bar{u} \quad \ldots\ldots 10$$

A is cross-sectional area of cave passage

$\bar{u}$ is the mean flow velocity

5.4 Discussion

The results of flow rate calculations using scallop lengths for cave passages at Moira River are shown in Table 2. Since the Sauter-mean of the longitudinal lengths of the scallops in the sample sets ranged between 3.30 cm and 3.99 cm, it was expected that high mean flow velocities would be calculated. This was found to be true, with velocities ranging from 1.06 m/s to 1.40 m/s found for water at 5^{o}C for the Cave 1 passages.

Flow rate calculations were carried out for water temperatures of 5^{o}C and 15^{o}C. This was done to illustrate the effect water temperature, which is inversely related to kinematic viscosity, has on the flow rate calculations. When water temperature is raised to 15^{o}C, this reduces the kinematic viscosity of the water and causes the calculated flow velocities and rates to be reduced (Table 2). However,

Table 2 Flow Rate Calculations Derived from Scallop Lengths, Moira River

Location	T(°C)	n	L_{32}(cm)$\pm\sigma$	R_h(cm)	$\bar{u}$(m/s)$\pm\sigma$	A(m^2)	Q(m^3/s)$\pm\sigma$
Cave 1 - Site 1	5	25	$3.30^{+0.96}_{-0.74}$	29.24	$1.40^{+0.49}_{-0.37}$	2.33	$3.27^{+1.15}_{-0.86}$
"	15	25	$3.30^{+0.96}_{-0.74}$	29.24	$1.05^{+0.37}_{-0.28}$	2.33	$2.46^{+0.86}_{-0.64}$
Cave 1 - Site 2	5	25	$3.99^{+0.73}_{-0.61}$	22.14	$1.06^{+0.24}_{-0.19}$	1.19	$1.27^{+0.28}_{-0.23}$
"	15	25	$3.99^{+0.73}_{-0.61}$	22.14	$0.80^{+0.18}_{-0.15}$	1.19	$0.95^{+0.21}_{-0.17}$
Cave 1 - Site 3	5	25	$3.58^{+0.62}_{-0.53}$	24.55	$1.23^{+0.26}_{-0.21}$	1.27	$1.57^{+0.33}_{-0.20}$
"	15	25	$3.58^{+0.62}_{-0.53}$	24.55	$0.93^{+0.19}_{-0.16}$	1.27	$1.18^{+0.25}_{-0.20}$

the scallops formed in caves at Moira karst are assumed to be created at temperatures around 5°C or lower. This is assumed because the highest discharge rates found on the river, which subsequently floods the caves, are during the spring snow melt and water temperatures will be low.

To test the accuracy of the results, scallop length sample sets were taken at areas where a cave passage branched into two passages (Fig. 12). Measurements of samples were taken within the main passage (1) and in both of the branched passages (2) and (3). The reason for doing this was that the flow rate calculated for the main passage (1) should equal the sum of the flow rates for the two passages (2) and (3) into which it branched (ie. (1) = (2) + (3)). Results of flow rate calculations from Cave 1 indicate a relatively close relationship between passage (1) and the two branched passages combined:

Table 3 Flow Rate Comparisons within a Branched Passage, Moira River

	P(1)	P(2)	P(3)	P(2)+P(3)	P(1) - (P(2)+P(3))
Flow Rate T = 5°C (m^3/s)	$3.27^{+1.15}_{-0.86}$	$1.27^{+0.28}_{-0.23}$	$1.57^{+0.33}_{-0.21}$	$2.84^{+0.61}_{-0.50}$	$0.43^{+0.54}_{-0.36}$
Flow Rate T = 15°C (m^3/s)	$2.46^{+0.86}_{-0.64}$	$0.95^{+0.21}_{-0.17}$	$1.18^{+0.25}_{-0.20}$	$2.13^{+0.46}_{-0.37}$	$0.33^{+0.40}_{-0.27}$

The discharge in the main passage for water at 5°C is only 0.43 m^3/s higher than the two branched passages combined. This is a discrepancy of 13% which is considered reasonable and could be taken into account by the error terms on the values. Curl (1974) estimates that the experimental results are ±15% correct, so the values of flow rates found for Cave 1 are adequate. Thus, the calculated results using the scallop lengths measured in Moira River caves appear to confirm that it is possible to calculate flow velocities and rates within a cave passage as well as determine flow direction by using scallops. This is a useful means of deducing paleo-hydrologic conditions in cave systems.

CHAPTER 6 ANASTOMOSES AND PENDANTS

A rather unique solutional karst form is located along the east bank of a section of the Moira River between lines 2 and 3 (Fig. 2). The presence of anastomoses and the resulting pendants on the underside of limestone clints that come in contact with the river are illustrated in Plates 10 and 11. Bogli (1980) describes anastomoses as being intricately twisted cavities which are connected to one another, ranging from a few centimeters up to 20 cm in diameter. These anastomoses form the spaces between features normally called roof pendants (Ewers, 1966). Bogli (1980) says that pendants, range from 10-100 cm, rarely becoming longer and that neighbouring cones end at the same height. This is attributed as proof that the pendants are remainders of a limestone strata in which dissolution created winding cavities in the form of channels, moving from the bottom upward (Bogli, 1980).

Finding these anastomoses along the river edge is somewhat rare as they are usually referred to in the literature (Bretz, 1942; Ewers, 1966; Pluhar and Ford, 1970; Palmer, 1984; Jennings, 1985) as forming along bedding-planes within cave passages. Palmer (1984) suggests that most cave researchers consider anastomoses to be the original phreatic solution channels which eventually coalesce to form cave passages. However, Cowell (1976, p. 84) cites an example in Ireland from Williams (1966, p. 164) and D.C. Ford (pers.

comm.) that resembles the features found at Moira. Deep pits with finger-like protrusions were found pointing downwards along the shore zone of freshwater lakes in Ireland. Although the shape of the resulting solutional forms may be slightly different, the basic environment in which they developed is quite similar. Cowell (1976) indicates that the features seen in Ireland are caused by solution as lake water laps up into rock overhangs.

Bretz (1942) and Bogli (1980) report on the formation of pendants on the ceilings of cave passages. Warwick (1962) suggests that the channels were created on the ceilings of caves when sediments filled the cavity and water had to force its way between the sediment and the ceiling. This could explain the development of anastomoses and the resulting pendants on the Moira River banks. The limestone clints that developed pendants came in direct contact with the river base unit. This may have occurred because erosion of a thin bed caused the anastomosing clint to drop or because a bedding-plane existed between the units. This allowed river water to force its way between the two rock units and create anastomoses in much the same way as Warwick (1962) suggests for cave ceilings. It would be convenient for the confirmation of this hypothesis if the overlying anastomosing bed was more soluble than the river bed. However, laboratory testing (Table 1) for purity of the two rock units indicates that they have essentially the same $CaCO_3$ content (90% for river bed, at Line 2 88% for anastomosing bed) and in fact, the river bed is slightly more soluble. It may also be possible that the formation method suggested in Cowell (1976) is the process acting at Moira River to form anastomoses on river edge clints.

CHAPTER 7 SUMMARY

This report has endeavored to describe and discuss some of the many karst features and processes found at Moira River. It has supplied the reader with a broad overview of the karst development at Moira River. Hopefully, this will illustrate the wide diversity of karst forms that can be found in a small area. The karst features studied range from a relatively rare form of karst, called a draped karst, to scallops in a cave.

The overlying theme that becomes apparent in this study is the role the river had in the development of the karst. Without the river's erosive action on the recessive thin beds, it is not certain they would have been preferentially removed, leaving the draped karst feature. The river is the main reason calculated erosion rates are higher than those found in the tropics when tropical erosion rates are expected to be higher due to higher runoff values. The mechanical erosion of the limestone beds by the river leads to the variation from expected values.

The river has helped in the formation of limestone pavement at Moira karst. The runoff channels have well developed pavement on their surface and well defined limestone clints proliferate in and near the river. The common flooding by the river can be seen as enhancing solution rates in areas it inundates by delivering new aggressive water. The river may also be responsible for removing glacial till from areas which otherwise would not experience karst development due to inhibition of solution by the calcareous till.

The river has formed caves at Moira karst by taking a short cut across a bend in the river. The caves flood during high discharge levels and scallops are formed at these high flow rates. The anastomoses and resulting pendants have formed on clints that come in contact with the river water. It is this contact between the rock and water that causes the anastomosing channels to form.

Thus, the river plays a major role in the karst development at Moira River. It is an important factor in the wide variation of karst features seen at Moira karst. Without its presence, the diversity of karst found in this small area would be greatly reduced.

Appendix 1

Relevant Figures (Charts and Diagrams)

The Moira River Karst

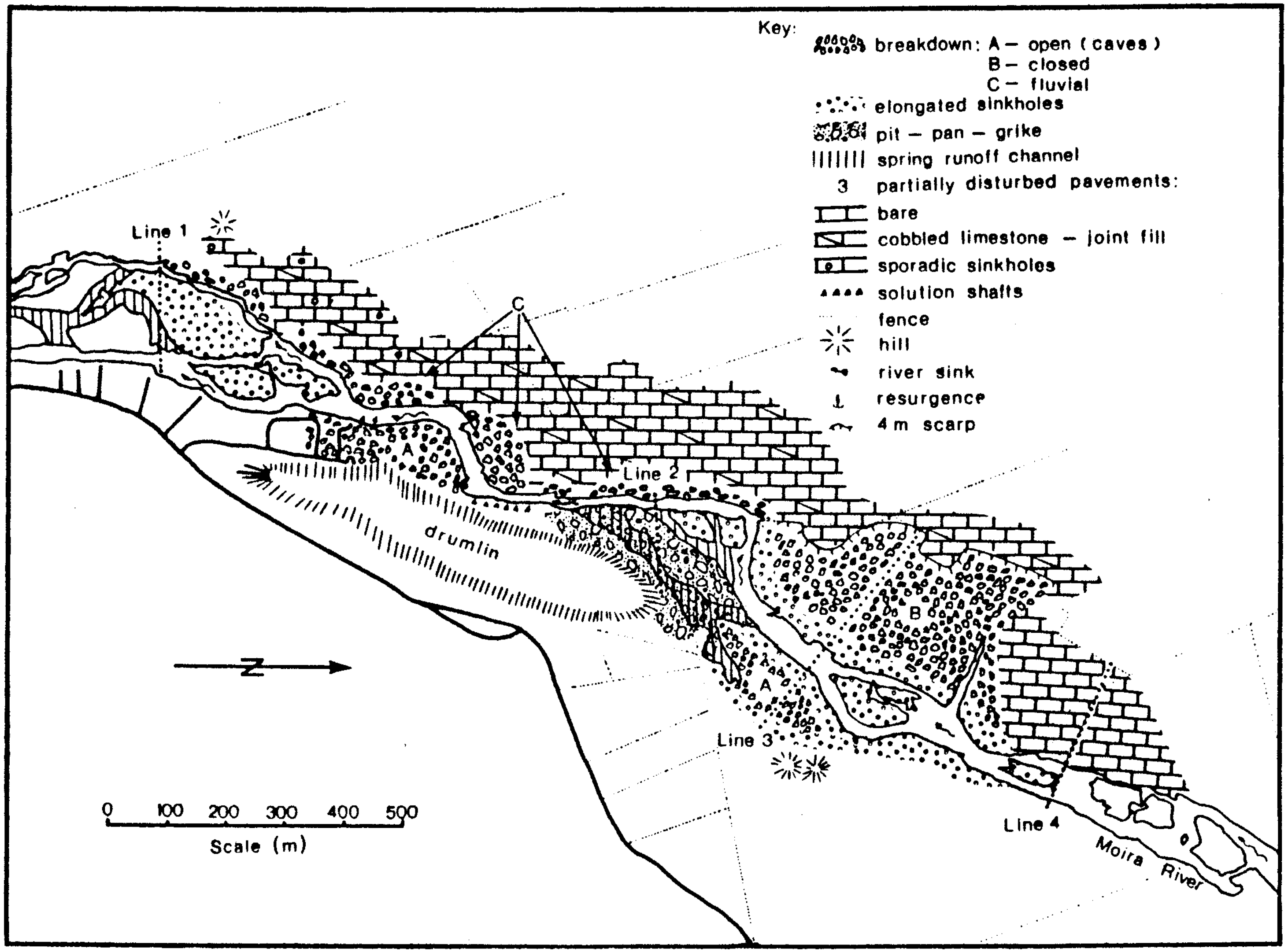

FIGURE 2.

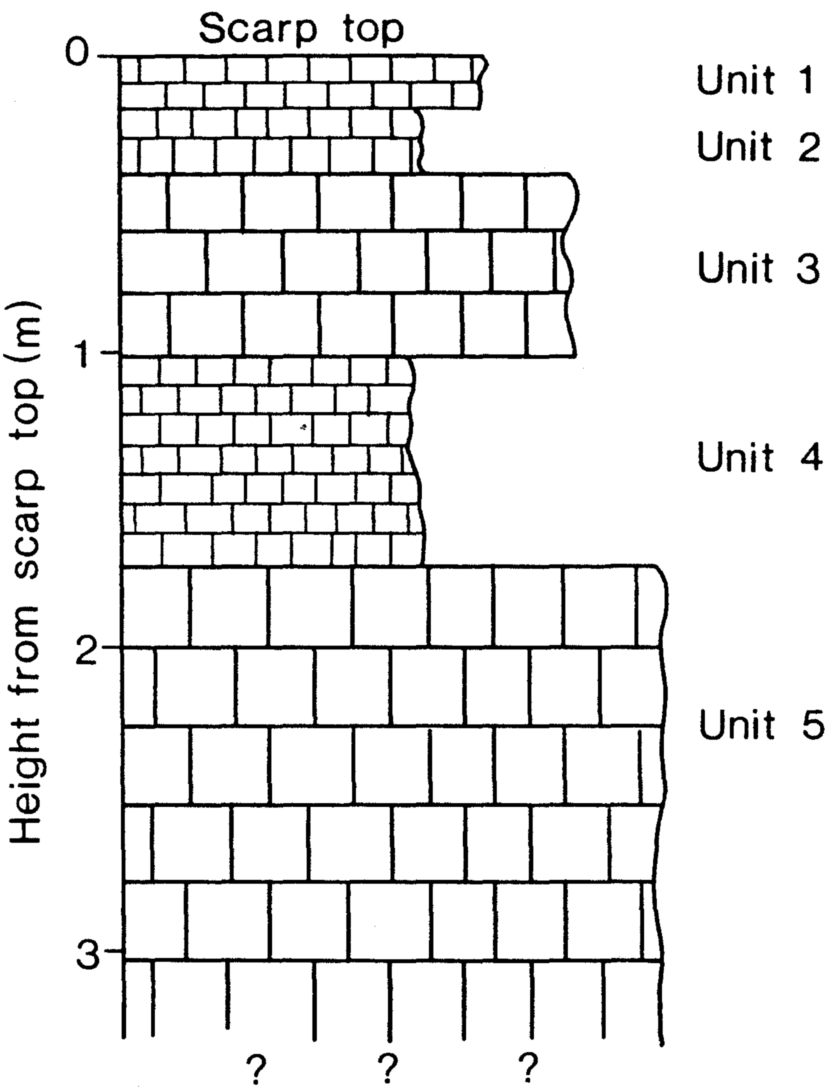

FIGURE 3. Vertical profile of escarpment - Line 2, Moira River.

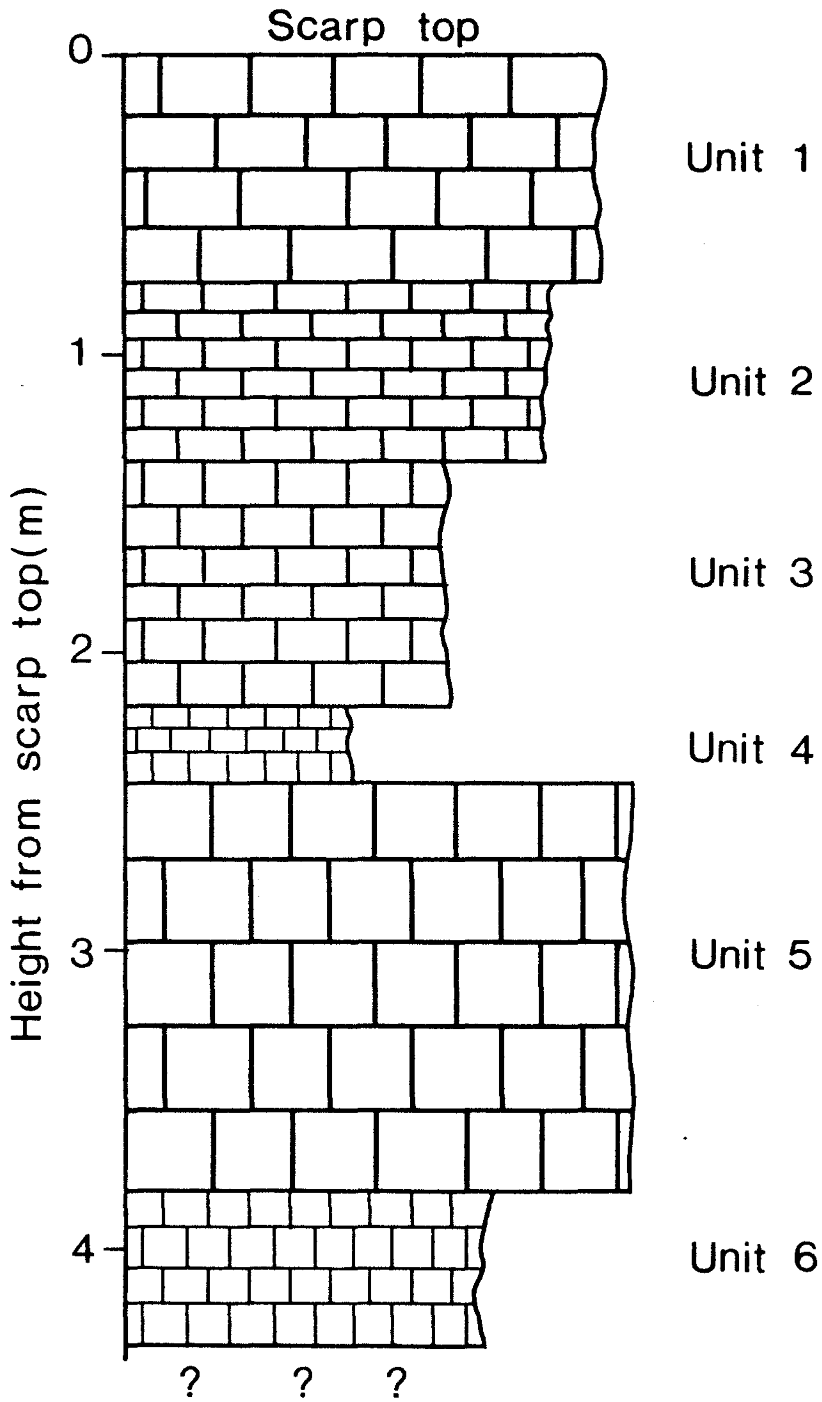

FIGURE 4 Vertical profile of escarpment-Line 3, Moira River.

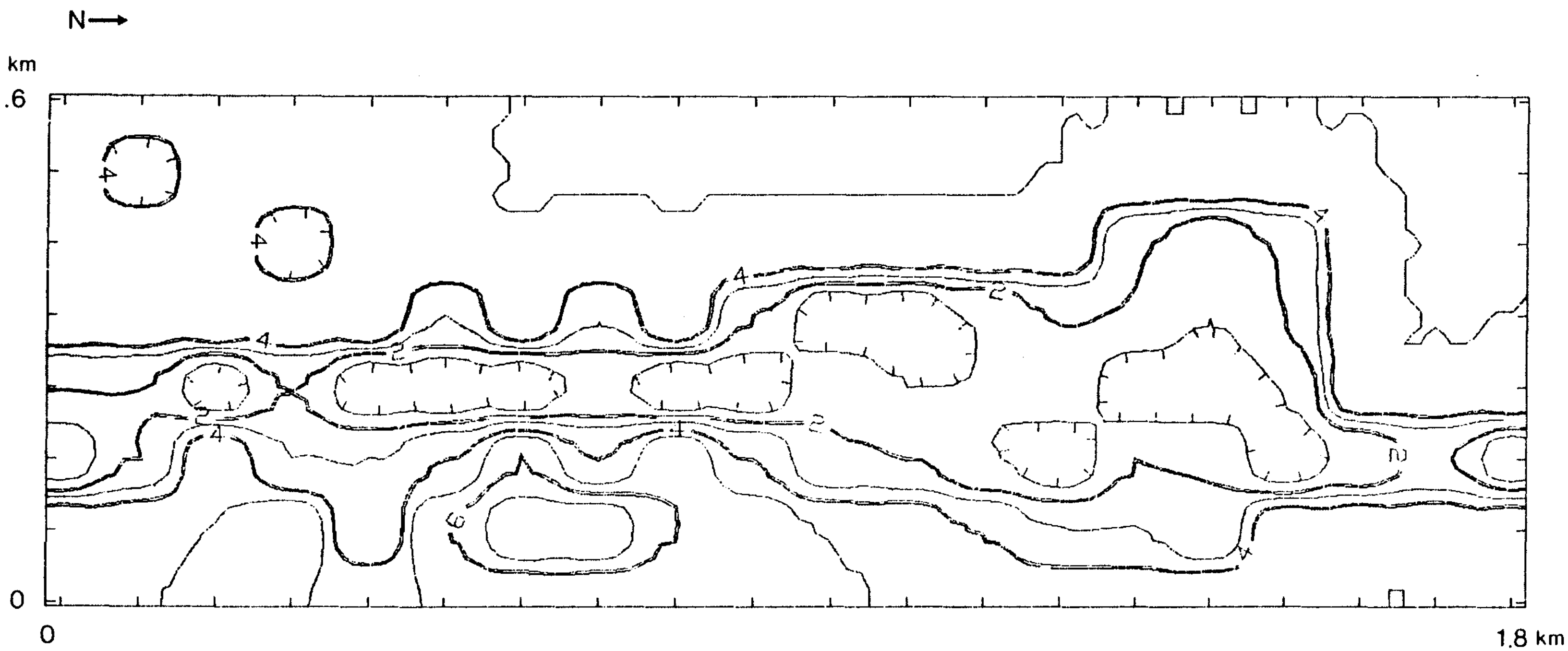

FIGURE 5. Contour map of the Moira River karst.

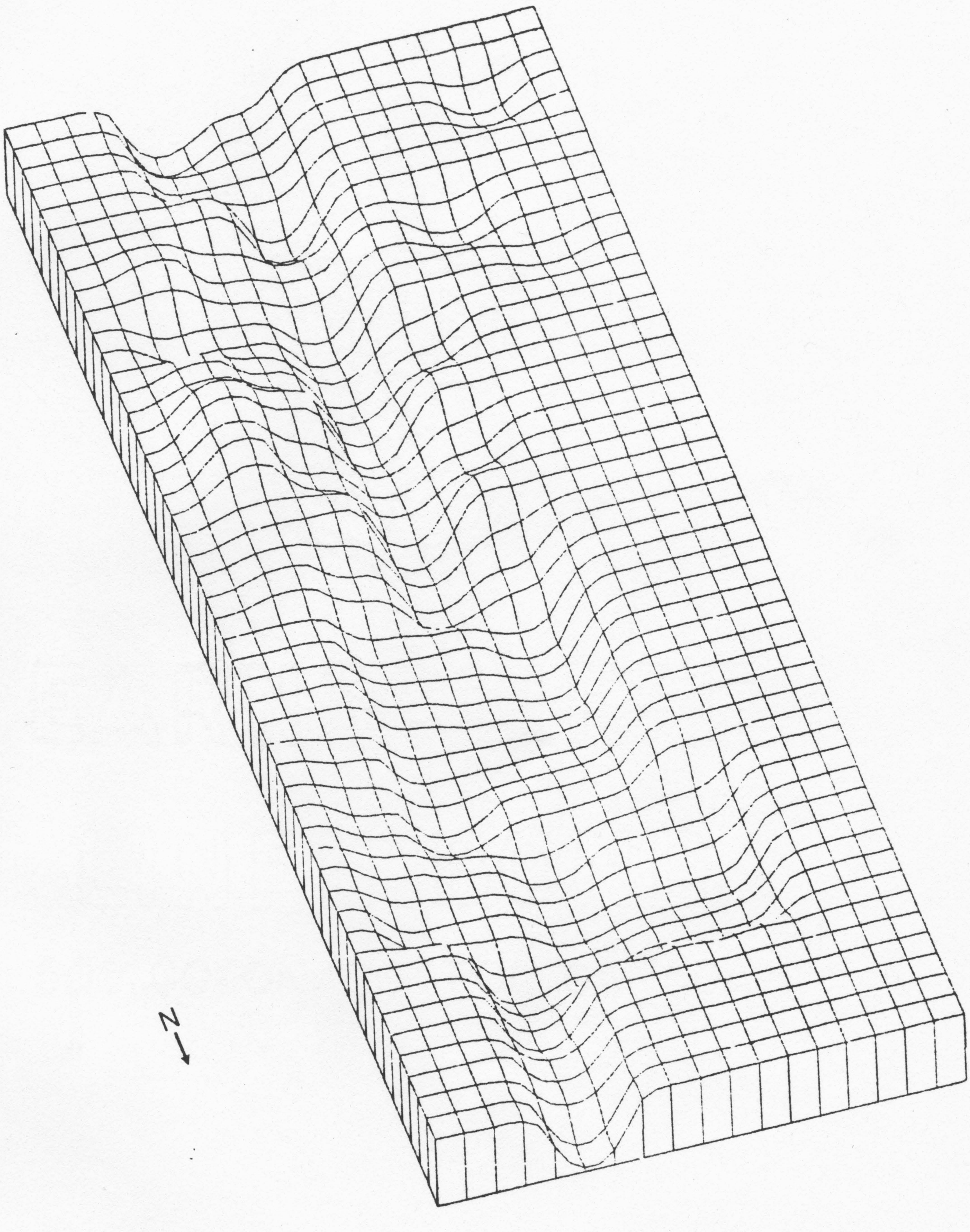

FIGURE 6. Three Dimensional simulation of the Moira River karst.

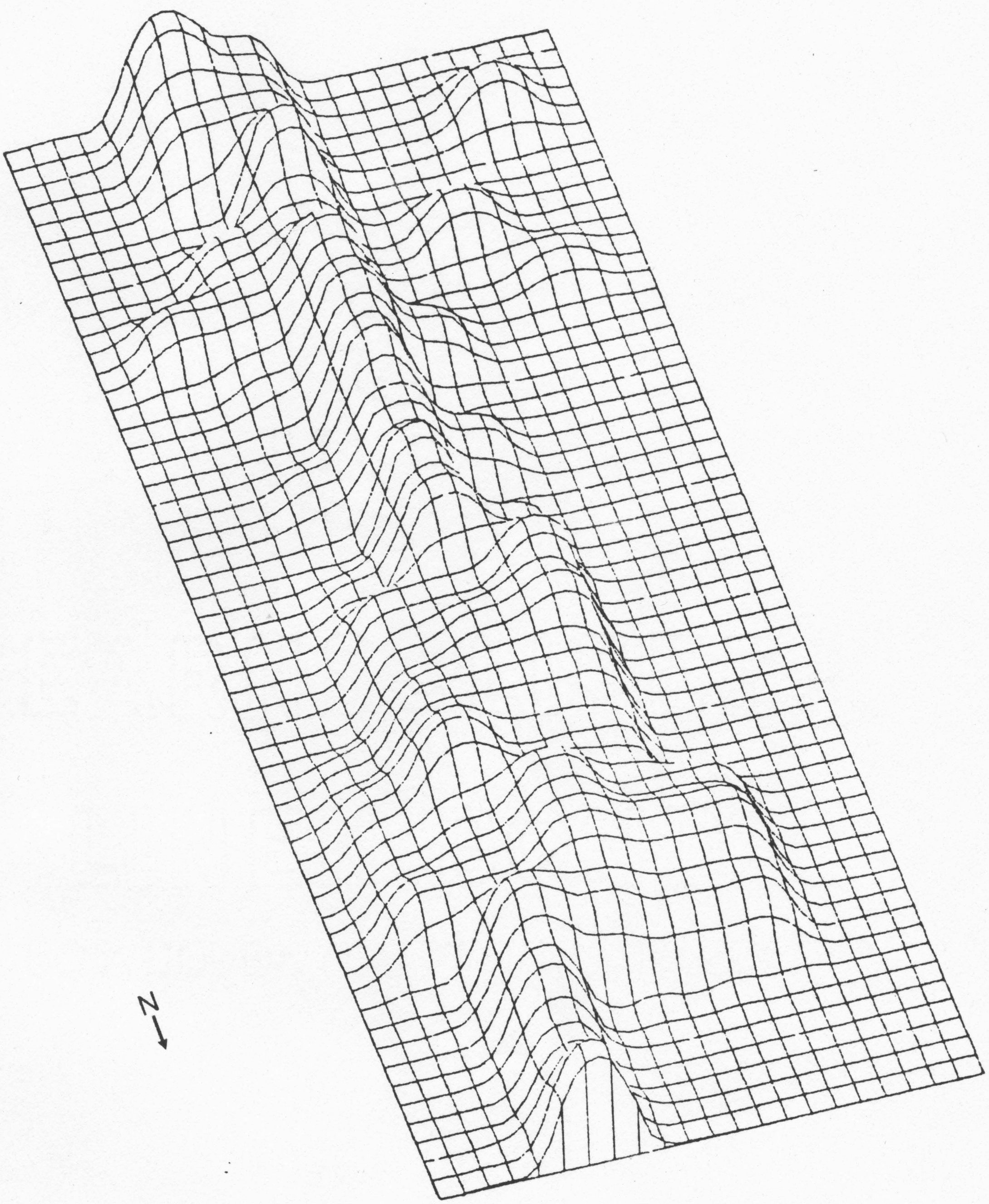

FIGURE 7. Inverted three dimensional simulation of the Moira River karst.

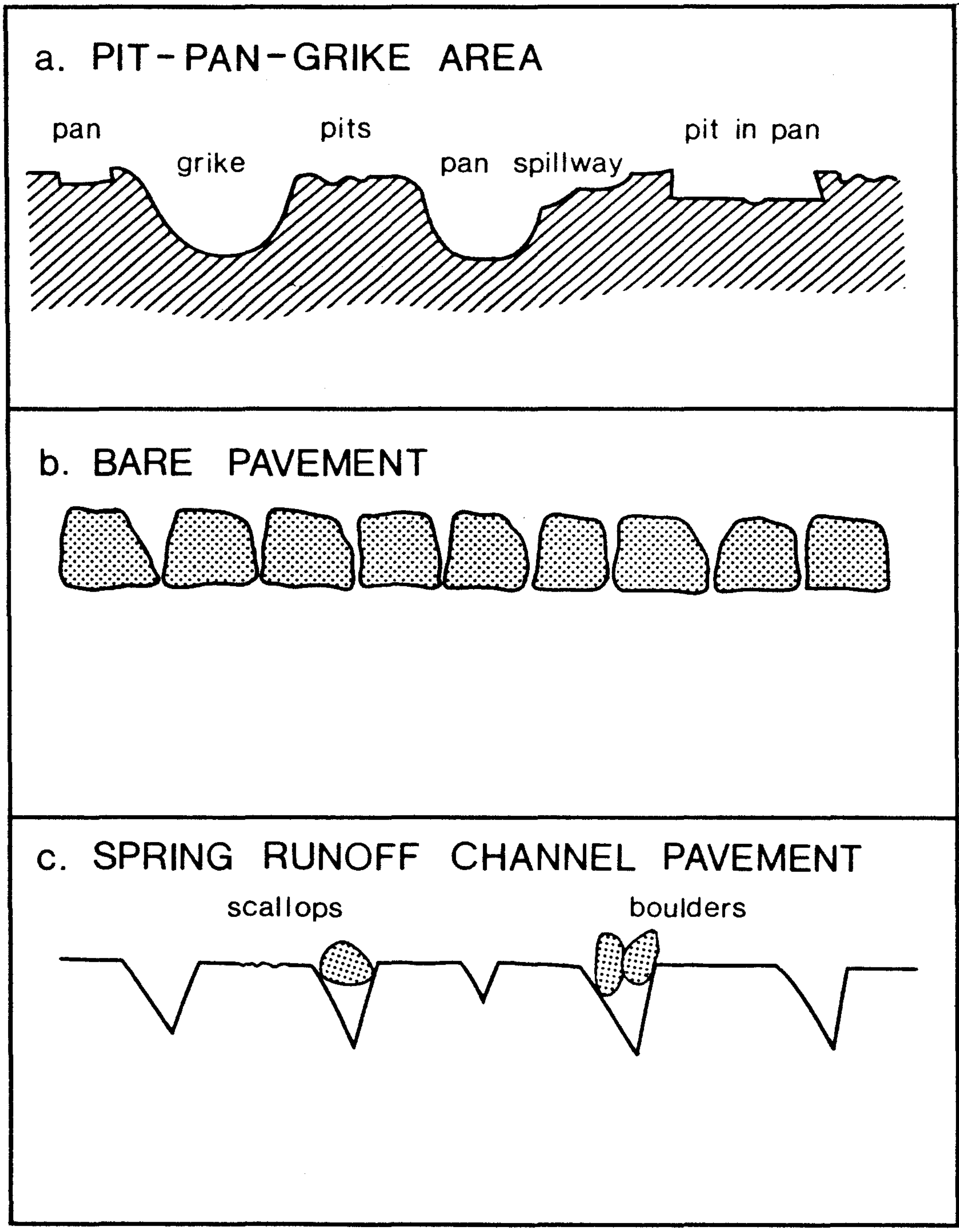

FIGURE 8. Cross-sectional views at Moira River.

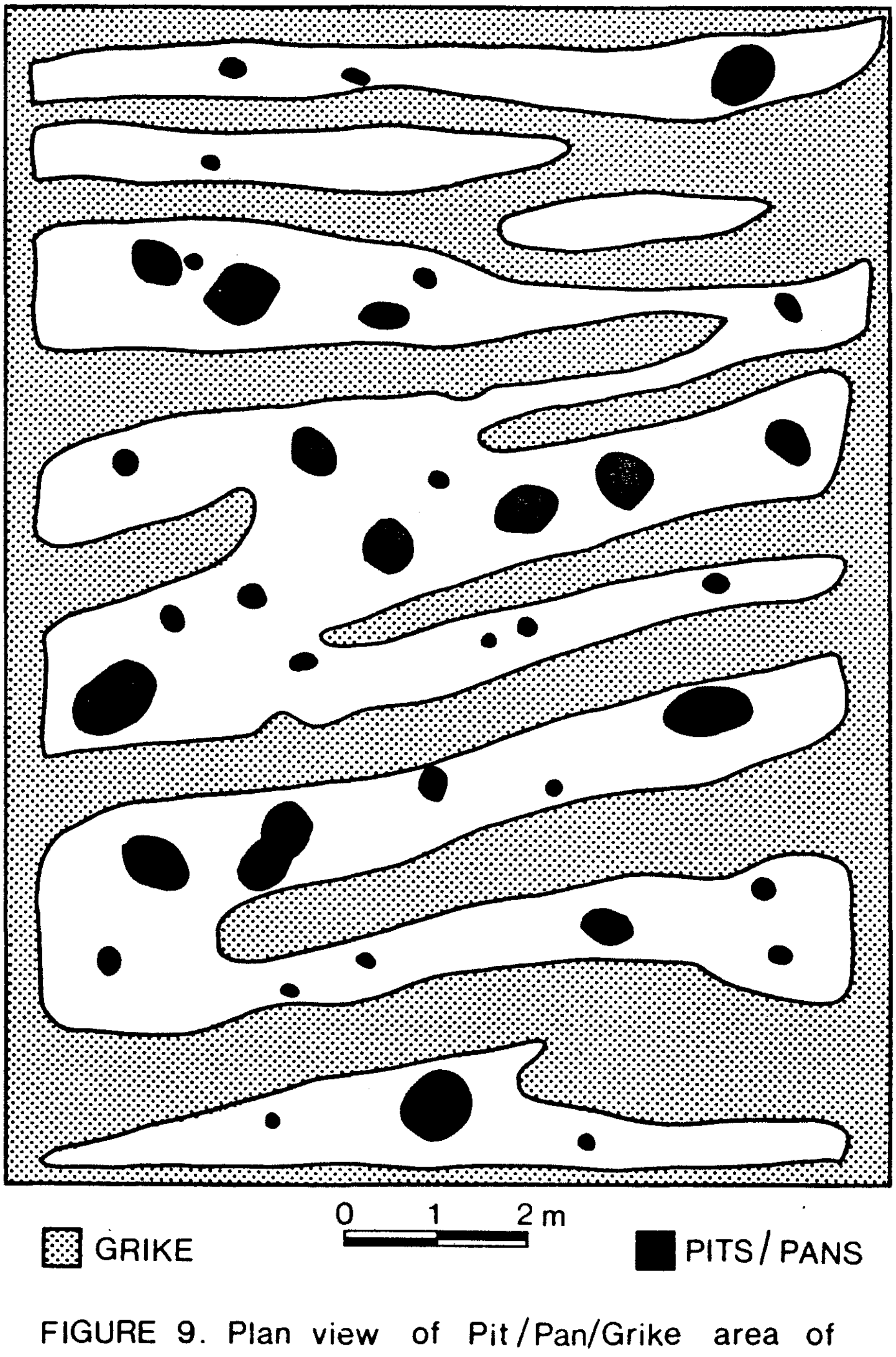

FIGURE 9. Plan view of Pit / Pan/Grike area of Moira River karst.

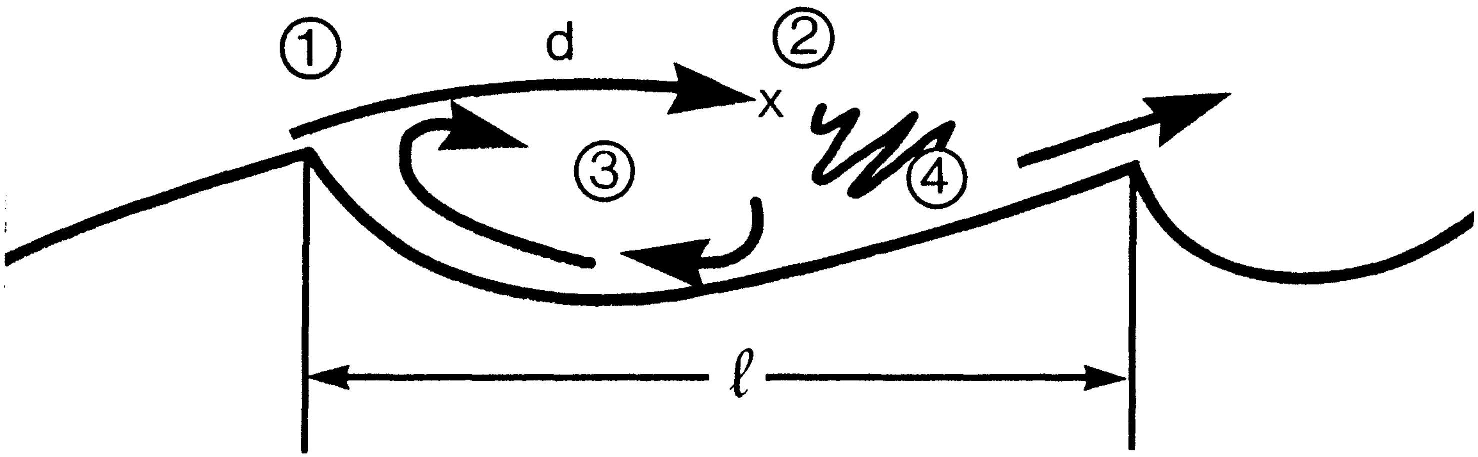

FIGURE 10. Longitudinal Profile and fluid motion in the vicinity of a scallop.

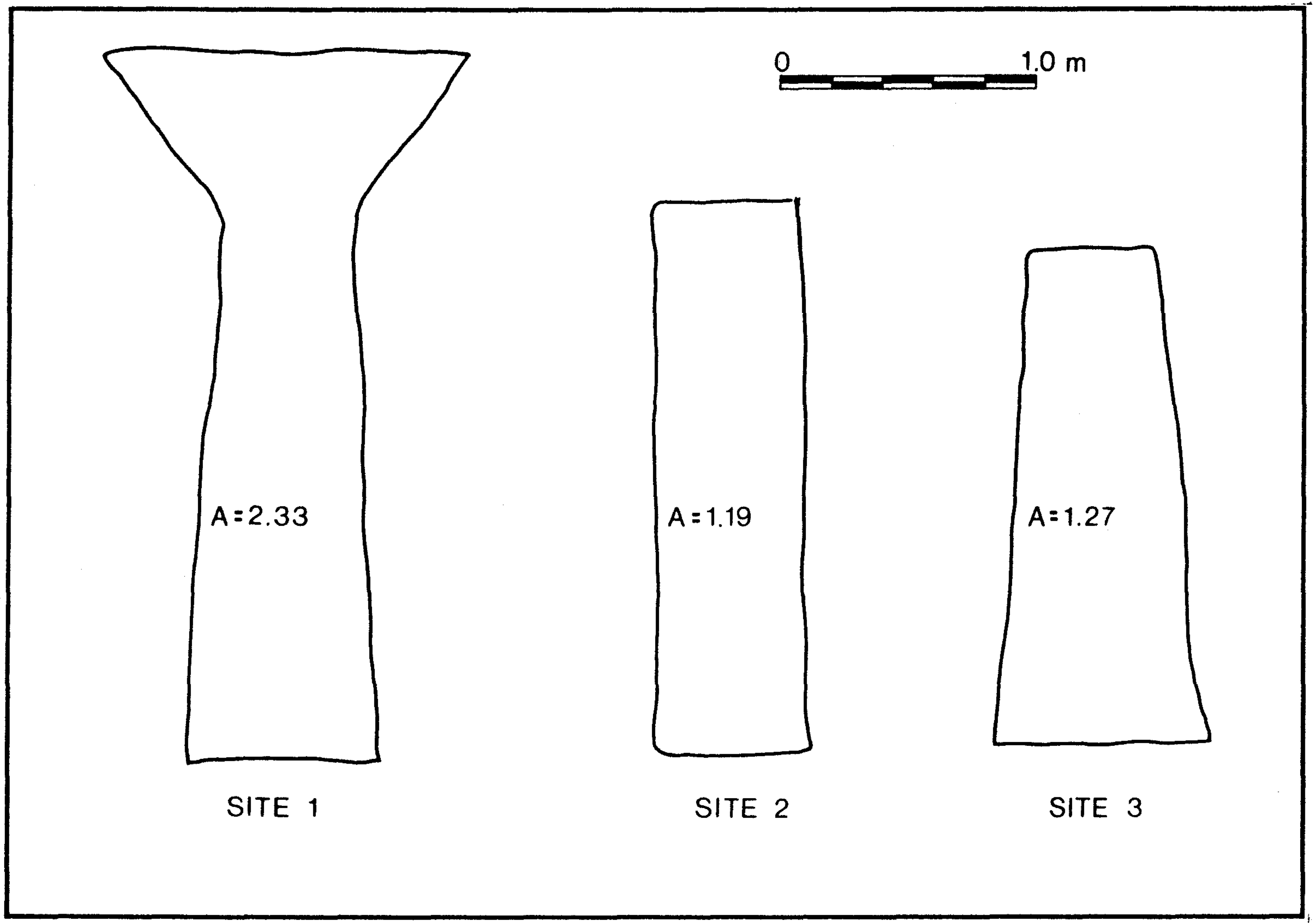

FIGURE 11. Cross-sections of cave passage at Cave One, Moira River.

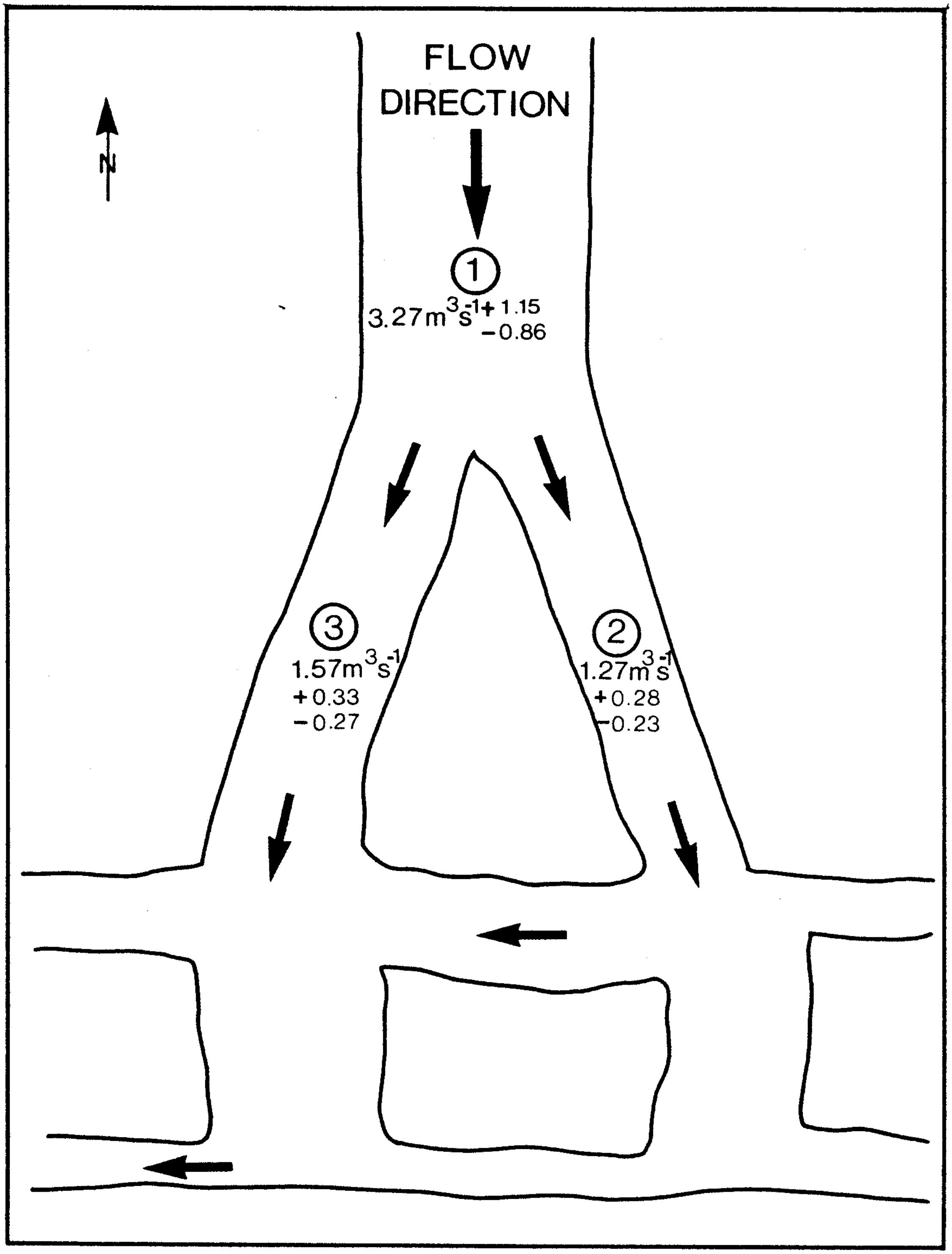

FIGURE 12. Plan view of Cave One, Moira River (not to scale).

Appendix 2

Illustrations

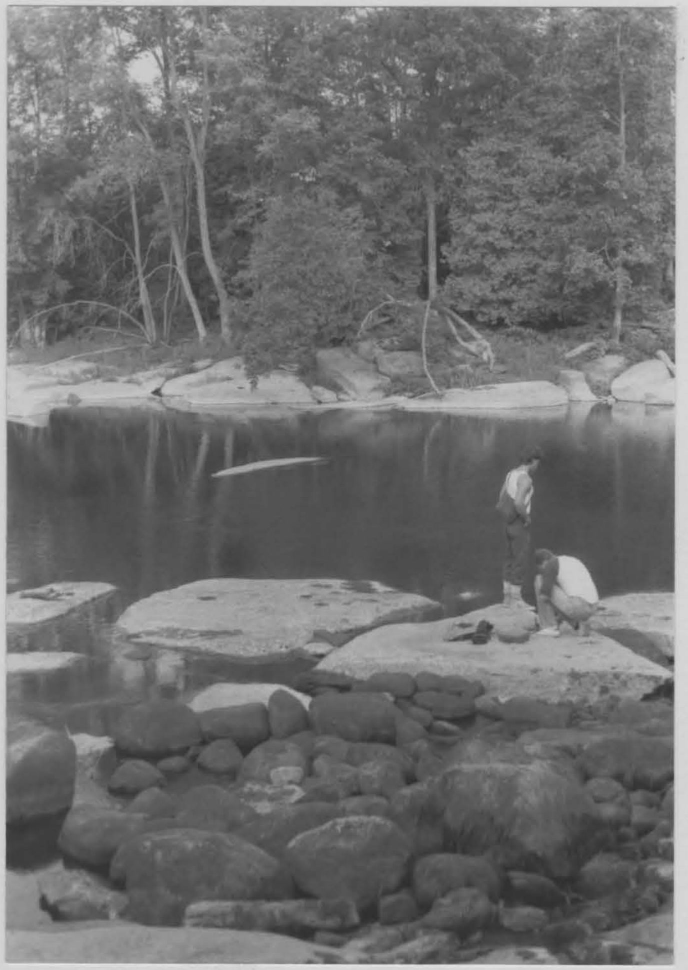

Plate 1 Well defined limestone clints are prominent along the banks of the Moira River. Can see small pits developing on clint to left of people. Note the size of boulders in foreground moved by the river during peak flow.

Plate 2 Spring runoff channel at Line 2, Moira River. Draped karst feature can be seen along channel banks. Limestone pavement on the channel floor shows joint patterns.

Plate 3 Escarpment on west bank of Moira River near Line 2. Note the massive units and the recessive, thinly bedded units found in the escarpment.

Plate 4 Limestone clints in the river are massive and resemble coffins.

Plate 5 Limestone pavement on spring runoff channel at Line 1, Moira River. Grikes are deeper than those seen on runoff channel at Line 2 (Plate 2). Note perpendicular orientation of jointing pattern.

Plate 6 Pits and pans on a limestone clint along the river banks. Pits are coalescing into a larger feature in foreground. Pits are seen in the bottom of some pans. Note blue pen in pan for scale.

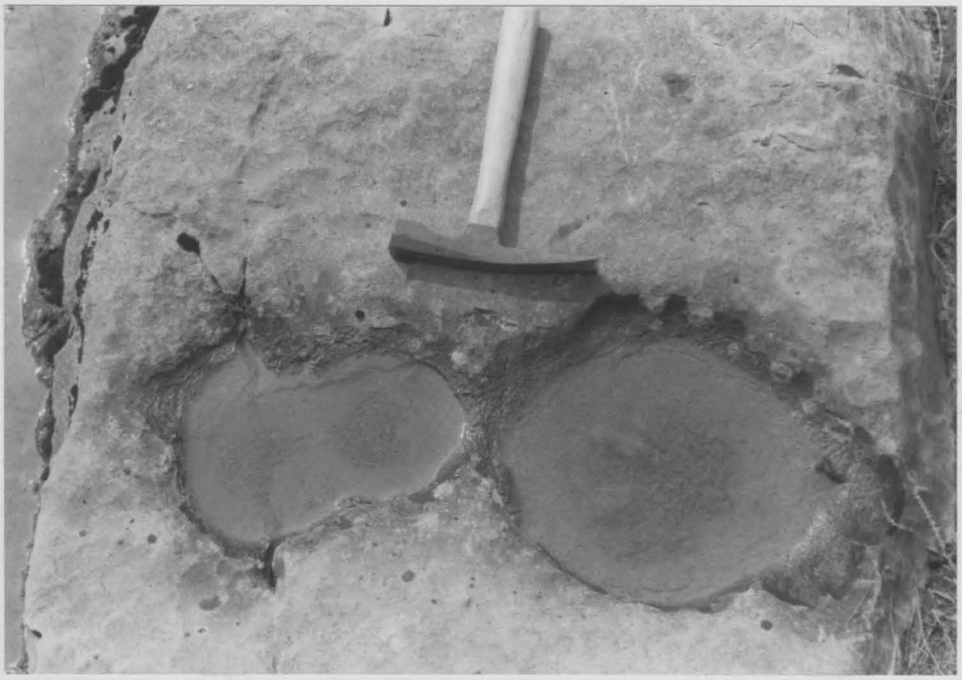

Plate 7 Adjoining pits in the "pit-pan-grike" area. Note irregular rim of pit on the right.

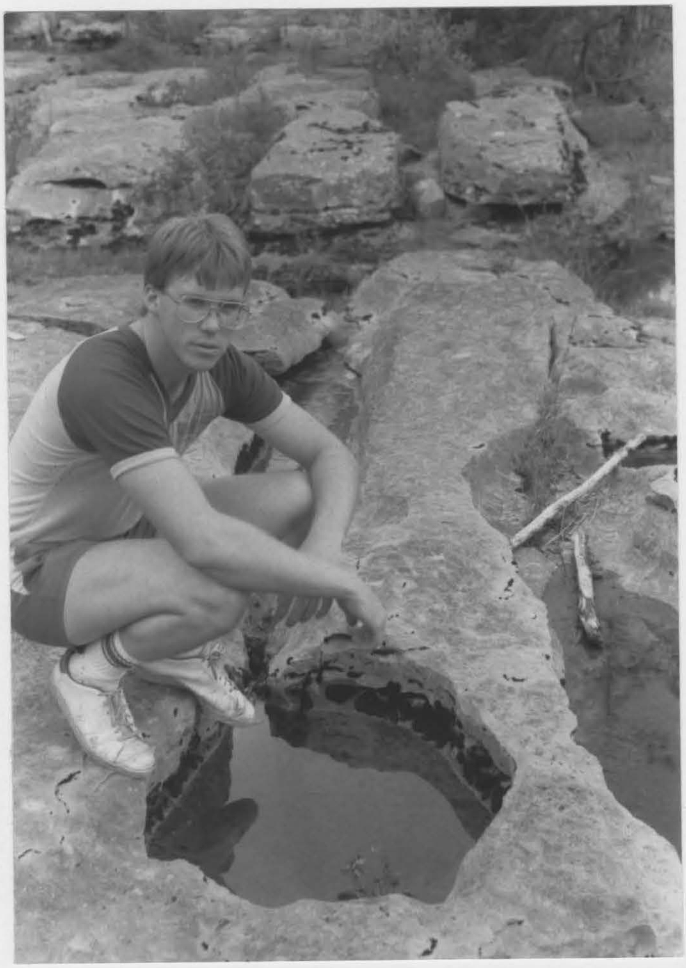

Plate 8 Large solution pan (kamenitza) at the "pit-pan-grike" area, Moira River. Note the moss growth on the vertical sides of the pan. Pan appears to be draining into a grike. In background are some large limestone clints.

Plate 9 Scalloped wall of cave passage at Moira River. Cave is narrow and is a solutionally widened joint within a massive limestone bed.

Plate 10 Anastomoses and pendants formed on the underside of a thin limestone clint on the bank of the Moira River. Some of the anastomoses have almost dissolved right through the thickness of the clint.

Plate 11 Anastomosing channels with resulting pendants along the bank of the Moira River. Note the sharpness of pendants.

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