KARST GEOMORPHOLOGY OF THE BRUCE PENINSULA, ONTARIO

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by

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ABSTRACT

This is the first detailed examination of the karst geomorphology of the Bruce Peninsula. It attempts to review all aspects including pavement phenomena and formation (microkarst features), surface and subsurface karst hydrology (meso to macro scale) and water chemistry. The latter is based on over 250 samples collected in 1973 and 1974.

The dolomite pavement is the best example of its kind that has been described in the literature. It covers much of the northern and eastern parts of the peninsula and can be differentiated into three types based on karren assemblages. Two of these are a product of lithology and the third reflects local environmental controls. The Amabel Formation produces characteristic karren such as rundkarren, hohlkarren, meanderkarren, clint and grike, kamenitzas and rillenkarren on glacially abraded biohermal structures. The Guelph Formation develops into a very irregular, often cavernous surface with clint and grike and pitkarren as the only common recognizable karren. The third assemblage is characterized by pitkarren and is found only in the Lake Huron littoral zone. Biological factors are believed to have played a major role in the formation of the pavement. Vegetation supplies humic acids which help boost the solution process and helps to maintain a wet surface. This tends to prolong solution and permit the development of karren with rounded lips and bottoms.

Three types of drainage other than normal surface runoff are found on the Bruce. These are partial underground capture of surface streams, complete underground capture (fluvio-karst), and wholly vertical drainage without stream action (holokarst). Holokarst covers most of the northern and eastern edge of the peninsula along the top of the escarpment. Inland it is replaced by fluvial drainage, some of which has been, or is in the process of being captured. Four perennial streams and one lake disappear into sinkholes. These range from very simple channel capture and resurgence, as shown by a creek east of Wiarton, to more mature and complex cave development of the St. Edmunds cave near Tobermory. Partial underground capture represents the first stage of karst drainage. This was found to occur in one major river well inland of the fluvio-karst and probably occurs in other streams as well. This chapter also examines the possible future karst development of the Bruce and other karst features such as isolated sinks and sea caves.

The water chemistry presented in Chapter 5 represents the most complete data set from southern Ontario. It is examined on a seasonal basis as well as grouped into classes representing water types (streams, Lake Huron and Georgian Bay, inland lakes, swamps, diffuse springs and conduit springs). The spring analyses are also fitted into climatic models of limestone solution based on data from other regions of North America. It was found that solution rates in southern Ontario are very substantial. Total hardness ranges from 150 to 250 ppm (expressed as $CaCO_3$) in most lakes and streams and up to 326 ppm in springs. These rates compare with more southerly latitudes. The theoretical

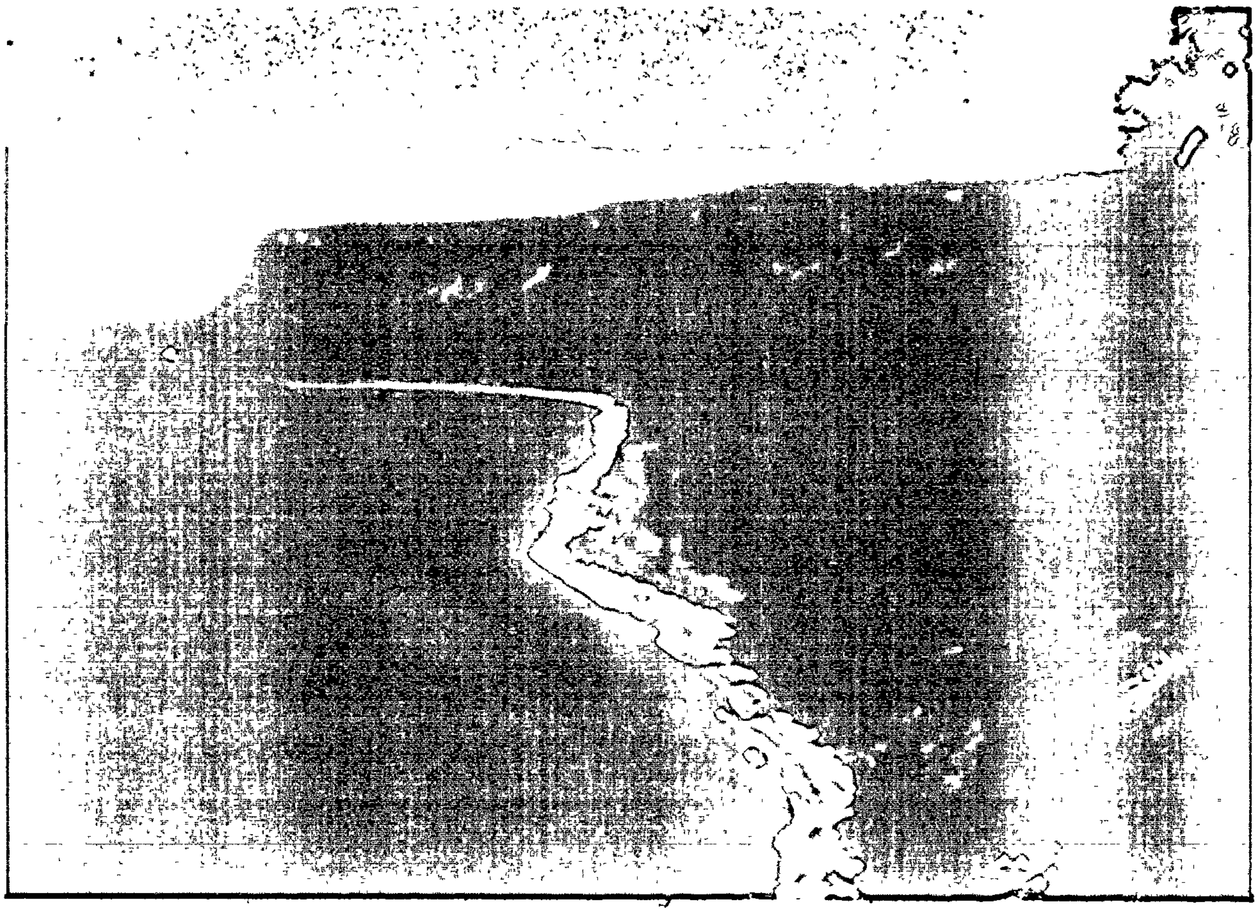
equilibrium partial pressure of CO_2 was found to be the most significant chemical variable for comparing solution on different kinds of carbonates and between glaciated and non-glaciated regions. Except for diffuse flow springs and Lake Huron, the Bruce data do not separate easily into water types using either graphical or statistical (i.e. Linear Discriminant Analysis) analyses. This is partly because of the seasonality of the data and because of the intimate contact all waters have with bedrock.

ACKNOWLEDGEMENTS

I wish to thank my supervisor, Dr. D.C. Ford for his helpful suggestions throughout this work and for his enjoyable informal evening seminar sessions. Although extremely busy he always found time to talk. The Geology and Mechanical Engineering departments at McMaster were helpful in the completion of this thesis. All chemical analyses of rock samples presented in Appendix 1 were performed in Dr. Shaw's atomic absorption laboratory. The Engineering Department's fluormeter was invaluable for proving the dye trace of the St. Edmunds cave.

The Ontario Ministry of Natural Resources was responsible for initiating and funding this study. Special thanks goes to Felix Barbetti, who first requested a karst survey of the Bruce, and to Ernie Martelle and Stan McClellan for the use of Cyprus Lake Provincial Park facilities. I especially wish to acknowledge the caving enthusiasm of the late A.G. Tracey, eventhough he was not too impressed with St. Edmunds. Glen Fisher willingly provided needed field assistance, philosophical discussion and in the interim became a good friend.

Last, but certainly not least, to the person who put up with this for three years, typed the original report, helped in the field and at the light table; the person I couldn't live without - Judy.



FRONTISPIECE Looking east from Rocky Bay toward Cabot Head.

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CHAPTER 1

INTRODUCTION

The Bruce Peninsula is a part of the Niagara Escarpment extending southern Ontario northward into Lake Huron (Figure 1.1). It has also been called the Rocky, Saugeen or Ontario Peninsula (Fox 1952) but the term 'Bruce' is the one by which it is best known. The southern end of the peninsula geographically extends from Owen Sound westward to approximately Southampton on Lake Huron (Figure 1.2). The town of Wiarton, which lies on Colpoy Bay, calls itself the "Gateway to the Bruce Peninsula" and marks the southern boundary of the study area for this thesis. The area thus comprises all of the peninsula north of Wiarton plus the major islands in Lake Huron north of Tobermory. This encompasses about 1,150 square km (445 sq. mi) between latitudes 44°45' to 45°20'N and longitudes 80°50' to 82°30'W.

The peninsula is approximately 70 km (43 mi) long and varies in width from 35 km (22 mi) across the top or the 'tip'o the Bruce' to only 7.9 km (5 mi) between Stokes Bay and Lions Head. Average width is 15 to 19 km (10-12 mi) along much of its length. The northern tip appears to represent a change in the trend of the peninsula from north to north-west as the Niagara Escarpment frames the east and north sides. The topography presents strong contrasts from the abrupt, rugged escarpment shoreline fronting Georgian Bay and reaching a maximum height of just

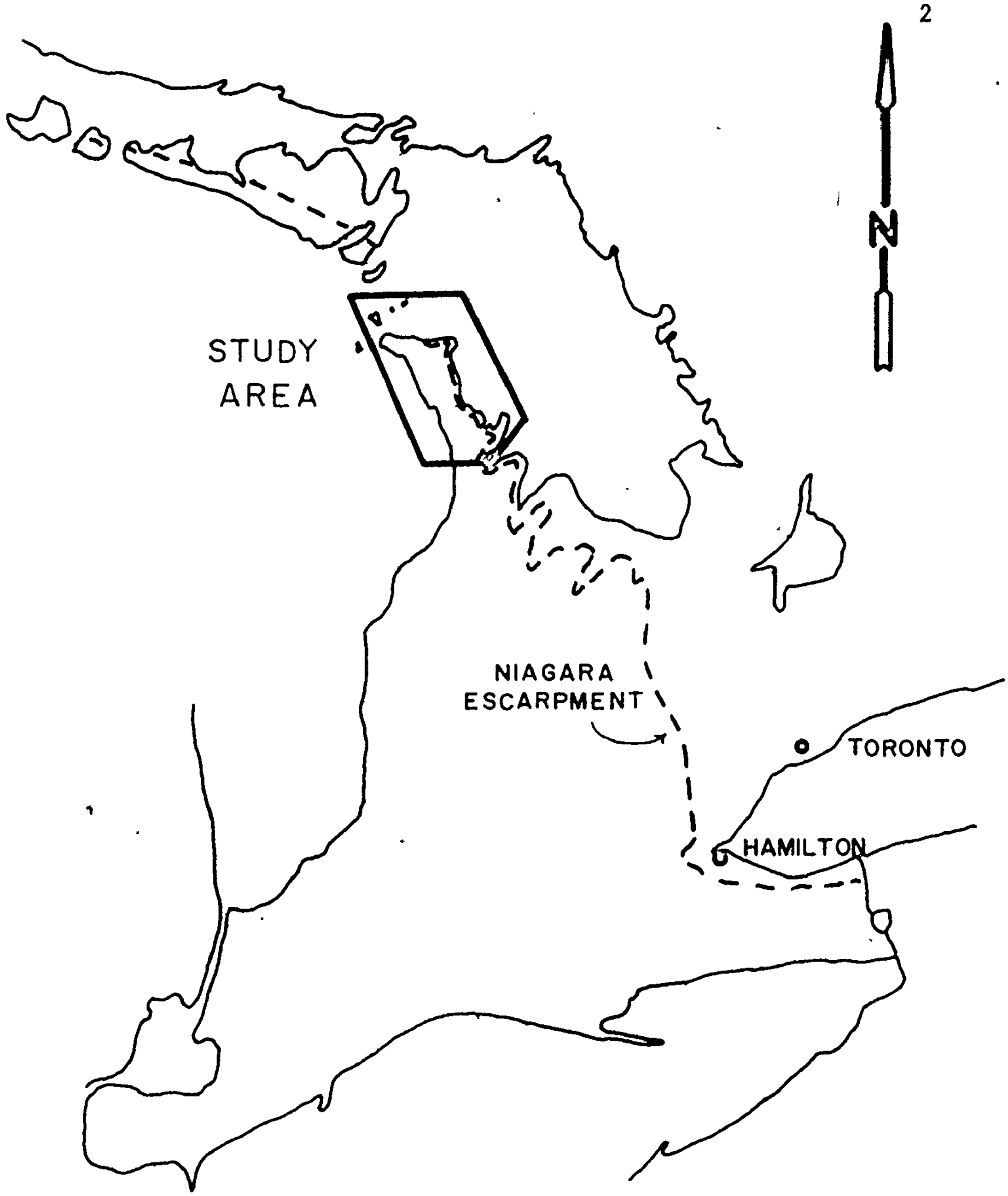

FIGURE 1.1 Location of study area.

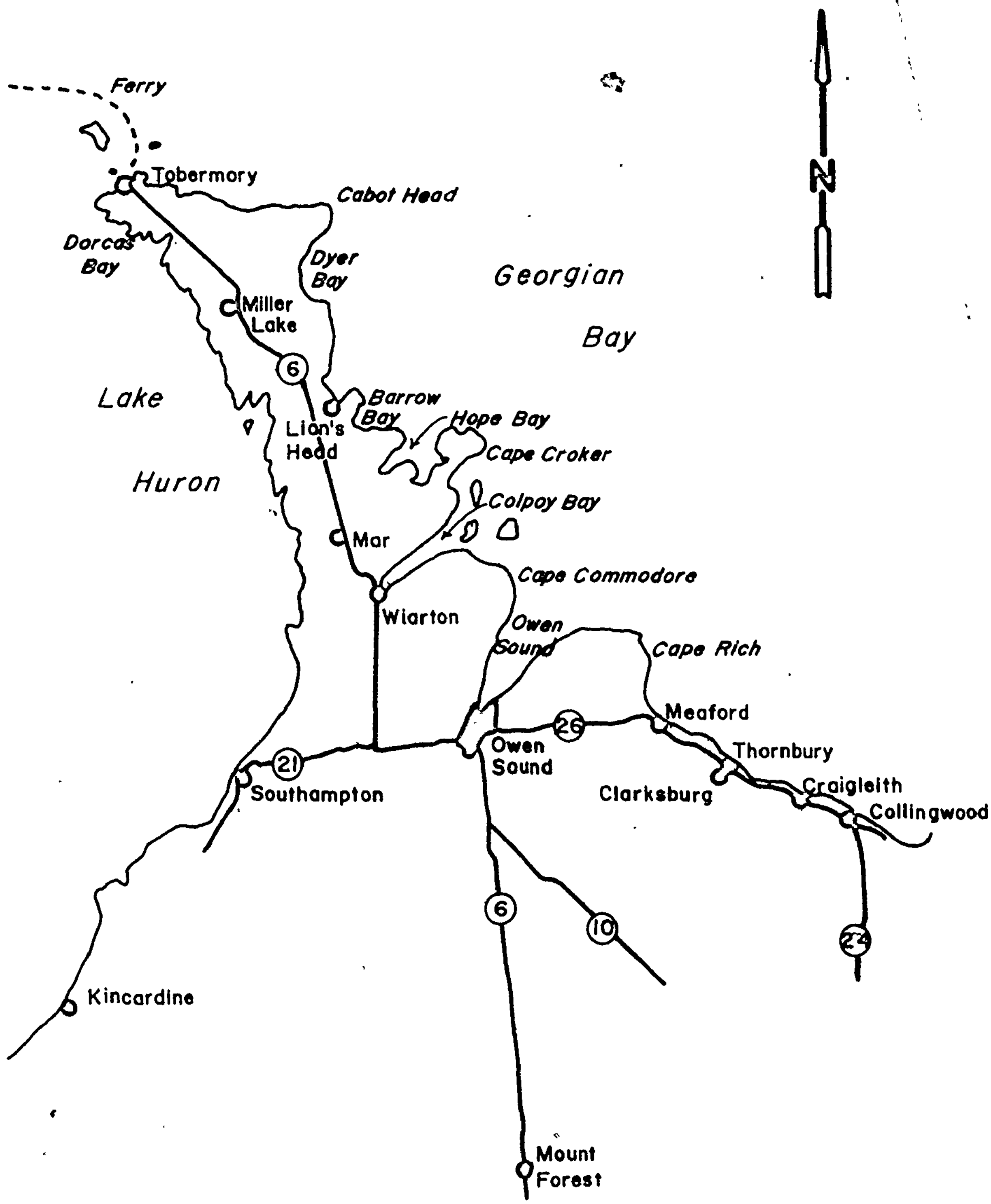

FIGURE 1.2 The Bruce Peninsula.

over 975 ft a.s.l. to the very gentle, poorly drained Lake Huron shoreline at about 585 ft a.s.l. (Figure 2.5). The maximum relief is thus about 400 ft (122 m). The escarpment itself varies in elevation being between 800 to 975 ft a.s.l. on the prominent bluffs but becoming much lower in bay-heads and toward Tobermory. On the east side of the Eastnor Clayplain at Lions Head the escarpment is all but missing altogether.

Settlement of the peninsula began in the late 1800's during and following extensive logging operations from about 1850 to 1900 (Fox 1952). Excellent stands of red, white and jack pines, along with white and black spruce, white cedar, maple, birch, beech, red oak and basswood were shipped to the lower Great Lakes. Logging was accompanied and succeeded by large forest fires and thus the present dominant vegetation is a secondary, though dense, growth consisting primarily of white cedar with some birch and aspen. The Bruce lies in the Transition Forest zone between the species of the northern Boreal Forests and the Eastern Deciduous Forests of southern Ontario.

Agriculture is limited in extent and is confined to marginal farming and beef cattle due to a lack of overburden. The extensive logging operations probably resulted in severe erosion of the already limited soil cover. The majority of the peninsula is classed as Breypan by the Bruce County soil survey report of 1954 (University of Guelph). It is described uncompromisingly as having "no capability for arable culture or permanent pasture due to stoniness, rockland and soils which are less than 1 m above bedrock" (Environment Canada, Canada Land Inventory, 1968). Local pockets of till, glacio-fluvial deposits and lacustrine sediments permit patchy agricultural development. The largest such deposit is the Eastnor Clayplain which occupies much of Eastnor township (Figure 2.4). This is a poorly drained lacustrine plain (now artificially drained) deposited during the Nipissing stage of the postglacial Great Lakes.

In recent years the Bruce Peninsula has become a popular area for recreation. It is within a 2 to3 hour drive of the major metropolitan areas of southern Ontario and is one of the least developed areas in this part of the province. Cottage developments can be found along Lake Huron, Georgian Bay and many of the inland lakes. The Niagara Escarpment, together with the Bruce Trail, is a very popular recreational attraction.

Wiarton (population 2,200) is the largest community on the Bruce Peninsula followed by Lions Head (about 250) and Tobermory (about 200). These originated as fishing ports and for shipping timber. Wiarton was the main access and distribution centre being the only community served by a rail line. However, this has since been removed. The city of Owen Sound lies southeast of Wiarton. It is the largest community on Georgian Bay (population 18,000) and is an important ship building centre.

The climate is Dfb according to the Köppen-Geiger climatic classification (Strahler 1969). That is, a cool temperate climate with the warmest mean monthly temperature greater than 10°C (50°F) and less than 22°C (71.6°F) and at least four months with means above 10°C. Table 1.1 shows the temperature and precipitation statistics at Tobermory, Wiarton and Owen Sound. Precipitation may occur at any time being derived mainly from westerly cyclonic storms. Snow cover is usually continuous all winter which lasts from mid-November till April, although short

TABLE 1.1

Yearly Mean Temperature and Precipitation Statistics for Tobermory, Wiarton Airport and Owen Sound (from the Temperature and Precipitation Tables for Ontario Vol. 4)

	TOBERMORY (45°15'N,81°41'W) 600'a.s.l.	WIARTON (44°45'N,81°06'W) 720'a.s.l.	OWEN SOUND (44°34'N,80°55'W) 597'a.s.l.
Mean daily temp.°F(°C)	43.8 (6.5)[1]	43.7 (6.5)[2]	44.5 (6.9)[1]
Mean daily max.temp.°F(°C)	50.6 (10.3)[1]	51.4 (10.8)[2]	53.4 (11.8)[1]
" " min. " "	36.9 (2.7)[1]	35.9 (2.2)[2]	35.5 (1.9)[1]
Mean rainfall ins(cm)	25.7 (65.3)[1]	24.98(63.4)[3]	24.7 (62.7)[1]
Mean snowfall ins(cm)	78.9(200.4)[1]	118.6(291.2)[3]	107.9(274.1)[1]
Mean total precip.ins(cm)	33.6 (85.3)[1]	36.8 (93.5)[3]	35.5 (90.1)[1]

1. period of record 25 yrs to 30 yr. from 1931 - 1960.
2. 10 yr. record, 1951 - 1960 adjusted to standard normal period 1931 - 1960.
3. 10-24 yr. record, 1931 - 1960 with no adjustment factor.

sudden thaws are common. The winter of 1974-75 was especially mild, preventing Georgian Bay from freezing even along the shore and maintaining high flows in most streams.

This thesis represents the first attempt to describe and quantify the karst landforms and processes of the Bruce Peninsula. It was in part initiated by the Ontario Ministry of Natural Resources in order to inventory and preserve significant earth science features of the Niagara Escarpment. The author worked in conjunction with the Owen Sound District of the Ministry during the field seasons of 1973 and 1974 to gather information to be used for planning purposes in the district as well as a basis for this thesis (Cowell 1974). During that time karst features were systematically examined throughout the Bruce and detailed water chemistry surveys were set up.

In 1973 the study was concentrated in the northern part of the peninsula, north and west of Dyer Bay. It included a detailed hydrochemical investigation of the seasonal variation in the water chemistry of various water types (e.g. streams, springs, lakes and swamps). Nineteen sampling stations were established and samples were taken more or less continuously from June until December, 1973. Major karst features and systems were located, described and where applicable, traced with fluorescent dye.

During 1974 the remainder of the peninsula was studied. Water samples for hydrochemical analysis were taken on a spot-sample basis except for temporal and depth surveys at selected sites.

1.2 Karst and Previous Studies in Ontario

Although most of southern Ontario is underlain by carbonates (Ordovician to Devonian) karst landforms are not well represented. Those which have been found are almost entirely postglacial (<10,000 yr. old) and are generally immature. This is not due to a lack of solution by surface and groundwaters as these have high hardness loads wherever they are in contact with carbonate rocks (Cowell and Ford 1975, Jeffs and Hore 1972). The main reasons for poor karst development can be attributed to the lack of thick carbonate sections, a large number of shale interbeds and thick shale sequences (particularly in the Ordovician), and the presence of dolomite (particularly in the Silurian), which is slightly less susceptible to solution than limestone. Karst features which may have developed prior to the Pleistocene period were probably of only local extent (although not necessarily) and were removed by the ice. Thick glacial deposits averaging 75 to 100 feet thick in southern Ontario (Chapman and Putnam 1966) have also served to limit karstification. Consequently there has not been a great deal of research into karst morphology and process in Ontario.

The greatest concentration of karst features of all scales may be along the Niagara Escarpment, especially in the Bruce Peninsula area. The escarpment is one of the most prominent of landforms in southern Ontario and has received the greatest attention in the literature in Ontario with respect to karst landforms. The escarpment is created by the presence of a dolomite caprock which is mechanically stronger than underlying strata. The solubility of the caprock combined with locally high hydraulic gradients near the escarpment edge has aided karst development.

One of the first published accounts of caves in Ontario was by Panton (1887). He briefly described a cave in the Eramosa River gorge at Rockwood, just west of the escarpment near Guelph. Hitchcock (1949) located and very briefly described several caves in eastern Canada including about 14 from Ontario. He included the Rockwood Cave, as well as several others on the escarpment. He listed three areas of caves on the Bruce Peninsula, including Flowerpot Island, Mar near Berford Lake and others east of Wiarton on Colpoy Bay (Bruce's Caves). Weber (1960) again described the Rockwood cave plus five others in the Eramosa Gorge. He showed the locations of ten areas on the escarpment where caves are found and noted caves at Lions Head, Hope Bay and east of Wiarton on the Bruce Peninsula. The Hope Bay cave was the only one he considered in any detail. He presented a plan diagram of the cave and mentioned the presence of abundant flowstone and speleothems in a rear upper chamber. This proved detrimental because numerous people in the early 1960's went speleothem hunting following the publication of this article. Limestone caves in a small gorge on the Bonnechere River in eastern Ontario were investigated and reported upon by Ford (1961). These are a type of by-pass cave, parallelling the main river at different levels. Part of these caves are used as commercial caves. Reider and Grove (1964) briefly described 3 caves along the north shore of the Bruce Peninsula. They did not show the locations of the caves very well but from their brief description of the area and the caves they were probably looking at wave cut caves near Cyprus Lake Provincial Park and Cave Point (Section 4.4.3). The most complete listings of karst features including caves and sinkholes, for Ontario were made by Ongley (1965) and Ford and Quinlan (1973). Ongley, however, merely listed 8 sites on the Bruce Peninsula which he did not discuss other than for giving locations, poor at that. Ford and Quinlan listed five of these sites including Flowerpot Island, Cyprus Lake Provincial Park (Horse Lake), Gillies Lake, Hope Bay and Hepworth (south of Wiarton). They accurately located the features, listed known references, briefly described and considered the significance (in a Canadian context) of each area.

These papers, where the Bruce Peninsula is concerned, do not make any attempt to systematically describe nor discuss genesis of the karst. Instead they simply list and in some cases give general morphologic information, usually from an exploration point of view. Ford and Quinlan made the only attempt to obtain a systematic listing of all karst features, not just caves, from a geomorphological perspective.

Small-scale karst features known as karren or lapies have not been studied very much at all. Packer (1965) discussed a few examples of what he called 'lag mound features' on the dolomite pavement of the Bruce Peninsula. These are simply residual soil mounds on the top of pavement blocks (clints) which thin toward solutionally widened joints (grikes) due to slumping of the soil into the joints. He claims that their development is directly related to removal of the forest cover during logging operations on the Bruce in the late 1800's. Karren forms were described in detail by Pluhar (1966) and Pluhar and Ford (1970) on dolomite pavement near the edge of the Niagara Escarpment at Hamilton, about 175 km (110 mi) south of the study area. These two papers will be considered in more detail in Chapter 3.

The most recent study of karst landforms, and the first to report upon measured solution processes in the dolomites was by Cowell (1973) and Cowell and Ford (1975). This was a detailed study of a small creek which disappeared into the side of a rôche moutonnée and reappeared on the face of the escarpment in two main spring complexes. It lies southeast of the study area in the Beaver Valley, near the village of Kimberley. The springs also drain a small but well developed and complex assemblage of sinkholes. The whole system was initiated as a result of certain glacial features in the area and thus is considered as a glacio-karst. It is still in a youthful stage because the system is inaccessible and floods out the sinkhole plain during spring freshet. At that time of the year the sinkholes overflow and drain into another creek which was formerly fed by Wodehouse Creek. The sinkholes are referred to as suffosion sinkholes which means they have most of their topographic expression in the till mantle. Solute concentrations are high (250 - 300 ppm total hardness) but are derived predominantly from the calcareous till. There is however a substantial increase in hardness between the sinks and springs, particularly in late summer and early fall (20 to 30 ppm). The hydraulic gradients for this system are 21:1 for the nearest spring and 35:1 for the furthest.

CHAPTER 2

PALEOZOIC AND QUATERNARY GEOLOGY OF THE BRUCE PENINSULA

2.1 Paleozoic Geology

The stratigraphy of the Bruce Peninsula is shown in Table 2.1 and Figures 2.1 and 2.2. It consists of carbonate and shales of Ordovician and Silurian age. The carbonates are almost entirely dolomites but minor limestone does occur, particularly interbedded with the Ordovician shales. Most of the bedrock surface of the peninsula is composed of pure dolomites of the Guelph and Amabel formations with the former most prominent in the west and north. The remaining formations shown in Figure 2.1 and 2.2 outcrop only at the foot of the Niagara Escarpment. The Guelph and Amabel units thus form a soluble dolomite plain perched on shale and bounded on the north and east by an escarpment. This is the basic geological framework upon which karst processes are currently operating.

The Bruce Peninsula makes up part of the northeast rim of the Michigan sedimentary basin. The basin is centred in the state of Michigan and encompasses parts of New York, Ohio, Indiana and Wisconsin as well as all of southwestern Ontario, including Manitoulin Island. It is one of a series of basins and domes which developed during the Paleozoic on the crystalline Precambrian basement known as the Canadian

TABLE 2.1

Stratigraphic Classification for the Bruce Peninsula

(after Bolton 1957, Liberty and Bolton 1971)

System	Subsystem	Series	Group	Formation / Member		Karst +
SILURIAN	MIDDLE	NIAGARAN	Albemarle	Guelph		///
				Amabel	Eramosa	|||
					Colpoy Bay-Wiarton	///
					Lions Head	///
			Clinton	Fossil Hill		|||
				Cabot Head	St. Edmunds	
	LOWER	ALEXANDRIAN	Cataract		Wingfield	
					Dyer Bay	|||
					Cabot Head	
				Manitoulin		|||
ORDOVICIAN	UPPER	CINCINNATIAN		Queenston		
			Nottawasaga	Georgian Bay	Upper Lower	

\+ Formations (Members) affected by karst process.

/// very susceptible to karstification

||| dolomitic (may act as a karst aquifer) but do not form characteristic karst features

☐ no karstification

Shield. The strata of the Michigan Basin are more than 1500 m (5000 ft) thick at their greatest (beneath Lake Erie - Poole et al., 1970) and were deposited within fluctuating epeiric seas. Such seas periodically covered most of central North America from the Cambrian to Cenozoic times, transgressing from the west. Sediment was supplied to the basins from the shield uplands to the north and the Appalachian Mountains in the east and southeast (Clark and Stearn 1968).

The basin area was rapidly subsiding during the Silurian, particularly in the Niagaran Seas. This resulted in the formation of bistromal and bioheŗmal reefs along the shallower rim (Poole et al., 1970). The Guelph and Amabel Formations of the Bruce Peninsula and Manitoulin Island are characterized by extensive reef complexes. Coral bioherms of the Guelph are up to 25 m (80 ft) high (Liberty and Bolton 1971) and have had a profound affect on quaternary erosion. During the latter stages of the Silurian and into the Devonian the Michigan Basin was partially cut off from circulation and high-saline waters occurred. Limestone, gypsum and halite were deposited at this time, especially in the central parts of the basin.

The deposition of gypsum in evaporite conditions greatly increases the Mg/Ca ratio in seawater as Ca^{++} is precipitated out of solution (Blatt, Middleton and Murray 1972). It was probably at this time that the lower and middle Silurian carbonates of the study area (Manitoulin to Guelph Formations) were regionally dolomitized. These domomites have a consistent chemical composition throughout southwestern Ontario wherever they have been analysed (see Appendix 1). They are Ca-rich dolomites having the general formula $Ca_{1.2}Mg_{0.8}(CO_3)_2$, the subscripts denoting molar ratios (Cowell 1973, Hewitt and Vos 1972).

The solid geology of the Bruce Peninsula has been studied by several authors. One of the earliest was Williams (1919) followed by Caley (1945, 1947), Bolton (1953, 1957), Sanford (1961, 1964, 1969), Liberty (1966) and Liberty and Bolton (1971). A good summary is also given in Poole et al (1970).

Figure 2.2 is the stratigraphic column of the lithostratigraphic formations which outcrop on the peninsula. The bedrock of the study area has been divided into seven formations based on lithostratigraphy (Liberty and Bolton 1971). Their distribution is shown in Figure 2.1. Due to the scale of mapping the Manitoulin and Cabot Head formations were mapped as a single unit as were the Fossil Hill and Amabel formations. The strata are nearly horizontal with a primary dip of only 5.6 m/km (30 ft/mi) to the southwest. A secondary dip to the northwest has been superimposed on this making the true dip westerly or slightly north of west. The secondary dip is a result of the Algonquin Arch which is a structural high that trends NE to SW across southern Ontario, south of Georgian Bay. The Paleozoic strata drape over the arch to the NW and its affect on the study area can be seen in Figure 2.1. On this map younger strata outcrop in the southwest and in the northwest (secondary dip). For example, at Cape Croker the oldest strata in the study area, the Georgian Bay Formation, outcrops at lake level. However, to the southwest at Oliphant and to the northwest at Tobermory the youngest formation (Guelph) is found at lake level.

The closing of the Ordovician in Ontario is marked by the Queenston Formation. It is described by Liberty and Bolton (1971) as

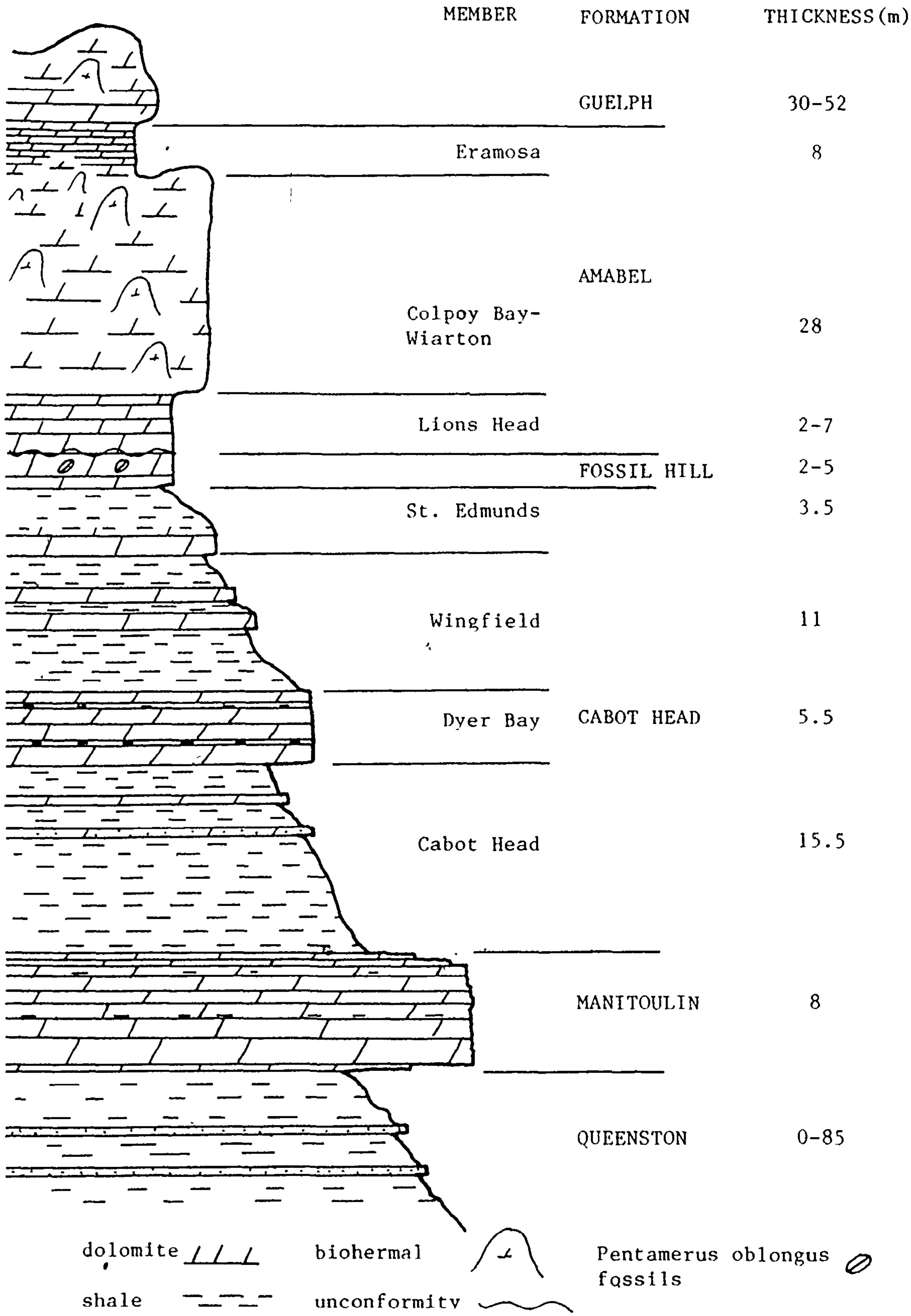

FIGURE 2.2 Composite stratigraphic column for the Bruce Peninsula after Liberty and Bolton, 1971 (not to scale).

consisting of "brick red, thinly bedded, micaceous and arenaceous shales and clay shales". Green shales may also be present. It is 85 m (280 ft) thick southeast of the peninsula and thins toward the northwest to around Tobermory where it is replaced by intertonguing carbonate beds extending south from Manitoulin Island (Liberty and Bolton 1971).

The Manitoulin Formation is a grey to bluish-grey argillaceous dolomite with shale partings. It weathers into thin, flaggy beds, brown to dark grey in colour and averages about 8 m (26 ft) thick in the study area (Plate 1).

Throughout most of the Bruce the Cabot Head Formation has four members while south of the study area the whole formation resembles its lower member and cannot be subdivided. At Rocky Bay, west of Cabot Head it is composed of 34 m (113 ft) of calcareous red and green shales plus thin argillaceous dolomite interbedded with shale (Figure 2.2). The Dyer Bay and St. Edmunds members of this formation are the most dolomitic. The dolomite is impure and appears bluish to brownish grey in outcrop.

The Fossil Hill Formation is a grey to tan, fine crystalline dolomite which is extremely fossiliferous (Plate 2). It is composed entirely of the brachiopod _Pentamerus_ _oblongus_ in many outcrops (Liberty and Bolton 1971). Bedding thickness varies from thin to massive and its overall thickness ranges from 2 to 4.5 m (6 to 15 ft).

The main caprock and scarp former of the Niagara Escarpment is the Amabel Formation. It, and the Guelph Formation are the purest carbonates of the Bruce Peninsula and the most susceptible to karst processes. The Guelph Formation usually outcrops back from the edge

Plate 1 Contact of the Manitoulin (top) and Queenston formations southeast of the study area near Meaford. The Manitoulin weathers into a very 'dirty', flaggy dolomite which is not very susceptible to karst processes. Springs are occasionally seen at this contact. (note hammer, lower centre, for scale)

Plate 2 Contact of the Fossil Hill (top) and Cabot Head formations near Owen Sound. The Cabot Head shales are a major acquiclude on the Bruce Peninsula and numerous springs occur along this contact.

of the escarpment but does cap the escarpment just north of Lions Head and along the north shore of the Bruce Peninsula. These two formations are generally referred to as the Niagaran Dolomites and on the Bruce Peninsula present a maximum thickness of up to 100 m (330 ft). They are best displayed on the bluffs at Cabot Head.

The term "Amabel" was proposed by Bolton (1953) for the thick succession of dolomites found at Wiarton in Amabel township. They can be divided into 3 members; the Lions Head, Colpoy Bay-Wiarton and Eramosa. The Amabel Formation is laterally equivalent to the Lockport Formation of the Niagara Peninsula but presents a facies change to massive biohermal strata and an overall increase in thickness north of Hamilton (Plates 3 and 4).

The Lions Head member is a blocky, dense, dark brown weathering, white dolomite in beds of 5 to 15 cm (2 to 6ins). It is characteristically well-bedded and jointed and hence its blocky nature.

The Colpoy Bay-Wiarton member is a massive biohermal member with locally thin-bedded interreefal strata. It is this unit which generally forms the top of the escarpment as it is very resistant to mechanical erosion. Colpoy Bay-Wiarton dolomite is very pure, light-grey with blue-purple mottling, fossiliferous and coarse-to fine-grained.

The uppermost member, the Eramosa, is a thin-bedded, grey to light brown dolomite usually bituminous and having a petroliferous odour. It is believed that it is mainly an interreefal deposit, and on the Bruce Peninsula is thought to be time transgressive between the Colpoy Bay-Wiarton and Guelph biohermal facies (Liberty and Bolton 1971).

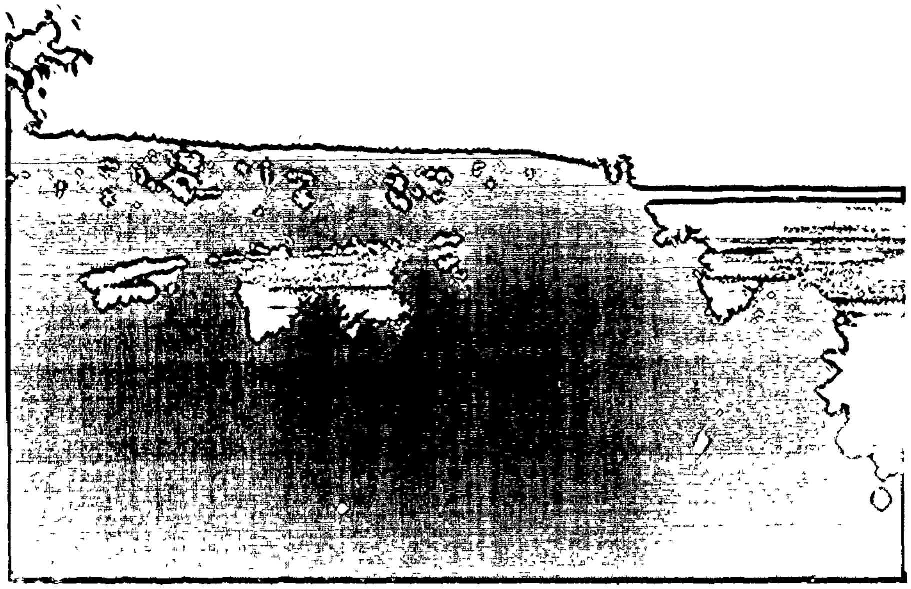

Plate 3 Amabel Formation cliffs of the Niagara Escarpment at Dyer Bay. Here the escarpment is capped by the massive Colpoy Bay-Wiarton member which, along with the Guelph Formation, composes the extensive dolomite plain of the Bruce Peninsula.

Plate 4 Small bioherm in the Guelph Formation on highway 6 (west of Dyer Bay). Thin bedded material surrounding the massive beds are interreefal. The bioherms have been re-excavated by glacial scouring during the Pleistocene.

The Guelph Formation is nowhere completely exposed in the study area. It is primarily a reefal complex of "greyish, tan or dark brown, fine to medium granular or fine to coarse crystalline" dolomite (Liberty and Bolton 1971). It has a sugary texture when broken which is a result of dolomitization. Its appearance is very distinctive when weathered, being rough and vuggy due to its high porosity.

All of the dolomites discussed above have essentially the same chemical composition w.r.t. the carbonate fraction (Appendix 1) but are not susceptible to karst erosion to the same degree (Table 2.1). The massive biohermal dolomites of the Amabel and Guelph Formations are the purest and exhibit the greatest number and variety of karst features. Even within these formations thinly bedded strata such as interreefal material and the bituminous Eramosa member of the Amabel tend to be less susceptible, particularly to the development of small-scale karren forms. The Fossil Hill Formation generally acts as a karst aquifer in association with the overlying Amabel (Plate 2) but its very fossiliferous nature inhibits karren development. Its surface tends to break up and be irregular as fossils are weathered out. The Dyer Bay member (Cabot Head Formation) and Manitoulin Formation dolomites are argillaceous and tend to be the least susceptible to solution. They may or may not pass water and never exhibit karren features.

The Cabot Head and Queenston formations are major aquicludes. Many springs appear at the Fossil Hill-Cabot Head contact (Plate 2) all along the Niagara Escarpment. All of the karst features described in this thesis are situated stratigraphically above the Cabot Head shales.

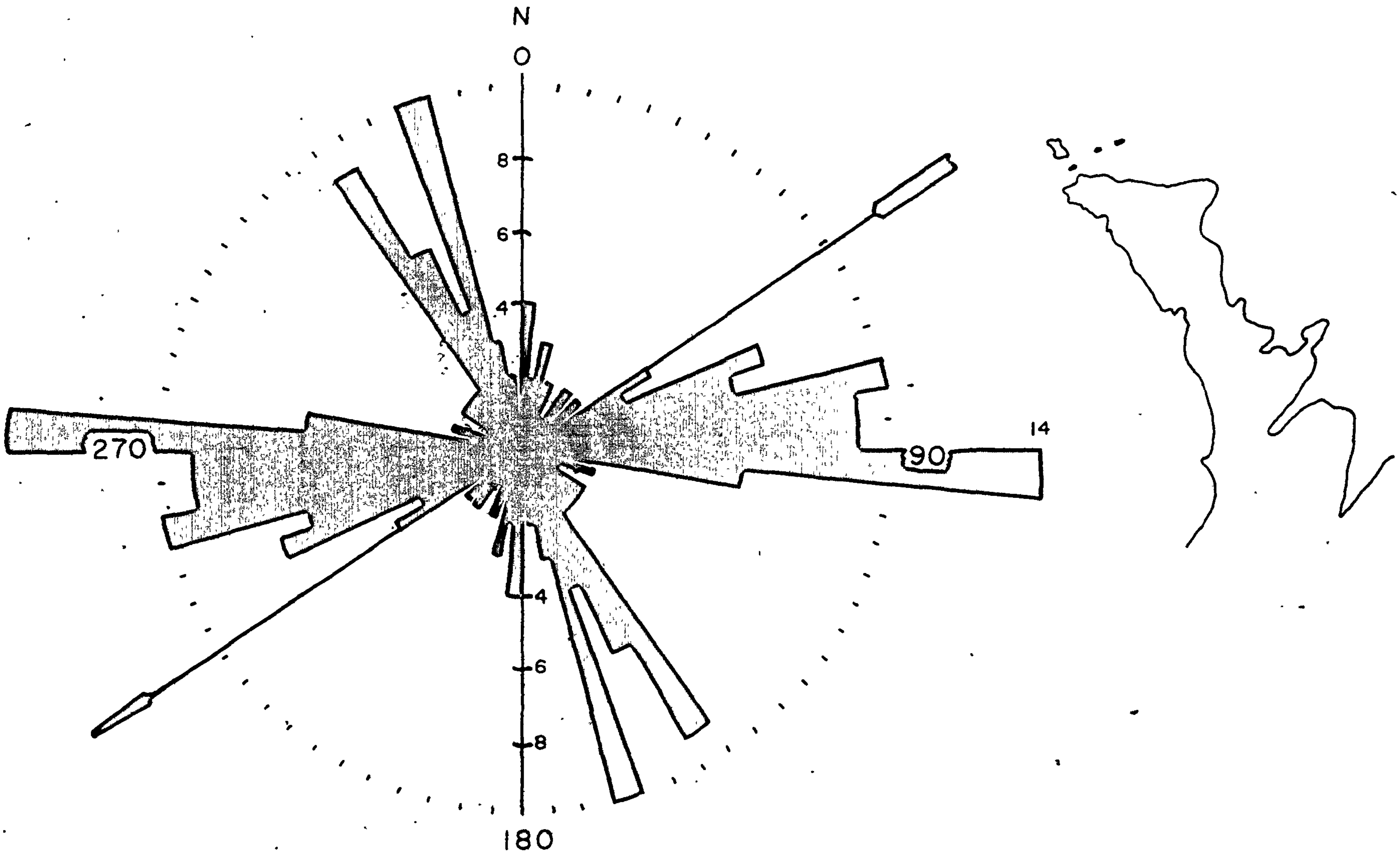

FIGURE 2.3 Compass rose showing the orientations of 134 joints in 5° intervals. Arrow indicates last direction of ice movement (av. of 8 striae).

Small springs do however occur at or near the Manitoulin - Queenston contact.

West of Rocky Bay in the northern part of the Bruce Peninsula all of the shales lie below Georgian Bay. Here it is the bay which limits vertical karstification and modern springs appear at or just above the level of the lake. There may be a number of drowned springs in this area which developed during lower lake stages of the glacial Great Lakes.

The strata of the Bruce Peninsula are devoid of major structural features other than the Algonquin Arch. The beds dip only slightly and for karst hydrologic purposes can be considered as horizontal. Locally the dip may be as high as 20° but this is confined to interreefal strata draping off bioherms. The Niagara Escarpment provides locally steep groundwater hydraulic gradients along its edge which completely overwhelms the dip direction (Figure 2.5). The subsurface hydrologic regimen is controlled primarily by this steep hydraulic gradient in combination with major joint planes which provide the actual route of flow. Figure 2.3 is a compass rose showing the orientation of 134 joints measured by the author within the study area. There appear to be two major joint sets about 60 to 70° apart, oriented ENE to WSW and SES to NWN.

2.2. Pleistocene Geology

The last epeiric seas withdrew from the Michigan Basin during the Cretaceous and early Tertiary Periods (Clark and Stearn, 1968) and thus the study area has been exposed to subaerial erosion for at least 60 million years. Very little is known about this period except for the last 1 to 2 million years encompassing the Pleistocene. The youngest sediments of the Michigan Basin are Pennsylvanian in age whereas the youngest of the study area, on its rim, are Silurian. Assuming that the study area experienced deposition similar to the rest of the basin, then there has been considerable erosion. Rocks even younger than Pennsylvanian may have existed here at one time.

Several writers at the turn of the century (Spencer 1890, Grabau 1901) postulated extensive Tertiary erosion in southern Ontario by large preglacial rivers. They believed that the glacial period had almost no effect in shaping the present macro-landscape, particularly the cuestas of the Michigan Basin. Straw (1968) refuted these arguments and showed that the Niagara Escarpment and its many large valleys (re-entrants) are largely a product of glacial abrasion. Since 1968 there have been very few published references dealing with this problem and it is not certain what most people accept. Straw has not received much support and the preference appears to be toward the earlier theory (White and Karrow 1971). I tend to agree with Straw that the re-entrants are predominately glacial in development.

Little is accurately known about the glaciation and deglaciation of the Bruce Peninsula either during the Wisconsin or before it. This is because there is little or no glacial drift to record the history of the Pleistocene. The most detailed history of glacial events in this area considers the various stages of the glacial and postglacial Great Lakes, beginning about 12,800 to 12,700 years B.P. (Prest 1970). These stages are well preserved in a number of raised shoreline features found throughout the peninsula.

Glacial deposits were either not deposited or were deposited then washed away by the glacial lake waters. This is in strong contrast with the rest of southern Ontario where glacial drift averages 22 to 30 m (75 to 100 ft) in thickness. A few small wave-washed drumlins are located on the south part of the peninsula north of Wiarton (Figure 2.4). Local deposits of stratified sand and gravel can be found southeast of Tobermory and south of Lions Head. These appear to be ice-contact or outwash deposits. The one near Lions Head is closely associated with a large complex of glacio-fluvial potholes and streamways in bedrock. Much of the central part of the peninsula around Lions Head is covered by the flat, poorly drained Eastnor Clayplain. The remainder of the study area is a glacially abraded dolomite pavement with small deposits of till and muck.

The Bruce Peninsula was last glaciated by the Georgian Bay Lobe of the 'Classical' Wisconsin glacier moving from the northeast. This was almost parallel to a major joint set direction and resulted in extensive scouring (Figure 2.3, Plates 5 and 6). Many bioherms were stripped of their interreefal strata and left standing in relief as rôches moutonnées. Most of the promontories of the escarpment are large bioherms. The material between these was removed forming various sized bays, coves and re-entrants. This can be seen to advantage at Lions Head, Cabot Head and Halfway Rock (in Cyprus Lake Provincial Park). The islands north of Tobermory are composed of Guelph bioherms which proved more resistant to the ice than the surrounding material.

The surface of the Bruce Peninsula can be considered a stratimorph

Plate 5 Deep glacial scour along a joint surface, located about 4km southeast of Tobermory. This scour has been re-excavated by a stream which disappears into a cave, below the person.

Plate 6 Glacial striations in the Guelph Formation on the north Bruce. The striations have been protected from solution by an overlying deposit which has recently been removed.

in which erosion has been guided by structure. The topographic dip is in the same direction as the stratigraphic dip and scouring was concentrated along joints.

The majority of sand, gravel and cobble material on the Bruce are deposits of the glacial and postglacial lakes which occupied the Lake Huron and Georgian Bay basins. Sand dunes, raised beaches, raised bars, sea caves, sea stacks ('flowerpots'), natural bridges and large under-cuts are found at various levels on the peninsula, the latter four being characteristic of the escarpment face (Cowell 1974). At the highest stage of Lake Algonquin, immediately following the last retreat of the ice, the entire peninsula as far south as Hepworth was inundated except for a few of the higher cliffs presently above 890 ft a.s.l. (Table 2.2). Lake levels continually dropped until they reached their lowest level during Lakes Stanley and Hough. This was as much as 75 m (250 ft) lower than the present level of Lake Huron. During this time the Bruce Peninsula was connected to Manitoulin Island. The Nipissing postglacial lakes followed the Stanley and Hough phases as the basins were raised by isostatic rebound. At their maximum they were 15 to 20 m (50 to 60 ft) above present levels and represent the longest lived lakes, marked by extensive deposits and erosional features (Plate 7). The history of these glacial and postglacial lakes is discussed in more detail by Chapman and Putnam (1966), Hough (1966) and Prest (1970).

The various lake levels strongly influenced the geomorphology of the Bruce Peninsula both directly and indirectly. Besides creating a complex variety of shore features they also affected groundwater movement

TABLE 2.2

Glacial and Postglacial Lake Stages in the Huron and Georgian Bay Basins at Cabot Head, Bruce Peninsula (after Sly and Lewis 1972)

Stage	Original Elevation a.s.l.		Present Elevations a.s.l.	
	Ft.	M.	Ft.	M.
Glacial Lakes				
Main Algonquin	605	184	883?	269?
Ardtrea	590?	180?	865?	264?
Upper Orillia	579?	174?	831?	253?
Lower Orillia	550?	168?	812?	247?
Wyebridge	540?	165?	788?	240?
Penetang	510?	155?	749	228
Cedar Point	495?	151?	727?	222?
Payette	465?	142?	688?	210?
Sheguiandah	430?	131?	653?	199?
Korah	400?	122?	623?	190?
Postglacial Lakes				
Stanley (Lake Huron)	150?	46?		
Hough (Geogrian Bay)	100?	30?	332?	101?
Nipissing I and II	600	183	635	194
Algoma	595	181	608?	185?
Huron and Georgian Bay	580	177	580	177

Plate 7 Sea stacks, called 'flowerpots' because of their shape, are part of the character of the Bruce Peninsula. This one ('Devil's Pulpit') on Dyer Bay is approx. 8m high. Its base is approx. 15m above Georgian Bay. It is likely a product of the Nipissing postglacial lakes.

and hence karst development. This will be discussed later in the thesis (Chapter 4).

2.3 Physiography

The Bruce Peninsula is a glacially scoured and abraded dolomite plain bounded on the east and north by the Niagara Escarpment. The escarpment here is characterized by abrupt cliffs rising up to 122m (400 ft) above Georgian Bay (Figure 2.5, Plate 3). Extensive talus deposits mantle the base in places, continuing down into the bay. From the brow of the escarpment the peninsula slopes toward the southwest in the direction of the stratigraphic dip gradually meeting Lake Huron. Most of the runoff is carried in this direction guided by the slope and by glacially scoured ridges (Figure 2.4).

The surface of the peninsula varies from very flat, such as on the Eastnor Clayplain, to a very rugged bedrock topography. Relief on the bedrock varies from only about a meter up to several tens of meters, especially on large bioherms.

There are nearly 30 lakes on the Bruce. Most drain to the southwest into Lake Huron. They tend to be quite shallow with marl bottoms and fluctuate widely in volume throughout the hydrologic year. Gillies Lake, near Cabot Head, is an exception as it is over 35 m (120 ft) deep and is entirely spring fed. It is drained by a small stream which sinks into its channel and reappears just above Georgian Bay. One of the interesting features of this lake is that its deepest end is only about 300 m (about 0.2 mi) from the edge of the escarpment. Its overall profile is scallop-shaped. Four lakes are joined in series within Cyprus

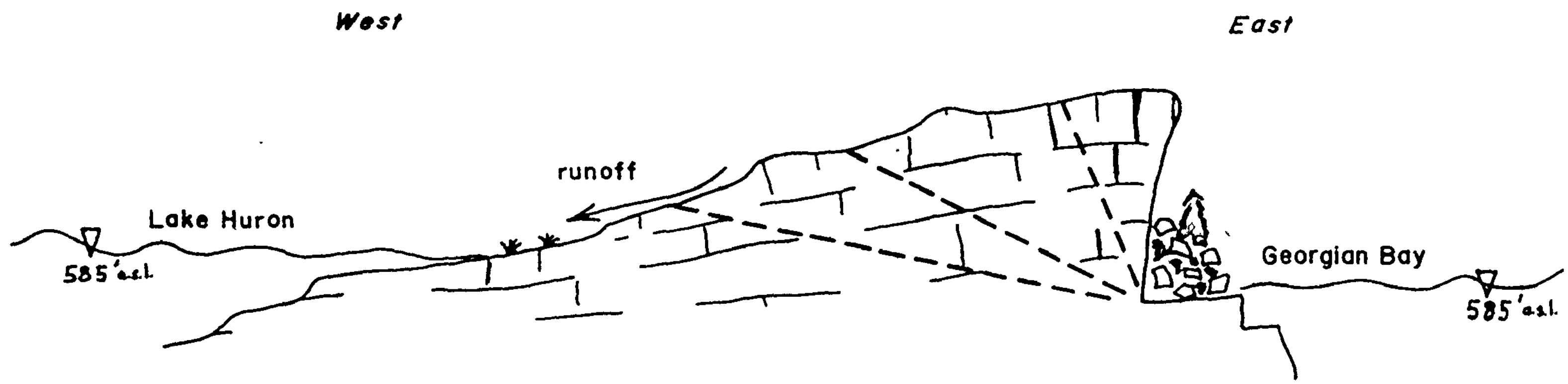

FIGURE 2.5 Generalized cross-section of the Bruce Peninsula showing relative hydraulic gradients toward Georgian Bay (dashed lines).

Lake Provincial Park and these also drain into Georgian Bay, partly via underground flow, although they may have once flowed in the other direction to Lake Huron. Only one surface stream of any consequence crosses the escarpment to flow into Georgian Bay. This is Judges Creek which drains the low lying Eastnor Clayplain.

The edge of the escarpment is very dry and is characterized by vertical drainage into the rock. This has resulted in extensive widening of joints along the brow and many small springs either at Georgian Bay or within the shaley Cabot Head Formation. Solutional widening of joints along the escarpment is an important factor in talus accumulation and makes development of any kind very hazardous.

The Lake Huron shore is a complete contrast to Georgian Bay. Here the topography is flat and swampy. There is little impetus for water to sink as the base level is near the surface and hence water accumulates in densely vegetated wetlands.

The Bruce Peninsula presents a complex association of geomorphological features and processes both active and fossil. Its physiography is a product of glacial and glacio-lacustrine processes in the past and fluvial and karst processes at present. It has a rugged, beautiful landscape and is a region unlike any other in Ontario.

2.4 Karst Overview

This thesis deals specifically with karst landforms and processes, both fossil and active, of the Bruce Peninsula. The Karst is truly a glacio-karst because its origin is a direct result of glacial processes of the Pleistocene, particularly the Wisconsinan. Preglacial and interglacial solution features which may have existed were removed during the Wisconsin. This sets a maximum age of between 11,000 and 13,000 years for karst development.

The Bruce Peninsula in combination with the escarpment southeast of the study area, in Grey County, presents the largest and most diverse assemblage of karst landforms in Ontario. This is primarily a result of (1) the location of the escarpment edge permitting high groundwater hydraulic gradients, and (2) the presence of relatively small, localized surficial deposits. The latter factor has led to the development of karst features common to both exposed (pavements) and covered carbonate areas.

Karst landforms are the product of solutional processes operating in carbonate terrains. Solution operates primarily in a vertical direction creating landforms that are isolated, appearing unorganized and disparate (Sweeting 1972). This has made it difficult to produce universally accepted morphological classifications. The classification of Ford and Quinlan (1973) is perhaps one of the easiest and most acceptable to work with. It separates karst features into surface and subsurface forms. Each is then subdivided according to scale; microforms - less than 10 meters in their greatest dimension, mesoforms - 10 to 100 meters in their greatest dimension, and macroforms - more than 1000 meters. Although the subdivisions of this classification may seem somewhat arbitrary they tend to fit observation. Thus surface microforms refer primarily to the karren forms whereas surface mesoforms include sinkholes (dolines). Caves and cave phenomenon (such as scalloping) of various dimensions make up the subsurface landforms.

This thesis follows the above classification. Chapter 3 deals with the small-scale karren forms which collectively compose the Bruce Peninsula pavements. Surface mesoforms including disappearing streams and lakes, dolines and springs will be discussed in Chapter 4. This chapter also considers active and fossil caves, only one of which can be considered a macroform (St. Edmunds Cave system - Section 4.2.5). Surface and subsurface hydrology are discussed in order to develop models of present and potential karstification on the peninsula. Chapter 5 describes solution characteristics of the dolomite based on geochemical investigations of various water types sampled during 1973 and 1974. It is hoped that this will help tie together the previous discussions of morphology and hydrology. If the reader is not familiar with karst processes this chapter can be taken out of context and read prior to Chapters 3 and 4. In such a case I also recommend the reader to see Jennings (1971, Chapter 3), Sweeting (1972, Chapter 3) and Drake (1974). The final Chapter 6, is a summary of the main findings.

CHAPTER 3

THE BRUCE PENINSULA PAVEMENT
(surface micro-forms)

3.1 Introduction

Carbonate rocks exposed to intense solutional attack from precipitation and biological activity are frequently characterized by a variety of small-scale erosional forms on their surfaces. These are known as the karren forms (Fr. lapies). When these features occur over a large area that is free of overburden they collectively constitute a 'pavement'. Solution along structural elements, such as joints, carves the rock surface into blocks resembling man-made pavements, and hence the name. Sweeting (1972, p.95) notes that "limestone pavements form a complex group of karren phenomena, and result from the glaciation of a limestone surface followed by solution".

The absence of thick glacial deposits on the Bruce Peninsula has resulted in the development of a quite extensive dolomite pavement encompassing much of the peninsula. It is particularly well developed between Wiarton and Mar east of highway 6 and north of Monument Corners. It is limited on the east and north by the Niagara Escarpment and on the west by Lake Huron. With respect to both size and degree of karren development this pavement rivals any described in the literature.

The intent of this chapter is to give a summary of features represented on the Bruce Peninsula along with some idea of the major limiting controls and hence establish a framework for possible future studies.

3.2 Limestone Pavements and Karren Classification

There is an extensive literature dealing with limestone pavements and karren forms. For a good review the reader is referred to Williams (1966, p.155-158) and Sweeting (1972, p.74-79, 95-101). Jennings (1971, p.39-60) and Sweeting (1972, p.79-96) also present karren classifications, which are based primarily on the work of Bögli (1960). There is very little published work dealing with dolomite pavements and their similarities with limestone pavements are not accurately known. The main references for small-scale dolomite karst features are Pluhar (1966) and Pluhar and Ford (1970). On an a priori basis one would not expect a great difference between dolomite and limestone pavements because the solution processes are similar (see Jennings 1971, p.29-30, 52-53). The rate of solution is the prime difference and this may or may not affect morphology.

The term 'limestone pavement' was first used in the literature in 1874 (Sweeting 1972, p.96) but accounts of their morphology go back to at least 1708 (Williams 1966, p.156). One of the earliest detailed descriptions of karren forms was by Heim in 1874. More recent work has been carried out primarily by J. Corbel and A. Bögli (Williams 1966, p. 156-171). The study of pavements and their associated karren forms is burdened with a complex terminology. French, German and English equivalents exist for most features and each is fairly well entrenched in the literature. The most commonly used names will be used in this thesis with other well used terms indicated at some point.

Limestone pavements (Fr. trottoirs and champs des lapiés) consist of a "geometrical pattern of blocks"[1] called clints (Ger. flachkarren) created by the "intersection of widened fissures"[2] called grikes (Ger. kluftkarren). The exposure and preparation of the pavement surface is now believed to be a direct result of intense glacial scour during the most recent glaciation (Sweeting 1972, p.97) although this fact was questioned at one time (Williams 1966, p.156). The concept of glacial origin for pavements is reinfored by the fact that they are poorly developed outside the limit of the last major glaciation. For example they do not occur at all in the 'Classical Karst' of Slovenia (Sweeting 1972, p.101). The most intensively studied pavements are found in Ireland, northern England and in the French and Swiss Alps.

Limestone pavements display a wide range of morphologies. The prime controls of pavement morphology are geologic structure, particularly angle of dip and degree of jointing; lithology; past and present chemical and biological processes; and climate.

Williams (1966, p.168-69) recognizes three main types of pavements based on structure - flat, inclined and arched - of which the first two may develop into more than one level as stepped pavements. He also notes that the best development is found on horizontal pavements with the surface parallel to bedding.

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1. Sweeting, 1972, p.96
2. Ibid

With respect to lithology, pure dense massively bedded limestones are the most susceptible to karren development (Williams 1970, p.118). Thinly bedded or very highly jointed carbonates do not make good pavements as they tend to break up too easily (Sweeting 1966, p.188).

It has been argued that climatic parameters also influence pavement morphology, particularly the amount and intensity of rainfall, but also indirectly through vegetation. In general, sharper features occur in areas receiving intense precipitation (e.g. alpine environments) whereas more rounded forms occur in areas where drizzle predominates (Sweeting 1972, p.76). Solution intensity and potential is also partly controlled by climate and this will be examined in more detail in Chapter 5.

Past and present biological processes are extremely important to pavement development and karst processes in general. The importance of vegetation and soil in karren formation has been realized since at least the turn of the century (Sweeting 1972, p.74). There is still however a great deal of controversy regarding the actual development and relative importance of karren formed under soil as opposed to a free air situation. This is explored in some detail by Williams (1966) and Sweeting (1972). The presence of vegetation either directly on the carbonate surface or in a soil overburden tends to enhance the solution process. This is due to the production of organic acids and the concentration of biogenic CO_2 which boosts the dissolving capacity of natural waters (see Chapter 5). Karren created by these processes tend to be much more rounded and of larger size than those created on a bare surface (Table 3.1). This is mainly a result of permanent wetting, (of the whole rock surface), and more aggressive waters under vegetation and soil covers. Very deep subsoil solution of limestones, especially along joints has been observed in areas outside the limit of Pleistocene glaciations (Howard, 1963). Calcareous soils however, such as tills and outwash produced by glacial action, tend to protect the carbonate surface (Williams 1966, p.166). This effect is quite variable depending on the soil thickness and permeability but generally rock solution is inhibited due to the neutralizing of aggressive waters by the calcareous deposit.

The term 'karren' was "originally used to describe solution runnels cut into limestones ... in the strictest sense karren refer to solutional holes and runnels formed directly on bare limestones and to the solutional features of limestones formed under a moss or vegetational cover" (Sweeting 1972, p.74). Pluhar (1966, p.7) defines karren (lapiés) as "structure-controlled, selective solutional or solutional-erosional pits, groovings and trenches, developed in carbonate rocks which are deteriorating into rectangular blocks and ridges with or without regolith cover". Their dimensions are usually measured in mm/cm but may reach as much as 15 to 20 meters in length (Sweeting 1972, p.74).

Morphology and genesis have been used as a basis for classifying karren forms and most classifications relate to both (Sweeting 1972, p.75, Pluhar and Ford 1970, p.398). Table 3.1 presents a classification based mainly on morphology but with some reference to genesis (i.e. the presence or absence of a soil cover). This table lists and briefly describes the most common forms in the literature to date. This list certainly does not include all karren forms. It should be noted that even those included may vary in morphology slightly from place to place depending on the

TABLE 3.1

The Karren Forms
(Modified after M.M. Sweeting 1972, p.75)

TYPE	OTHER NAMES	AVERAGE SIZE	GENESIS	FLAT OR INCLINED COVER	SHARP OR SMOOTHED CRESTS
Rillenkarren	runnels, solution flutes, rillensteine	1-2 cms deep up to 50 cm long	bare surfaces	inclined	sharp
Trittkarren	solution bevels	3-50 cm high 20-100 cm wide	bare surfaces	flat	sharp
Rinnenkarren	solution runnels, spitzkarren	50 cm deep up to 20 cm long	bare and partly covered	inclined	sharp, sometimes slightly rounded bases
Meanderkarren	meandering runnels, mäanderkarren	50 cm deep up to 20 cm long	bare and partly covered	slightly inclined	sharp, rounded bases
Rundkarren	runnels, furrows	12-50 cm deep up to 15 cm long	covered	inclined	smoothed
Groovekarren	stylolitekarren	few cm width and depth up to 2 m long	bare and partly covered	usually vertical surfaces	smoothed but sometimes sharp crests
Pitkarren	pits, pot holes, tinajitas	1-5 cm diam. generally quite shallow (<5cm) but variable	bare and partly covered	flat	bases usually rounded edges sharp or smoothed
Kamenitzas	solution basins, solution pans, tinajitas	few cm to over 3 m diam. up to 50 cm deep	bare and covered	flat	sides smoothed when covered, sharp when bare. Flat floor.
Grikes	kluftkarren, trench-karren	few cm to 4 m deep up to 4 m wide	bare and covered	along joints flat or slightly inclined	usually smoothed but have sharp sides
Hohlkarren	mohrkarren, undercut runnels	60 cm - 1 m deep 50 cm wide	covered (under peat)	variable	smoothed
Deckenkarren	root grooves	few mm or cm deep	covered-direct action of plants	variable	smoothed

relative influence of the controlling factors.

i) Rillenkarren - These are sharp crested rills, densely packed on steeply inclined limestone blocks. They originate at the uppermost edge of the block and usually die out quickly within a few 10's of cm. They are generaly attributed to direct solution by rainwater and occur frequently in alpine environments where rainfall is intense, although they are seen anywhere where bare, sloping limestone is present.

ii) Trittkarren - are flat steps or bevels often with a steep back slope riser. They are usually found together as a series of steps (Sweeting 1972, p.81).

iii) Rinnenkarren and Rundkarren - are solutional runnels often referred to as 'fluvial forms' because of their similarity to surface river channels. They are often sinuous and dendritic. These are sometimes confused in the literature with rillenkarren (particularly the rinnenkarren forms) but are larger in size, often more rounded, may occur on more moderate slopes and do not head at the crest of a slope. Rinnenkarren are sharper and straighter than rundkarren and are a result of concentrated runoff. Rinnenkarren may or may not be found with rillenkarren. Rundkarren are formed by more aggressive waters in association with covered or partly covered surfaces. Both these forms are created during the slower phases of solution after the initial contact of rain and rock or rain and vegetation (i.e. solution controlled by atmospheric and biogeneic CO_2 diffusion).

iv) Meanderkarren - refers to highly sinuous and meandering rundkarren.

v) Groovekarren - are horizontal grooves lying in the zone between two stylolites. They occur on vertical surfaces such as within widened joints and their formation is attributed to biogenic acid production by bacteria and mosses (Pluhar and Ford, 1970).

vi) Pitkarren - are small pits, usually very circular in plan-view, sometimes considered as small kamenitzas (Corbel 1963). These may be a direct result of precipitation whereas smoother more distinct pits are likely the result of biological activity although lithology must also be considered (Section 3.3).

vii) Kamenitzas - are larger solution pans with a variable plan-shape. Their bottoms are usually flat and often covered with a thin layer of mineral residuum and organic materials. Where this occurs the edges of the pans may be undercut slightly due to concentrated horizontal solution by standing water.

viii) Grikes - are the largest and most important of the karren forms found within the range of the last major glaciation. They are deep, usually straight clefts which may extend for many 10's of meters. They follow joints and tend to widen into well-like hollows or small sinkholes where they intersect. The blocks left between the grikes are called Clints (or helks) and are of variable dimensions depending on the jointing frequency.

ix) Hohlkarren and Deckenkarren - refer to a variety of karren forms created by the direct action of vegetation (peat, mosses, plants) on bedrock. Hohlkarren specifically refers to the formation of karren and alteration of previously formed karren under a peat cover whereas deckenkarren refers to the creation of grooves and pits by the action of plants, particularly plant roots (rootgrooves). In all cases the forms are smooth. In the former case gravity and structure guide solution and in the latter case it is the location of plants which controls solution.

There is a strong correlation between the smoothness of karren forms and whether or not they formed under a vegetation cover (Table 3.1). It should be pointed out that vegetation cover refers to a continuous vegetation such as forests, mosses and plant litter without the presence of a thick calcareous soil (glacial till). Partly covered refers to the patchy, discontinuous nature of certain vegetation and peat covers, particularly characteristic of moss and lichen colonization (bryophytes and thallophytes). The presence of such vegetation covers results in the production of many smooth, rounded karren forms.

3.3 Bruce Peninsula Pavement Morphology

> "The limestone [dolomite] 'pavements' may be seen at their best in the Bruce Peninsula ... where it appears as though the country were artificially paved with sterile flat slabs of limestone, [dolomite] separated at intervals of four or five feet by vertical cracks, a few inches in width, of considerable depth and with little or no trace of vegetation"[1]

This quote aptly describes the regional morphology of much of the Bruce Peninsula. It is this feature in particular which establishes the peninsula as a region apart from the rest of Ontario. The micromorphology of the pavement is quite complex. It displays a variety of karren forms similar to those previously described in the literature (Table 3.1) as well as other solutional-weathering features. Figure 3.1

[1] Fox, W.S., 1952, p.23.

shows the locations of the main pavement exposures on the Bruce Peninsula examined by the author.[1] Figure 3.2 illustrates the relationships of pavement, environment geology and covering material (water and soil) on the northern part of the peninsula where the pavements are the most extensive. The reader should also refer to Figures 2.1 and 2.4 (geology and physiography).

There are two factors which control the karren morphology of the Bruce; lithology and environment. The former appears to be the most significant but the latter is locally important, primarily due to biological controls. These are difficult to precisely determine because of the comparatively recent and complete logging operations as well as subsequent severe fires. The extent of the soil cover and its affect on solutional weathering at the micro-scale before 1850 AD is not known; some infâuences will be examined following a description of the micromorphology.

Classification of the pavement by controls upon morphology, as presented here, appears to hold up well to observation. The karren assemblages with some exceptions conform well with lithological and environmental characteristics. The karren types described below can also be classified by their mode of formation; i.e. gravity forms (produced on exposed surfaces - rinnenkarren, kamenitzas and pit karren),

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1. Note: the 6 digit numbers on Figure 3.1 are the UTM grid reference numbers taken from the N.T.S. 1:50,000 map sheets (e.g. 543103).

structural forms (grikes, groovekarren and splitkarren) and biological forms (hohlkarren, deckenkarren and kamenitzas). This classification follows from Table 3.1 and is not considered in detail in this paper. It is felt that the range of karren forms found on the Bruce Peninsula and the major controls which have produced three very different assemblages of karren are most important at this stage.

Small-scale solutional weathering on the Bruce can be separated into three groups or assemblages and thus three pavement types. Two of these are controlled by differing lithology and the third by specific environmental factors.

3.3.1 Lithology

The two main carbonate rock units on the peninsula, the Guelph and Amabel, have identical chemical compositions ($(Ca_{1.2} Mg_{0.8} CO_3)_2$ - Appendix 1) but display very different solutional weathering characteristics. The difference is due primarily to differences in the physical lithologies of the two units. Although both are reefal facies, the Guelph is more biostromal and after dolomitization was left more porous than the Amabel (Liberty and Bolton 1971). This has consequently affected subaerial weathering. The importance of lithology in controlling karren morphology is well known (Sweeting 1966 and Williams 1970) and has been previously demonstrated by Pluhar (1966) and Pluhar and Ford (1970) on the Niagara Escarpment.

i) <u>Amabel Formation</u>:

The Amabel is composed of three members of which only the Colpoy Bay-Wiarton member develops good solutional weathering features. The other members are much thinner bedded and consequently less well exposed (i.e. eroded to a greater extent) and less susceptible to small-scale etching (Williams 1970).

The Copoy Bay-Wiarton member develops well-formed recognizable karren on smooth, glacially moulded outcrops (roches moutonnées). Flat pavements formed of this unit are rare and none have been observed on the Bruce Peninsula. True rillenkarren, meanderkarren (rundkarren), groovekarren, pitkarren, kamenitzas, grikes, split karren and even hohlkarren and deckenkarren have been recognized (Table 3.1). The most common assemblages found at any given outcrop usually include clint and grike, splitkarren, kamenitzas and rundkarren. Outcrops showing well-developed karren are found throughout the Bruce Peninsula near the escarpment. In fact these are common all along the escarpment in Ontario, on the Amabel Formation (called the Lockport in the Hamilton area), but outcrops are more restricted south of the study area.

The following description was taken from an Amabel outcrop at Dyer Bay (733004-Figure 3.2). Well-developed karren are displayed on several low glacially-scoured ridges less than 1.5 m high (Plate 8). They lie in a field which has been cleared of vegetation. The surrounding regolith cover was found to be 50 cm (1.5 ft) in thickness. In hand specimen the dolomite was light grey, weathering white and finely crystalline with low porosity. Clint and grike, kamenitzas splitkarren and rundkarren were well-developed although the latter may be more properly considered as a type of hohlkarren. In order to observe the affects of the soil cover on the bedrock a trench about 2 m (6 ft) long was dug from the base of the outcrop.

a) Clint and Grike - These are not as well developed as is

Plate 8 Glacially polished outcrops of the Amabel Formation in a field near Dyer Bay.

usually found in the Guelph pavement. The grikes follow two orientations, 100°-280° and 155°-355° and tended to be sinuous, probably reflecting the behaviour of joints found in massive biohermal strata. The intervening blocks were thus quite irregular in shape and appeared to have shifted and tilted to some degree. Grikes were narrow, compared to many Guelph exposures, being 2-15 cm in width. In many cases they were difficult to follow because of abundant grass and weed growth (Plate 11). Their edges were well rounded and inside had smooth walls, lacking stylolite karren (groovekarren).

b) Splitkarren - these are here defined as short, shallow, V-shaped forms which occur everywhere on the outcrop, even cutting across runnels (Plate 14). They have not previously been described in the literature. Splits are 1-2 mm width, up to 3 mm deep and vary from 4 to 30 cm (2 to 12 ins) in length. They resemble marks made on smooth ice surfaces by skates. Their orientations roughly parallel joint orientations - 155°-335°, 110°-290° and 9°-189° (compare to Figure 2.3). Pluhar and Ford (1970) referred to a feature they termed split groovekarren which were controlled by secondary joints and were larger in size than those at the Dyer Bay site. They may be part of a continuum; however, split groovekarren were not observed anywhere on the Amabel pavement. They do occur in places on the Guelph pavement (Plate 24) where they are found parallel to well-developed grikes. Both splitkarren and split groovekarren appear to be structurally controlled.

Plate 9 Trench dug to expose bedrock beneath the soil at the Dyer Bay karren site. Rundkarren does not continue beneath the soil but two openings in the rock indicate another type of karren (deckenkarren).

c) Rundkarren (hohlkarren) - The runnels at this site do not appear to be true fluvial forms as the term rundkarren implies (see Table 3.1). They are straight downslope but vary considerably in their dimensions (Plates 10 and 11). Near the upper part of the outcrop they tend to be more regular but these are restricted in length. Their dimensions are: width, 1 to 10 cm (0.5 to 4 ins); depth, 4 to 7 cm (1.5 to 3 ins); and length, up to 130 cm (4.3 ft). They occur on slopes of 8 to 16°, which included most of this Dyer Bay site except for the higher parts of the outcrop. All the forms are smooth with rounded edges.

The fact that single furrows cannot be traced completely downslope but may suddenly stop or be offset, plus their variability in dimensions and roundness of outline, suggest that these were formed under a soil cover and are presently being exhumed. Many of the furrows contain thick mats of moss (Plate 11). An alternative explanation would be that they were formed subaerially but via the solutional boosting effect of a vegetation cover, i.e. lichens and mosses. This latter possibility is given credence by the fact that the furrows do not continue beneath the present soil cover (Plate 9). Also, on flatter surfaces, the runnels are replaced by solution pans some of which are filled with moss. Thus it seems most likely that the runnels were formed under a vegetation cover but close enough to the surface to allow gravity flow of runoff. This vegetation cover may have been either spotty as at present(allowing complete

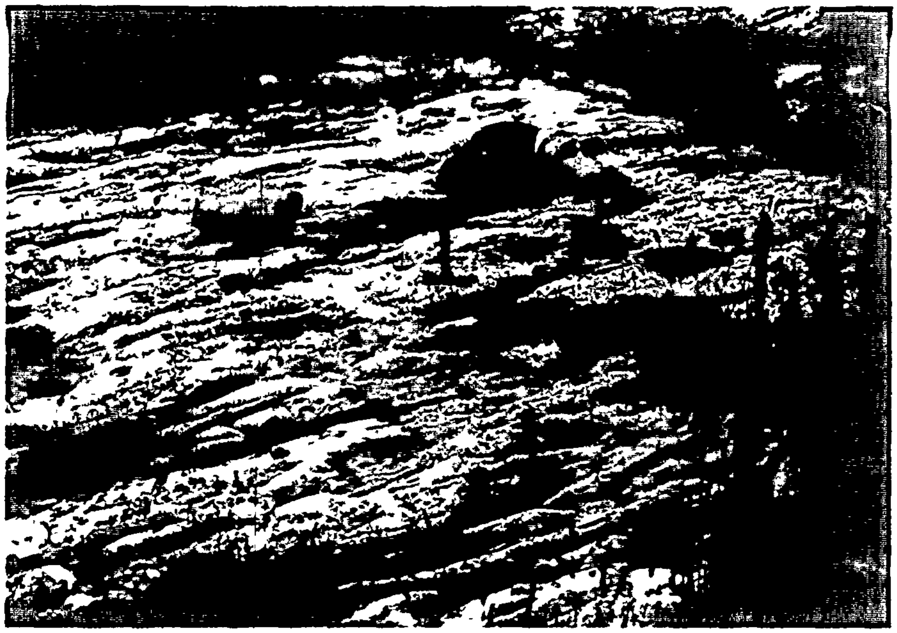


Plate 10 Rundkarren or possibly hohlkarren descending to the left. The furrows are well rounded and are discontinuous downslope.

Plate 11 Furrows, many of which are occupied by a thick mat of moss, are well developed at the Dyer Bay outcrop. Downslope is toward the viewer. Note the grike filled with vegetation running across the photo just below centre.

gravity flow in unoccupied furrows) or much more continuous.

Beneath the soil cover the rock surface was found to be smooth except for two holes which punctured a thin bed revealing a narrow space beneath (Plates 9 and 12). The holes are probably deckenkarren or root grooves produced by acids concentrated around roots of the former, more extensive forest cover.

d) Kamenitzas (solution pans) - On level surfaces (up to 4° slope) at the top of the outcrop are a number of irregularly shaped pans (Plate 13). They are variable in size but generally less than 10 cm (4 ins) deep. Several are filled with the same, thick mat of moss observed in the furrows. Their profiles are also quite smooth and rounded although some were observed to have their sides undercut. The undercutting occurred in pans which are floored with a thin layer of mud and likely resulted from lateral solution by rainwater.

Hohlkarren as described at this outcrop tend to be the exception rather than the rule. Most Amabel pavements have runnels which can be considered true rundkarren (or meanderkarren). Good examples of these were found at Cave Point (618092) and northeast of Cape Chin (764921 - Fig. 3.1, Plate 14). The example in Plate 14 is 2.5 m (8 ft) long and is the longest observed by the author. Runnels were never found to be continuous on either side of grikes and thus must postdate the grikes. They usually end either at the base of an outcrop or at grikes. Pavements which display runnels tend to be completely exposed with free rapid drainage.

Plate 12 Close-up of holes beneath soil shown in Plate 9. These are most likely deckenkarren forms (root grooves) produced during a more forested period.

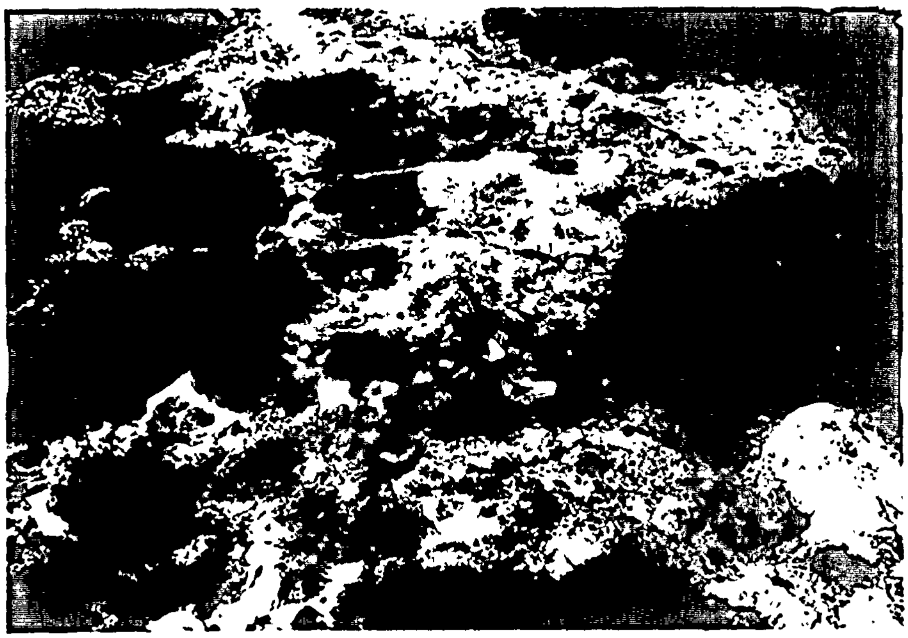


Plate 13 Irregularly shaped solution pans (kamenitzas) on the top of the Dyer Bay outcrop. Some of the irregularity may be due to primary reef structures of the bedrock. Note the thick mosses in many of the depressions.

Plate 14 Meandering rundkarren on a section of Amabel pavement northeast of the village of Cape Chin. The outcrop gradient is 7° toward viewer. The short 'skate' marks of various orientations on the outcrop are splitkarren, as defined here (ex. immediately to right of field book).

Plate 15 shows an example of runnels occupied by roots which suggests that these are deckenkarren (root grooves). They occur outside of the study area, near Owen Sound, but are in the Amabel Formation. This sort of situation presents the problem of which came first, the runnels or the roots? It is quite possible that the runnels existed first. At any rate the roots are presently aiding their enlargement and thus they can be considered as deckenkarren or at least hohlkarren.

The best example of true rillenkarren (i.e. small, sharp crested rills) was observed at the brow of the escarpment just west of Rocky Bay (709096- Fig. 3.1, Plate 16). The rills are less than 10 cm (4 ins) long and about 1.5 cm (0.6 ins) wide. They occur at the sides of several small kamenitzas. Nearby are areas of very densely packed, sharp crested (interfluves) pitting (Plate 17). This type of pitting was not observed anywhere else on the Amabel dolomites but is characteristic of the Guelph Formation (Plate 20). Pitkarren on the Amabel Formation are commonly less densely packed, usually occurring singularly, and have rounded lips.

Excellent outcrops of Amabel-type pavement can be seen north-west of Cape Chin (736922), south of Hope Bay on Bruce County road 9 (874691 - Figure 3.1) and around Cave Point.

ii) Guelph Formation

The Guelph Formation is characterized by intense but very irregular solutional weathering. Various types of pitkarren, plus clint and grike and groovekarren are the only recognizable karren forms which are prevalent. The surface of this pavement is commonly very craggy,

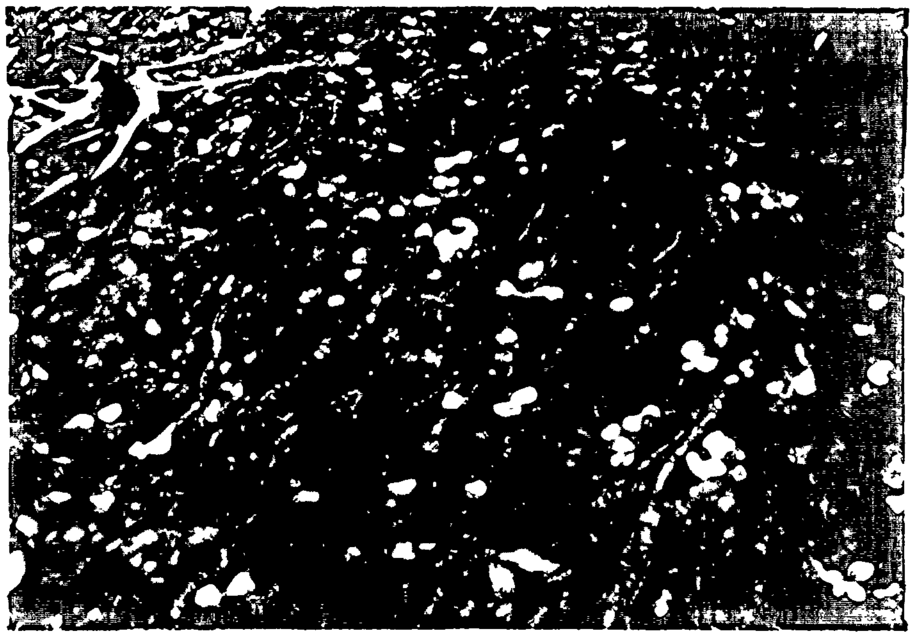


Plate 15 Furrows occupied by soil and roots in the Amabel Formation, near Owen Sound. Downslope is to the lower left.

Plate 16 Sharp crested rills (rillenkarren) on the side of small solution pans west of Cabot Head (709096). These are located very close to the brow of the escarpment and were not found anywhere else on the Bruce Peninsula.

Plate 17 Densely packed pitting (pitkarren) with sharp interfluves, located near the rillenkarren features shown in Plate 16.

almost cavernous in appearance (Plates 18 and 19) and lacks gravity controlled karren such as rundkarren even on steeply sloping surfaces. Kamenitzas and splitkarren are also absent. The texture of the surface varies from coarse, cavernous (Plate 18) to finely-pitted (Plate 20). These textures are not restricted aerially and may occur anywhere, even in combination, the fine-pitting superimposed on the coarse surface (Plate 21).

The best and largest expanses of this pavement are found at the northern end of the peninsula where the Guelph Formation makes up most of the surface outcrops (Figure 3.2). Over the remainder of the peninsula the Guelph is restricted mainly to the west side and is covered to a greater extent. Its surface appears either flat or strongly ridged, depending upon the presence of bioherms in the strata. Where it is flat it may also be stepped, as seen along highway 6 between the Crane River and Cameron Lake (Plate 22). Whether ridged or flat this pavement nearly always displays a pitted or cavernous appearance. Exceptions to this have been found on some of the Guelph bioherms. Southwest of Gillies Lake an area mapped as Guelph (northwest of the village of Dyer Bay - Figure 3.2) displays weathering similar to that more characteristic of the Amabel Formation, i.e. a smooth surface with rundkarren, splitkarren and kamenitzas. This also occurs northwest of Monument Corners (Figure 3.1). There may be other exceptions as well. The flat Guelph pavements located above approximately 600-625 ft elevation invariably show the characteristic irregular weathering. Below this elevation the drainage is very poor and corrosion tends to be more horizontal than vertical.

Plate 18 Irregular, vuggy texture of the pavement surfaces characteristic of the Guelph Formation. Grikes (trenchkarren) can be seen at left and centre.

Plate 19 Very cavernous, irregular weathering typical of much of the Guelph Formation on the Bruce Peninsula. This outcrop occurs near Brinkman Corners (700998).

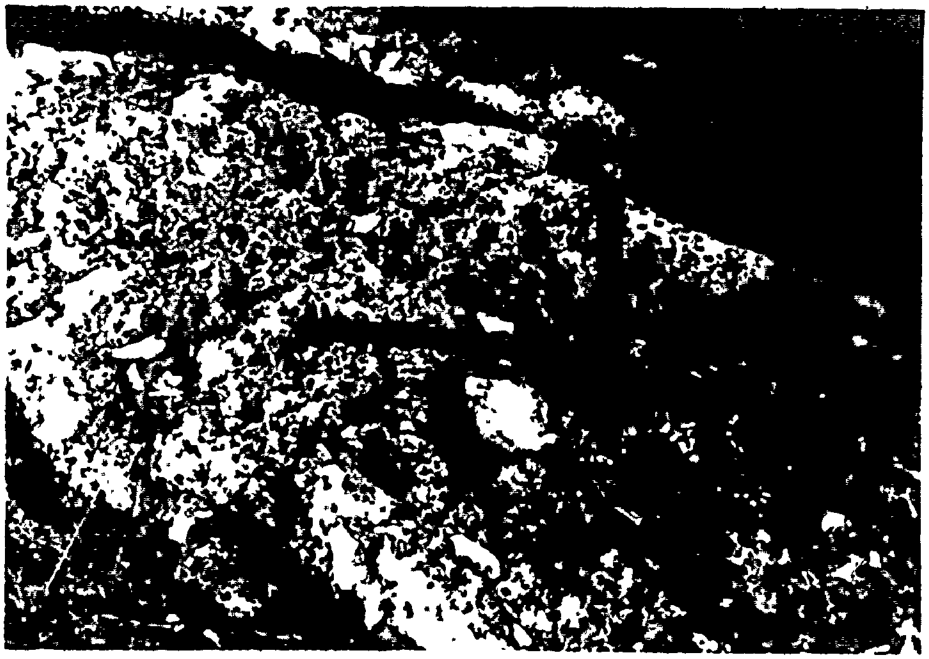


Plate 20 Finely pitted texture of the Guelph Formation.

Plate 21 Coarse weathering on Guelph bedrock with superimposed fine-pitting.

An interesting outcrop of Guelph pavement occurs on the Hay Bay road just south of Tobermory (474107 - Figure 3.1). It consists of a complex of ridges mostly less than 2 meters (6 ft) in height above the surrounding terrain. The ridges are completely exposed but are surrounded by a fairly dense coniferous stand. The micromorphology of the pavement is the finely - pitted texture dissected by a high frequency of grikes (Plate 23). Clint and grike, pitkarren and groovekarren were the only recognizable karren forms although some restricted, poorly developed rundkarren (or possibly rimmenkarren) were observed. In hand specimen the dolomite was porous, stylolitic, and light grey on fresh surfaces but coated on the outside with dark grey lichen.

a) Clint and Grike - Grikes are well developed along two major joint sets (162° - 342° and 75° - 255° - see Figure 2.3) and less well developed along a third set (010-190°). They were mostly straight but some meandered slightly (Plate 23), especially those oriented 075-255°. Depths are variable but appear to be related to the height of the ridges. They contain much forest litter such that their true depths were difficult to measure. Two grikes were excavated to a depth of 76 cm (2.5 ft) and found to be occupied by extensive root systems from nearby trees. Both grikes maintained constant widths to the bottom of the excavations. In plan-view however many grikes do not maintain a constant width. Widths ranged from approximately 2.5 cm (1 in.) up to 28 cm (11 ins)[1]. Intervening

1. It should be noted that these dimensions are not representative of the Guelph pavements for the whole peninsula because local gradient and topography plays major roles -- see page 86.

Plate 22 Flat, stepped pavements created on the biostromal Guelph Formation as found along highway 6 between the Crane River and Cyprus Lake Provincial Park (looking east).

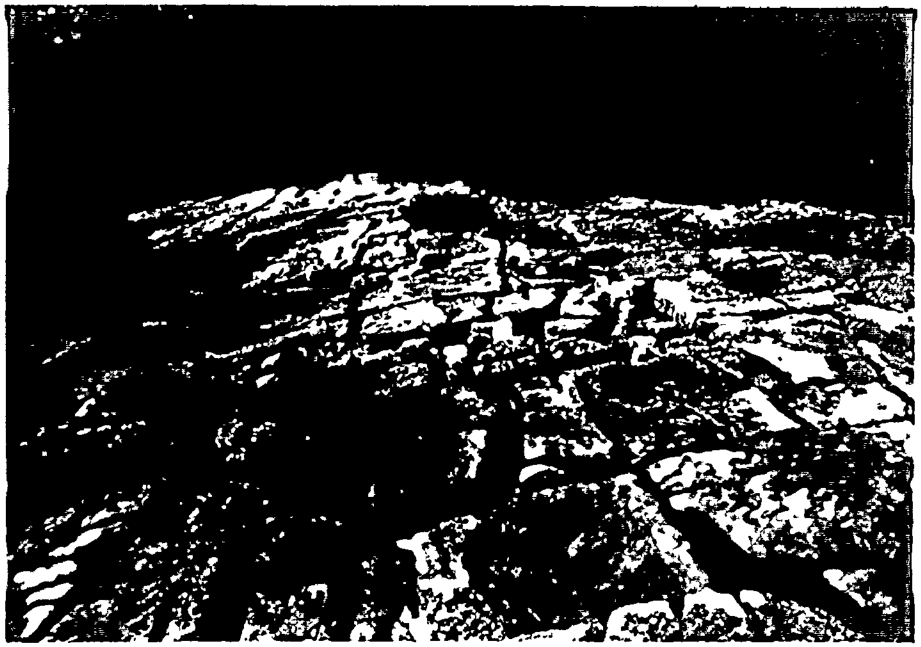
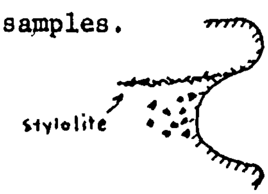


Plate 23 Guelph pavement showing well developed clint and grike. Located south of Tobermory on the road between highway 6 and Hay Bay.

clint blocks varied in size from about 7.6 x 7.6 cm (3 x 3 ins) the largest which was 2 x 3.0 m (7.5 x 10.5 ft). Grikes tend to widen at intersections as found also by Pluhar (1966 - Plate 24).

Split groovekarren of Pluhar and Ford (1970) are also present (Plate 24) and tend to parallel one major grike orientation. These features are essentially developing grikes and are not considered here as a separate karren type.

b) Groovekarren (Stylolite) - These were found within all the grikes (Plate 24). The relationship between the groove and the stylolite, the former occupying the more porous zones between stylolites, can easily be observed on freshly broken samples.



Grooves tend to be less than 1 cm in depth or width but may be traced horizontally over more than 2 meters, even on either side of grikes. They are rounded forms with slightly rounded to sharp interfluves.

c) Pitkarren - Most of the pitting is in the form of very small (10-15 mm maximum depth), densely packed, sharp-crested pits. Many are occupied by moss (Plates 24 and 25). They occur over most of the clint blocks, even upon their vertical walls to a lesser extent. In places several appear to have amalgamated to form slightly larger pitkarren.

A number of unusually large pits were observed on the outcrop but occurred on only two clint blocks. They are circular shafts up to 12.7 cm (5 ins) deep which pass completely

Plate 24 Clint and grike of the Hay Bay road outcrop. Split groovekarren of Pluhar and Ford (1970) can be seen on several of the clint blocks (ex. under field book). These appear to be the result of solution along joints but have not developed as completely as grikes. Note the groove karren (stylolite karren) on the walls of the blocks, parallel to their surfaces.

through a bed to the first bedding plane (Plate 25). At the surface they are between about 1.25 cm (0.5 ins) and 6.3 cm (1.5 ins) in diameter and narrow downward only slightly. The origin of these features are unknown but it is possible they may be a form of remnant root groove from a more vegetated period. However, this would not explain why they are found in only two clint blocks. Zotov (1941) reported similar features which he called solution cups. He attributed their development to rhizoid growth following deforestation. There was no evidence at the Hay Bay site of any living matter in the shafts (except for lichen).

d) Rundkarren - A series of poorly developed runnels 2-3 cm wide and 1-2 mm deep were found near the edge of the outcrop (Plate 26). They occur on a gradient of 26° and may have formed from the amalgamation of a number of pits. These were the only features resembling any kind of runnels observed on typical Guelph surfaces.

An excellent example of biologically induced solution on the Guelph Formation was found next to a swampy area north of Cyprus Lake. A large cedar tree had overturned on the edge of of the swamp. A circular depression in the bedrock, where the tree had stood, outlined the root mesh of the tree perfectly (Plates 27 and 28). The position of the main root was marked as a deeper depression within the larger hole. This is the only true example of deckenkarren found on the Guelph dolomite but it is probably very important, especially in poorly drained

Plate 25 Small, densely packed pitting and vertical pipes on a clint of Guelph pavement. Black specks in the smaller pits are mosses.

Plate 26 Poorly developed runnels (rinnenkarren) to right of field book. These may still be in the process of forming via the amalgamation of smaller pits.

Plate 27 Root depression (deckenkarren) in Guelph dolomite beneath an overturned cedar. Persons' left foot is in depression.

Plate 28 Deep root groove within larger depression shown in Plate 27. It is the part near the hand, cleared of soil.

areas where the root-bedrock interface is wetted for a large part of the year. It should be noted that another overturned tree in dry sandy soil revealed a smooth rock surface with no sign of concentrated solution.

Good exposures of the ridged, typical Guelph-type pavement can be seen immediately west of the Crane River at highway 6 (629997), and in Cyprus Lake Provincial Park on the large ridge complex east of Cyprus and Horse Lakes (centred on 597087) and west of Marr Lake (580095). Excellent flat pavement occurs all along highway 6 between the Crane River and Cyprus Lake Provincial Park (Plates 18-21), west of Driftwood Cove (543103), Overhanging Point (583101) and around Big Tub Harbour at Tobermory. These locations are shown on Figures 3.1 and 3.2 and can be found on the National Topopgraphic Series, 1:50,000 scale maps $41^H/_3$, $41^H/_4$ and $41^H/_5$E.

3.3.2 Environment

The third karren assemblage consists of just one feature - pitkarren. Pitkarren are found throughout the peninsula on both the Amabel and Guelph formations in association with other karren forms. In certain areas however they are found in high densities and without any sign of other karren forms. These areas correspond to a particular environmental zone only, which suggests that the local environment may be the limiting factor. The zone corresponds to the narrow shore or littoral zone of Lake Huron and at least one of the inland lakes (Marr Lake). In these areas morphologically similar pitkarren completely cover the bedrock surface (Plates 29 and 30). They are restricted to bare pavement, usually of the Guelph formation, which is subjected to wave and spray action and continue beneath the lake (Plate 31). The best examples are found on the west side of Marr Lake and in many of the bays on the northern end of the peninsula (Figure 3.2). They are also present at Big Tub Harbour (Tobermory) and on several of the islands north of Tobermory. Many of the bays further south are mantled with Nipissing and later sand deposits and consequently do not exhibit extensive pitting. They are also less prevalent on the Georgian Bay side but may be found along the north shore of the peninsula on vertical surfaces and isolated blocks. The Georgian Bay shore is a higher energy zone (Plate 52) which likely inhibits karren formation. Similar pitting also occurs on Manitoulin Island.

The pits are very regular having a similar morphology, except where 2 or more have amalgamated, and occupy most of the bedrock surface. Unlike those on the Guelph pavement described earlier (Plate 20), the interfluves are flat and pits tend to be more isolated from one another. The flat surface between pits is probably a result of the lower density in combination with smoothing effect by wave action. Their dimensions vary from place to place. The average depth of 50 pits measured at Warner and Dorcas bays was 14.33 mm with a range of 5-32 mm. The average diameter was 18.1 mm with a range of 9-25 mm. Fifteen pits measured on Bears Rump Island had an average depth of 23.6 mm (8-31 mm) and an average diameter of 30.2 mm (20-48), almost twice as large on the average. Pits on the Lake Huron floor attain even greater dimensions.

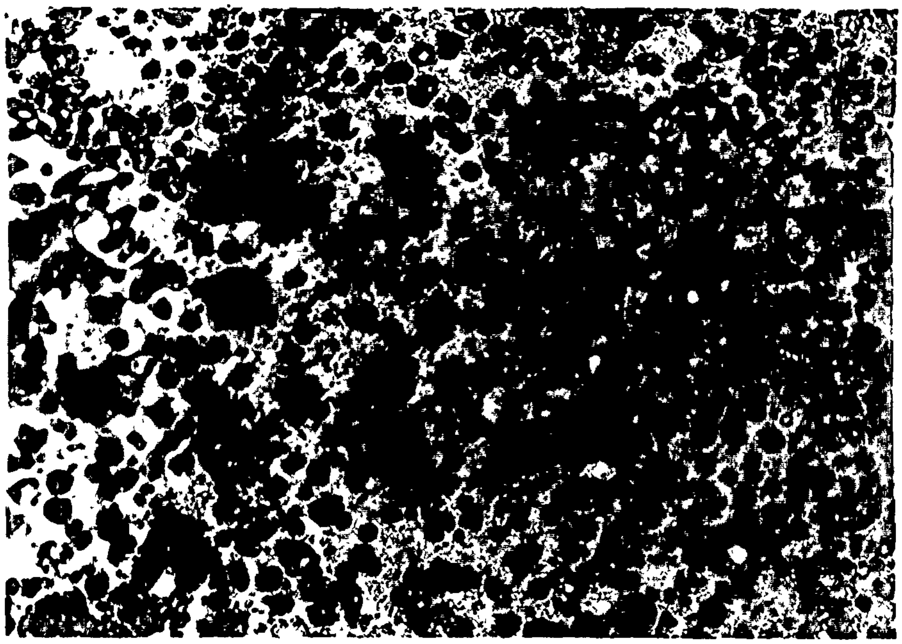


Plate 29 Pitkarren in the shore zone of Lake Huron at Warner Bay. Black features are mosses.

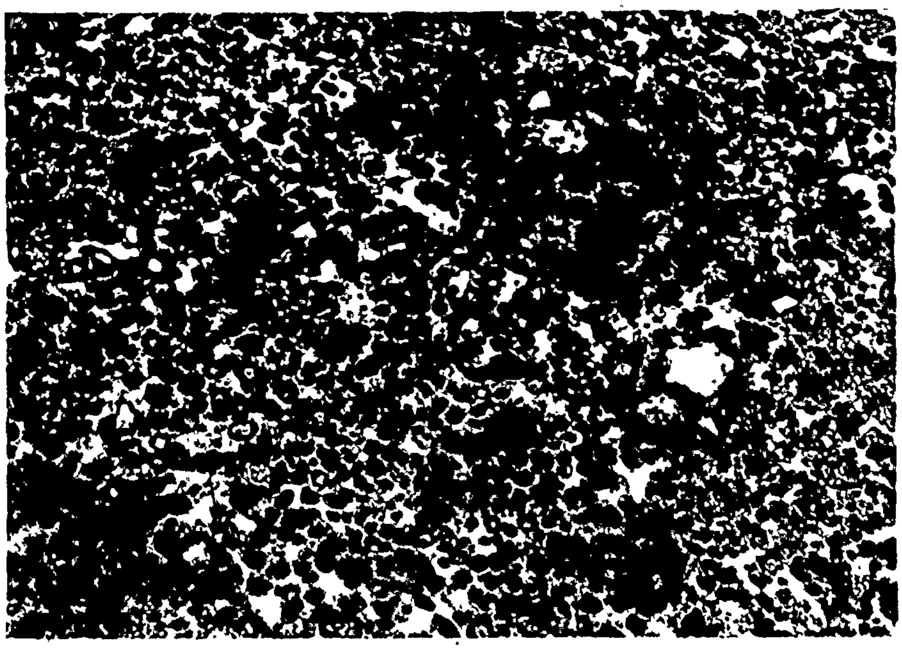


Plate 30 Pitkarren at Warner Bay.

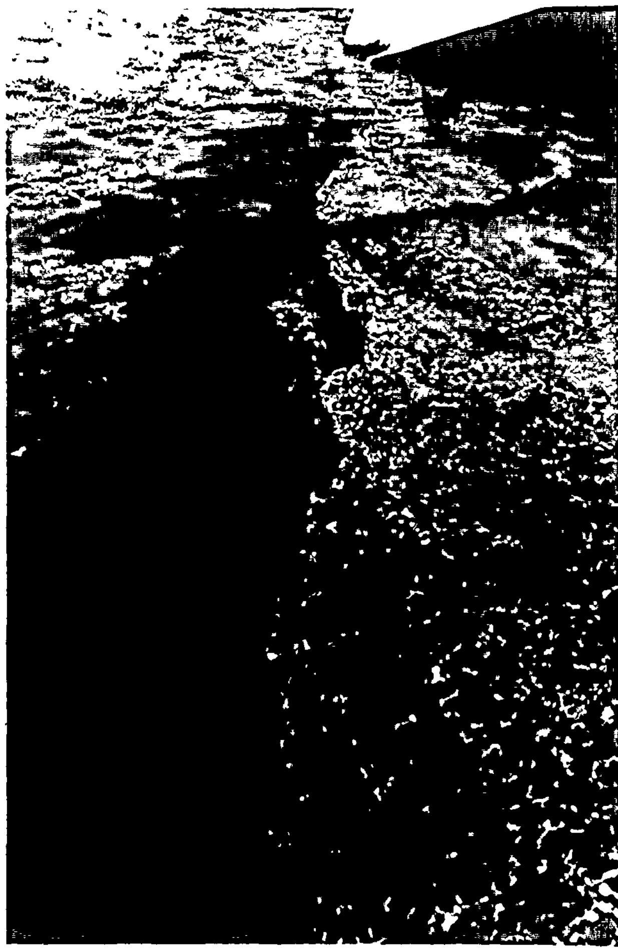


Plate 31 Pitting in the shore zone continues into the lake and is not restricted by permanent wetting. This photo was taken at Big Tub Harbour in Tobermory.

Plates 32 and 33 show the typical deep pitting found on submerged bedrock. Pits on the sample shown in Plate 33 have an average depth of 45.9 mm (10 measurements only) but showed little corresponding increase in diameter, although nearly all the pits had coalesced.

Away from the shore zone the pitting dies out and is replaced by shallow clint and grike with minor, irregular pitting or wetlands.

The positioning of individual pits is probably structurally controlled. This would account for the lower density of pitting than on the more exposed Guelph surfaces where pitting is more random due to rainfall. Structural control is provided by two features micro-jointing and glacial striations. Evidence of the first control was provided by a rock thin section taken through the centre of a pit from Dorcas Bay. This showed a small micro-fissure extending several mm below the base of the pit. The fissure could also be seen on the cut hand specimen where at least two pits were aligned along it. The second control was clearly seen at Marr Lake where pits were aligned in very straight lines exactly parallel with the long direction of small bedrock ridges over which they crossed (Plate 34).

The origin of these pits is not known for certain and there is very little about them in the published literature. Corbel (1963 and 1968) described features from northern Scandinavia which he called tinajitas (see plates IB and IIA of his 1968 paper). According to Corbel they were found only in a zone which was periodically flooded with fresh water - "Les tinajitas sont toujours liées aux zones d'inondation periodique". He also observed decomposing vegetation in the bottoms of the hollows -

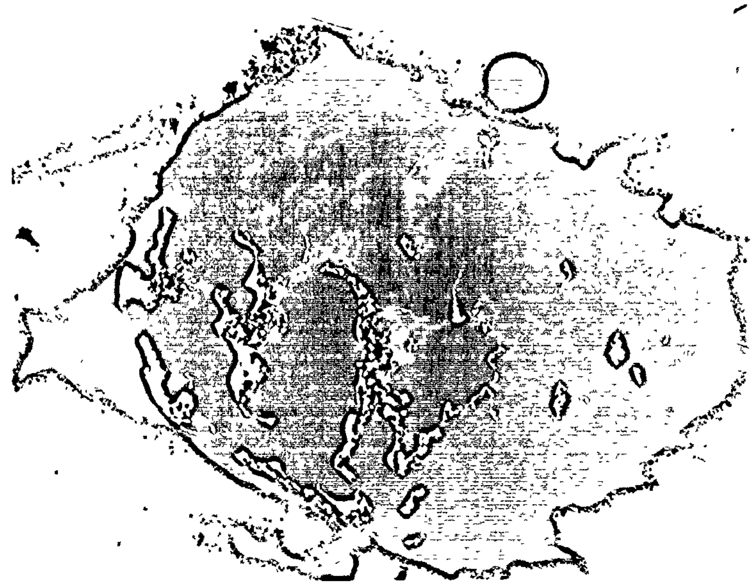


Plate 32 Well pitted sample raised from the Lake Huron floor by divers (quarter for scale).

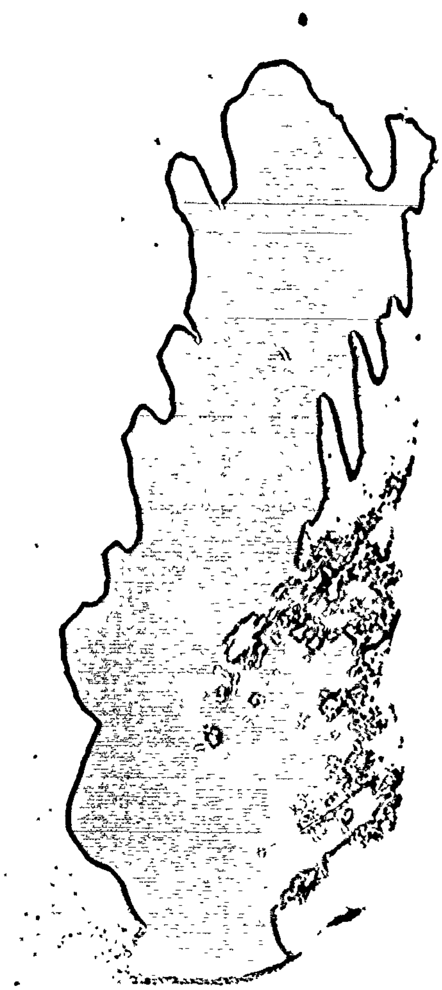


Plate 33 Finger-like protrusions on sample found 55ft below the lake surface in Big Tub Harbour (dime on sample at left for scale).

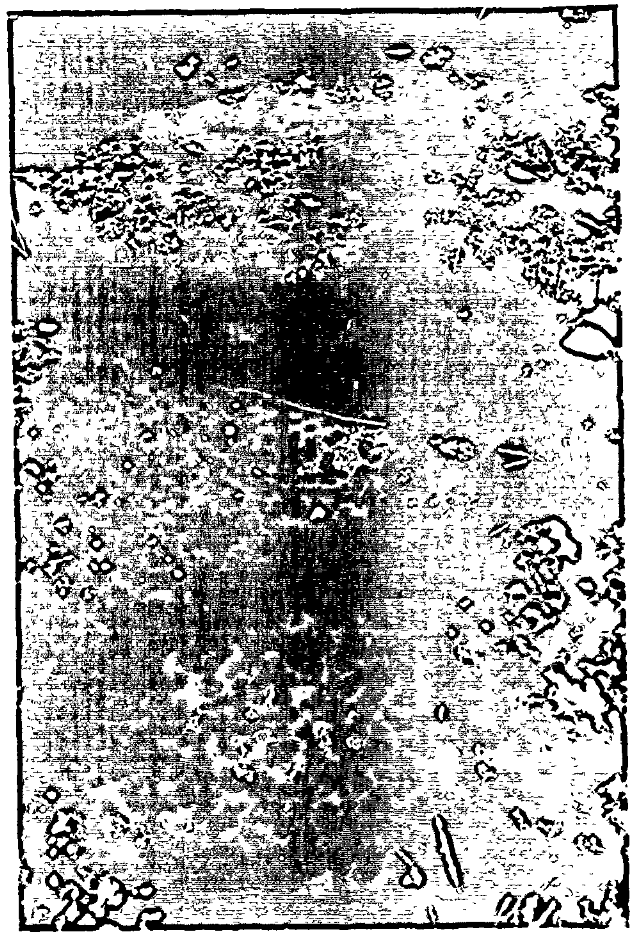


Plate 34 Pitting at Marr Lake showing the linear arrangement of pits along former glacial straie.

"notez la pourriture végétale au fond des vieux" (1963, p.129). Extensive pitting has also been observed on limestone bedrock surrounding fresh-water lakes in Ireland (Williams 1966, p.164 andD.C. Ford pers, comm.). Deep pits with finger-like protrusions similar to those in Plate 33 were described. Those in Ireland however were found in the shore zone and were pointing downward. They were believed to be the result of solution by the lake waters lapping up into rock overhangs. This is not the case in the Lake Huron samples because divers reported the rocks to appear to be in situ on the lake floor, pointing up. No overhangs occur on the Lake Huron shore (except on some of the islands) and even if they were formed in this manner, having later fallen into the lake, the protrusions would have broken off.

The most likely explanation of the development of these littoral pits on the Bruce Peninsula concerns biological solution in a fresh water environment. In all cases the rock surface is completely or patchily coated with lichens, algae or mosses. In some cases lichen patches can be seen near pits and they have diameters similar to those pits (Plate 35). Many of the pits above the permanent wetting zone are occupied by moss (Plate 30). Even the submerged samples were completely coated with some form of light grey algae. Corbel (1963) believed biological solution played a major role in the development of the pits. Periodic wetting washes out any saturated solutions and provides fresh water to carry out further solution, boosted by biogenic acids.

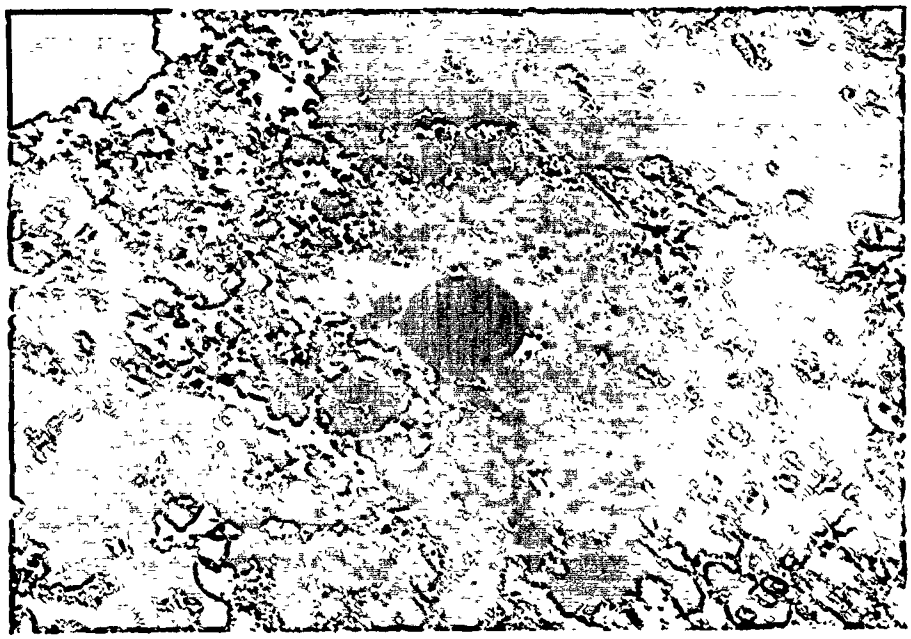


Plate 35 Round patches of dark lichen in the Lake Huron shore zone on Bears Rump Island. These may be responsible for creating the initial depressions which later become enlarged (by rain and moss) to form pitkarren.

3.4 Discussion

The above descriptions have of necessity been kept quite general and the pavement is much more complex than they might suggest.

The Bruce Péninsula pavement is composed of two strongly glacially-scoured dolomite units of similar chemical composition. Its macromorphology is extremely variable as a result of primary stratigraphic structures (particularly bioherms) and the erosional disposition of these stratigraphic structures. Extremely flat, often stepped pavement may grade into low amplitude ridges or much higher biohermal reefs moulded by glacial action (up to 20 m or more of local relief). The pavement may be continuous as for most of the peninsula north of Monument Corners or may be sporadic, consisting mainly of exposed ridges above mantled lowlands as is more common to the south.

A third factor - macro-relief or topography - can be added to lithology and environment as a control on pavement development but does not necessarily affect the type of karren produced. Its affect is primarily related to clint and grike development in both the Guelph and Amabel formations. The high relief and consequent high groundwater hydraulic gradients along the Niagara Escarpment is very favourable to grike development (both solutionally and mechanically) and thus very wide, deep grikes in excess of 15 meters deep are associated with the eastern and northern sides of the peninsula. Both rock formations are affected in the same manner and thus the grikes described above for the Amabel (at Dyer Bay) are not necessarily representative. In areas along the escarpment where soil and till have accumulated, such as the promontory between Hope and Barrow bays (Cape Dundas, Figure 3.1), preferential

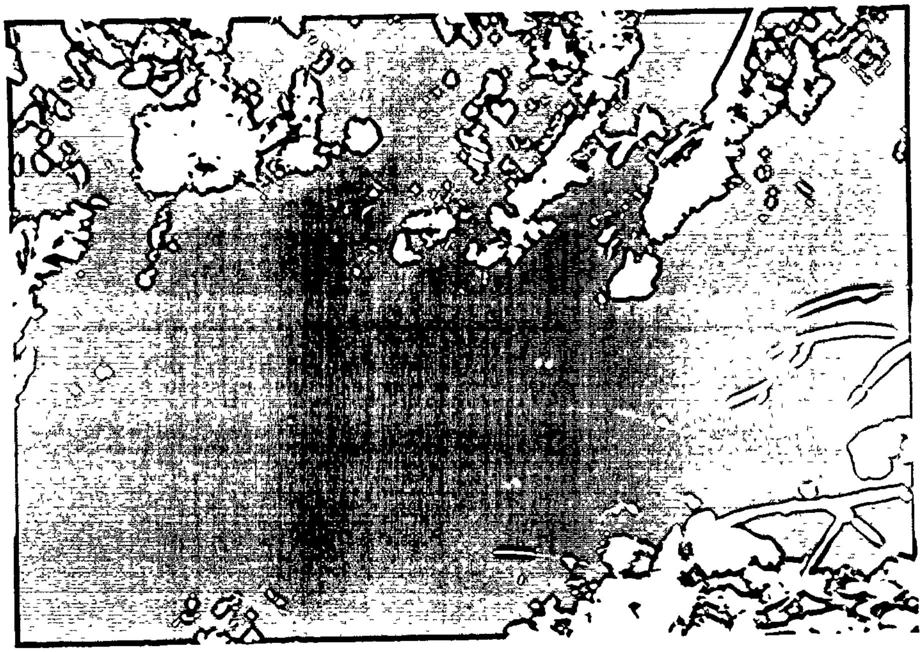


Plate 36 Deep grike in the Amabel Formation north of Hope Bay. This feature acts as a sinkhole for a small local catchment. Note the deep vertical groove left of the persons' foot. The groove is probably the result of localization of peaty water draining into the joint at that spot.

enlargement of certain joints is common. These have developed essentially as sinkholes (dolines) which drain small local catchments. One such 'grike' is 7.5 m deep (25 ft) in bedrock with 4 m (12 ft) of overburden surrounding it (Table 4.1). Contrasting with the Niagara Escarpment is the flat Lake Huron side of the Peninsula, formed almost entirely of the Guelph Formation. This is a groundwater discharge area and thus only shallow grikes, if any, can develop. Between the shore and the 650 ft contour (Figure 2.4) are large poorly drained areas which have inhibited pavement development, except where ridges occur. Local ridges (roches moutonnées) commonly have fairly good clint and grike development wherever they occur. In these cases the deeper grikes are found toward the higher parts of the ridges. The area between ridges and rock knobs are very often quite swampy and covered with vegetation. Along the edges of many of the roches moutonnées solution is aiding the deterioration and break-up of the ridge. Grikes carve up the surface and allow faster solution by exposing more surface area to attack. Undermining by solution along bedding planes and on the edge of the ridges causes blocks to loosen and even fall away from the ridges (Plate 37). This will ultimately lead to the destruction of the ridges and consequently of the pavement surface.

It was noted earlier that there is a strong association in the literature between the smoothness of karren forms and the presence of a vegetation cover (Sweeting 1972, p.76 and 195-197). Jennings (1971) states that the most important factor affecting the nature of pavements is the presence or absence of some cover, whether soil, plant litter, superficial deposits or vegetation. What then can we say about the development and nature of the Bruce Peninsula pavement? The abundance of rounded

b

Plate 37 Destruction of a low ridge by block separation along one edge. This is a common feature on the peninsula. Many ridges may eventually be destroyed by this process. Solution acts both vertically and horizontally, undermining the blocks, and causing their collapse.

karren forms, and obvious relationship of certain forms to vegetation, (i.e. Plates 11, 12, 15, 27, 30 and 35) in all three assemblages suggests that biological factors have played a major role in the development of the pavement. Perhaps there was a more extensive vegetational cover at one time. Soil is protective w.r.t. the dolomite on the Bruce as evidenced in the trench at the Dyer Bay site. Wherever glacial deposits have recently been removed glacial striae cover the rock surface, solution being almost totally inhibited.[1] A greater soil cover previous to logging if anything would thus have prevented pavement development. It would seem then that for the most part the aerial extent of the pavement has not changed substantially since the Wisconsin. This does not mean that there has not been a greater vegetation cover in the form of mosses and higher forms. Even today many areas of bare pavement are very densely forested with trees rooted in grikes. Such a 'cover' helps to maintain higher moisture levels (especially by mosses) as well as supply organic acids and biogenic CO_2 to aid the solution process. It would also reduce the initial rapid solution by rainfall, believed to be an important factor in creating sharp karren forms (esp. rillenkarren) in alpine environments. Slower solution due to the water being in contact with the rock for a longer time would produce more rounded forms (Sweeting 1972, p.76).

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1 Glacial striae beneath recently removed deposits can be seen at the Tobermory town dump, a small wayside pit on the Johnston Harbour road, another such pit at the Crane River southwest of highway 6, another east of Cape Chin and also at the Hope Bay Anglestone Quarry.

Certain fluvial-type karren forms such as rundkarren can be formed under these conditions because gravity flow of runoff is still permitted beneath the vegetation. Sharp pitting on parts of the Guelph formation thus may not be totally lithologically controlled but partly a result of rainfall activity on recently exposed pavement (Plates 20 and 21).

Another explanation for the roundness of karren morphology could relate to the solution process on dolomite and have very little to do with the presence or absence of vegetation. Most of the literature deals with limestone Pavements. Perhaps rounded forms are characteristic of the solution process on dolomite which inhibit sharp-crested features. However, the presence of at least a limited number of sharp karren (Plates 16, 17 and 20) plus the fact that it is a Ca^{++}-rich dolomite suggests that this is not the case. The rillenkarren in Plate 16 may represent a localized kind of environmental control. They probably receive the most intense rainfall of anywhere on the Bruce. They occur in a very exposed location facing the longest fetch of Georgian Bay and on the highest part of escarpment in this area. Although not observed on the Guelph Formation is is very likely that other rillenkarren have formed in similar environments, particularly the high Amabel bluffs at Cabot Head.

It would seem then that vegetation plays an important role on most of the Bruce with respect to karren development. It permits greater wetting, lowered rainfall intensity and thus slower and longer solution resulting in mature, rounded karren forms. The importance of vegetation is shown directly by the presence of deckenkarren (root grooves) in both the Guelph and Amabel formations (Plates 27 and 28) and hohlkarren in the Amabel.

The pitting phenomena on parts of the Lake Huron shore also appear to be a product of biological solution. They occur within a particular environment and represent a distinct karren assemblage. Lake Huron and Georgian Bay waters were found to be non-aggressive chemically (high saturation and pH see Table 5.1(B)) and thus their waters would require local boosting to permit solution. Lichens and algae which coat the rock surface in this zone could possibly provide the required local boosting; "solution caused by lichen hyphae gives rise to hollows 0.1 mm deep" (Sweeting 1972, p.95). This is probably also a major factor in pitkarren development elsewhere. Both at the shore and above it higher life forms such as mosses effectively enlarge pits initially created by lichens (Plates 30 and 35). The deeper pits found on samples taken from the lake floor (Plates 32 and 33) may be a result of more active biological organisms common to submerged, freshwater environments. Bryophytes (mosses) and thallophytes (algae and lichens) are known to produce strong organic acids and have a high nutrient uptake capacity, (including Ca^{++}, Moore and Bellamy 1974). Ombrotrophic peat bogs out of the influence of mineral substrate usually have a pH in the range of 3 to 4 (Sjörs 1963) which is extremely acid. It is thus easy to see what the effect of these plants growing directly on carbonate bedrock would be. The effectiveness of solution by such processes is a field which requires a great deal more study, especially from a biological (lichenometric) perspective similar to that of Jones (1966).

The lithological controls produced by the Amabel and Guelph formations relate primarily to porosity. The Colpoy Bay - Wiarton member of the Amabel is essentially a biohermal unit whereas the Guelph Formation is predominantly biostromal (Liberty and Bolton 1971). The Amabel dolomite is described as "fine crystalline with minor coarse crystalline and porous zones" whereas the Guelph dolomites are described as "fine to coarse crystalline" with "well developed porosity" (Liberty and Bolton 1971). Also, in the Guelph Formation "vugs of various sizes represent an integral part of the rock". It would seem that the high porosity of the biostromal Guelph has resulted in a very cavernous, vuggy pavement with few true karren forms. The Amabel in contrast has permitted better karren development although it is limited in outcrop extent (because it is biohermal). Intervening strata (interreefal) are much weaker and in most places have been removed by mechanical erosion. The biostromal Guelph Formation on the other hand has formed both massive flat pavements and biohermal pavements.

Pluhar (1966) and Pluhar and Ford (1970) studied karren forms and their relationship to soil and lithology, on the Niagara Escarpment near Hamilton. The carbonate bedrock of the Hamilton area is the Lockport Formation, which is the lateral equivalent of the Amabel Formation. These units are chemically the same (refer to Appendix 1 and Pluhar 1966, p.78-79) but differ slightly in lithology. The Lockport Formation is less biohermal and more regularly bedded than the Amabel. Glacial deposits are also more extensive in the Hamilton area and consequently there is poorer pavement development. Nearly all the bedrock exposures are found close to the brow of the escarpment.

Pluhar recognized five main types of karren including cleft and trenchkarren (joint controlled grikes), pitkarren, groovekarren, split groovekarren and runnels (rinnenkarren). All but the last of these are structure controlled, ('rock-controlled types'), via joints and stylolites. Pitkarren were found both singly and in series along joints - 'pit-and-tunnel karren'. Amalgamation of the latter resulted in the formation of trenches which are grikes that terminate at the first prominent bedding plane. As in the Bruce Peninsula, karren were mostly smooth, rounded features and thick overburden was found to protect the rock surface (Pluhar, 1966 p.64). Pluhar (p.59-60) also noted that biological factors were important in karren formation in the Hamilton area. At least some biological influence was found in all cases and groovekarren were believed to be produced completely by the action of vegetation (lichen and moss). Porosity was very important in karren formation. For groovekarren Pluhar (p.30-31) noted that the relative porosity between adjacent zones was as important or more so than the absolute porosity. Even variations as low as 1% could result in very strong grooves.

In general, similar karren types and dimensions were found on the Lockport Formation near Hamilton as on the Amabel Formation of the Bruce Peninsula. The main differences are a lack of hohlkarren and deckenkarren plus fewer gravity controlled features in the Hamilton area. This may simply be a result of thicker and more extensive overburden around Hamilton. The presence of bioherms on the Bruce Peninsula also presents more impetus for gravity forms such as meanderkarren. Guelph-type pavements and the extensive pitting common to the Lake Huron shore were not found in the Hamilton area.

CHAPTER 4

HYDROLOGY AND MESO TO MACRO KARST

4.1 Introduction

Drainage from the Bruce Peninsula can be separated into four types:- wholly surface runoff (i.e. normal fluvial action), wholly subsurface flow (i.e. holokarst), partial underground capture of surface channel systems (i.e. immature fluvio-karst) and complete capture of surface channels (i.e. fluvio-karst). The most significant active, meso and macro karst features (surface and subsurface) are a result of the fluvio-karst. Figure 4.1 shows the distribution of the four drainage types. Stream divides are only approximate because of the small scale of the map and because of the inherent difficulty in separating basins in karst areas. Interflow across divides is common. Streams are fed by both wetland areas and by shallow springs. The holokarst boundary was determined using relief and the extent of exposed bedrock along the escarpment. This area is devoid of 'normal' surface flow having only short, intermittent, disappearing streams. Subsurface flow through the holokarst is directed mainly toward the escarpment but some likely also feeds streams, particularly Willow Creek and Crane River.

There is little or no seasonal data concerning discharge on the Bruce Peninsula. Because most of the drainage is east-west there are no major rivers. Catchments are small and the presence of exposed dolomite limits runoff. Flow regimes are likely similar to the rest of southern Ontario, that is Spring and Fall maxima with mid-season peaks corresponding to storm activity. Peaks may be smoothed out more than in southern Ontario because of greater subsurface flow. Many streams are active for most of the winter and sudden thaws are common.

More than half of the peninsula's 30 or so lakes are on the northern tip. Most are less than 9 m (30 ft.) in depth[1] and many fluctuate quite radically in stage. Horse Lake, for example, drops over 2.5 m (8 ft.) from April to August (Plate 44). Crane, Lower Andrew and George lakes in the Cabot Head area, behave similarly. These fluctuations may be due to evaporation but are more likely in response to immature underground capture. This is definitely the case with Horse Lake (Section 4.2) and possibly George Lake as well (W. Mungall, Owen Sound, pers. comm.). Gillies Lake is notably out of scale with the other lakes, having a depth of 36 m (120 ft.). Also, its stage is more stable.

Shuster and White (1971) distinguish two types of springs, based on chemical and physical criteria. Diffuse flow springs are characterized by many small inputs which become integrated within the bedrock. Conduit flow springs on the other hand are connected by a cave to a single major input, such as a disappearing stream, but may also have diffuse inputs. Chemically, conduit springs tend to have lower total hardness, lower partial pressure of carbon dioxide and greater seasonal fluctuation. They can also be identified in the field comparatively easily by the use of dye traces.

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1 Ontario Ministry of Natural Resources, unpublished data, Owen Sound District Office.

There are many springs on the Bruce Peninsula. They are found on the surface and in the face of the escarpment. Diffuse and conduit flow springs are represented and most are intermittent. Vertical penetration in the vadose zone (i.e. above the water table) is limited by the Cabot Head shales or the level of Georgian Bay where the shales are absent (Chapter 2).

Twelve perennial springs were sampled and analyzed for Ca^{++}, Mg^{++}, temperature, pH and alkalinity. The data are listed and discussed in Chapter 5. Their locations are shown in Figures 4.1 and 4.2. Of these twelve, seven are in the escarpment face including four conduit springs which are discussed in Section 4.2. Two of the remaining three are believed to be diffuse. One lies immediately east of Rocky Bay and the other west of Cape Dundas. The third is in Dyer Bay and is likely fed by Britain Lake.

The other five springs[1] feed streams and lakes above the escarpment and all but one are believed to be diffuse. The rising on the east side of Marr Lake is conduit because it is fed by Horse Lake (Section 4.2). The spring on the west side of Marr Lake is probably diffuse and is somewhat different from the rest. It displayed one of the lowest temperatures (10°C) and deposited sulphate (gypsum) where it flowed into the lake. The $CaSO_4$ content however was found to be only about 30 ppm. Gypsum deposition was also observed at the spring between Cameron Lake and Dorcas Bay but only for a short time during the Fall of 1973.

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[1] A 6th spring is shown in figure 4.1 feeding Spring Creek but it was not sampled.

4.1.1 Fluvial Drainage

Most of the surface runoff from the Bruce Peninsula flows into Lake Huron[1] (figure 4.1). Willow Creek and Crane River drain thirteen of the peninsula's lakes. Their basins are large, given the lack of surficial deposits which greatly increases the opportunity for underground capture. West of these streams are only a few short, unnamed creeks (except for Sideroad Creek) and much of the area is characterized by either poor drainage (wetlands) or vertical drainage. Brinkman, Sadler, Spring, Stokes, Black, Old Woman, Sucker, Albemarle and Rankin are the other main streams on the Bruce. These drain the western half of the peninsula with their headwaters near the centre. Vertical drainage dominates the east side along the escarpment. In contrast, the Lake Huron shore is poorly drained because of a low gradient and high water table.

All streams are close to bedrock or flow directly on it except Judges Creek which is perched on the Eastnor Clayplain. Where glacial, lacustrine or alluvial materials occur they are being removed by stream action, exhuming bedrock. The bed of Crane River at highway 6 consists of glacially polished bedrock even though alluvium lies above the river on either side.

4.1.2 Holokarst Drainage

Areas dominated by vertical drainage and lacking normal surface channels (or relict channels) are referred to as holokarstic. At present these correspond to zones where the groundwater hydraulic gradient is greatest, such as along the top of the escarpment and on its promontories

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1 Colpoys Creek on the north side of Colpoy Bay, Judges Creek and the lakes in Cyprus Lake Provincial Park flow into Georgian Bay.

(Figures 2.5 and 4.1). The impetus for underground drainage is very good in such areas, particularly if there is no drift. Precipitation and snowmelt drain almost immediately into grikes and other sinkholes. Only small ponds and swamps remain at the surface. Some runoff probably occurs near the edges of the holokarst, especially during storms, but numerous large grikes in these areas attest to the degree of vertical drainage.

Extension of the holokarst inland is variable. Across the top of the peninsula it is confined to a zone about 1.5 km (1 mi) wide. However, it is as much as 3 km (2 mi) wide on the Cabot Head Promontory. The head-lands at Lion's Head, Sydney Bay Bluff, Jones Bluff and Kings Point (an outlier) are completely holokarstic. This is also true of Flowerpot, Bears Rump and many of the smaller islands north of Tobermory. Cape Dundas has more surficial deposits than the other promontories but it too is a holokarst. It is characterized by a few very large grikes draining small, covered catchments and by short, intermittent disappearing streams (examples occur at 870742 and 875762). One such stream (870742, Plate 38) flows from a small swamp into a cave in the side of a ridge. The cave consists of a circular chamber 8.5 m (28 ft.) in diameter and 1.5 m (5 ft.) high at the centre. A small circular passage less than 30 cm across leaves the cave at the rear.

Very little is known about the internal drainage of these holokarst areas. The lack of concentrated runoff has inhibited the development of explorable passages although several may lie at depth. The only active, explorable cave on the escarpment is associated with a fluvio-karst. Other caves on the escarpment are dry and probably owe much of their development

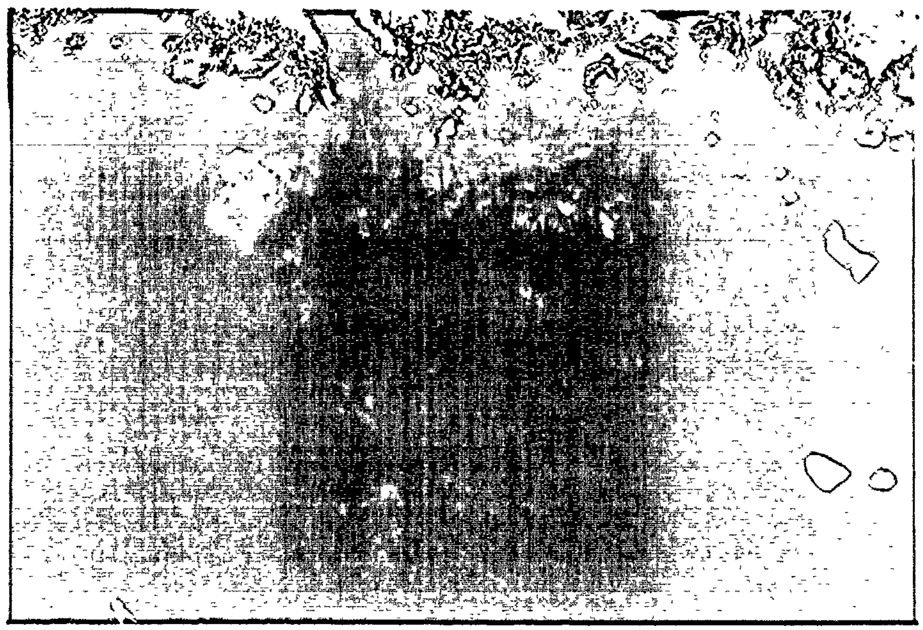

Plate 38 Small stalactites inside circular cave on the Cape Dundas promontory. This cave was probably formed during a time when more water was available. The presence of the stalactites suggests that it is now dry most of the time although mud and small sticks on the wall indicate it still floods out seasonally. The small tube to the left of the figure drains this cave.

to mechanical processes, such as waves (Section 4.4). The presence of many small intermittent springs, as opposed to large perennial resurgences, suggest that the holokarst drainage is completely diffuse. Some may be lost down dip toward the southwest. Cape Dundas is the only promontory having a major, perennial spring[1]. It is also the only headland not completely free of overburden and hence has more concentrated inputs. The spring issues from talus. Its flow was not observed to fall below an estimated 2 or 3 c.f.s. and early in the year was about 10 c.f.s. Explorable passages may be within this promontory but if so are below the top of talus accumulation and thus are inaccessible. However, the presence of numerous intermittent springs nearby suggests that Cape Dundas drainage is not well integrated. A local resident asserted that in early Spring water emerges from many additional points on the surrounding cliffs.

4.1.3 Immature Fluvio-karst Drainage

Because of the lack of drift on the Bruce Peninsula it is likely that many of the surface streams are in the process of being captured underground. The escarpment presents a very high groundwater hydraulic gradient in the opposite direction to the gentle surface gradient. Karst processes presently operating near the edge of the escarpment further increase the likelihood of underground capture.

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1 The perennial spring east of Rocky Bay (Fig. 4.1) is small (< 2 or 3 c.f.s.) and flows out of beach gravel on a shelf below the escarpment. The other springs on the escarpment are fluvio-karst resurgences.

It is common in karst areas bordered by an escarpment, to have the karst continually expand away from the edge of the scarp (D.C. Ford, pers. comm.). As karst processes become established the effective hydraulic gradient in adjoining zones is increased. The lowest point of vertical solution becomes the new base level resulting in shifts of the greatest potential for vertical solution away from the escarpment. On the Bruce Peninsula this would eventually mean a complete reversal of most of the existing drainage toward the north and northeast (Section 4.3).

At least one major basin may be in the process of underground capture. The Crane River was found to be losing water over a distance of about 1000 m (3300 ft.). Two discharge determinations were performed on this river on the same day using a Gurley-type flow meter. The flow was found to decrease by 17%[1]. The upstream discharge was 11.47 c.f.s. This loss is especially notable because water is added to the river between the two stations by a perennial spring. Thus, on Figure 4.1 the Crane River basin above the lower gauging station is shown as an immature fluvio-karst. Its headwaters touch the holokarst area and consequently one can expect a high potential for underground capture. The entire stippled area in Figure 4.1 may not necessarily be captured all at once. It may happen in stages working downstream from the holokarst. Alternatively, the recorded loss in flow could be along bedding planes toward Lake Huron.

Similar discharge determinations were made for Willow Creek and no loss was found. However, the discharges were made over a distance of 5.5 km (3.5 mi.) and additional inflow could have overwhelmed any subsurface losses.

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1 The downstream discharge was taken at highway 6.

4.2 Fluvio-karst Drainage

There are five basins possessing regular surface channel systems that feed entirely to sinks (Fig. 4.1). All of their runoff is drained underground for at least part of the year. During high flow, such as at Spring freshet, ponding may occur over the sinkholes and there is simultaneous surface and subsurface drainage. Four of the five basins are in the northern tip of the peninsula and are shown in Figure 4.2. They have formed by underground capture and include two lakes (Horse Lake and Gillies Lake) and three unnamed creeks. Seasonal water chemistry data were collected for the four northern systems in 1973 and are presented in Chapter 5 (Table 5.1, Figures 5.2 to 5.5) and will be briefly discussed in this section. The St. Edmunds fluvio-karst near Tobermory is the most significant of the five systems and will be discussed last.

There are also numerous short, intermittent streams which disappear. These are not considered in detail. They occur primarily within the holokarst areas, especially on the Cape Dundas promontory. Some are natural, drainage overflow from nearby wetlands (Plate 38) but many are man-made or at least man-improved. It is common to see trenches dug through otherwise poorly drained fields and leading to a small sinkhole or rock outcrop (Plate 39). In many cases this practice has been successful in improving the drainage. These have been observed at Cape Dundas (887757), Miller Lake Corners (659956), and west of Cape Chin (766953).

4.2.1 Colpoy Creek

This is a small unnamed creek which flows into Colpoy Bay east of Wiarton. It occupies a meltwater channel which is cut into bedrock. The

Plate [illegible] Small [illegible] hole dug cut to improve drainage of a farmer's field on the Cape Dundas promontory. A small depression probably existed here prior to the trench. (note field book and compass, at centre, for scale).

channel appears to have been formed to drain overflow water from Hope and Sydney bays into Colpoy Bay probably during the retreat of the Wisconsinan ice. The creek presently occupies only about $^1/_3$ of the length of the channel and the upper part is either poorly drained or drains vertically.

The creek disappears into sand ahd bedrock about halfway along its route (898605 to 898603) and reappears within its channel in the village of Colpoy Bay. It rises from numerous bedding planes and joints where County Road 9 crosses it. The sinks are not well developed as closed depressions but capture water via open joints in the stream bed. The underground route appears to parallel the present stream bed and probably lies fairly close to it, following bedding planes, approximately along the strike. Total capture takes place fairly late in the season (late June) as the route is as yet too inefficient to swallow all of the Spring runoff. Thus the system acts much like a normal surface stream until the discharge drops to a volume that can be completely swallowed leaving the lower half of the channel dry. The drop in elevation from the sinks to the springs is only about 9 m (30 ft - 690' a.s.l to 660' a.s.l) over a distance of 1.6 km (1 mile) giving an hydraulic gradient of about 176:1.

This system is very young or immature representing simple underground capture along favourable bedding planes. It is unlikely that there will be much of an increase in the efficiency of the underground path as it is essentially the same as the overland route and with the same hydraulic gradient. Solution will continue as long as water is fed through the cave but collapse along the channel would probably be the end result unless deeper, more efficient subsurface routes are found.

4.2.2 Dyer Bay

This fluvio-karst lies about 1 km southwest of the village of Dyer Bay. It consists of a short channel draining a large swampy area. The creek disappears into a joint oriented 84-264° on the side of a low ridge (Plate 40). The total area involved is quite small but it is included in this section because the stream is perennial. Its drainage appears to have been improved because the channel is very straight and located in a pasture. It is not known whether or not this sink was active prior to improved drainage but it likely functioned as an overflow drain for the swamp. A suffosion sinkhole, i.e. a closed depression with all of its expression in the mantle, lies immediately east of the streamsink and suggests that karst processes have been operating here for some time. This sinkhole is about 1.5 m in diameter and is presently filled with field stone.

The resurgence of the streamsink is not known for certain but is believed to be a spring which issues from beneath a cobble beach deposit in the village of Dyer Bay (Fig. 4.2). A dye trace was not attempted because the spring is used for drinking water. The total hardness of this spring was found to be higher than at the streamsink each time the two were sampled (4 occasions, Figure 5.3). The difference varied between 2 and 24 ppm.

The springs are at 625' a.s.l., the streamsink at about 700' a.s.l. and the separation is 0.55 mi yielding an hydraulic gradient of 38.7:1.

This appears to be a fairly simple system which has been altered somewhat by man. There is no evidence of any overland channel beyond the streamsink so it is likely that this does not represent capture of a fluvial system. The present streamsink probably originated as a local wetland drain and may

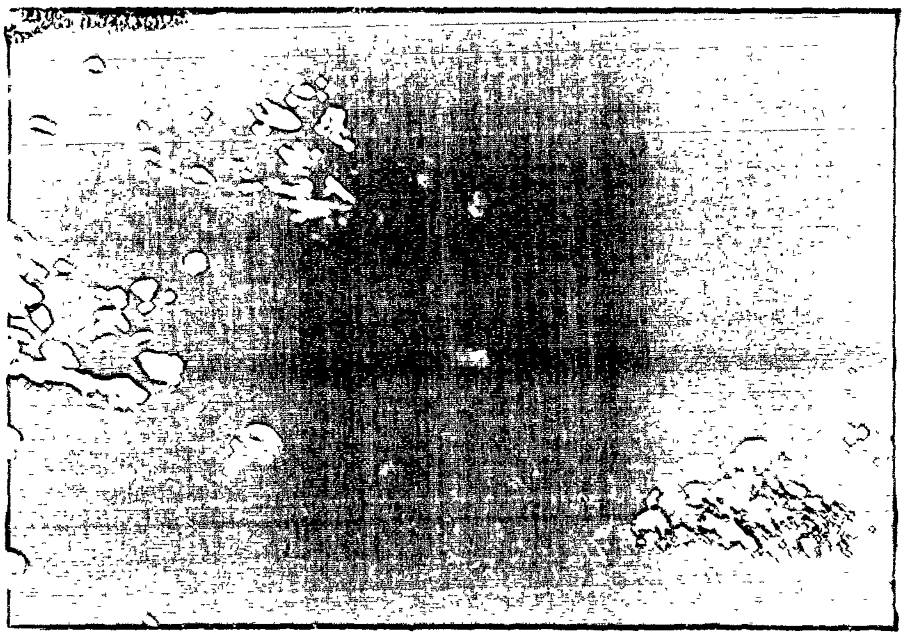

Plate 40 Streamsink southwest of Dyer Bay. Stream enters from lower right and disappears into boulders and bedrock in the centre of the photo.

be considered as part of the holokarst which surrounds it on the north, east and south. The potential for karstification is better here than at Colpoy Bay because of the higher hydraulic gradient. However, it is more limited in the sense that it has a much smaller drainage area (and thus less input to the system).

Another resurgence lies 3.7 km (2.3 mi) to the southeast (Figure 4.1). This issues from well bedded strata near the top of the escarpment and it is not known whether it is connected to Dyer Bay. It seems more probable that it is fed by Britain Lake which lies less than 1 km to the west. If connected to the Dyer Bay streamsink the hydraulic gradient would be only 486:1 which seems much too low.

4.2.3 Gillies Lake

Gillies Lake, located north of the village of Dyer Bay, is drained eastward by a sinking stream. The channel continues past the point of sinking and over the escarpment but it is not known for certain whether this represents an original surface route. The channel was deepened and improved in the late 1800's to support a log flume (Fox 1952). It is presently 3-4 m deep (10 ft), is cut through gravel and boulders and exposes bedrock (Plate 41). It may still be active in early spring, however, this was not observed. Gillies Lake is spring fed and occupies a depression up to 36.5 m (120 ft) deep. Its deepest point is near the eastern end within a few hundred meters of the escarpment. The Gillies Lake depression has been interpreted as a karst collapse feature draining into Georgian Bay from its base (Fox 1952). There is no field evidence to support these contentions. The edges of the lake are smooth from glacial polishing and the outlet stream appears to control the lake level. Also, for this to be a collapse feature a large cavern would

Plate 41 Channel leading from Gillies Lake. Water disappears all along the channel which is almost completely dry in the foreground.

have to have formed in shale because the bottom of the lake lies in the Cabot Head Formation. It is my opinion that the depression was formed by glacial scouring. Its long axis parallels the direction of ice flow and it is scallop-shaped in the same direction.

The outlet stream sinks into its channel at several points over a distance of 200 m (650 ft). As lake stage lowers during the summer the stream shortens, disappearing closer to the lake and leaving a dry channel in its place.

The water resurges near the base of the escarpment within the Cabot Head Formation. It emerges at several points over an elevation of about 8 m (25 ft) and flows directly into Georgian Bay (Plate 42).

The cave system between the sink and the springs is too small for exploration. The connection was proven by the use of rhodamine WT. Approximately 250 ml of dye was injected into the stream. The dye took 20 minutes to completely disappear (visibly), reappearing at the springs 45 minutes after it was first injected. The total vertical drop is about 50 m (160 ft) and the hydraulic gradient is 5:1.

The inputs to the system are quite small and dispersed as indicated by the long distance over which water sinks into the channel and because it took 20 minutes for the dye to completely disappear. This is not to say that the springs are of the diffuse type because the inputs are relatively well concentrated. Once the water enters the system it is delivered quite efficiently to the springs indicating conduit type flow.

Water chemistry results are shown in Figure 5.4. Total hardness increases between the sink and spring by 2 to 8 ppm although on occasion it decreased. This solution rate is not as high as found elsewhere on the escarpment (Cowell and Ford 1975) but is likely sufficient to account for

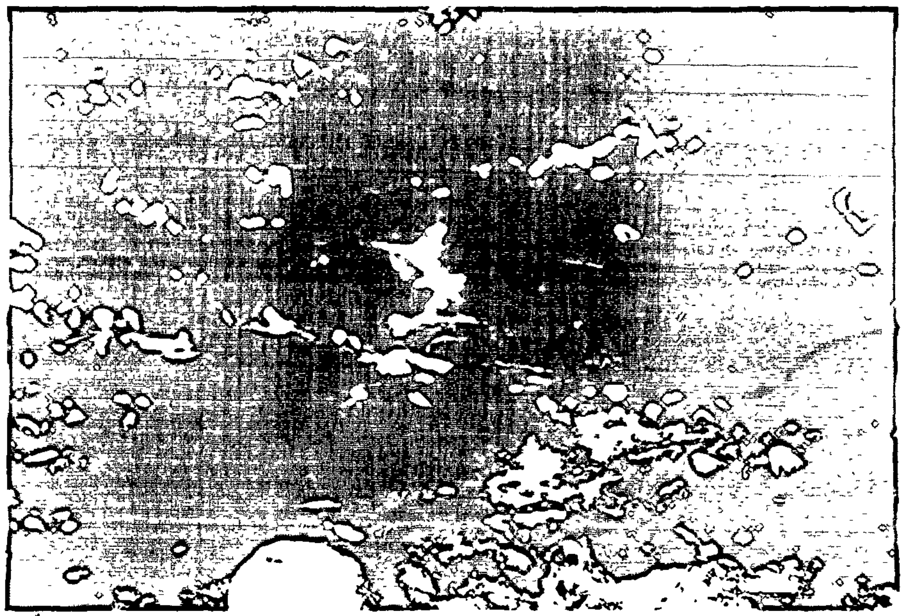

Plate 42 One of several springs at the base of the escarpment discharging water from Gillies Lake. Red shales of the Cabot Head Formation outcrop just below the spring point.

the size of the system. Higher solution rates probably occurs during early development when flow was less efficient and residence time of the water was longer. Another indication of short residence is given by the temperature curves. Water never cools more than 2.0°C between sink and spring in summer. This is in sharp contrast with the St.Edmunds cave (Fig. 5.5) which has a much longer flow-through time.

The karst at Gillies Lake is very localized but an efficient system has developed. Capture of the stream channel has not been in historical times because the spring was described by seamen in the 1800's (Fox 1952). Further enlargement of the cave could lead to its destruction by collapse. This is because of the shallow nature of the karst and the general instability of the escarpment face.

4.2.4 Horse Lake, Cyprus Lake Provincial Park

Cyprus Lake Provincial Park touches on four lakes all of which are connected and flow north into Georgian Bay. They lie in a bedrock trough which crosses the peninsula between Lake Huron (Dorcas Bay) and Georgian Bay (Figure 4.2). Two of the lakes drain via subsurface flow. Horse Lake drains along joints (115°-295°) toward the northwest into Marr Lake which in turn filters through beach cobbles into Georgian Bay. The first sink represents concentrated underground flow and the second diffuse flow in a granular aquifer. Marr Lake was formerly a cove of Georgian Bay which was cut off from the bay by a complex of storm beaches. Seven distinct ridges can be seen across the widest part of this beach (Plate 43).

The stage of Horse Lake is the most variable of the four lakes, changing more than 2 m (8 ft.) between spring and late summer. The high water mark is clearly visible on trees which are innundated each spring

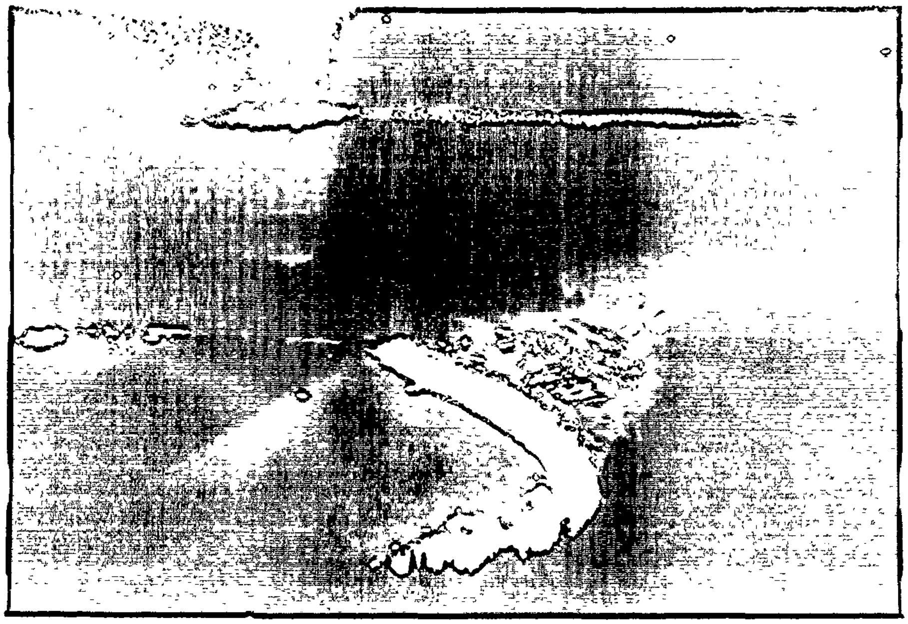

Plate 43 - Aerial view of Marr Lake (centre) and Horse Lake (upper) with Georgian Bay in the lower left. The springs fed by Horse Lake are on the far side of Marr Lake (to the left). Note the extensive storm beach deposits between Marr Lake and Georgian Bay.

(Plate 44). A surface channel leads toward Marr Lake but is terminated by bedrock ridges about 6 m (20 ft.) in height. It is not known whether this was a channel which drained Horse Lake or just an arm of the lake. There is no evidence of drainage across the ridges. The channel is presently occupied by a small stream which carries water only during spring and after precipitation. A compound sinkhole, i.e. two sinkholes joined along their rims and known as a uvala, lies at the end of the channel at the base of the ridges (Plate 45). The two sinks are 3 m (10 ft.) and 1.2 m (4 ft.) in depth and together are 18 m (60 ft.) long. They are oriented 125° - 305°. When observed in May they were dry and 300 m (1000 ft.) downstream of the last point of sinking of Horse Lake. Between the uvala and Horse Lake are a number of very small closed depressions and an explorable cave which cuts downward into the southern edge of the channel. The cave can only be followed for a few meters and likely feeds into the underground connection between Horse and Marr Lakes.

At low water Horse Lake drains via a number of small outlets on its northwest shore, upstream of the uvala. As its stage drops a large closed depression is revealed (Plate 44). This sinkhole appears as an unstable area of mud, boulders and falling trees. It is several meters in diameter. Bedrock is exposed in a few places beside this doline but most of the water drains through mud and vegetation.

Four springs enter Marr Lake directly across the ridge from the uvala. They occur over a distance of about 50 m (160 ft.) along the shore. Their connection to Horse Lake was proven in June 1973 using rhodamine WT. About 250 ml was injected at high stage, near the sinkpoints. Within 90 minutes the dye appeared visually at the two springs furthest south on Marr Lake.

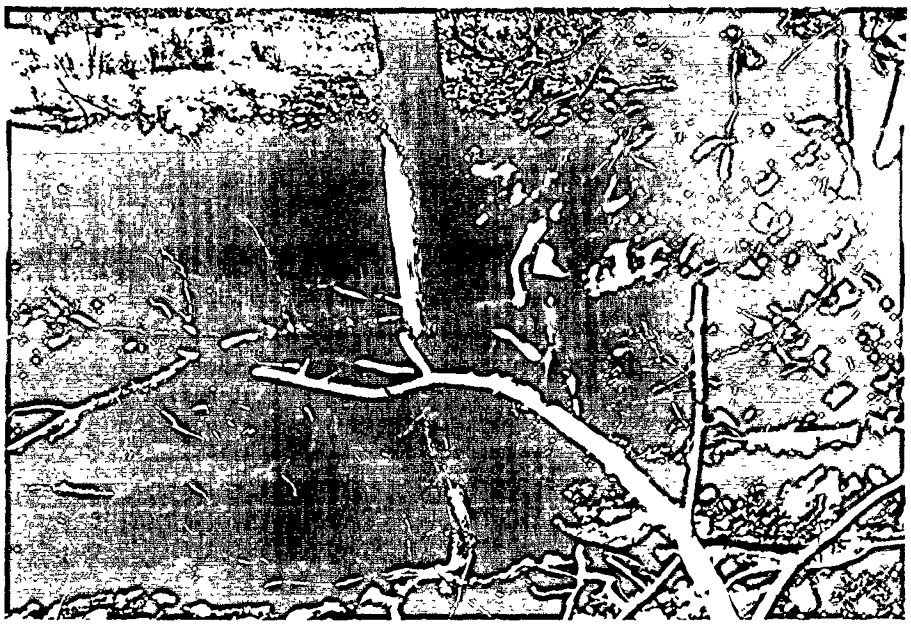

Plate 44 Large sinkhole that is flooded by Horse Lake in the spring and fall. The sink drains water from the bottom of the lake until late July or mid August when it becomes dry. Note the high water mark on the tree in the foreground.

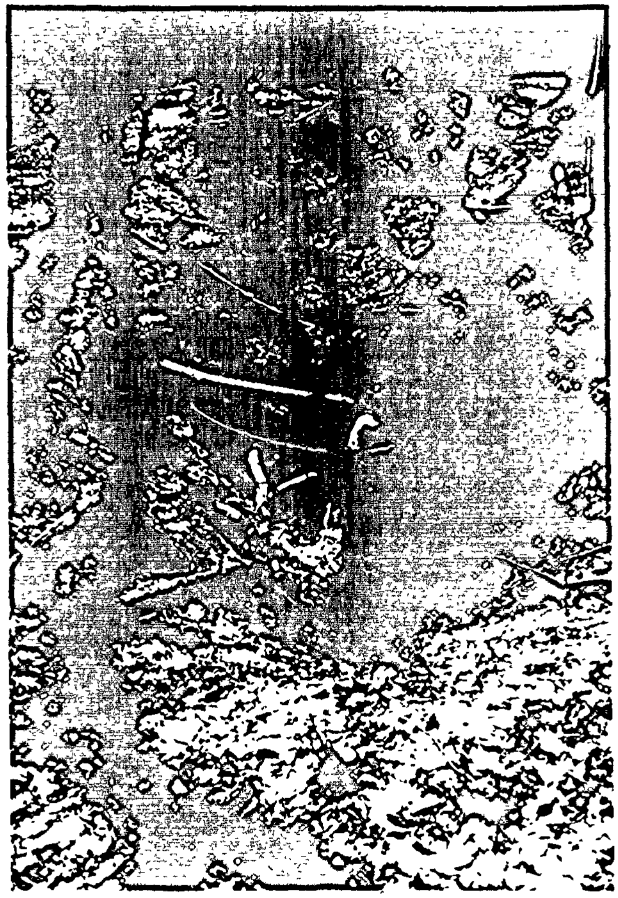

Plate 45 Compound Sinkhole between Horse and Marr Lakes. Marr Lake and the springs on Marr Lake are just across a ridge to the right of the photo. Person is standing in deepest part of the uvala which extends toward the top of the photo.

The other two did not show dye during the period of observation which was about 3 hours. An activated charcoal detector left in the spring furthest to the north was removed four days later and gave a strong positive detection (see Section 4.2.5 for an explanation of fluorescent dye detection). Thus either the dye travelled to the north springs within the first 3 hours but was too diluted to see, or it was stretched out somewhere between 3 hours and 4 days. It is unlikely that the dye travelled to these springs during the same time as the others because the visual detection for the others was so strong. It seems more likely that the two northerly springs are only indirectly connected to Horse Lake and may be predominantly soil and bedrock exsurgences. Discharge of all four springs steadily decreases over the summer until they dry up completely. The most northerly springs cease first (which also suggests they are poorly connected to Horse Lake) while the southern spring stopped after the level of Horse Lake fell below the largest sinkhole (in 1973 this occurred after August 14). It is probable that there is still some karst drainage at this time.

The hydraulic gradient is 42:1 having a drop of less than 7.5 m (25 ft.) over a distance of 375 m (1200 ft.). The conduits must therefore be close to the surface. Except for the one small cave already noted the connections are unexplorable.

Cyprus, Horse and Marr lakes as well as the springs on the latter lake were sampled frequently in 1973. Results are shown in Figure 5.2. There is an increase in both PCO_2 and total hardness from the sinks to the springs. The increase in total hardness varied from 2 to 16 ppm over the sample period. There is a consistent drop in pH and, as expected in temperature. The fall in pH coincident with increases in total hardness suggest the addition of CO_2 within the system. This addition makes the waters more aggressive, lowering the pH and permitting more solution to take place. CO_2 is likely added at the sinkpoints as water filters through mud and vegetation before reaching the cave system. This biologically produced CO_2 is an important boosting mechanism to the karst process (Chapter 5). CO_2 may also be added by seepage of soil water into the cave system.

The fluctuation in stage of Horse Lake is due to the presence of the karst. In its early history the lake probably extended toward Marr Lake and drained into either Marr Lake or directly into Georgian Bay. The uvala developed next to Marr Lake at the base of the rock ridges and thus initiated karst drainage to Marr Lake. Water drained from Horse Lake into a number of sinkpoints along the channel including the small cave. The stage was lowered as water kept disappearing closer to the centre of the lake. The present fluctuation in seasonal lake stage results from the inability of the many small inputs to drain the spring-melt efficiently. The sinkpoints, including the large sinkhole shown in Plate 44, are choked with mud and are unstable. An old beaver dam is found upstream of the largest sinkhole. This was constructed to help maintain a more constant stage in Horse Lake but was probably unsuccessful. At its lowest stage Horse Lake falls below the dam so that some underground drainage must occur above the largest sinkhole. The cave system is well developed considering the gentle gradient. It delivers water to Marr Lake within 1.5 hours. The low gradient means the system must be close to the surface and thus its development is restricted, even though there is sufficient drainage and an effective solution rate (2 to 16 ppm). Further vertical solution is limited because the springs are within a meter of Georgian Bay.

4.2.5 St Edmunds Cave System[1]

The St. Edmunds cave system is the best example of fluvio-karst on the Bruce Peninsula. It drains an area covered by glacio-fluvial and glacio-lacustrine deposits near Tobermory (Figures 4.1 and 4.2). This is the largest deposit north of the Eastnor Clayplain and is surrounded by bedrock exposures. It appears to be outwash, possibly a small kame delta, having well-stratified sands and gravels. It was partially reworked by glacial lake Algonquin and postglacial lake Nipissing. A large Nipissing bar can be seen along its southwest side (Figure 4.2) forming the 650 ft contour.[2] The presence of these deposits played an important role in the formation of the karst and together have a rather unique and interesting history. The St. Edmunds cave is the longest active cave presently known in Ontario.

The cave is a northeast-trending, joint-guided passage (80°-260°) which terminates at Georgian Bay in Little Cove. Its upstream end lies approximately 4 km (2.5 mi.) south-east of Tobermory and north of Highway 6. This is the main entrance to the cave. It consists of a vertical shaft about 9 m (30 ft.) deep and elongated along a joint at the side of a ridge

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1 Named by the author after the local township.

2 This is mainly the author's interpretation, the only reference to this deposit to date is Stadelmann (1973).

(Plate 46, Figure 4.4). Other sinkholes and shafts occur along the projectdon of this joint (Figure 4.3). These are not explorable for very far but are likely connected to the main cave. There are 6 of these which have been observed including 4 vertical shafts, 6 to 9 m (20 - 30 ft.) deep, and 2 major closed depressions near the main shaft (Plate 5). Although all are active during snow-melt most of the input is via the large sinkhole and entrance cave. The latter is fed by a stream which disappears into sand at the base of the ridge, about 10 meters from the open shaft. When the capacity of this sink to take water is surpassed the stream overflows along the edge of the ridge and disappears into the closed depression shown in Plate 5. This is also fed by a shallow spring and a nearby swamp. The main stream is active all year although in 1973 it ceased flowing for 2 weeks in mid-July. It drains a large swamp east of the Little Cove road (Figure 4.3) and has probably been deepened slightly to improve the drainage.

Explorable passage is found at each end of the system (Figure 4.4) but most of the centre portion is flooded. The entrance cave was well known by local residents but its continuation and resurgence were not known. The largest spring which was found along the escarpment in this area was in Little Cove. On July 28, 1973 a dye traceusing rhodamine WT was attempted.

Rhodamine WT is a fluorescent dye which can be detected either visually or after being absorbed on activated charcoal detectors (even if too dilute to see). Charcoal detectors placed in a resurgence (charcoal packets wrapped in fibreglass screening) following dye injection at a sinkpoint will adsorb the dye. When eluted with a strong base such as ammonium hydroxide the charcoal releases the dye. Detection in this solution may be visual but can more accurately be determined using a flurometer. For this study

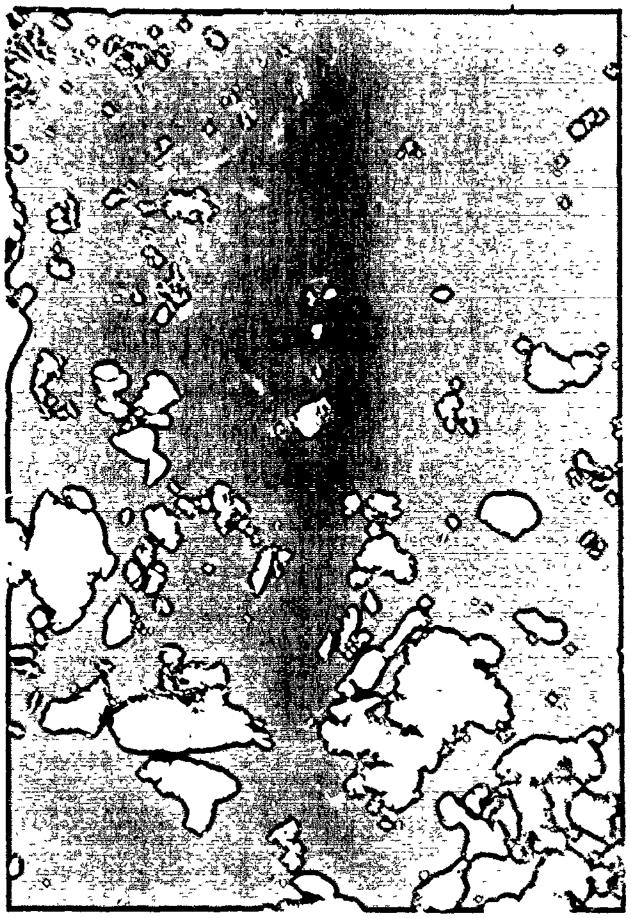

Plate 46 Vertical shaft about 9 m deep leading to the main entrance cave of the St. Edmunds system. Stream disappears to upper right of photo. Elongation is along a joint beside a ridge (on the left).

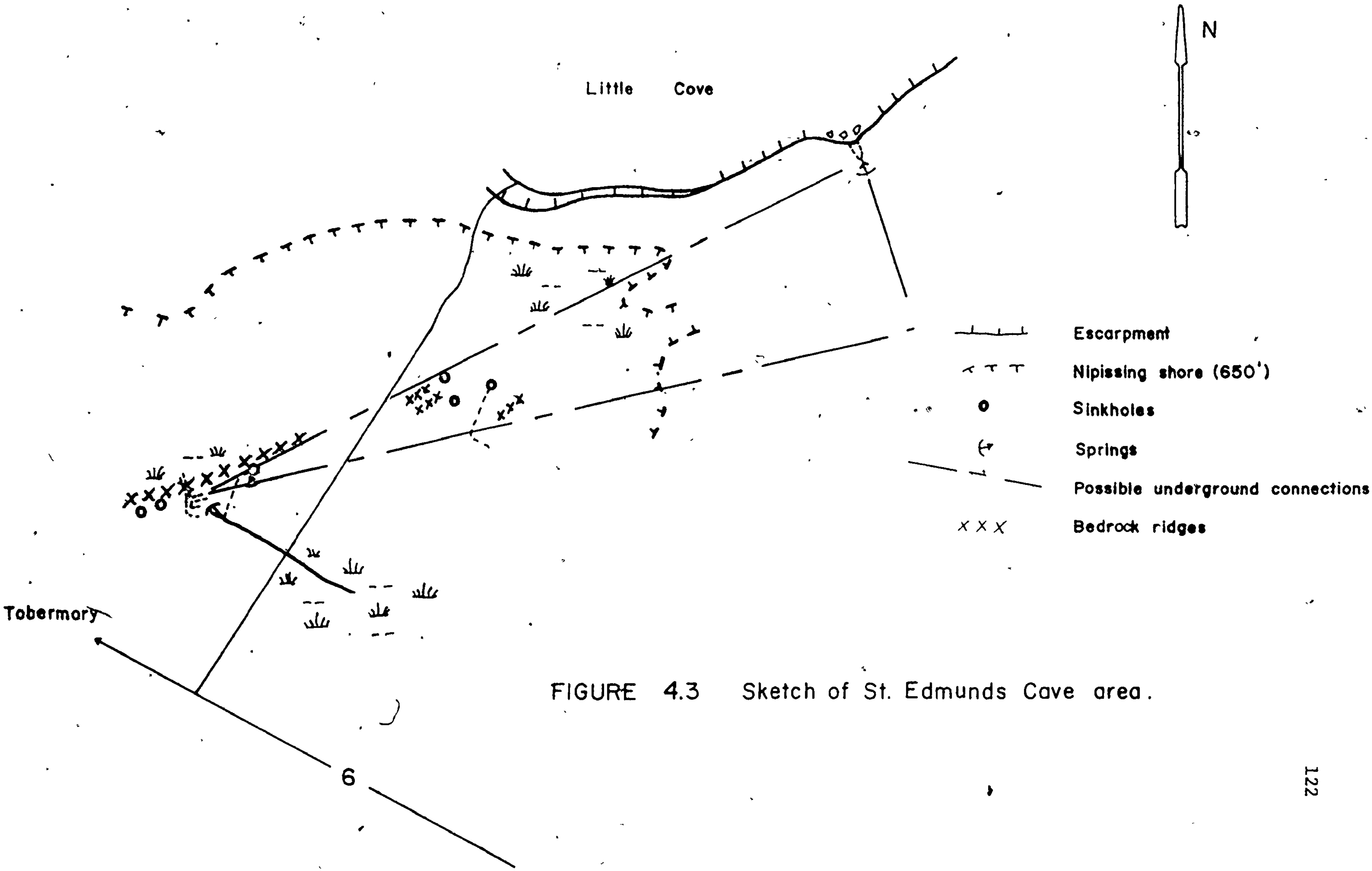

FIGURE 4.3 Sketch of St. Edmunds Cave area.

charcoal detectors were eluted using a mixture of 1-proponol alchohol plus 20% aqueous solution of NH_4OH in a 51:43 proportion. Fluorescence was determined using a Turner, model III fluorometer, provided by the Mechanical Engineering Department of McMaster, and a Corning 1-60 and a Wratten 58 primary filter plus a Wratten 23A secondary filter. This fluorometer has a total range of 3000 divisions in units of fluorescence with one division corresponding to a rhodamine concentration of about 1 part in 10^{10} (one thousandth of visibility). For more information on these methods of tracing refer to Aley (1971), Smart (1972) and Coward (1970).

Dye was injected at 1030 hours on June 28 into the stream near the entrance cave. Discharge was 0.93 c.f.s. as determined by Gurley-type flow meter. Activated charcoal detectors were placed in the mouth of the exit cave in Little Cove and changed twice a day until July 1. They were then changed once a day until July 6. Dye was first detected at 1040 hours on July 1, almost exactly 3 days after injection. The previous detector which showed no trace of dye was removed at 1940 hours on June 30. Thus the front of the dye cloud took between 57 and 72 hours to travel a minimum straight line distance of 2.5 km (1.5 mi.). Dye was still present on the last detector which was removed at 0940 hours on July 6.

The cave drops only about 18 m (60 ft.) over this distance of 2.5 km giving a hydraulic gradient of 139:1. The horizontal distance could be even greater, for example 3.8 km (2.4 mi.) if the passage followed a single joint (80° - 260°) before turning northwest into Little Cove, and thus 139:1 must be considered a maximum. Such a low gradient has resulted in flooding and ponding within the cave and this is reflected by the long flowthrough time and great stretching out of the dye cloud. Ponding occurs within the entrance cave. This creates somewhat of a paradox because it is the largest and most mature cave on the Niagara Escarpment yet it has one of the lowest gradients and is very inefficient w.r.t. flow.

Flow through the cave is more efficient during Spring freshet. At first water is ponded in the entrance cave and nearby fields but then it drains suddenly and completely within 24 hours (L. Wyonch, Tobermory, pers. comm.). Flooding the cave in this manner effectively increases the hydraulic gradient and supplies enough head to drive the water through more efficiently. The amount of increased head is not known but the entrance shaft is approximately 9 m (30 ft.) deep. If 2 m of water is ponded above this then the gradient is increased over the low flow situation by 11 m (36 ft.). The gradient of 139:1 presented above does not represent the low flow gradient because 9 m of the vertical drop occurs at the entrance shaft. It is closer to 277.8:1. During Spring freshet this would be increased to about 125:1 (using 11 m).

Total hardness of the resurgence is consistently higher than the surface stream, except during August (Figure 5.5). The increase ranged between 4 and 52 ppm. This is particularly interesting because the sinking water is amongst the hardest waters on the Bruce. The potential for solution may be increased by the addition of biotic CO_2 (increasing the aggressivity) or by a process known as 'mischungskorrosion'. The latter refers to the mixing of 2 waters equilibriated at different CO_2 partial pressures (example, stream and soil water mixing within the cave) and the resulting increased aggressiveness (Section 5). Biotic CO_2 from living and decaying vegetation could be added at the streamsink and within the cave. The higher pH of the spring reflects the increased hardness as CO_2 has been used to dissolve dolomite. An interesting aspect of the water chemistry is the consistently lower $CaCO_3$ content of the spring relative to the stream. Increased total hardness must therefore be due to substantial solution of Mg and precipitation of Ca. This is known as incongruent solution of dolomite and is discussed in Section 5.2.

Evidence of both vadose and phreatic conditions can be found in the cave (Plates 46, 47 and 48). 'Vadose' refers to development above the water table where passages are partly air-filled, allowing downward entrenchment. Phreatic conditions occur below the water table where voids are completely saturated. Caves formed under phreatic flow tend to be circular or elliptical. The entrance cave has elliptical and circular passages (Plates 46 and 47) but is entrenched. Its floor is covered by breakdown and finer crystalline material which has been washed in. One side passage is floored with mud. The exit cave has a key- hole cross-section (Plate 48) but some modification may have occurred by Georgian Bay which is only a few meters below. I have not yet been past the constriction in this cave but M. Davis[1] has surveyed an additional 125 meters. His survey suggests that the main cave follows the longer route shown in Figure 4.3. This has a minimum straight line distance of 3.8 km and an hydraulic gradient of 210:1. Exploration at this end was also stopped by a water sump. It would appear that nearly 3 km of passage is either completely flooded or comprises a series of ponds.

The St. Edmunds system is out of scale with other fluvio-karst areas

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1 Canadian Caver, Spring 1976 - the flow paths shown by Davis are incorrect.

Plate 47 Inside the main entrance to the St. Edmunds Cave System. The stream enters from behind the figure. The passage here is elliptical along a bedding plane and also slightly elongated along a joint (above persons head).

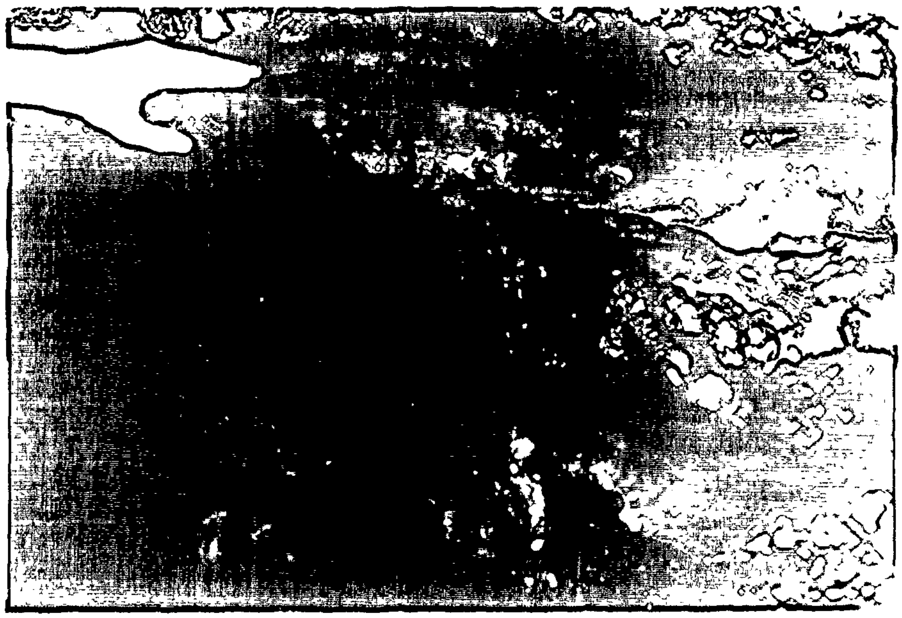

Plate 48 Circular phreatic tube leading into the main cave of the St. Edmunds Cave System.

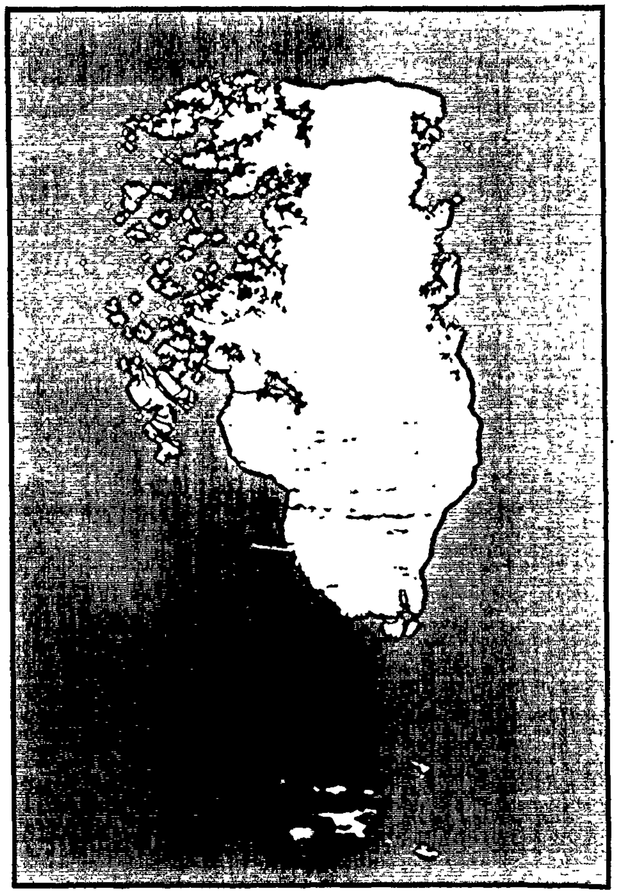

Plate 49 Exit cave of the St. Edmunds Cave system in Little Cove. The entrance here is about 3.5 m (12 ft) high. Note vadose entrenchment by the modern stream of the larger, more circular upper part of the cave opening.

on the escarpment. The Wodehouse karst for example, has comparable solution rates and a larger drainage basin but is unexplorable (Cowell and Ford 1975). One might consider this as evidence that the St. Edmunds cave is preglacial. However it is most probably postglacial because (1) in 4 years of field work on the Niagara Escarpment I did not find any other karst features which could be considered preglacial - all appear to be related to the present local drainage and are intimately associated with glacial features (Cowell and Ford 1975), and (2) the St. Edmunds cave is directly affected by Wisconsinan and post-Wisconsinan features. The main entrance is on the side of a glacially scoured ridge, the closed depression nearby has an excellent glacially polished wall (Plate 5) and the catchment of the cave is on glacio-fluvial and lacustrine deposits.

The most likely explanation for the development of the cave centres on the presence of a lake in the vicinity of the present sinkholes. If a post-Wisconsinan age is accepted then it is plausible that waters from lakes Algonquin and Nipissing (Chapter 2) were perched on the glacio-fluvial material. Much of this deposit is still poorly drained and the main entrance to the cave is situated in a depression which can be picked out on aerial photos. It is less than 8 m (25 ft.) deep as indicated by the 1:50,000 N.T.S. contours but occupies several acres. A low shore bluff faces inland above Little Cove (about 2.5 m high, Fig. 4.3). It is composed of beach cobbles and rises above a poorly drained, muck floor. It is topped at 650' a.s.l. which corresponds to the Nipissing level in this area. The cave probably resulted from water seeping into joints at the bottom of the lake, eventually forming a route to Georgian Bay. The ponded water provided the necessary head to effectively increase the hydraulic gradient. This would also explain the phreatic (circular) tubes within the cave. It is presently being abandoned because more water flows into it than is seen resurging. Water is seeking new lower routes to the bay. This is common in karst areas when the base level of a spring drops (Jennings 1971).

A Nipissing age for the cave puts its origin at 6,000 to 7,500 BP. If initiated during Lake Algonquin it could be as old as 12,500 yr. BP. (Prest 1970). The top of the exit cave corresponds approximately to the Algoma postglacial level (Sly and Lewis 1972, p.85). This would make the Nipissing age more plausible. Another cave, located on the south side of the deposit, is definitely Nipissing in age. It is located inside and immediately at the foot of the Nipissing bar shown in Figure 4.2. It is also surrounded by poorly drained fields. Several meters of explorable passage are found in the cave but its continuation is as yet unknown.

4.3 Discussion

Most of the peninsula is drained by normal surface streams. Many of these are probably losing water to subsurface drainage as in the case of the Crane River. Favourable bedding planes and major joints serve to capture and direct this water. The latter are probably responsible for guiding most of the subsurface flow because these are the most continuous of structural features. Bedding is more localized because of the presence of reef structures. At least three of the fluvio-karst systems developed along joints (Dyer Bay, Horse Lake and St. Edmunds) and in particular along 2 orientations. These correspond to the 2 major sets on the Bruce Peninsula (E-W and SE-NW, Figure 2.3). They are probably responsible for most of the subsurface flow which is directed primarily toward the escarpment.

The internal drainage is not integrated. The five fluvio-karst systems are isolated from one another and appear to operate separately from nearby holokarst areas. Even the holokarst is drained by many intermittent springs as opposed to few perennial springs. Karst drainage usually tends to be integrated and resurge at fewer points than it is recharged (Jennings 1971). Non-integrated drainage on the Bruce Peninsula is probably a result of two factors: not enough time and the nature of the bedrock. The present fluvial drainage and fluvio-karst is postglacial (Section 4.2.5). The Cabot Head shale unit prevents substantial vertical karstification and acts to discharge water from the rockmass.

Further evidence of the immaturity of the karst is the inefficiency of the inputs, even though the conduit may be well developed. At Horse Lake this results in a 2 meter seasonal fluctuation of stage. Cowell and Ford (1975) also described deep ponding above sinkholes in Spring at an otherwise efficient fluvio-karst on the escarpment.

Although all of the karst appears to be postglacial the situation is more complex. The present pavement development and fluvio-karst are intimately associated with glacial preparation, especially the presence or absence of deposits. However the bedrock is over 400 million years old and has therefore had a complex history, including at least four glaciations. The absence of recognizable pre-Wisconsinan karst does not mean it does not exist nor ever did. There may be some remnant passages which are blocked by Wisconsinan deposits and it is possible that stratigraphically higher karst features have been removed by glaciation. At any rate the bedrock on the Bruce has a complex diagenetic history and must have been affected to some degree by karstification.

The present drainage system probably became established very quickly following the Wisconsin. Some karstification may have been initiated by glacial lakes which inundated the peninsula (Sections 4.2.5 and 4.4). Much of the holokarst, as shown on Figure 4.1, probably existed at this time due to the lack of drift and presence of numerous joints, at least partly opened by pressure release phenomena (with the retreat of the heavy Wisconsinan ice). Fluvio-karst became established more gradually as streams and lakes were captured and re-routed by underground drainage.

The five fluvio-karst systems display a varied morphology and degree of maturity. They range from the very simple channel capture of the Colpoy Creek to the more complex and interesting St. Edmunds cave. Hydraulic gradients are variable between 210:1 at St. Edmunds (or possibly 139:1 if the most direct route is taken) to 5:1 at Gillies Lake. They tend to be above the surface runoff gradient which is about 170:1 (6 m/km).

Some comments about future karstification were presented in Section 4.2 for the fluvio-karst systems. Except for the St. Edmunds cave their development is quite limited because of their shallow nature. The Dyer Bay cave has vertical potential but its catchment is small. The St. Edmunds will continue to enlarge the new lower routes below the main cave and this will eventually drain most or all of the presently flooded passages. One may also expect continued underground capture of surface streams and lakes on the Bruce. Eventually much of the drainage could be completely reversed, flowing underground to Georgian Bay.

The holokarst zone will also expand and capture the headwaters of the streams. Figure 4.5 is an attempt to illustrate the pattern of potential karstification. The lines on this map suggest how the holokarst may expand. These are isolines of equal groundwater hydraulic gradient. The easterly line indicates where the gradient to Georgian Bay (to the top of the Cabot Head shale where this lies above the bay) is equal to the surface gradient of approximately 1° to the west. A constant runoff gradient is assumed for the whole surface and it is also assumed that water will sink at that gradient as easily as it will run-off. Positions of the lines were determined using simple trigonometry based on two angles and the length of a side (relief above Georgian Bay or the Cabot Head shales) at 10 locations. These are Driftwood Cove, Cave Point, Rocky Bay, Cabot Head, Cape Chin, Lions Head, Cape Dundas, Sydney Bay Bluff, Jones Bluff and Malcolm Bluff. Each of these are prominent cliffs and promontories and thus the lines represent maximum distances from the edge. The two central isograds were determined in the same manner but using each preceding line as the edge of the escarpment. As karst processes expand away from the scarp the base level position continually moves inland and thus the groundwater hydraulic gradient at a given point increases (i.e. as the karst expands toward the point). Because of the surface slope this new gradient will not be as high as that nearest the escarpment. The fourth line represents the maximum potential limit of holokarst and major fluvio-karst. It is fitted in a more arbitrary manner than the other isograds; it is the elevation at which the Crane River was found losing water (approx. 650 ft a.s.l., Fig. 4.1). It also happens that west of this contour drainage is very poor. Should karst drainage occur it would probably be minor and very localized. Stokes River is a good example. Before flowing into Lake Huron it disappears into and follows shallow bedding planes for 40 to 50 meters.

The isograds can be considered time lines of westward karstification. As this develops along the escarpment it enhances the opportunity for karstification further away. The processes is continuous and not in stages as suggested by the isograds. They are drawn to show the broad pattern and degree of potential holokarst expansion. They do not, of course, pertain to pavement development or even strictly to fluvio-karst which will develop throughout the Bruce Peninsula given the opportunity. Expansion of the holokarst may proceed faster than in the past because of postglacial preparation by fluvial erosion and karren formation (widening joints, etc.) This will, however, be countered by a continually decreasing groundwater hydraulic gradient.

On Figure 4.5 the Eastnor clayplain was excluded as an area of potential karstification. The clays and silts here are substantial in thickness and will continue to inhibit karstification. Also, the bedrock surface beneath the clayplain is below the level of Georgian Bay in places. Other local deposits and the availability of widened joints will alter the pattern of karstification accordingly.

There is a 69.3% match in area between the modern holokarst zone (Figure 4.1) and the area enclosed within the first isolines of Figure 4.5. Therefore this seems to be a reasonable means of modelling karst expansion on plains bounded by an escarpment. Figure 4.1 utilized the distribution of exposed bedrock and the absence of surface channels to define the holokarst. This gives a larger area than that shown in Figure 4.5, particularly at Cape Dundas, Dyer Bay and west of Driftwood Cove. The accuracy of the model could easily be increased using large scale aerial photos and minor ground truthing. At any rate, the patterns appear to fit very well and one may expect the future holokarst development of the Bruce Peninsula to proceed in a manner close to that shown in Figure 4.5.

4.4 Other Meso to Macro Karst Features

There are a number of karst features on the Bruce which are either not directly related to the present major drainage or are products of former hydrological conditions. These include isolated sinkholes,dry solutional caves and sea saves. They contribute substantially to the overall karst character of the Bruce Peninsula but cannot be described individually in this thesis. A few sea caves and sinkholes are shown in Figure 4.1. The sea caves and some of the dry solutional caves (e.g. Mar caves) are well known locally have been located and partly described in Weber (1960), Ongley (1971), Ford and Quinlan (1974) and Cowell (1974).

4.4.1 Sinkholes

These are not discussed in detail but are listed by location in Table 4.1. Most are active only during Spring freshet and following heavy precipitation but those with improved drainage may be active for longer periods. The subsurface drainage routes of the sinkholes are not known but they can be considered generally as diffuse inputs.

4.4.2. Dry Solutional Caves

Numerous caves occur in glacially-scoured, biohermal ridges throughout the Bruce Peninsula. They appear to be solutional in origin and have phreatic characteristics such as circular or elliptical cross sections, although recent breakdown gives deviations; immature scalloping and solutional pocketing on walls and ceilings[1]; and fine grained sediments on some of their floors. These features are considered indicative of phreatic passage development (Bretz 1942). The existence of these caves presents problems because phreatic

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1 These are negative, erosional features formed in caves under phreatic conditions. Scallops are shaped like scallop shells and point in the direction of the former flow. They are also inversely proportional in length to the velocity of flow (Goodchild and Ford 1971).

TABLE 4.1

Isolated Sinkholes Observed on Bruce Peninsula

Location (NTS. grid)	Map Sheet	Closed depression(s) or Rock Face CD - RF	Approx. diameter-depth of closed depressions (m)	Recognizable channelized Inflow (Y or N)	Bedrock Exposed (Y or N)	Small Explorable Cave present (Y or N)	Remarks
597087	41 H/4	C.D.	elongated about 3m, < 1m deep	N	N	N	small compound sinkhole (uvala) probably mostly in bedrock but covered by forest litter and located between two ridges
658956 & 660956	41 H/3	C.D.	4 prominent depressions 1m, 3m and 2.5m deep	Y (in largest only)	Y (in largest only)	N	located in a cleared field these are suffosion dolines with all of their topographic expression in the mantle which consists of a clay till. Largest sink has a man-made channel leading from a nearby small wetland. One of the sinks is filled with field stone. The three largest are elongated 80°-260° which corresponds to a major joint orientation.
765954	41 H/3	C.D.	< 1m diam. or depth	Y	Y (?)	N	small depression located in cleared field with man-made drainage channel.
762893	41 H/3	C.D.	< 1m " "	Y	Y	N	"
878769	41 A/14	C.D.	1.5-2.0m diam 1.5m deep	N	N	N	
890769	41 A/14	C.D.	2 small depressions < 1m diam. and deep	Y (poor)	N	N	lowermost corner of cleared field
889760	"	C.D.	1.5m diam 1m deep	N	N	N	

continued over...

TABLE 4.1 (continued)

Isolated Sinkholes Observed on Bruce Peninsula

Location (NTS grid)	Map Sheet	Closed depression(s) or Rock Face CD - RF	Approx. diameter-depth of closed depressions (m)	Recognizable channelized Inflow (Y or N)	Bedrock Exposed (Y or N)	Small Explorable Cave present (Y or N)	Remarks
887757	41 A/14	C.D.	< 1m diam.& deep	Y	N	N	man-made channel in cleared field leads up to sink which is partly filled with field stone (Plate 39)
875755	"	C.D	dia. > 4m depth about 6m	N	N	N	not certain whether this is true sinkhole because may be dammed by road on one side and is partly filled with field stone
876746	"	C.D.	dia 3m depth about 2m	Y	N	N	well-developed suffosion sinkhole which floods after heavy rain, located south of laneway of Mrs. Butchard's home and partly filled with waste, cans, bottles etc.
875762	"	C.D. & R.F.	many depressions along deep joints with mantle being washed into them deepest is 2m in mantle + 6m in rock, up to 18m long	Y (where sinks into rockface) N (for C.D.)	Y	Y (in joints)	small swampy area drains via short channel and disappears into joint on rockface (blind valley) 6m high. All these features are located in bush on the property of Mr. Richardson and are known to flood out in spring.
870742	"	R.F.		Y	Y	Y - circular chamber 1.5m high and about 8.5m diameter	swamp drains into circular cave on side of a ridge and disappears down small tube in cave, located at Hopeness on Mrs. Butchard's property (section 4-1, plate 38).
872738	"	C.D.	4m deep in till, 7.5m deep in bedrock	N	Y	Y (in joint)	large joint opened up beside cleared field with mud and garbage on floor.

continued over ...

TABLE 4.1 (continued)

Isolated Sinkholes Observed on Bruce Peninsula

Location (NTS.grid)	Map Sheet	Closed depression(s) or Rock Face CD - RF	Approx. diameter-depth of closed depressions (m)	Recognizable channelized Inflow (Y or N)	Bedrock Exposed (Y or N)	Small Explorable Cave present (Y or N)	Remarks
878735	41 A/14	C.D.	up to 10 suffosion sinkholes from about 1m to 3.5m deep	N	N	N	3 especially well-developed suffosion dolines assymetric in plan with signs of slumping. Side slopes as high as 40° were measured and they are now being revegetated after early clearing (early 1900's?) They are located near the edge of the escarpment north of Hope Bay and just off the Bruce Trail. Numerous deep open joints occur near here where mantle is much thinner
840719 & 864719	"	C.D.		N	N	N	2 small depressions in cleared fields
894564	"	C.D.	< 1m diam. & deep	Y	N	N	small sink located behind abandoned farm home in old field now being re-vegetated. Channel is probably man-made as mantle is clayey and poorly drained.

C.D. = closed depression
R.F. = rock face
Y = yes
N = no

passages form at some depth below a water table. They are presently dry and thus considered as fossil landforms. The caves are all small, terminating quickly. They have been observed on ridges east of Horse Lake, on the Lions Head Promontory and in a large ridge on the northwest side of Berford Lake (Mar caves). Others have been described to me from George Lake (V. Last, Wiarton, pers. comm.) and north of the highway between Willow Creek and Crane River (P. van Stam, Wasaga, pers. comm.). There are undoubtedly many more.

Mar caves are some of the most interesting. There are several caves within a large ridge complex which rises between 8 and 15 m (25 to 50 ft.) above Berford Lake. They can be explored for a few 10's of meters but do not appear to be interconnected. Their development was controlled by local reefal structures, such as steeply dipping interreefal beds and major joints. The largest cave has an elliptical entrance 2m (7 ft.) high by about 4.5 m (15 ft.) wide and is floored with well-packed silt. Two karst windows (i.e. roof openings) are present.

It is not certain how these caves formed but three possibilities may be considered: (1) they are pre-Pleistocene having been partly destroyed, (2) they formed by meltwater action during the late Wisconsinan, or (3) they developed beneath Lake Algonquin. The first and third explanations are the least likely.

The caves occur only in glacially-scoured ridges and close-off within them, never passing completely through. This suggests they postdate glacial scouring.

In theory the waters of glacial Lake Algonquin will have been too weak chemically to carry out much solution. It was ice-dammed and thus was probably biologically too sterile to boost solution processes. It was also relatively shortlived and probably lacked sufficient circulation to replenish saturated water at the bedrock surface.

Glacial meltwaters are also very weak chemically (Ford 1971a) but are under high hydrostatic pressures and consequently are quickly and continually replenished. Bedrock irregularities (i.e. the ridges) beneath and in front of a retreating ice sheet would strongly affect meltwater flow and circulation. Under these circumstannes it would be possible to produce a large number of small, randomly located caves.

A similar situation appears to account for cave development in biohbrms in the Eramosa River gorge northeast of Guelph, Ontario. They are located within a major meltwater channel (Karrow 1963) and possess drained caves similar to those at Mar.

4.4.3 Sea Caves

Many of the well known caves on the face of the escarpment, on the Bruce Peninsula, are sea caves. They are predominantly wave-cut but some may have had solutional origins. Sea caves occur at numerous elevations including the present shore. Bears Rump Island has more than 25 on its eastern end (Plate 50). They are also found at Cave Point, White Bluff (4 km north of Lions Head), Lions Head (north of the harbour), the south side of Barrow Bay ('Greig's Caves'), the north side of Hope Bay ('Hope Bay Cave', Plate 51) and east of Wiarton above Colpoy Bay ('Bruce's Caves'). The well known 'grotto' at Cyprus Lake Provincial Park is another example (Plate 52).

Sea caves are characterized by very large angular openings (Plate 50) although irregular forms are also common. Many display a prominent joint in their ceilings which trend through the centre of the cave toward the rear.

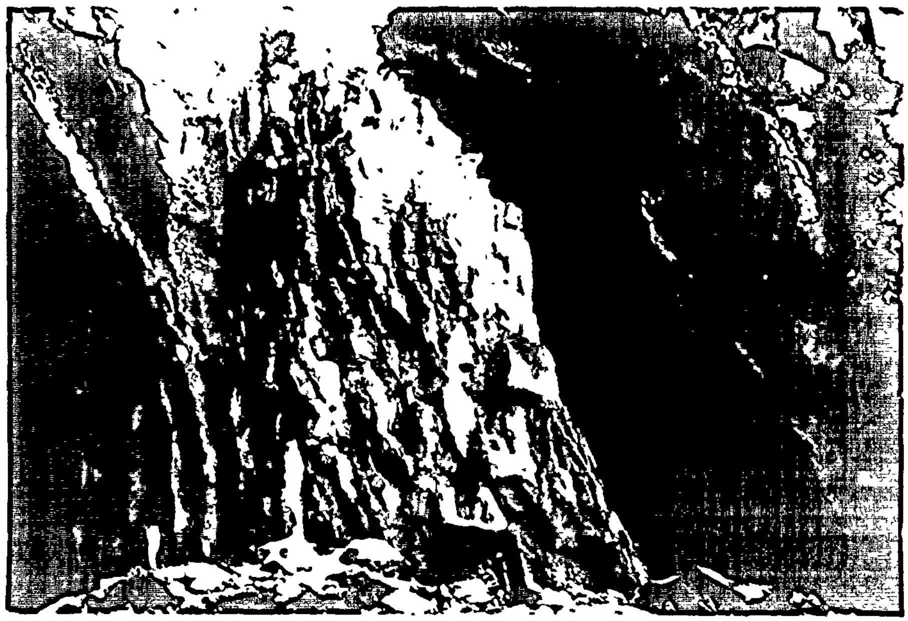

Plate 50. Large rectangular sea caves on Bears Rump Island. The cliffs around the eastern end of this island are perforated with many similar caves. (note person, centre foreground, for scale).

Plate 31 Lower, main portion of the Hope Bay cave on the north side of Hope Bay. This chamber is 43m (140 ft) long and has suffered a great deal of breakdown. Note the joint plane at the top of the cave.

Plate 52 The Georgian Bay shore, especially along the north side of the peninsula is one of high wave energy. This photograph shows waves breaking on the cliffs near the 'grotto' at Cyprus Lake Provincial Park in December, 1974.

Typically they consist of single large chambers, as much as 35 to 40 m (100 to 150 ft.) long, terminating in a blind wall which may taper slightly along the joint. Irregularly shaped caves are associated with less massive unevenly bedded strata. Several of these have a rock pillar in their entrance (e.g. 'Bootlegger's Cave' at Cave Pt.).

Solutional origins are indicated in several sea caves. Grieg's caves and Hope Bay cave, for example, have what appear to be solutional passages at their terminations. A good example of a key-hole conduit, indicative of vadose conditions, feeds into one of Grieg's caves. Hope Bay cave has an upper chamber which may have been solutional. It is presently coated by flowstone (Plate 53). It may, however, be a blow-hole which are associated with many sea caves (Dury 1966). The lower cave is more characteristic of wave-cut caves (Plate 51). It seems possible that many of these had solutional origins, either in the form of a small conduit or simple joint enlargement. In any case they would be points of weakness where they intersected the escarpment and could have been later enlarged by wave action (Plate 52). Cave elevations may thus mark stillstands of the postglacial lakes. The solutional phase operated to drain water from the top of the peninsula as it emerged from glacial Lake Algonquin. This was probably short lived as cave openings were quickly modified by lake action. The first phase thus represents the initiation of holokarst drainage along the escarpment. Caves presently out of the range of wave action are being further modified by breakdown. The formation of these caves is shown diagramatically in a recent publication by the Readers Digest (Scienic Wonders of Canada), based on my report for the Ontario Ministry of Natural Resources (Cowell 1974).

Flowstone is rare on the peninsula. Martin Davis (pers. comm.)

Plate 53 Flowstone and small stalactites in the upper chamber of Hope Bay cave.

Plate 54 Broken stalactites in the upper chamber of Hope Bay cave.

reported some in the St. Edmunds exit cave along a joint paralleling the escarpment. The joint probably opened by forward slumping, rather than by karst processes, and is now being filled in with flowstone. The owner of Bears Rump Island (D. Love, pers. comm.) reported a cave on that island which had speleothems. Hope Bay cave was well decorated with stalactites at one time but it has been severely damaged (Plate 54). The absence of flowstone in most sea caves is due to their continued breakdown. Cave precipitates appear to be restricted to small isolated chambers and it is possible that there are many well decorated caves which have not yet been found.

CHAPTER 5

WATER CHEMISTRY

5.1 Introduction

The geochemistry of karst waters has been investigated by many researchers to explain spatial patterns of limestone solution and to infer characteristics of karst hydrogeological systems, (e.g. Brown 1970, Langmuir 1971, Shuster and White 1971, Drake and Harmon 1973). Drake (1974) notes that the basics of solution have been known for some time and thus the main process of karst landform development can be quantified. This is especially helpful because it is rarely possible to examine the morphology of entire karst systems. Much of the development occurs underground in conduits of inaccessible dimensions. This is particularly true in an area of immature karst such as the Bruce Peninsula. A knowledge of the whole system is very important because karst processes create unique problems of groundwater flow and instability which in turn affects local planning for water supply, sewage control, construction, etc.

The present experimental and field approach to karst studies is primarily aimed at a better understanding of morphogenetic processes relating to cavern development (Ewers 1966, Ford 1971b), hydrological and chemical interrelationships, (Drake 1974) and the development of karst terrains including rates of solution, (Harmon et al. 1972, 1975, Drake and Wigley 1975). The last of these has been one of the most intensely studied in the karst literature and will form the main thrust of this chapter.

The first part of this chapter considers the seasonal water chemistry in the north Bruce. The second assesses all the data, seasonal and other, in an attempt to classify water types by their chemical signature. The third part examines the solution rates of spring water on the Bruce Peninsula to see how they fit into models of regional limestone solution.

More than 250 water samples were collected from the Bruce Peninsula. These were analysed in the field for pH, alkalinity (HCO_3^-), temperature, Ca^{++} and Mg^{++} (both expressed as $CaCO_3$). The equilibrium partial pressure of CO_2 (PCO_2) and the saturation state of the water with respect to calcite (SI_c) and dolomite (SI_d) were determined from the measured variables by computer programme[1]. PCO_2 is the theoretical partial pressure of CO_2 with which the water is in equilibrium.

Determinations and methodology follow those of Langmuir (1971), Ford (1971a) and Drake and Harmon (1973). $CaCO_3$ and $MgCO_3$ (expressed as $CaCO_3$) were determined by colorometric titration and alkalinity by potentiometric titration with 0.01N, HCl (Appendix 2a and 2b). pH was measured in the field using a battery operated meter. All analyses were performed within 24 hours of sampling.

The chemical process involved in a three phase carbonate system, rock-water-gas (CO_2), can be defined by six chemical equations:

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1 program Tomchem, T.M.L. Wigley, University of Waterloo, revised by J.J. Drake, McMaster University (Appendix 3).

$$CO_2 + H_2O \rightleftharpoons H_2CO_3 \quad (1)$$

$$H_2CO_3 \rightleftharpoons H^+ + HCO_3^- \quad (2)$$

$$HCO_3 \rightleftharpoons H^+ + CO_3^{--} \quad (3)$$

$$H_2O \rightleftharpoons H^+ + OH^- \quad (4)$$

$$\underline{CaCO_3} \rightleftharpoons Ca^{++} + CO_3^{--} \quad (5)$$

$$\underline{Ca\,Mg\,(CO_3)_2} \rightleftharpoons Ca^{++} + Mg^{++} + 2CO_3^{--} \quad (6)$$

where underlined formulae represent the solid phase. Carbon dioxide from the atmosphere dissolves in water to produce carbonic acid (equation 1). This dissociates producing hydrogen ions and bicarbonate (eq. 2). The liberation of hydrogen lowers the pH of the solution making it more aggressive to carbonate bedrock. The bicarbonate also dissociates liberating more hydrogen and further lowering the pH (eq. 3). Equation 4 represents the hydrolization of water, which is a continuing process, whereas equations 5 and 6 represent the dissociation of calcite and dolomite, respectively. Solution of dolomite (and limestone) thus occurs as equations 1 through 4 move to the right and weaken the Ca-CO_3, Mg-CO_3 bonds in the bedrock, forcing equations 5 and 6 to the right as well. This is accomplished via the attraction between liberated hydrogen ions in the water and CO_3 in the bedrock (Fig. 5.1). The reaction will continue until equilibrium is reached, i.e. no further net solution of CO_2 can take place unless the PCO_2 in the air reservoir is increased.

It follows that one of the most important controls on the solution process is abundance of CO_2. The greater the partial pressure of CO_2 the more equations 1 through 6 will react to the right and thus the greater the amount of rock solution. In the absence of CO_2, natural waters can

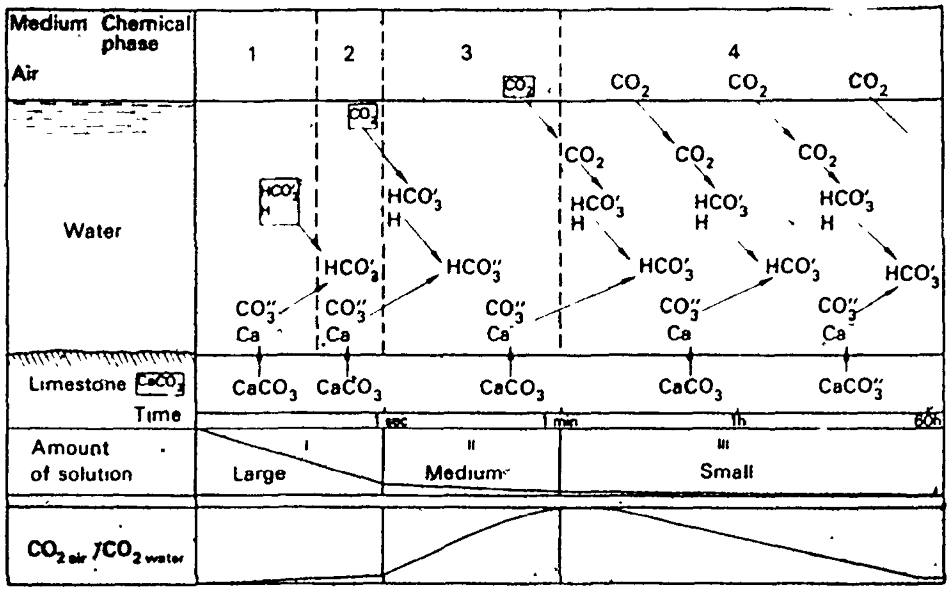

FIGURE 5.1 Diagrammatic representation of the solution of limestone in an open system. Note that most of the potential solution is carried out within the first second in this system (from Sweeting, 1972 and after Bögli, 1960).

dissolve only about 12 ppm (parts per million) of $CaCO_3$ (Sweeting 1972). In an open system with the PCO_2 equal to that of the atmosphere (0.03% or $10^{-3.5}$ atm.) theoretically these same waters can dissolve up to 55 ppm $CaCO_3$ at 25°C (Sweeting 1972). The fact that many carbonate waters are found to have $CaCO_3$ in excess of 200 ppm and up to 400 ppm suggests that the PCO_2 must be raised appreciably higher than 0.03%. This has been found to occur in soils and forest litter where biotic activity may increase PCO_2 by several orders of magnitude. Concentrations of 5 to 7% are frequently measured (Ford and Quinlan 1973). The importance of soil CO_2 as a boosting agent for karst waters is well known (Pitty 1966, Sweeting 1972, Harmon et al. 1973). The presence of extensive and very mature karst areas in humid tropical and subtropical latitudes attests to this. However, glaciations have not intervened and these regions have also had a long period for karst process to operate. Solution rates in upper and middle latitudes have been found to be as high as, if not higher than in the more tropical areas (Sweeting 1964). The major difference in these regions is the greater seasonality of the process. These facts will be considered in more detail in Section 5.4.

The solution rate is not limited by the rates of chemical uptake of the carbonate bedrock. These tend to be very quick and up to 90% saturation is attained within 60 seconds (Bögli 1960, Fig. 5.1). 100% saturation would likely never be reached because of increased ion activity in the solution and other complexing ion effects. However, saturation and even super-saturation does occur. This situation is primarily a result of changing temperature and pressure conditions of a parcel of water over time. Decreased air pressure (i.e. PCO_2) and/or increased temperature such as usually occur as groundwater reaches a spring may lead to supersaturation and precipitation of limestone. Soil water seeping into an open stream or lake may behave likewise. The opposite effect, i.e. increased solution, may occur by cooling or by mixing two chemically distinct waters. This latter is known as mixing corrosion or 'mischungskorrosion' (Bögli 1964). When two waters, at saturation and containing different amounts of dissolved CO_2, are mechanically mixed the result is an undersaturated solution capable of dissolving more limestone because mechanical mixing occurs along a straight line but chemical mixing along a curve ($CaCO_3$ in ppm). After mixing the water is supercharged. This pertains primarily to cave situations where for example soil seepage may mix with stream waters.

The ability to determine the saturation states of carbonate waters in recent years has greatly aided karst studies. They are calculated from the measured variables and are expressed as the indices "SI_c" and "SI_d", for the saturation with respect to calcite and to dolomite respectively. They are logarithmic determinations of IAP/K, where IAP is the ion activity product of calcite, $[Ca^{++}][CO_3^{--}]$ or dolomite, $[Ca^{++}][Mg^{++}][CO_3^{--}]$ in solution, K is the theoretical activity product of the two minerals and brackets denote activity of the enclosed species. These are strongly dependent on pH. Errors in pH determination can lead to errors of the indices in a 1:1 ratio. SI_c and SI_d are expressed as relative units with 0.00 equal to saturation. There is an uncertainty factor of ± 0.1 which is related to the accuracy and precision of the original measurements. This is particularly important when near to saturation.

The presence of Mg^{++} in the bedrock lowers the solubility of limestone (Sweeting 1972) although just a little Mg^{++} may actually enhance the solution process. The best developed karst areas of the world are thus restricted primarily to limestones and dolomitic limestones. The Niagaran dolomites of southern Ontario are Ca-rich, having the general formula, $Ca_{1.2}\ Mg_{0.8}\ (CO_3)_2$ (Appendix 1). Their karst waters have been found to exceed 300 ppm total hardness (Cowell and Ford 1975, Table 5.1), and are in the range common to many limestone areas. This is partly due to their Ca-rich nature but also to high biotic activity on a seasonal basis. In most instances Ca/Mg ratios (determined from Ca^{++} and Mg^{++}) are either equal to or greater than that of the general formula (i.e. greater than or equal to 1.5). However the saturation of these waters with respect to dolomite is consistently higher than for calcite at or above the saturation point (Table 5.1). This is common in dolomite areas due to the phenomenon of incongruent solution (Wigley 1973) which occurs after saturation WRT calcite and dolomite is reached. Further solution (as a result of supercharging via an increased PCO_2 reservoir etc.) is accomplished only after calcite is precipitated.

5.2 Seasonal Data of the North Bruce Peninsula

Figures 5.2 to 5.10 are graphs of total hardness (Ca + Mg as $CaCO_3$), $CaCO_3$ hardness, pH and temperature measured during June to November, 1973. Locations of samples are shown in Figure 4.2. The scale factors on the figures relate each graph to those on Figure 5.2 for which the scale = 1. Figures 5.2 to 5.5 have been briefly discussed in Chapter 4. These are the four main fluvio-karst systems. Table 5.1 lists many of the data points of the 9 graphs and includes Ca/Mg, alkalinity, SI_c, SI_d and PCO_2.

The main features to observe in Figure 5.2 to 5.5 are the

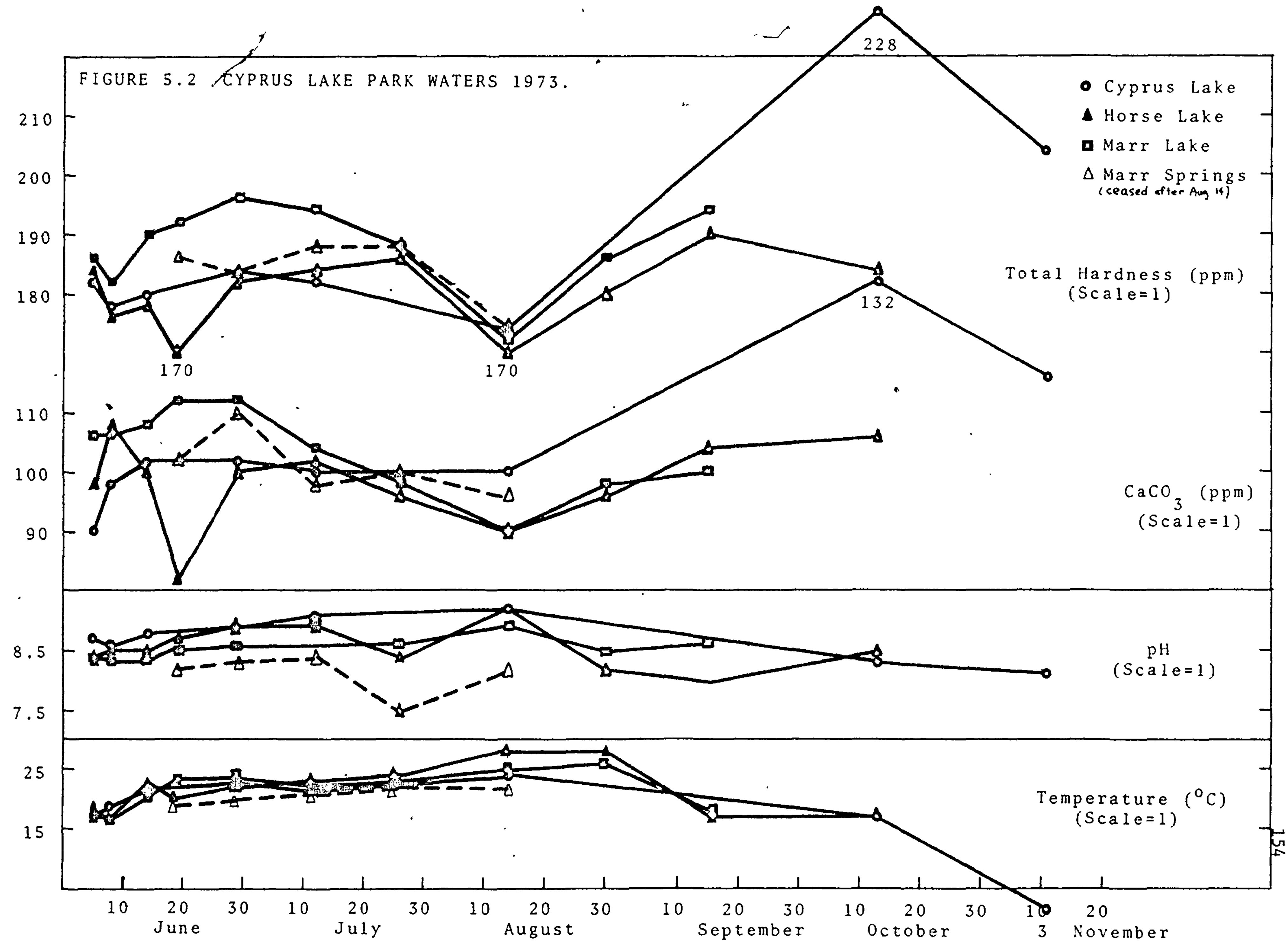
FIGURE 5.2 CYPRUS LAKE PARK WATERS 1973.
Cyprus Lake
Horse Lake
Marr Lake
Marr Springs
(ceased after Aug 14)
228
210
200
190
180
170
170
132
Total Hardness (ppm)
(Scale=1)
110
100
90
CaCO3 (ppm)
(Scale=1)
8.5
7.5
pH
(Scale=1)
25
15
Temperature (°C)
(Scale=1)
10 20 30 10 20 30 10 20 30 10 20 30 10 20 30 10 20
June
July
August
September
October
3 November

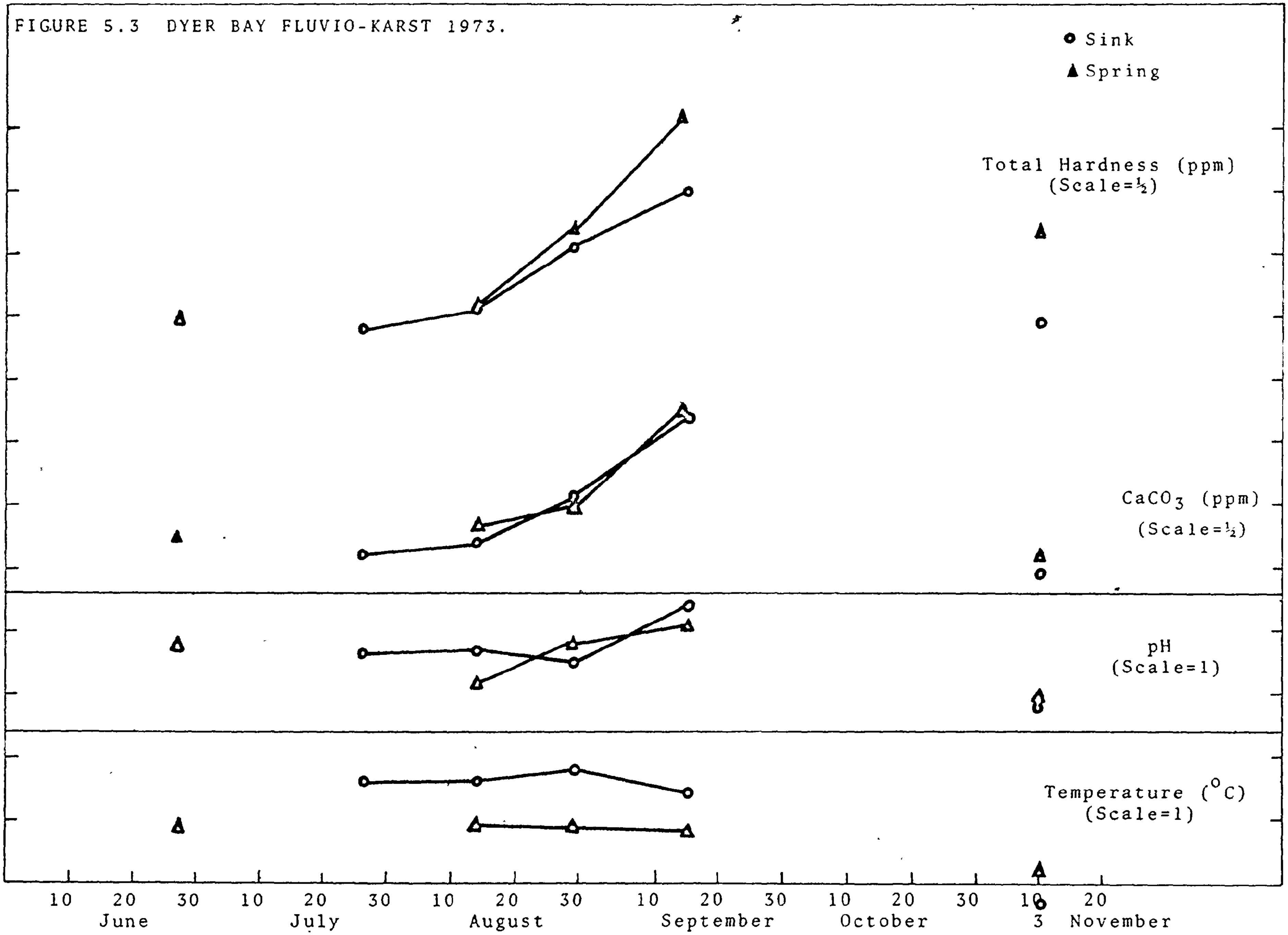
FIGURE 5.3 DYER BAY FLUVIO-KARST 1973.
Sink
Spring
260
240
220
200
180
160
140
120
8.0
7.0
25
15
Total Hardness (ppm)
(Scale=½)
CaCO3 (ppm)
(Scale=½)
pH
(Scale=1)
Temperature (°C)
(Scale=1)
10 20 30 10 20 30 10 20 30 10 20 30 10 20 30 10 20
June
July
August
September
October
3 November

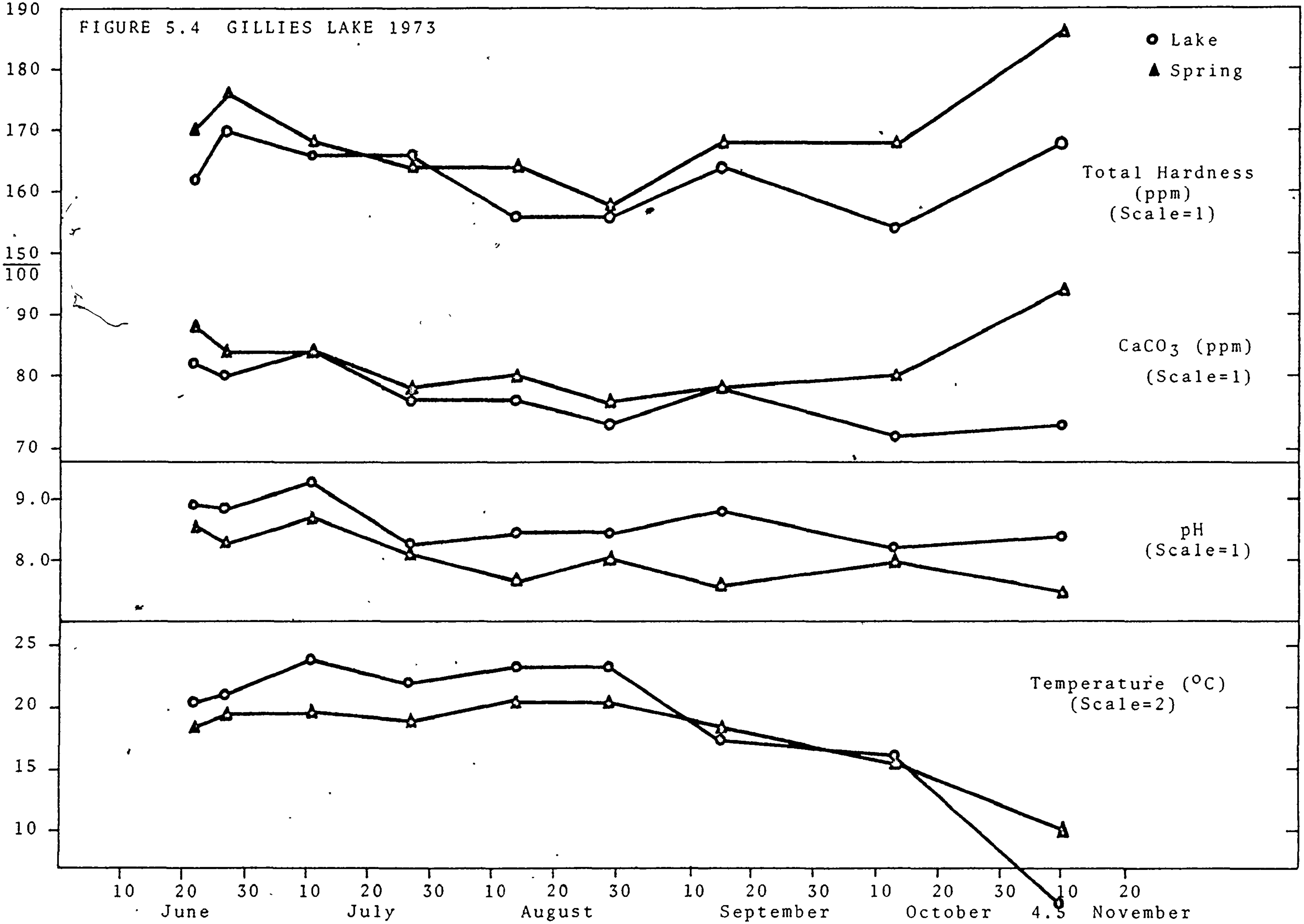

FIGURE 5.4 GILLIES LAKE 1973

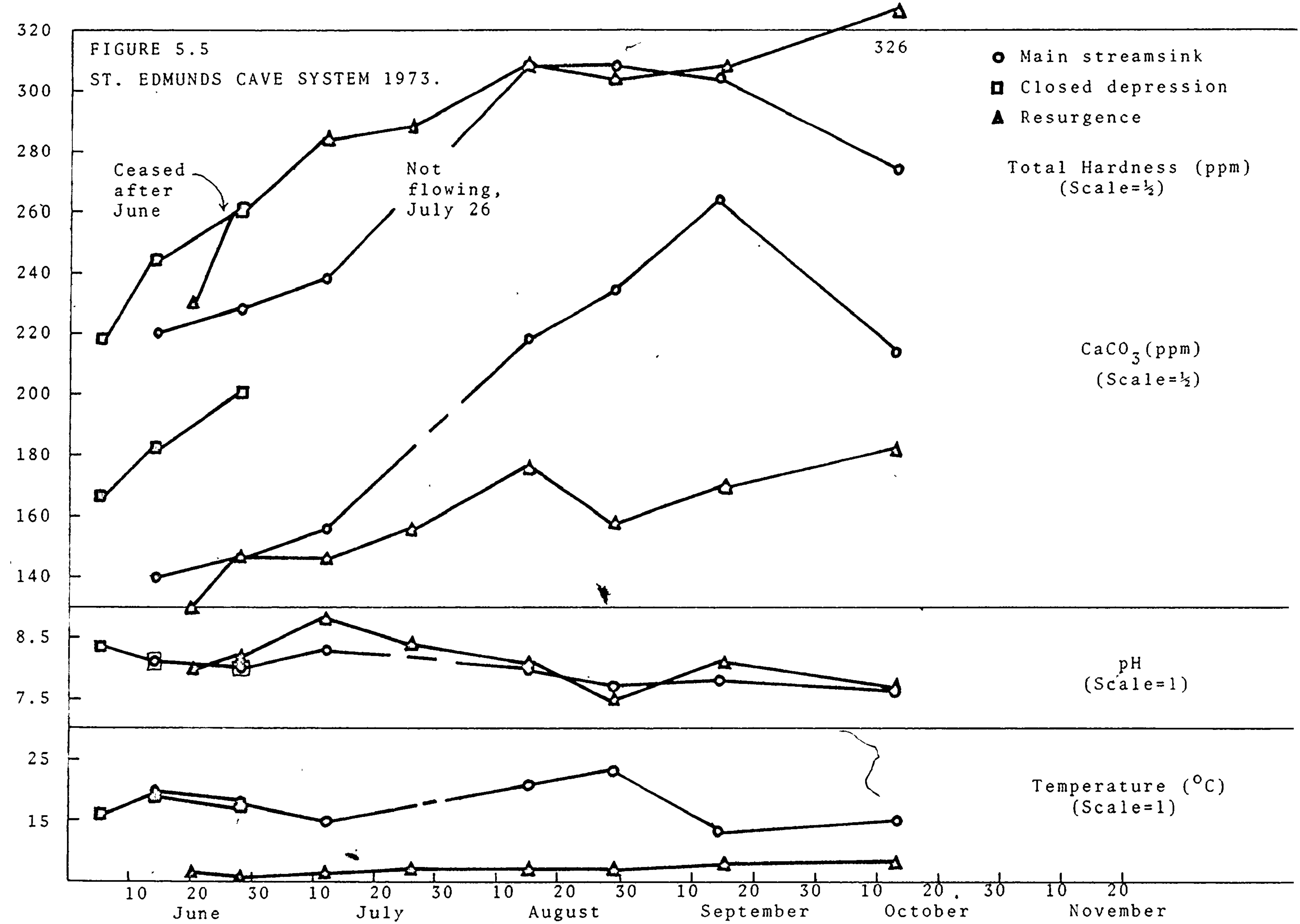

FIGURE 5.5
ST. EDMUNDS CAVE SYSTEM 1973.
Main streamsink
Closed depression
Resurgence
Total Hardness (ppm)
(Scale=½)
CaCO3 (ppm)
(Scale=½)
pH
(Scale=1)
Temperature (°C)
(Scale=1)
Ceased after June
Not flowing, July 26
326
320
300
280
260
240
220
200
180
160
140
8.5
7.5
25
15
10 20 30 10 20 30 10 20 30 10 20 30 10 20 30 10 20
June
July
August
September
October
November

relationships between sinking streams or lakes and their respective springs. The only sink to spring connection not proven is Dyer Bay (Figure 5.3).

As expected, spring waters were found to be consistently lower in temperature than others during the warmer months. This reflects the moderating influence of the rock. Water that probably has the longest underground residence time has the coolest and least variable seasonal temperature as shown by the St. Edmunds' spring (Figure 5.5).

Generally the springs have higher hardness values throughout the season than do the sinks. It is interesting that the $CaCO_3$ hardness of the St. Edmunds' resurgence is always lower than the streamsink (ponor) even though its total hardness is higher. The total hardness of the spring is thus due to a large increase of Mg, possibly at the expense of Ca i.e. precipitation of $CaCO_3$ in combination with solution of Ca Mg $(CO_3)_2$. Because on all but one occasion the resurgence was found to be supersaturated, (Table 5.1(E), samples 188-194), the loss of Ca is most likely due to the incongruent solution condition. It appears to have reached a maximum in early September. Although recharge waters are nearly always at or above saturation (Table 5.1(A) and (C), the consistently higher total hardnesses of the springs indicates that the equilibrium PCO_2 of the latter has changed within the cave systems. This change is most likely a result of one or both of two processes mixing corrosion or increased PCO_2 reservoirs within the systems. Mixing corrosion may be effective in the large St. Edmunds cave but generally these fluvio-karst features are too small to have much soil water input. Greater total hardness and lower pH of the springs are probably a result of the addition of CO_2 within the caves, especially within soils through which recharge waters drain. The equilibrium PCO_2 of the Gillies Lake spring, for example, is always higher than the lake waters which were sampled before sinking into mud and vegetation (Table 5.1(C) samples 127-135 and (E), samples 196-204)[1].

The pH of stream and spring waters of the St. Edmunds cave are more variable than at the other sites. Higher pH of the resurgence is probably a result of de-gassing of CO_2 as the waters leave the cave atmosphere.

The Cyprus Lake Park waters show some interesting characteristics. From Cyprus Lake to Horse Lake total hardness decreases and then increases from Horse to Marr Lakes. This reflects the differing drainage of the three lakes. The first two lakes are linked by a normal surface channel. The lake waters warm up and degass as they pass through the shallow channel, resulting in calcite deposition. Horse Lake, on the other hand, discharges underground to Marr Lake. This is a cooler route and richer in CO_2 (lower pH of spring waters) and hence further dolomite is dissolved.

The decrease of total and $CaCO_3$ hardnesses in early to mid-August for most waters is a result of dilution by rainfall. Weather data collected at Cyprus Lake Provincial Park show a concentration of precipitation between August 5 and 14. Over 50 mm (2 in.) of rain was recorded, most of which fell within 24 hours on August 7 and 8. The dilution effect also appears on Figures 5.6, 5.8 and 5.9. Figure 5.7 is 1974 data. It does not appear at the St. Edmunds spring. The stream flowing into the St. Edmunds cave was stagnant in late July. It is reasoned that the rain of early August reactivated it, flushing out very hard waters. The August 15 sample thus did not show any dilution effect, being a sample of the flushed waters.

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[1] NOTE - PCO_2 values in Table 5.1 are listed as negative log values and thus the higher the number, the lower the value. PCO_2 of 3.5 = the atmospheric mean.

Georgian Bay and Lake Huron (Fig. 5.10) show a slight dip in late August. These are very deep lakes with mixed chemical inputs and would not be expected to show so much of an effect or as fast a response.

Figure 5.6 shows the chemical behaviour of two large streams, Willow Creek and Crane River, and Figure 5.7 is a Crane River time series in July-August 1974. The 1973 data for this river suggested a possible bi-monthly cyclic pattern (Fig. 5.6). Total hardness decreased 8 ppm in 1973 but increased 12 to 16 ppm over the same period in 1974. The low hardness of August 14, 1973 is probably not part of a bi-monthly cycle but a result of dilution by the rain of August 7-8. Similar precipitation did not occur in 1974 and thus the gradual rise is a seasonal response to either increased biotic activity or decreased discharge (permitting more contact between water and bedrock), or both. Willow Creek did not react to the 1973 rainfall event in the same manner as the Crane River. Either the dilution effect occurred prior to sampling on August 14 or was represented by the slight decrease on August 29. The latter is unlikely because total and $CaCO_3$ hardnesses remained depressed after August 29.

Figure 5.8 shows 3 known diffuse springs. One of these drains into the Crane River at highway 6, another flows into Dorcas Bay and the third discharges into the St. Edmunds cave (Fig. 4.2). They contrast with the resurgences shown in Figures 5.2 to 5.5 which are conduit springs. Except for the St. Edmunds' resurgence, the diffuse springs (exsurgences) have more consistent temperatures and greater hardnesses. This contrast is to be expected (Shuster and White 1971). The St. Edmunds' resurgence is the exception because its waters are very hard before entering the cave. They also remain in the cave for a long time (up to 8 days) thus permitting them

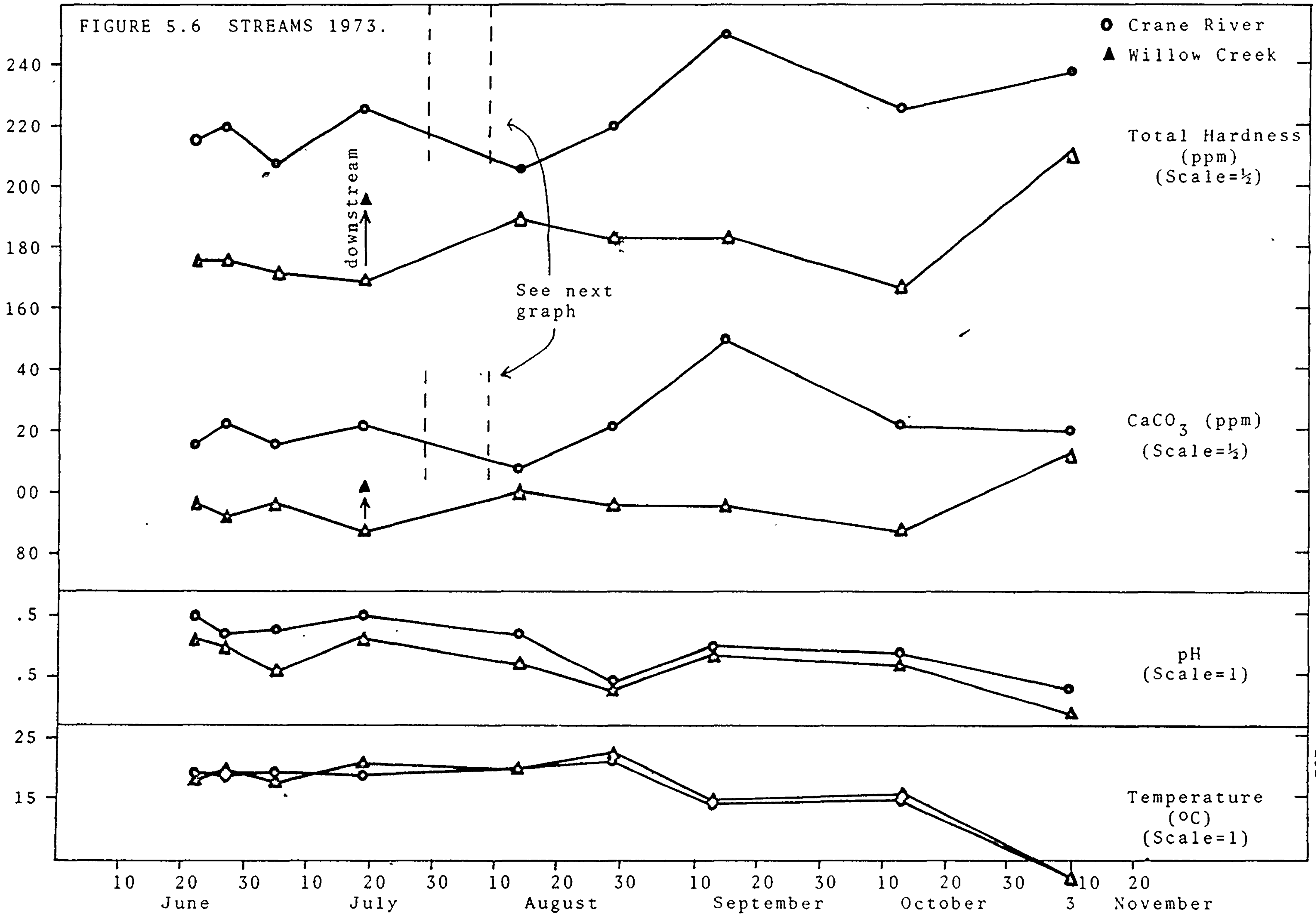

FIGURE 5.6 STREAMS 1973.
Crane River
Willow Creek
240
220
200
180
160
40
20
00
80
.5
.5
25
15
downstream
See next graph
Total Hardness (ppm) (Scale=½)
$CaCO_3$ (ppm) (Scale=½)
pH (Scale=1)
Temperature (°C) (Scale=1)
10 20 30 10 20 30 10 20 30 10 20 30 10 20 30 10 20
June July August September October 3 November

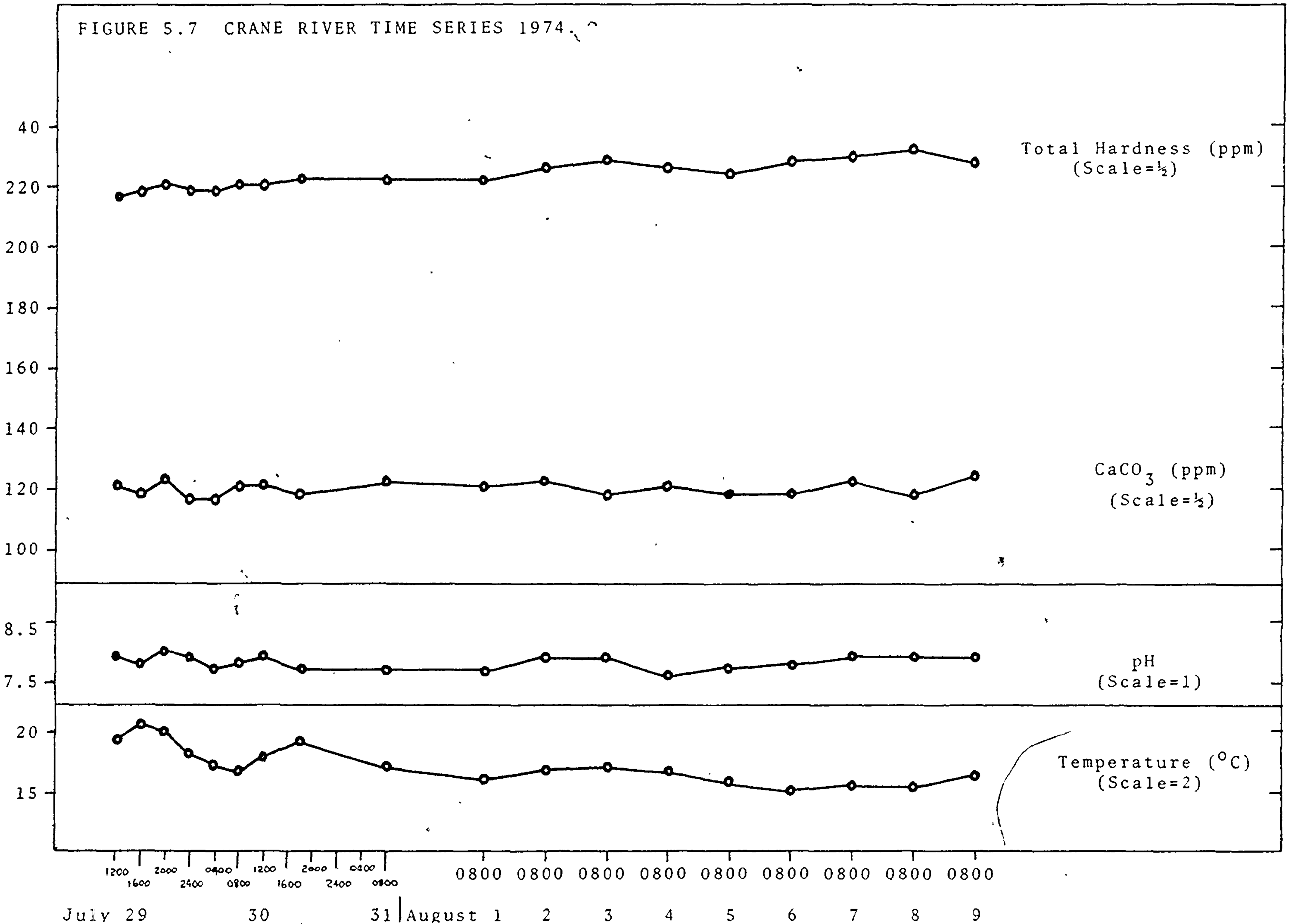

FIGURE 5.7 CRANE RIVER TIME SERIES 1974.

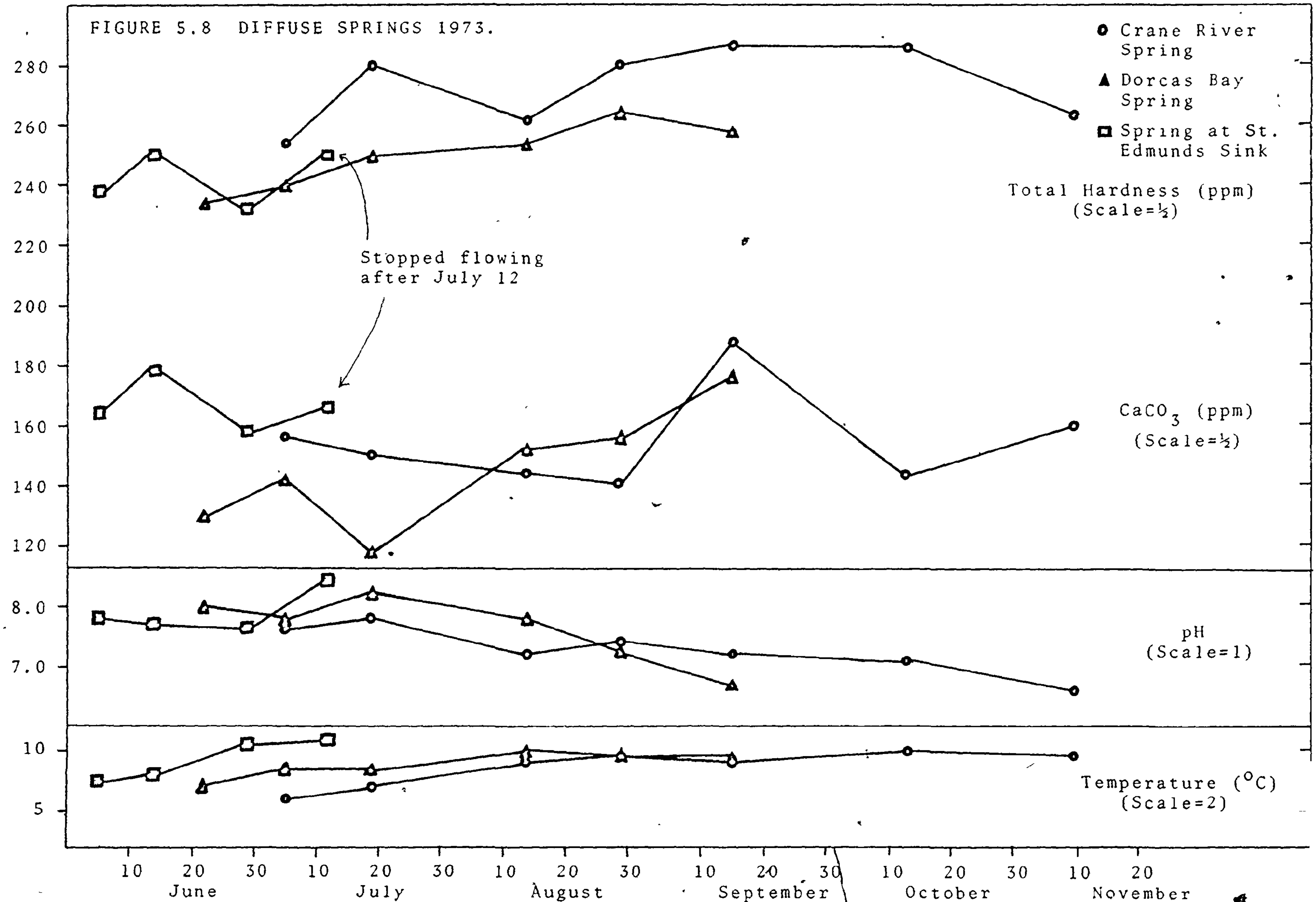

FIGURE 5.8 DIFFUSE SPRINGS 1973.
Crane River Spring
Dorcas Bay Spring
Spring at St. Edmunds Sink
Total Hardness (ppm) (Scale=½)
Stopped flowing after July 12
CaCO3 (ppm) (Scale=½)
pH (Scale=1)
Temperature (°C) (Scale=2)
280
260
240
220
200
180
160
140
120
8.0
7.0
10
5
10 20 30 10 20 30 10 20 30 10 20 30 10 20 30 10 20
June
July
August
September
October
November

to cool down to the temperature of the rock. pH values of the two spring types are similar but those of the exsurgences are slightly lower, particularly later in the year. A lower pH is consistent with the nature of diffuse springs because their waters drain more slowly through soil and forest litter. Thus they can more easily equilibriate with the soil PCO_2 environment (compare the PCO_2 values in Table 5.1(E) with those of 5.1(F).

A small swamp adjacent to the Dorcas Bay road presents a very definite cyclic behaviour of total and calcium hardness (Fig. 5.9). The cycle repeats two and a half times with one cycle lasting about two months. It should be pointed out that this pattern could be an artifact of the sampling interval and there may actually be more than $2^1/_2$ cycles. It is not known why this repetition occurs but the low values in early August are probably due to precipitation. However, no such event was recorded in early October when hardnesses are also depressed. The cycles most likely relate both to weather and biological activity, each of which has much influence in swamps. Following the dilution by rain (early August) hardness increases due to evaporation. At the same time biological activity is increasing, first, permitting further solution but later removing much of the Ca by nutrient uptake. This is suggested because the trend of total hardness follows that of Ca hardness closer here than in any of the other waters. The final increase in hardness may result from reduced nutrient uptake as botanical activity diminishes (but still enough CO_2 is available to permit some solution). The cycles are not reflected as strongly in the pH and temperature data. Two cycles may be recognized but they occur slightly ahead of those of the hardnesses. If the second hardness peak was due mainly to evaporation one would also expect a corresponding increase in temperature which did not occur. Much of the solution in swamps is

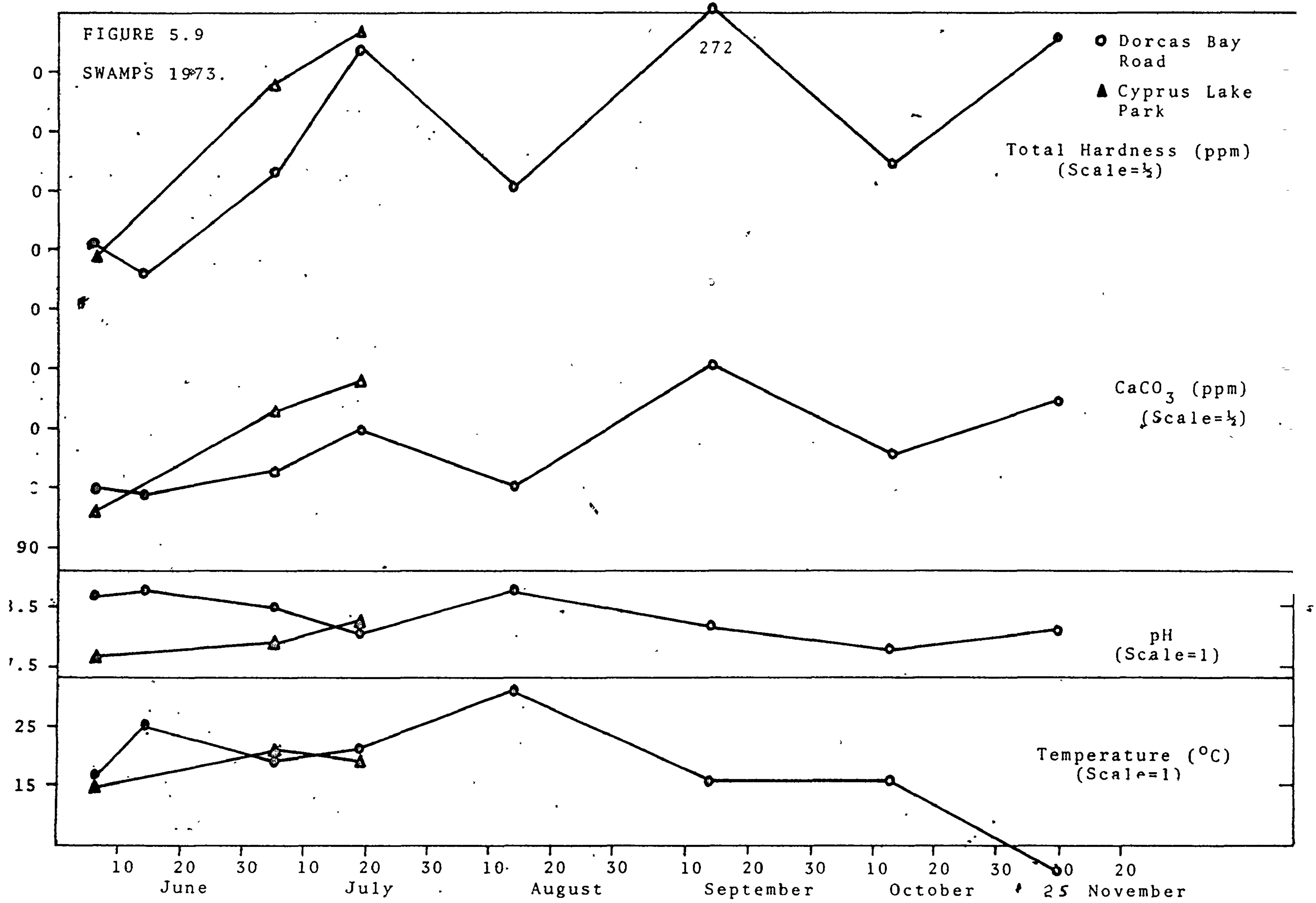

FIGURE 5.9
SWAMPS 1973.
Dorcas Bay Road
Cyprus Lake Park
Total Hardness (ppm) (Scale=½)
272
CaCO3 (ppm) (Scale=½)
pH (Scale=1)
Temperature (°C) (Scale=1)
90
25
15
10 20 30 10 20 30 10 20 30 10 20 30 10 20 30 10 20
June
July
August
September
October
25 November

horizontal rather than vertical. Dead organic matter plus a high water table near Lake Huron would inhibit downward solution.

Figure 5.10 illustrates the behaviour of Lake Huron and Georgian Bay. Samples were taken from the nearshore surface waters. The two water bodies behave similarly throughout the year. Lake Huron is slightly harder and warms up faster than Georgian Bay. This is because it is shallower at the peninsula. The higher hardness probably reflects the greater stream runoff into Lake Huron. Both lakes however appear quite distinct from the other water types, having much lower hardnesses (almost $^1/_2$ that of the inland lakes, Fig. 5.2, Table 5.1(A) and (B)), less seasonal variation of hardness and higher pH values. Mg concentration relative to $CaCO_3$ is also much less in these lakes. Georgian Bay and Lake Huron are not aggressive chemically (Table 5.1(B)). Because of their size soil water and biogenic CO_2 is of little importance and their surfaces are thus equilibriating with the PCO_2 of the ordinary atmosphere (0.033% or - log 3.5). Run-off from the peninsula maintains the total hardness near 100 ppm which is above that expected for water bodies equilibriating with the atmosphere. Consequently they are supersaturated in most cases.

All of the waters except Lake Huron and Georgian Bay display a consistent increase in total hardness and $CaCo_3$ concentration over the season. Despite the oscillations discussed above the trend is toward highest hardnesses occurring in late summer and early fall. This same trend was found elsewhere in southern Ontario (Cowell and Ford, 1975). The early seasonal increase (June-July) is likely partly a result of decreasing discharge following spring melt. Inverse relationships between hardness and discharge have been observed in many karst areas (Pitty 1966, Ford 1971a).

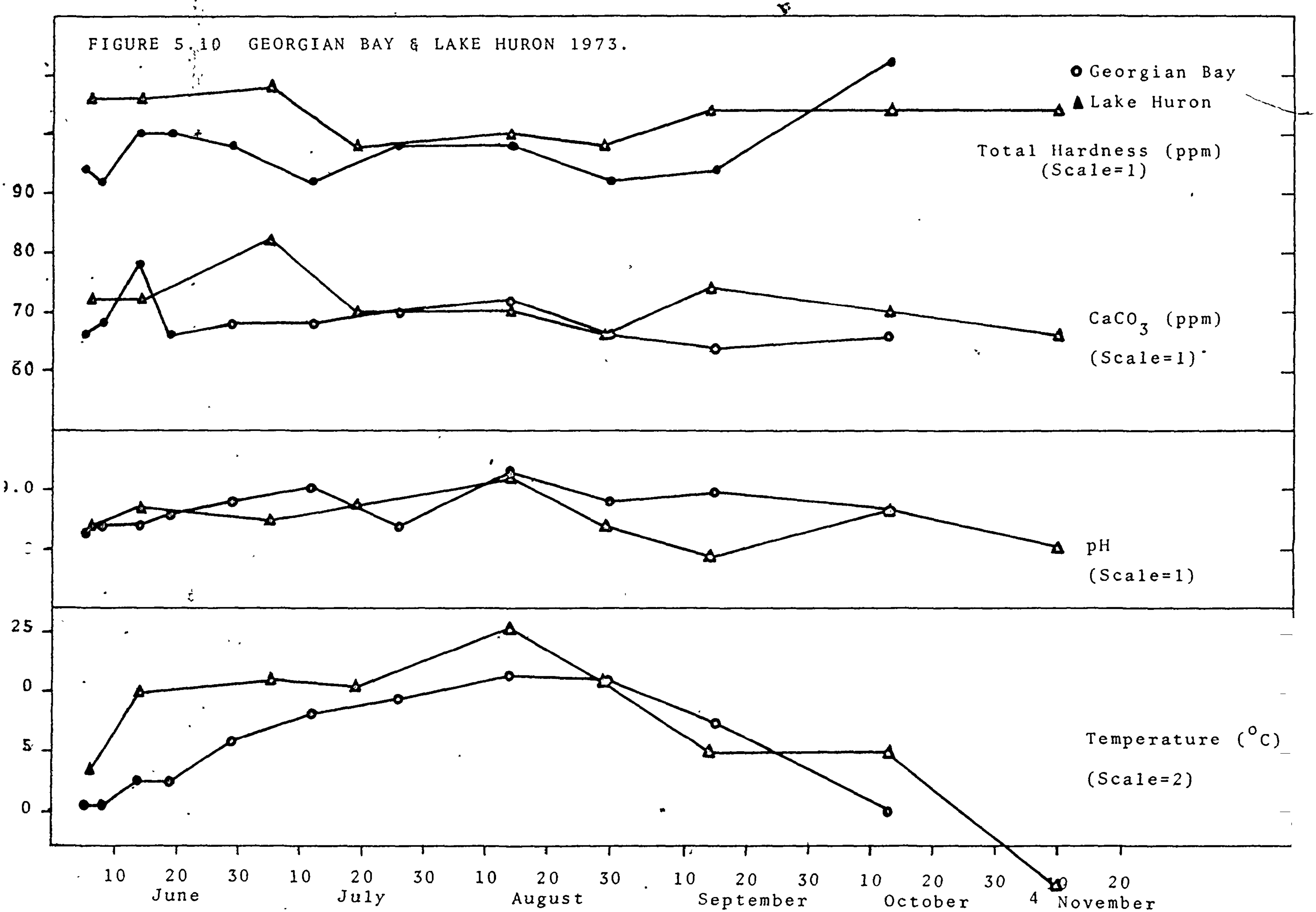
FIGURE 5.10 GEORGIAN BAY & LAKE HURON 1973.
Georgian Bay
Lake Huron
Total Hardness (ppm)
(Scale=1)
90
80
70
60
CaCO3 (ppm)
(Scale=1)
pH
(Scale=1)
25
0
5
0
Temperature (°C)
(Scale=2)
10 20 30 10 20 30 10 20 30 10 20 30 10 20 30 10 20
June
July
August
September
October
November

It is also partly due to higher biotic activity and soil CO_2 production which appears to reach a maximum in September and October. Cowell and Ford (1975) noted a rapid decrease in hardness of waters in mid-December precisely when the first hard seasonal frost acted to halt biotic growth and inhibit soil water seepage.

Cowell and Ford also noted a trend to lower pH values in the fall that is found in many of the Bruce Peninsula waters, particularly the springs. Late season pH values of some of the diffuse spring samples were below 7.0 which was not found earlier in the year (Fig. 5.8). This too is attributed to late summer biotic activity. Soil water is beginning to equilibriate to a very high PCO_2 (Table 5.1(F)) but does not dissolve enough dolomite to bring up the pH.

The seasonal data presented in this section indicate two facts. Firstly, a great deal of dolomite is removed in solution from the Bruce Peninsula. Solution rates are in excess of 150 ppm total hardness for most waters and 300 ppm for subsurface waters. The prime rate-limiting factor to the solutional denudation of the Bruce Peninsula, because of the high biotic CO_2 available, is thus the amount of water supplied by precipitation during the spring, summer and fall.

Secondly, it appears that different water types (i.e. springs, lakes, streams, etc.) have fairly specific chemical signatures. Seasonal variability, hardness, temperature and PCO_2 appear to reflect differing hydrological environments.

5.3 Chemical Signatures of Water Types

Harmon et al (1972) and Drake and Harmon (1973) found that the chemical evolution of karst water could be traced through an aquifer and that each water type in the aquifer (soil seepage, sinking water, vadose water, etc.) carried a particular chemical signature. Ford (1971a) was able to differentiate among differing kinds of surface and aquifer water sampled at various altitudes in the Canadian Rocky Mountains. Seasonal variability in chemistry was used by Shuster and White (1971) to distinguish between diffuse and conduit springs in Pennsylvania. These studies indicate that the most useful chemical parameters for characterizing karst waters are $CaCO_3$ hardness (and total hardness), PCO_2, temperature and SI_c.

Seasonal and random samples of various Bruce Peninsula waters were examined to determine what, if any separation could be made using their chemistry and how this may relate to chemical evolution. The data were grouped into seven classes based on a priori physical characteristics. There were; 1. large lakes (Lake Huron and Georgian Bay); 2. inland lakes; 3. streams and rivers; 4. swamps; 5. conduit springs; 6. diffuse springs; 7. miscellaneous (Table 5.1.1).

After eliminating analyses with an ion balance error of > 10% the data set consisted of 172 samples. Each had 9 chemical parameters comprising the 5 measured variables (temperature, pH, Ca^{++}, Mg^{++} and HCO_3^-) and 4 calculated variables (Ca/Mg, SI_c, SI_d and PCO_2). They are listed in their groups in Table 5.1. Table 5.2 lists the means and standard deviations of the variables in each group. It should be noted that the cations are shown as Ca and Mg ion, not as $CaCO_3$ which was used in Section 5.2. The Ca/Mg values are based on Ca and Mg as $CaCO_3$.

Grouping the data in this manner ignores seasonal variation as a

TABLE F.1(A) WATER CHEMISTRY DATA USED IN DISCRIMINANT ANALYSIS— INLAND LAKES.

I.D.	TEMP	PH	CA++	MG++	CA/MG	ALK	SIC	SID	PCO2
1	17.4	8.68	36.	22.1	1.01	3.63	0.84	1.68	3.45
2	18.4	8.60	39.2	19.2	1.25	3.37	0.61	1.53	3.38
3	21.5	8.80	40.8	18.7	1.37	3.65	1.08	2.03	3.55
4	22.5	8.90	40.8	19.7	1.31	3.10	1.12	2.12	3.74
5	21.5	9.10	40.	19.7	1.33	3.33	1.26	2.41	3.95
6	24.	9.15	40.	17.8	1.49	2.98	1.31	2.45	4.07
9	18.1	8.70	41.6	20.2	1.27	3.32	0.90	1.70	3.50
10	22.1	8.9	37.6	19.7	1.19	3.14	1.0	1.93	3.62
13	22.0	8.9	36.8	20.6	1.15	3.18	1.07	2.10	3.73
15	21.8	8.9	37.6	19.2	1.24	3.10	1.08	2.07	3.73
16	18.	8.4	39.2	20.6	1.15	3.37	0.66	1.27	3.11
17	16.5	8.49	43.2	16.3	1.61	3.59	0.73	1.26	3.25
18	22.8	8.52	40.	18.7	1.31	3.61	0.85	1.60	3.24
19	20.	8.72	32.8	21.1	0.97	3.65	0.89	1.41	3.47
20	22.	8.88	40.	19.7	1.28	3.12	1.08	2.07	3.71
21	23.	8.92	40.8	19.7	1.32	3.48	1.18	2.25	3.71
22	24.	9.4	38.4	21.6	1.08	3.55	0.74	1.46	3.11
25	17.5	8.0	45.6	18.2	1.49	4.22	0.36	0.56	2.67
27	17.	8.38	42.4	19.2	1.33	3.39	0.6	1.09	3.10
28	16.7	8.29	42.4	18.2	1.39	3.43	0.52	0.92	3.05
29	20.5	8.35	43.2	19.7	1.32	3.52	0.67	1.23	3.07
30	23.2	8.52	44.8	19.2	1.43	3.62	0.91	1.67	3.24
31	23.5	8.59	44.8	20.2	1.35	3.37	0.95	1.76	3.34
32	22.	9.02	41.6	21.6	1.25	3.56	1.25	2.42	3.83
33	23.	8.6	39.2	21.6	1.11	3.35	0.89	1.74	3.36
36	18.	8.61	40.	22.6	1.09	3.34	0.8	1.57	3.41
37	24.	9.35	41.6	19.7	1.39	3.96	1.36	2.57	3.8
38	22.	8.55	47.2	17.3	1.68	4.31	1.	1.78	3.2
39	22.	8.56	48.8	11.	2.71	3.75	0.95	1.57	3.27
41	23.5	8.9	34.4	11.5	1.38	2.65	1.03	1.78	3.78
42	20.6	8.6	29.6	19.2	0.94	2.71	0.65	1.37	3.40
43	20.2	8.9	35.2	15.8	1.4	2.55	0.36	1.78	3.81
44	25.	8.7	38.4	18.2	1.31	3.17	0.93	1.87	3.48
45	24.	7.5	39.2	12.	1.93	2.71	-0.21	-0.69	2.29
46	21.7	8.6	30.4	8.2	2.27	1.95	0.58	0.8	3.58
47	20.4	8.7	34.4	19.2	1.11	3.82	0.83	1.63	3.53
48	20.2	7.9	38.4	16.8	1.36	3.04	0.14	0.15	2.68
49	21.5	8.7	29.6	15.8	1.15	2.60	0.75	1.43	3.59

TABLE F.1(B) LAKE HURON AND GEORGIAN BAY

I.D.	TEMP	PH	CA++	MG++	CA/MG	ALK	SIC	SID	PCO2
51	10.5	8.39	27.2	5.8	2.83	2.13	0.12	-0.18	3.38
52	12.5	8.4	31.2	5.3	3.55	2.	0.21	-0.10	3.41
55	18.2	9.05	27.2	5.8	2.96	1.61	0.78	1.29	4.18
59	17.5	8.95	25.6	7.2	2.21	1.61	0.65	0.97	4.07
61	13.5	8.35	28.8	8.2	2.12	1.24	0.2	0.08	3.31
64	20.5	8.75	28.	6.7	2.36	1.76	0.62	0.33	3.79
67	15.	7.9	29.6	7.2	2.45	1.82	-0.23	-0.93	2.93

TABLE 5.1(C) STREAMS AND RIVERS

I.D.	TEMP	PH	CA++	MG++	CA/MG	ALK	SIC	SID	PCO2
70	18.	8.55	40.	18.2	1.34	4.05	0.83	1.54	3.25
71	16.8	8.7	70.3	18.2	1.33	3.36	0.95	1.6	3.5
72	21.	8.7	36.	20.6	1.04	3.69	0.94	1.34	3.44
74	22.	9.	38.4	19.2	1.29	3.53	1.21	2.71	3.8
75	23.2	8.58	36.	21.1	1.05	3.37	0.54	1.67	3.33
76	27.	9.1	43.2	15.8	1.70	3.12	1.36	2.31	3.94
79	18.9	8.49	46.4	24.	1.18	4.19	0.35	1.05	3.18
80	18.9	8.2	49.8	23.5	1.24	4.21	0.61	1.14	2.87
81	19.2	8.25	45.4	22.1	1.26	4.01	0.37	1.15	2.94
82	18.5	8.5	48.8	25.	1.19	4.09	0.34	1.81	3.12
83	20.	8.22	47.2	23.5	1.1	3.58	0.54	1.05	2.95
84	21.	7.4	49.8	23.5	1.22	4.18	-0.17	-0.35	2.05
85	14.	8.	50.	24.	1.48	4.7	0.43	0.72	2.64
88	17.3	8.4	45.6	20.6	1.33	3.94	0.71	1.31	3.11
93	17.1	7.7	46.4	24.5	1.12	4.09	0.05	0.07	2.38
104	15.5	7.95	48.8	25.9	1.11	4.27	0.3	0.57	2.32
107	18.5	8.1	38.4	19.2	1.19	3.37	0.33	0.59	2.86
108	19.5	8.02	36.8	20.2	1.09	3.27	0.24	0.46	2.78
109	18.2	7.62	39.4	19.2	1.24	3.23	-0.16	-0.40	2.39
110	20.8	8.09	35.2	19.7	1.07	3.37	0.33	0.63	2.92
111	21.	8.65	40.8	23.	1.09	3.8	[illegible]	1.47	3.78
113	22.5	7.3	38.4	21.1	1.07	3.32	-0.39	-0.74	2.02
114	15.	7.85	38.4	21.1	1.07	3.66	0.04	0.06	2.59
117	16.	8.36	66.4	12.5	3.2	4.7	0.37	1.26	[illegible]
118	18.9	8.08	72.8	14.0	2.9	5.25	0.75	1.35	2.55
119	16.5	7.99	80.	14.4	3.27	5.29	0.71	0.33	2.5
120	19.8	8.1	56.	19.2	1.73	4.39	0.56	1.09	2.58
121	18.	7.35	58.4	19.7	1.75	4.41	0.48	0.73	2.76
122	15.	8.32	70.4	14.0	2.94	5.56	0.9	1.36	2.9
123	21.	7.32	91.2	19.2	2.8	5.5	0.74	1.14	2.46
124	23.5	7.72	93.6	17.8	3.09	5.73	0.63	0.77	2.22
125	13.5	7.75	105.6	9.0	6.43	5.26	0.51	0.24	2.28
127	20.5	8.89	73.6	13.7	2.14	3.37	1.02	1.96	3.71
128	21.	8.35	32.8	21.1	0.90	3.23	0.99	1.95	3.05
129	24.	9.25	34.4	19.0	1.21	3.47	1.37	2.55	4.1
130	22.	8.25	31.2	21.1	0.89	3.1	0.43	0.91	3.02
133	17.5	8.75	32.	20.2	0.98	2.98	0.76	1.58	3.51
135	4.5	8.4	29.6	22.0	0.79	2.88	0.11	0.37	3.29
136	21.	7.68	49.6	17.3	1.59	3.73	0.12	0.02	2.37
138	23.	7.52	56.8	13.2	1.74	4.24	0.1	-0.04	2.15
139	19.5	8.4	67.2	17.3	2.35	4.95	1.	1.65	3.01
140	3.	6.82	47.2	13.0	1.44	3.45	-1.22	-2.55	1.52
141	18.	8.78	38.4	20.0	1.16	3.77	0.98	1.90	3.54
142	13.4	8.2	60.	21.6	1.66	4.35	0.58	0.97	2.59
143	18.3	8.1	50.4	34.1	0.88	5.18	0.58	1.23	2.68
144	14.8	7.8	60.8	24.	1.49	4.56	0.25	0.35	2.45
145	19.4	8.	45.6	16.8	1.61	3.54	0.34	0.49	2.73
146	12.3	7.7	50.	22.1	1.39	3.95	-0.03	-0.19	2.43
147	16.8	7.9	35.2	16.3	1.28	2.7	-0.02	-0.14	2.75
148	24.5	7.8	49.6	19.7	1.49	3.93	0.33	0.40	2.44
149	18.9	7.8	32.9	16.3	1.19	2.72	-0.10	-0.26	2.03
150	21.7	7.9	43.2	17.3	1.46	3.47	0.27	0.37	2.92
151	15.	7.9	69.6	27.	1.79	4.31	0.43	0.62	2.53
152	17.2	8.1	57.6	23.5	1.35	4.39	0.53	0.94	2.76
153	16.	7.9	59.2	24.5	1.43	4.6	0.37	0.6	2.54
154	18.2	7.7	58.4	25.4	1.35	4.73	0.23	0.34	2.31

COLOUR

TABLE 5.1(D)

I.D.	TEMP	PH	CA++	MG++	CA/MG	ALK	SIC	SID	PCO2
158	19.5	8.5	46.4	24.	1.13	4.34	0.86	[illegible]	[illegible]
159	21.5	8.05	52.	[illegible].7	1.	5.35	[illegible]	[illegible]	2.59
160	31.	8.8	44.	24.5	1.14	7.74	1.28	[illegible].81	[illegible]
161	16.	8.2	60.8	25.8	1.36	5.14	[illegible]	[illegible]	[illegible].81
164	14.9	7.65	43.8	[illegible]	1.16	4.37	-[illegible].07	-[illegible]	2.32
165	21.	7.85	54.4	26.4	1.22	4.78	[illegible].41	[illegible]	[illegible]
166	19.5	8.25	58.4	28.[illegible]	1.24	5.[illegible]	[illegible].43	[illegible]	[illegible]
167	19.1	7.8	46.4	21.1	1.3	[illegible]	0.17	[illegible].23	2.5
168	18.3	7.7	58.4	29.8	1.15	5.05	.25	[illegible]	[illegible]
169	19.2	7.9	58.4	24.5	1.41	4.74	.45	[illegible]	[illegible]

CONDUIT SPRINGS

I.D.	TEMP	PH	CA++	MG++	CA/MG	ALK	SIC	SID	PCO2
170	18.	8.12	45.	2[illegible]	1.18	[illegible]	[illegible]	[illegible]	[illegible]
171	19.8	8.2	43.8	19.7	1.24	3.15	[illegible]	[illegible]	[illegible]
172	20.5	8.45	40.	21.1	1.15	3.35	0.71	1.37	3.21
173	19.	8.24	40.8	20.2	1.21	3.77	0.5	[illegible]	3.
174	20.3	8.3	44.	17.8	1.49	3.19	0.50	[illegible]	[illegible]
175	21.5	8.4	39.2	21.6	1.1	3.36	0.68	1.3[illegible]	3.15
176	22.5	7.5	40.	21.1	1.12	3.32	-0.14	-0.3[illegible]	2.2
178	17.	8.28	40.8	20.2	1.21	3.7	0.53	[illegible]	3.1
179	16.2	8.36	41.6	18.2	1.37	3.5	0.57	[illegible]	3.12
180	20.	8.21	42.4	19.7	1.29	3.71	[illegible]	0.90	2.92
181	20.5	8.4	44.8	18.2	1.45	3.46	[illegible]	1.29	3.15
182	22.	8.6	45.6	18.7	1.49	3.3	0.93	[illegible]	3.37
183	22.	8.99	42.4	21.1	1.20	3.54	1.24	2.[illegible]	3.79
184	23.5	8.45	40.	21.6	1.13	3.53	0.79	1.[illegible]	3.17
185	25.5	8.	36.8	2[illegible]	1.06	3.03	0.32	0.62	3.[illegible]
187	18.	8.63	30.2	21.6	1.11	3.38	[illegible]	[illegible]	3.[illegible]
188	6.4	7.99	52.	24.	1.28	4.95	[illegible]	[illegible]	[illegible].64
189	6.	8.22	58.4	27.4	1.27	5.24	0.48	[illegible]	[illegible]
190	6.5	8.75	59.4	33.	1.[illegible]	5.57	1.21	[illegible]	3.37
191	7.	8.4	62.4	31.7	1.19	5.65	[illegible].72	[illegible]	3.[illegible]
192	7.	8.1	70.4	31.[illegible]	1.31	[illegible].57	[illegible].4[illegible]	[illegible].8[illegible]	2.71
193	7.	7.52	63.2	30.	1.[illegible]	[illegible].47	-0.14	-0.26	2.12
194	8.	8.08	68.	33.	1.21	6.15	0.5	[illegible]	2.55
196	18.5	8.55	36.	19.2	1.14	3.2	[illegible].7	1.[illegible]	3.35
197	19.5	8.32	34.4	21.6	0.90	3.1[illegible]	[illegible].49	1.	3.11
198	19.8	8.7	33.6	20.2	1.03	3.[illegible]	0.83	1.35	3.51
199	19.	8.12	32.	20.2	0.95	3.02	0.24	[illegible]	2.92
201	20.5	8.05	31.2	19.2	0.97	3.78	0.17	[illegible]	2.87
202	18.5	7.55	32.	21.1	0.89	3.19	-0.32	-[illegible]	2.33
204	10.	7.5	38.4	21.6	1.05	3.18	-0.50	-[illegible]	2.33
205	14.	7.82	52.	16.8	1.82	4.16	0.16	[illegible]	2.51
206	14.5	7.15	54.4	16.3	1.96	3.60	-0.52	-1.31	1.88
207	14.	7.78	56.	21.1	1.56	3.85	0.12	[illegible]	2.5
208	13.5	8.12	68.	22.6	1.79	4.98	0.61	0.39	2.75
209	7.5	7.	49.6	20.2	1.44	[illegible].62	-[illegible].89	-1.[illegible]	1.77
212	9.9	7.5	63.2	23.	1.61	4.79	-[illegible].15	-[illegible].5	[illegible].15

COLOUR

TABLE 5.1(F) DIFFUSE SPRINGS

I.D.	TEMP	PH	CA++	MG++	CA/MG	ALK	SIC	SID	PCO2
213	6.	7.67	62.4	23.5	1.55	4.85	-0.1	-0.34	2.29
214	7.	7.8	60.	31.2	1.13	5.22	0.1	0.19	2.43
217	9.	7.23	75.2	23.5	1.96	5.48	-0.3	-0.83	1.82
220	7.	7.95	52.	25.	1.23	4.58	0.15	0.24	2.63
221	8.5	7.8	56.8	23.5	1.42	4.59	0.07	0.03	2.47
222	8.5	8.22	47.2	37.3	0.89	4.76	0.41	0.91	2.89
223	10.	7.75	60.8	24.5	1.46	4.53	0.08	0.03	2.42
224	9.5	7.23	62.4	25.9	1.41	4.65	-0.42	-0.96	1.89
225	9.5	6.7	70.4	19.7	2.08	4.98	-0.87	-2.03	1.33
226	7.5	7.8	65.6	17.8	2.17	5.03	0.15	0.0	2.44
227	8.	7.7	71.2	17.3	2.41	4.98	0.09	-0.16	2.34
228	10.5	7.65	63.2	17.8	2.09	4.66	0.03	-0.23	2.31
229	10.8	8.38	66.4	20.2	1.98	4.99	0.78	1.30	3.03
230	8.	8.62	54.4	36.	0.92	5.91	0.9	1.87	3.23
231	10.	6.6	56.	20.6	1.59	3.93	-1.14	-2.46	1.33
232	10.	6.15	60.	20.6	1.7	4.45	-1.52	-3.23	0.92
234	8.2	7.3	75.2	28.3	1.55	5.59	-0.24	-0.64	1.89
235	8.4	7.9	76.8	29.3	1.54	5.43	0.35	0.59	2.51
236	7.7	7.8	56.	28.3	1.16	4.69	0.05	0.08	2.47
237	6.6	7.5	81.6	31.2	1.53	5.54	-0.06	-0.26	2.1
238	8.5	7.4	61.6	25.9	1.39	4.70	-0.28	-0.67	2.06

n = 1

TABLE 5.1(G) MISCELLANEOUS

I.D.	TEMP	PH	CA++	MG++	CA/MG	ALK	SIC	SID	PCO2
239	12.	8.05	100.	15.4	3.85	5.49	0.7	0.84	2.64
240	12.	7.68	36.	22.1	0.96	3.62	-0.23	-0.42	2.43
241	19.5	8.35	40.8	15.6	1.6	3.27	0.61	1.02	3.12
245	22.5	8.32	40.8	13.	1.9	3.25	0.64	1.01	3.07

n = 4

n total = 17[illegible]

*Temp. in °C
Ca++, Mg++ in ppm
ALK in m.mol./l [illegible]
$PCO_2 = 10^{-x}$

TABLE 5.1.1 Location of samples in Table 5.1

(A) Inland Lakes

1-15	Cyprus Lake	S - 1973*
16-25	Horse Lake	S - 1973
27-36	Marr Lake	S - 1973
37	Cameron Lake	July 12 1973
38	sm.lake east of Driftwood Cove	June 20, 1973
39	sm.lake west of Marr Lake	June 20, 1973
41	Britain Lake	June 5, 1974
42	Shouldice Lake	July 2, 1974
43	Miller Lake	July 2, 1974
44	Ague Lake	July 10, 1974
45	Ira Lake	July 10, 1974
46	Spry Lake	July 17, 1974
47	Sky Lake	July 17, 1974
48	Isaac Lake	July 17, 1974
49	Berford Lake	July 19, 1974

(B) Georgian Bay and Lake Huron

51-59	Georgian Bay	S - 1973
61-67	Lake Huron	S - 1973

(C) Streams and Rivers

70-76	stream connecting Cyprus and Horse Lakes	S - 1973
79-104	Crane River	S - 1973 and 1974
107-114	Willow Creek	S - 1973
117-125	2 streams sinking into St. Edmunds Cave	S - 1973
127-135	stream draining Gillies Lake	S - 1973
136-140	sinking stream at Dyer Bay	S - 1973
141	stream connecting Cameron and Cyprus Lakes	1973
142,143	Judges Creek	June 18 & July 12, 1974
144	sinking stream at Colpoy Bay	June 27, 1974
145,148	Stokes River	July 3, 10, 1974
146	Saddler Creek	July 10, 1974
147	Spring Creek	July 10, 1974
149,150	Rankin River	July 12,17, 1974
151	sm. creek near Cape Croker	July 16, 1974
152,153	Albermarle Brook	July 11,17, 1974
154	Sucker Creek	July 18, 1974

(D) Swamps

158-161	Dorcas Bay road	S - 1973
164-166	Cyprus Lake Park road	S - 1973
167	6 mi. south Brinkman Cors.	July 2, 1974
168	Pine Tree Harbour road	July 10, 1974
169	Red Bay	July 17, 1974

(E) Conduit Springs

170-176	Marr Lake (from Horse Lake)	S - 1973
178-187	granular drainage through beach cobbles from Marr Lake to Georgian Bay	S - 1973
188-194	St. Edmunds exit spring	S - 1973
196-204	Gillies Lake spring	S - 1973
205-209	Dyer Bay spring	S - 1973
212	Colpoy Bay creek rising	June 27, 1974

(F) Diffuse Springs

213-217	Crane River spring	S - 1973
220-225	east of Dorcas Bay	S - 1973
226-229	shallow spring sinking into St. Edmunds Cave	S - 1973
230	east of Rocky Bay	July 10, 1973
231, 232	cold rising on Marr Lake	Aug.30, Sept.15,1973
234, 235	Barrow Bay spring (Cape Dundas)	July 11, Aug.7, 1974
236	Cape Croker area	June 24, 1974
237	Cape Croker area	June 24, 1974
238	Cape Chin	July 9, 1974

(G) Miscellaneous

239	cave pool, St. Edmunds Cave	1973
240	cave drip, St. Edmunds exit cave	1973
241	open pool beside Georgian Bay	1973
245	open pool beside Lake Huron	1973

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* S = seasonal data

TABLE 5.2 Group means and standard deviations of the nine water chemistry variables from TABLE 5.1

5.2.1 Group means

	Temp (°C)	pH	Ca^{++} (ppm)	Mg^{++} (ppm)	Ca/Mg	Alk (mmol/litre)	SI_c	SI_d	PCO_2 10^{-x}
(A) Inland Lakes	21.12	8.63	39.37	18.42	1.37	3.32	0.86	1.60	3.42
(B) Georgian Bay & Lake Huron	15.39	8.54	28.23	6.6	2.67	1.88	0.33	0.25	3.58
(C) Streams & Rivers	18.33	8.14	50.0	20.28	1.58	4.08	0.50	0.85	2.84
(D) Swamps	20.0	8.07	52.0	25.87	1.21	4.65	0.55	1.04	2.69
(E) Conduit Springs	15.93	8.12	46.44	22.23	1.26	3.88	0.38	0.69	2.85
(F) Diffuse Springs	8.53	7.58	63.58	25.11	1.57	4.93	-0.08	-0.31	2.22
(G) Miscellaneous	16.5	8.1	54.4	16.53	2.08	3.91	0.43	0.61	2.82

5.2.2 Standard Deviations

	Temp (°C)	pH	Ca^{++} (ppm)	Mg^{++} (ppm)	Ca/Mg	Alk (mmol/litre)	SI_c	SI_d	PCO_2 10^{-x}
(A)	2.35	.33	4.43	3.17	.35	.46	.31	.64	.36
(B)	3.5	.4	1.83	1.02	.49	.25	.37	.74	.45
(C)	4.14	.47	16.32	3.84	.89	.86	.45	.90	.51
(D)	4.36	.37	7.14	3.52	.11	.63	.39	.8	.38
(E)	5.9	.45	11.33	4.78	.25	.94	.46	.93	.47
(F)	1.32	.58	8.87	5.7	.41	.47	.57	1.18	.58
(G)	5.34	.31	30.48	3.9	1.25	1.07	.44	.69	.34

factor. It follows from the previous section that seasonal variation will affect the separation of water types, especially if temperature, hardness or pH is used. For this reason the calculated variables may be more significant and useful in the classification.

5.3.1 Graphical Analysis

Ford (1971a) obtained good separation of water types using plots of SI_c vs $CaCO_3$ and PCO_2 vs $CaCO_3$. Drake and Harmon (1973) used PCO_2 vs SI_c to distinguish four kinds of aquifer water and two surface waters. PCO_2 vs SI_c and SI_d was also used by Cowell and Ford (1975) to separate a sinking stream, a conduit flow spring and a diffuse flow spring. All three studies noted springs, particularly diffuse springs, to be the closest to saturation. Ford (1971a) and Cowell and Ford (1975) working in glaciated regions found surface waters to be predominantly saturated or supersaturated except for Ford's samples from above the treeline. In contrast Drake and Harmon (1973) working in an unglaciated region, where runoff was from non-carbonate rocks, found recharge waters well undersaturated.

The Bruce Peninsula data are shown in Figures 5.11 to 5.13. These are plots of SI_c vs Ca^{++}, PCO_2 vs Ca^{++} and PCO_2 vs SI_c. At first glance there appears to be little or no separation of the data in any instance. The only waters which are well distinguished, especially in Figure 5.13, are Georgian Bay and Lake Huron. However, certain distinctions may be made:

i) Georgian Bay and Lake Huron - these waters have the lowest Ca^{++} hardness ($\bar{x}$ 28.2 ppm, Table 5.2) in a range from 25 to 31 ppm (66 to 78 ppm $CaCO_3$) of which all but one are supersaturated (Fig. 5.11). PCO_2 varies from $10^{-2.93}$ to

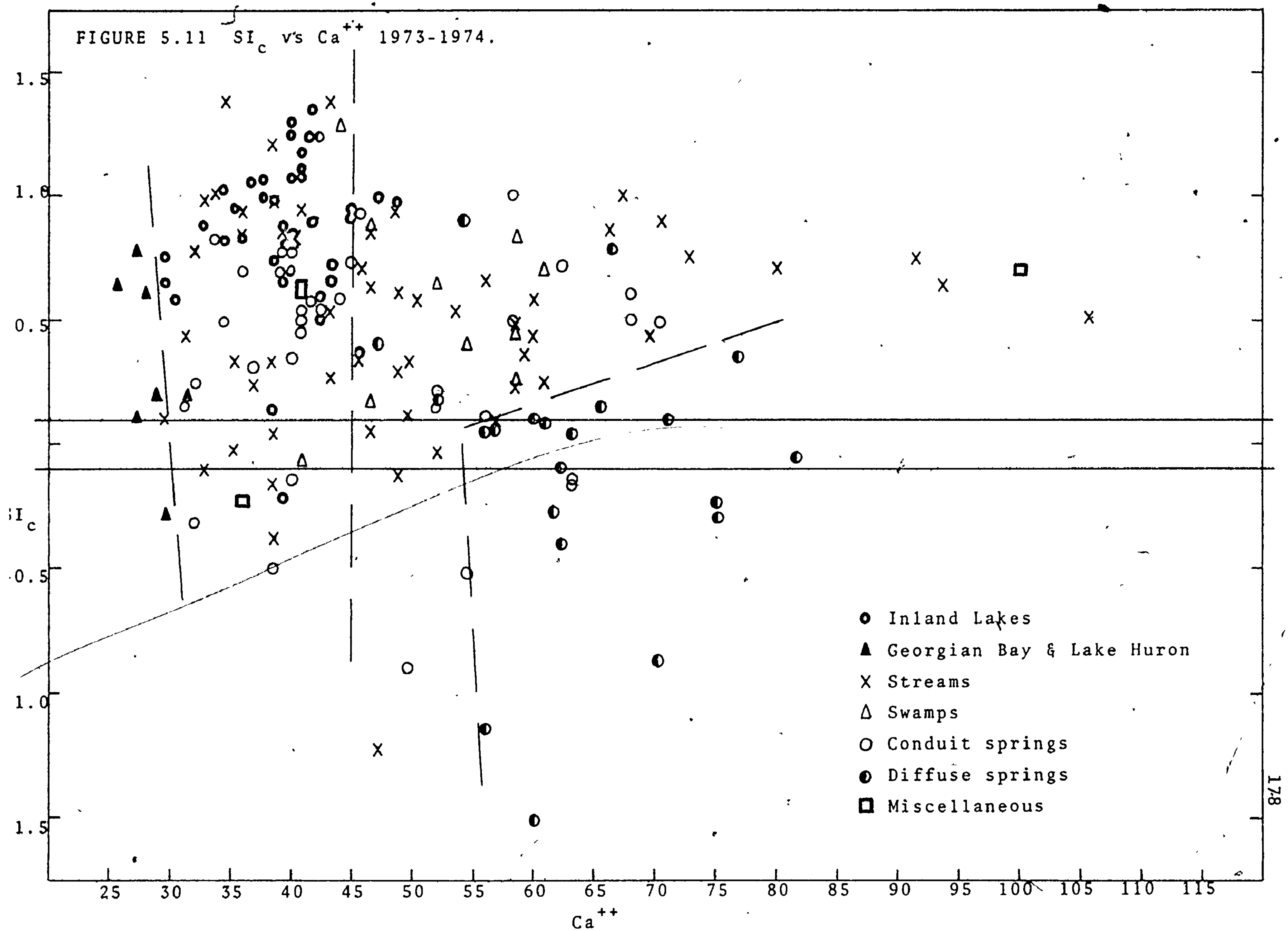


FIGURE 5.11 SI_c vs Ca^{++} 1973-1974.

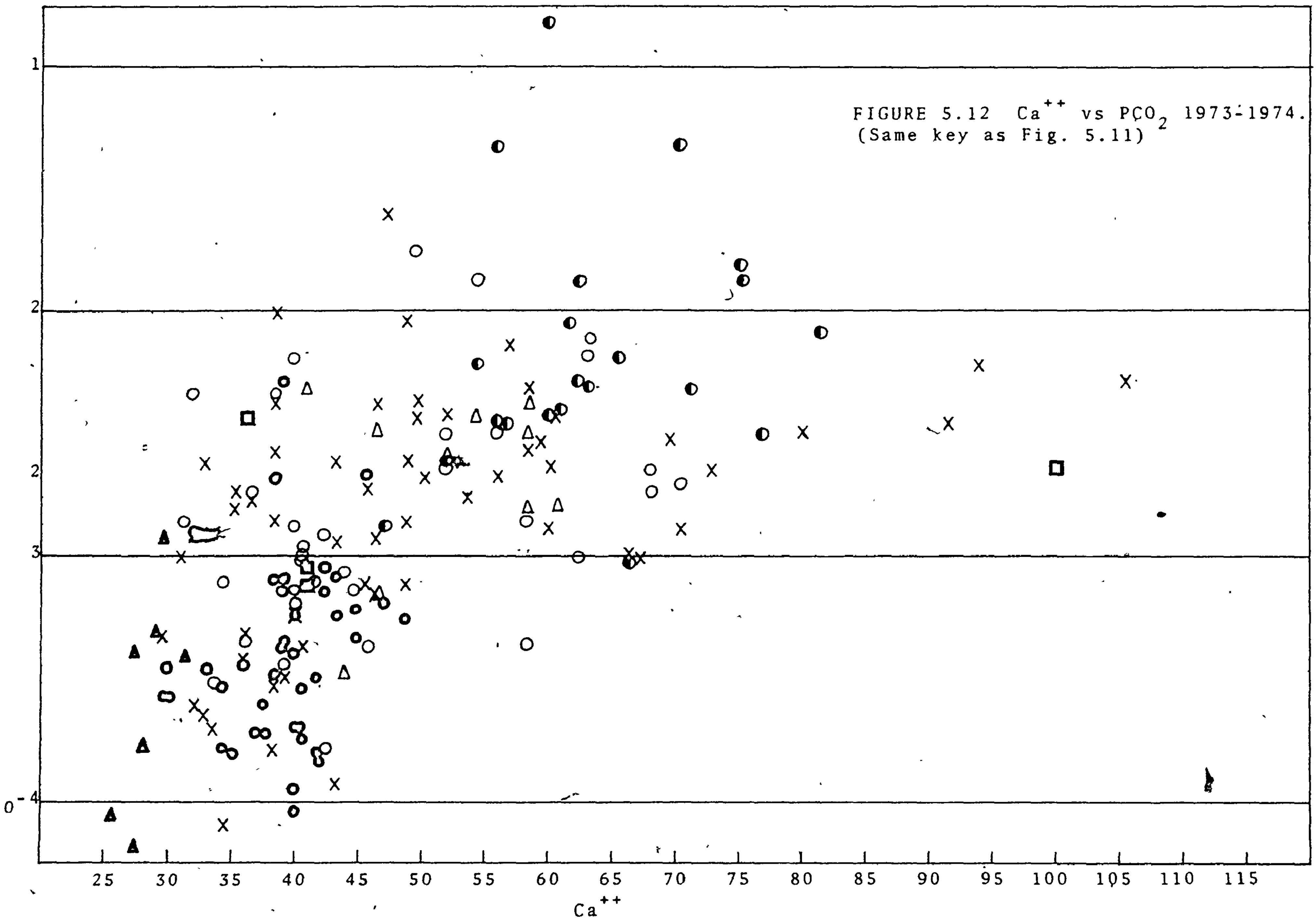


FIGURE 5.12 Ca^{++} vs PCO_2 1973-1974. (Same key as Fig. 5.11)

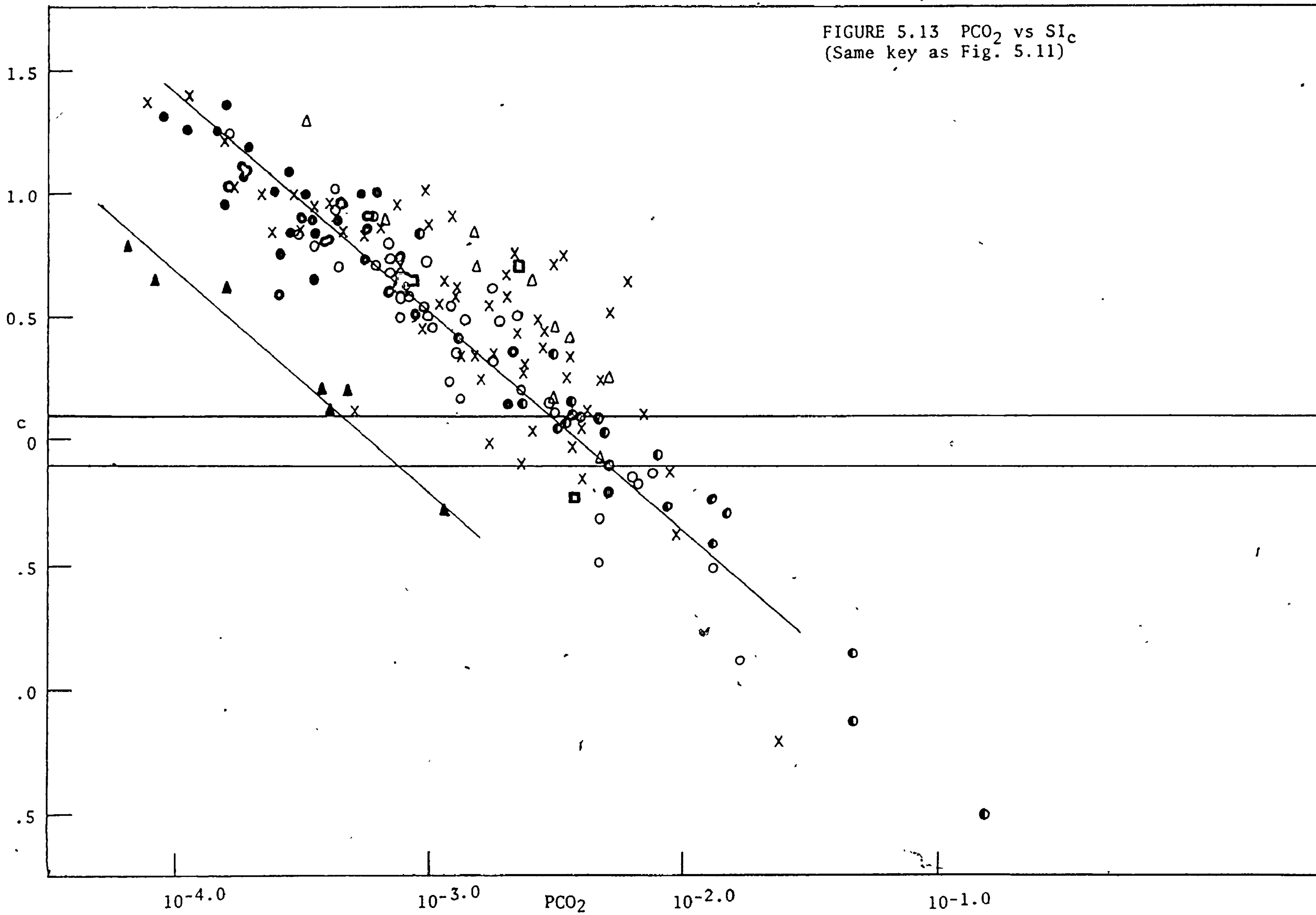


FIGURE 5.13 PCO_2 vs SI_c
(Same key as Fig. 5.11)

$10^{-4.18}$ atm. (Fig. 12). In Figure 5.13 they are aligned along a negatively sloping line which intersects the saturation line at $10^{-3.2}$ atm.[1] which is close to atmospheric ($10^{-3.5}$ atm.). The mean PCO_2 is $10^{-3.58}$ which suggests they are, on the average, equilibriating to the atmosphere. They are oversaturated in most instances because they have not precipitated enough of the Ca^{++} (and Mg^{++}) supplied to them by run-off. The 3 very low PCO_2 values (< $10^{-3.5}$ atm.) are difficult to explain but may be a result of internal water exchange bringing up deeper water which are equilibriating in a more anaerobic environment.

ii) Inland Lakes - these are harder and more saturated than the larger lakes. Ca^{++} ion averages 39.4 ppm and ranges from 29 to 48 ppm. They are the most saturated waters with mean $SI_c = +0.86$. PCO_2 is second lowest at $\bar{x} = 10^{-3.42}$. Thus they too are equilibriating to the atmospheric reservoir but are more saturated because of the concentrated input of Ca^{++} by streams and seepage. Consequently they are degassing and precipitating $CaCO_3$ in the form of marl. Figure 5.13 shows most of the inland lakes lying on a line which intersects 0.0 saturation at approximately $10^{-2.4}$ atm. This is well above the Georgian Bay and Lake Huron value and indicates that their waters are derived from an environment richer in CO_2 (i.e. streams and soil water).

iii) Streams - streams, rivers and creeks are well dispersed on all three plots. Ca^{++} concentration ranges from 30 to 105

1 The line suggests that these waters would be in equilibrium at $10^{-3.2}$ atm. but the PCO_2 of most of the samples are less than this. Their theoretical partial pressure reflect their PCO_2 reservoir (in this case the atmosphere) as well as that of contributing waters (i.e. streamflow and seepage).

ppm ($\bar{x}$ = 50 ppm). They vary from just saturated to well saturated and on the average are intermediate between the two lake types ($\bar{x}$ = +0.50). Figure 5.12 appears to separate the streams into two groups. One is chemically similar to the inland lakes whereas the other has higher Ca^{++} hardness (> 47 ppm) and PCO_2 in excess of $10^{-3.0}$ atm. This is not solely a chemical differentiation because the latter group consists of streams which drain wetlands, such as the St. Edmunds cave recharge and the sinking stream at Dyer Bay. It also includes the Crane River, at the lower end of the group which drains numerous swamps and marshes. The sampling location for this river was just downstream from a small diffuse spring which may also influence the data. Those streams lying in the same range of PCO_2 vs Ca^{++} as the inland lakes were mainly small streams sampled near lake outlets. Therefore they are essentially lake waters. Examples include the stream draining Gillies Lake and the short connection between Cyprus and Horse lakes.

iv) Swamps - the more concentrated, higher PCO_2 streams lie in the same range as swamp waters on all three plots. In Figure 5.13 they intersect the saturation line at the highest PCO_2 ($10^{-2.0}$ atm.). They are thus in contact with a strong PCO_2 reservoir which indicates that swamps must have substantial biogenic CO_2 production. Their average PCO_2 is $10^{-2.69}$, second only to the diffuse flow springs. Wetlands and the streams draining them therefore have substantial solution capacities when in contact with carbonate bedrock. As shown in Table 5.2 and Figures 5.11 and 5.17 they are among the hardest waters on the Bruce Peninsula.

v) Conduit Flow Springs - these waters are well dispersed, being characterized by a wide saturation range, -0.89 to +1.24 (figure 5.11), with a mean SI_c = +0.38. They are similar to both inland lakes and streams WRT Ca^{++} ion (30 to 70 ppm) and to streams for PCO_2 ($\bar{x} = 10^{-2.85}$). This is to be expected because they are essentially resurgences of stream and lake discharge. But despite the similarity it is known that a given conduit spring is slightly higher in hardness and PCO_2 than the source recharge (Section 5.2).

vi) Diffuse Flow Springs - these are characterized by high Ca^{++} concentration (50 to 80 ppm) and PCO_2 ($10^{-1.0}$ to $10^{-2.5}$). Mean Ca^{++} ion (64 ppm) and PCO_2($10^{-2.22}$atm.) are the highest of the seven groups. They also have the lowest average temperature (8.5°C) and are the least saturated (-0.08). Diffuse springs are thus easily separated from the other groups by the means of these four variables (Table 5.2). They are moderately well distinguished on the PCO_2 vs Ca^{++} plot (Fig. 5.12) and even more so on the SI_c vs Ca^{++} plot (Fig. 5.11). In Figures 5.11 and 5.13 most are found near the saturation line and in a narrower range than conduit springs.

The separation of water types on the three plots is not as good as that obtained by Ford (1971a). The Bruce Peninsula waters have a more uniform chemical environment, except for Georgian Bay and Lake Huron, than those of the Rockies. The latter were sampled from a wide altitudinal range (1010 m to 2600 m a.s.l.) and included waters from above and below the treeline and glacier melt. The Bruce samples fall within the PCO_2 range of Ford's Crowsnest Pass waters (taken from below the treeline) although the former were harder. Georgian Bay and Lake Huron were closer to the Mt. Castleguard samples, from above the treeline, WRT PCO_2 but also had higher Ca^{++} concentrations. These results are consistent with Ford's statement, "on a whole-basin scale, rate of limestone solution will be lower [in alpine areas] than in temperate forest regions."

The best visual separation appears on the plot of SI_c vs Ca^{++} (Fig. 5.11). Georgian Bay and Lake Huron and the diffuse flow springs can easily be distinguished from the rest of the data, the former by their low hardness and the latter by their high Ca^{++} concentrations and proximity to the saturation line. Within the remaining data one may also distinguish small streams (i.e. lake outlets) and inland lakes from swamps and streams draining wetlands (second vertical line on Fig. 5.11). This separation is slightly more evident on Figure 5.12. Conduit springs are thoroughly mixed with all but exsurgences and Georgian Bay and Lake Huron. However, the two types of springs can be distinguished using SI_c, PCO_2 and Ca^{++}. These findings are consistent with those of Shuster and White (1971), Drake and Harmon (1973) and Cowell and Ford (1975) although the first two studies found the conduit springs much less saturated. This is due to the nature of the recharge. Conduit flow springs in Pennsylvania are fed by very undersaturated waters whereas those in southern Ontario have very hard inputs. Only the diffuse springs drain slowly enough to equilibriate to the soil environment. Group means in Table 5.2.1 indicate that not only PCO_2, SI_c and Ca^{++} but also SI_d and temperature (in the case of diffuse springs) are useful in distinguishing groups. However this is not a reliable method for individual samples because of the relatively high standard deviations for some of the means (Table 5.2.2).

5.3.2 Statistical Analysis

To test the differentiation of the seven groups the data in Table 5.1 were analysed by linear discriminant function analysis (L.D.F.). When carried out in a stepwise manner, L.D.F. can determine the significance of a priori groupings and select the most powerful discriminating variables (Drake and Harmon, 1973). The L.D.F. program used was the BMD 07M from Dixon (1970). In it, group means and standard deviations are used to compute within-group covariance and correlation. Each variable is then considered in a stepwise manner to determine its significance with respect to the data set. The most significant variable to separate the groups at the 0.005 confidence level is entered in the first step. The two most significant variables are entered in the second step, and so on. At each step the variable entered is that which gives the greatest improvement in the F ratio of between-group variation to within-group variation. The program then re-groups the data based on a posteriori probabilities. It should be noted that L.D.F. analysis requires a priori grouping of data. It does not reveal any inherent grouping tendencies and assumes that individuals to be classified belong to one of the groups.

Krumbein and Graybill (1965) and King (1969) discuss L.D.F. analysis in more detail.

The nine variables used in the analysis are not truly independent because four of them (SI_c, SI_d, PCO_2 and Ca/Mg) are derived from the five measured variables. This makes interpretation of the results difficult but nearly all problems in geomorphology are multivariate, comprising variables which in many cases are not completely independent.

Drake and Harmon (1973) performed a L.D.F. analysis upon geochemical data from eastern Pennsylvania (166 samples). They considered the derived variables to reflect the geochemical constraints on the system $CO_2 - CaCO_3 - Ca\,Mg\,(CO_3)_2 - H_2O$ and as such to be admissible in the analysis. For ease of interpretation, however, the two types of variables were analysed separately. Thus in Step 1 they obtained one measured variable and one derived variable as the most significant. These were pH and SI_c. In the second steps HCO_3^- and PCO_2 were added. Their 6 _a priori_ groups were allogenic surface recharge, soil waters, conduit springs, diffuse springs, well waters and basin surface runoff (out of the carbonate basin). They concluded that SI_c and equilibrium PCO_2 were sufficient to distinguish groups and provide a reliable means to examine the geochemical evolution of carbonate waters.

Wigley et al. (1973) also examined karst water by means of a L.D.F. analysis (39 samples). They were working in a gypsum karst in British Columbia. Waters were separated into 6 groups; gypsiferous springs, surface rivers downstream, surface rivers upstream, Lussier Valley sink, Coyote Valley sink and ungrouped. Their results indicated that Ca^{++}, temperature and SI_g (saturation WRT gypsum) in that order were the most important variables, together explaining 99.9% of the variance. Equilibrium PCO_2 was not important. This is to be expected because CO_2 does not play a role in the sulphate system - $Ca\ SO_4 \cdot H_2O - H_2O$. All variables, measured and derived, were analysed together.

The results of L.D.F. analysis for the Bruce Peninsula are shown in Tables 5.3 and 5.4. The nine variables were analysed together. Temperature and Mg^{++} were found to be the most significant of the measured variables and PCO_2 and SI_d the most significant of the calculated variables (Table 5.3). Temperature, Mg^{++} and PCO_2 were selected in that order. The high significance of Mg^{++} plus the exclusion of SI_c is rather surprising. These results thus differ from those of Drake and Harmon and Wigley et al.

According to Table 5.4 the a priori groups are not very significant because 48% of the samples were misclassified . The most distinctive groups were: 1. Georgian Bay and Lake Huron (no misclassification), 2. diffuse flow springs (14% misclassified), 3. swamps (30% misclassified) and 4. inland lakes (36.8% misclassified). Streams and conduit flow springs were badly misclassified (62.5 and 72.2%, respectively). Most of the misclassification occurs between groups A and C and group E with groups A and C. This indicates that a priori grouping does not adequately distinguish certain streams from lakes, as in the case of lake outlet streams grouped with streams, nor conduit springs from surface recharge. If lake outlet streams had been grouped with the inland lakes the total misclassification would drop from 48% to about 40%.

It is interesting to note that most of the streams and rivers remaining in group C are those of higher Ca^{++} hardness and PCO_2 on the

TABLE 5.3 Variables entered into the discriminant analysis

STEP	VARIABLES
1	Temperature
2	Temperature, Mg^{++}
3	Temp., Mg^{++}, PCO_2
4	Temp., Mg^{++}, PCO_2, SI_d
5	Temp., Mg^{++}, PCO_2, SI_d, Alk.
6	Temp., Mg^{++}, PCO_2, SI_d, Alk., Ca^{++}.
7	Temp., Mg^{++}, PCO_2, SI_d, Alk., Ca^{++}, Ca/Mg.
not entered	pH, SI_c

TABLE 5.4 Posterior reclassification of data from Table 5.1

(A) Inland Lakes

Sample I.D.	Reclassified to
1-15, 19-21, 30-33, 37 41-44, 47-and 49	A
46	B
16,18,22,25,29,38, 45,48	C
27,36	E
17,28,39	G

Misclassified = 14 of 38 (36.8%)

(B) Georgian Bay and Lake Huron

Sample I.D.	Reclassified to
51-67	B

none misclassified

(C) Streams and Rivers

Sample I.D.	Reclassified to
70,79-81,88,107 109-110,118-124,130, 136,139,145,150,152	C
71-76,111,127-129, 133,141	A
82,84,93,113,138,143, 148,154	D
83,85,104,108,114,135, 114,146,147,149,151,153	E
140	F
117,125,142	G

Misclassified = 35 of 56 (62.5%)

(D) Swamps

Sample I.D.	Reclassified to
159-161,165,167 168,169	D
158,164,167	C

Misclassified = 3 of 10 (30%)

(E) Conduit Flow Springs

Sample I.D.	Reclassified to
170,171,173,178,197 199-202,207,208	E
172,181-183,187,196 198,	A
175,180,184,185	C
176	D
188-194,204,209,212	F
174,179,205,206	G

Misclassified = 26 of 36 (72.2%)

(F) Diffuse Flow Springs

Sample I.D.	Reclassified to
213-221,223-227,230-238	F
222	E
228,229	G

Misclassified = 3 of 21 (14.3%)

(G) Miscellaneous

Sample I.D.	Reclassified to
239,241	G
245	A
240	E

Misclassified = 2 of 4 (50%)

Total misclassification = 83 of 172 (48.3%)

plots in Section 5.3.1 (i.e. the streams draining wetlands). Those reclassified were divided among groups A, D and E. The results obtained from the L.D.F. are consistent with those of the graphical analysis. They indicate that there are only two or three types of waters on the Bruce Peninsula which can be chemically distinguished.

5.3.3 Discussion

Recent karst literature has obtained good results separating waters by graphical and statistical geochemical analyses. These studies concentrate on chemical evolution within aquifers and the differentiation of these from surface recharge from quite different chemical environments. Thus Ford (1971a) could separate aquifer waters from recharge above the the treeline (atmospheric PCO_2^* reservoir) and recharge below the treeline (soil PCO_2) as well as distinguish glacier melt (less than atmospheric). Shuster and White (1971), Harmon et al. (1972) and Drake and Harmon (1973) using data from eastern Pennsylvania found it easy to characterize the two types of aquifer discharge and distinguish them from recharge. This region was not glaciated and has well leached soils; recharge waters are very aggressive, and would be expected to show strong chemical changes depending on where they are in the aquifer, how they got there and how fast they are passing through (Drake and Harmon 1973 - Fig. 4).

In the present study only diffuse flow springs and Georgian Bay and Lake Huron can be distinguished by graphical analysis. Diffuse and conduit springs can be differentiated but the latter cannot be separated from recharge. Distinct types of recharge (swamps, streams and lakes) cannot be picked out although the plot of PCO_2 vs Ca^{++} (Fig. 5.12) suggests two chemical types of surface recharge - lakes plus small streams and swamps plus their drainage. The L.D.F. analysis confirmed this and selected temperature, Mg^{++} and PCO_2 as the most discriminating variables. SI_c and Ca^{++} are not significant in classifying the Bruce Peninsula waters. What then can be said about the chemical evolution of these waters?

Drake and Harmon (1973) considered SI_c to be "a direct measure of the residence time of a water within the drainage basin" and concluded that "two parameters (SI_c and PCO_2) ... provide a reliable way to examine the geochemical evolution of the waters in the carbonate basin." These statements are not consistent with the Bruce data nor, I doubt, would they hold for carbonate waters in recently glaciated areas or where carbonate bedrock is exposed. In southern Ontario, and in alpine areas below the treeline (Ford 1971a) recharge waters tend to be oversaturated. Further solution depends on conditions such as high soil CO_2 partial pressures, mixing corrosion and, in the case of dolomites, incongruent solution.

Swamp waters and diffuse flow springs have the highest PCO_2 on the peninsula ($\bar{x} = 10^{-2.69}$ and $10^{-2.22}$, respectively). The long residence time of the spring waters permits them to come the closest to the saturation line ($\bar{x} = -0.08$, SI_c) and become the hardest ($\bar{x} = 265$ ppm total hardness as $CaCO_3$). They approximate an open system situation within the soil atmosphere. This may also be true for very slow draining conduit systems such as the St. Edmunds cave which was reclassified as a diffuse spring. Most conduit springs are essentially the same as recharge with some CO_2 boosting. The latter constitute mixed runoff plus seepage and together with conduit springs approximate closed systems WRT the soil atmosphere.

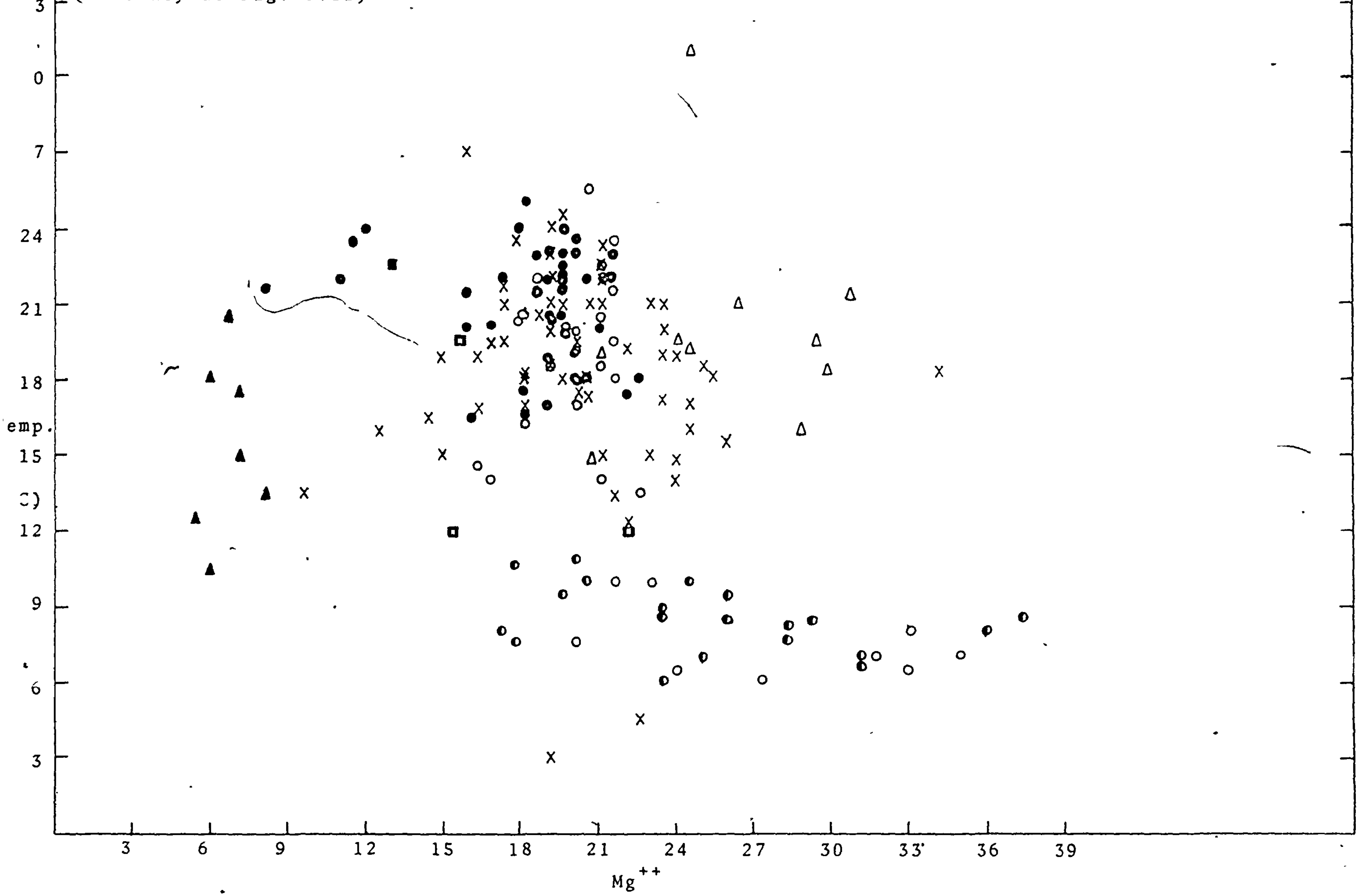
Lakes and streams are the most oversaturated because they are in the process of degassing to reach equilibrium with the atmosphere (Table 5.2, Fig. 5.11).

The selection of Mg^{++} as a significant variable and the exclusion of Ca^{++} indicates the importance of incongruent solution in the evolution of dolomite karst waters. If solution were strictly congruent one would not expect much difference in the discriminating power of Ca^{++} and Mg^{++}. Incongruent solution is restricted to aquifer waters (primarily diffuse springs) which have been boosted by the addition of soil CO_2.

Drake's and Harmon's conclusion regarding the importance of SI_c in carbonate areas must be rejected for two reasons, (1) surface recharge waters in glaciated regions or where bedrock is exposed tend to be saturated with Ca^{++}, and (2) the importance of Mg^{++} and SI_d as discriminating variables for dolomite waters. SI_c is directly related to residence time in areas of well leached soils but tend to be inversely proportional where recharge waters must flow over carbonate material before equilibrating to the soil atmosphere. Equilibrium PCO_2 is thus the only chemical variable which can be used on a regional or global scale for characterizing carbonate waters and comparing potential solution rates. Neither SI_c nor PCO_2 are significant in sulphate areas (Wigley et al. 1973) and therefore can be statistically compared to carbonate waters using only Ca^{++} ion. In such cases caution must be taken because of the different natures of the two chemical systems.

Figure 5.14 is a plot of the data using Mg^{++} ion and temperature. It improves the separation slightly better than the plots in Figures 5.11

FIGURE 5.14 TEMPERATURE vs Mg^{++} 1973-1974.
(Same key as Fig. 5.11)



to 5.13 but says very little about chemical evolution. Temperature is not strictly a chemical variable although it affects the dynamics of the system. It is primarily controlled by environmental factors such as climate, depth of water, rate of flow and moderating influence (such as bedrock temperature). Figure 5.14 tends to confirm a separation of swamps and certain streams from other recharge; however, the distinction is still not sharp.

Difficulty in separating data on plots and misclassification recognized by L.D.F. analysis are a result of two factors; chemical dynamics and seasonality of sampling. Drake and Harmon (1973) stated that "the overlap observed between the water classes is due to the dynamic nature of the systems which form a chemical as well as hydrologic continuum".

Seasonal data tends to enlarge the range of each water type creating more opportunity for overlap. This study was based primarily on seasonal analyses whereas those of Wigley et al. (1973) and Drake and Harmon used random samples. In several instances different data from the same spring, lake or stream were reclassified into two or more different groups (compare Tables 5.1.1 and 5.4). For this reason differentiation may be easier using random samples taken over a short period.

5.4 Regional Carbonate Solution

Carbonates cover 11 to 20% of the world's surface (Gilluly et al. 1968) and are found in every climatic region. Karst landscapes display marked morphological variation between humid tropical, arid tropical, temperate, alpine and arctic environments (Brook and Ford, 1974). This has led to the suggestion of climatic control on intensity of solution and attention has been focussed on two chemical variables, total hardness and PCO_2. The first measures the amount of rock carried off and the second describes the potential aggressiveness of natural waters toward carbonates.

As early as 1937 Adams and Swinnerton recognized that groundwaters in carbonate terrains are in equilibrium with higher than atmospheric levels of CO_2. They suggested that carbon dioxide enrichment occurs as waters infiltrate through soils. Consequently tropical areas, where plant growth and decay are rapid, were thought to have the highest potential to dissolve limestone.

Corbel (1959) initiated controversy by suggesting that the opposite relationship exists. Colder areas, he stated, should have greater limestone solution because CO_2 is three times more soluble in water at 0°C than in water at 35°C. To explain morphological variation in different climates he noted that most high-latitude karsts had formed in the short period since the retreat of Wisconsinan ice.

Since the introduction of Corbel's hypothesis a great deal of water chemistry data from throughout the world has been collected. At present the concensus is that the amount of solution may not be strictly related to climate. Sweeting (1964 and 1966), Pitty (1966), Ford (1971a) and others have found comparable concentrations of dissolved limestone in differing climatic regions. The spatial variation in the CO_2 content of soils is now believed to be the most important chemical variable controlling solution.

To date climatic models of regional solution rate include a factor for mean total hardness and one for runoff (e.g. Corbel 1959). They do not attempt to isolate relationships between climate and chemistry, nor do they account for the variation in hardness of different water types within basins. Such variation is significant (Section 5.3) and could lead to false comparisons between regions. Harmon et al. (1972, 1973 and 1975) and Drake and Wigley (1975) attempted to examine regional variations systematically and isolate significant relationships. Their approach is the most useful and utilizes the largest data set of adequate quality ever assembled.

These authors recognize that controls on chemical variation can be separated into contributions from the effect of hydrogeologic setting, short-term seasonal effects and climatic effects. To isolate the third, the first two had to be minimized. The effect of hydrogeologic setting was limited by using only one water type to represent each region. Seasonal effects were limited by choosing springs. Shuster and White (1971) showed that certain springs (diffuse) do not vary seasonally. Conduit flow springs in contrast may vary by up to 25% and are a chemically distinct water type (Drake and Harmon 1973). Both types were used by Harmon et al. because they found it difficult to separate them when taking data from the literature. They found that the problem was minimized by using grand averages. Over 300 samples from Canada, the United States and Mexico were grouped into seven geographical areas. Ca^{++}, HCO_3^-, SI_c and PCO_2 were averaged for each group and plotted against water temperature, (the independent climatic variable), which was found to correlate very highly with latitude and air temperature. They obtained significant positive, linear relationships with all but SI_c. Their

TABLE 5.5

Linear regression equations obtained by Harmon et al (1973) for correlation of water temperature with chemical parameters.

$$Y = a + bx$$

Independent Variable x	Dependent Variable Y	a	b	Correlation Coefficient [r]
Latitude	Air Temperature	40.08	-0.70	r = -0.996
Latitude	Water Temperature	38.50	-0.68	r = -0.983
Water Temperature	Ca^{++} Concentration	-11.25	5.70	r = 0.903
Water Temperature	HCO_3^- Concentration	37.20	11.37	r = 0.966
Water Temperature	SI_c	-0.675	0.024	r = 0.839
Water Temperature	Log PCO_2 #	-3.33	0.081	r = 0.962

Harmon et al (1975) regression equation

results are summarized in Table 5.5.

The location of their seven groups are shown in Figure 5.15 (solid circles). From this map it can be seen that four of their seven data sets are within a narrow latitudinal range (C, D, E and F). These four groups contain 241 of the total of 305 samples (Harmon et al 1975). Only 10 analyses are from Canada and 29 are from Mexico. Further they observed that mean water temperatures for Mexico and Texas are the same as are those for Pennsylvania and the Virginias. Therefore their dependent variable distinguishes only five groups. The authors consider that the presence of sulphate and chloride does not strongly influence the grand averages. However the Ca ion concentration for Mexico is too high because of the samples have in excess of 50 ppm SO_4^{--} (J. Fish, McMaster University, pers. comm.). $CaSO_4$ is more soluble in water than $CaCO_3$ and its solubility increases with temperature. There is also a problem with the Canadian data. They were taken from a wide altitudinal range in the Rocky Mountains and include springs fed by water from above the treeline. These cannot be considered representative of Canada. The regression line drawn by these authors for Ca^{++} indicates that at 0°C there would be no Ca^{++} in the water. Clearly there are some problems with the data.

The regression lines obtained by Harmon et al are shown in Figure 5.16 to 5.19. Five other data points have been added (open circles). These were handled in the same manner as the Harmon et al data. The Bruce Peninsula analyses are summarized in Table 5.6 and include two springs from Cowell and Ford (1975). The others are from the Nahanni, N.W.T.[1], Mt. Castleguard, Alberta[2], Crowsnest Pass, Alberta[2] and Transvaal, South Africa[3] (Figure 5.15).

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[1] George Brook, Department of Geography, University of Georgia
[2] D.C. Ford, Department of Geography, McMaster University
[3] M.E. Marker, University of Johannesburg.

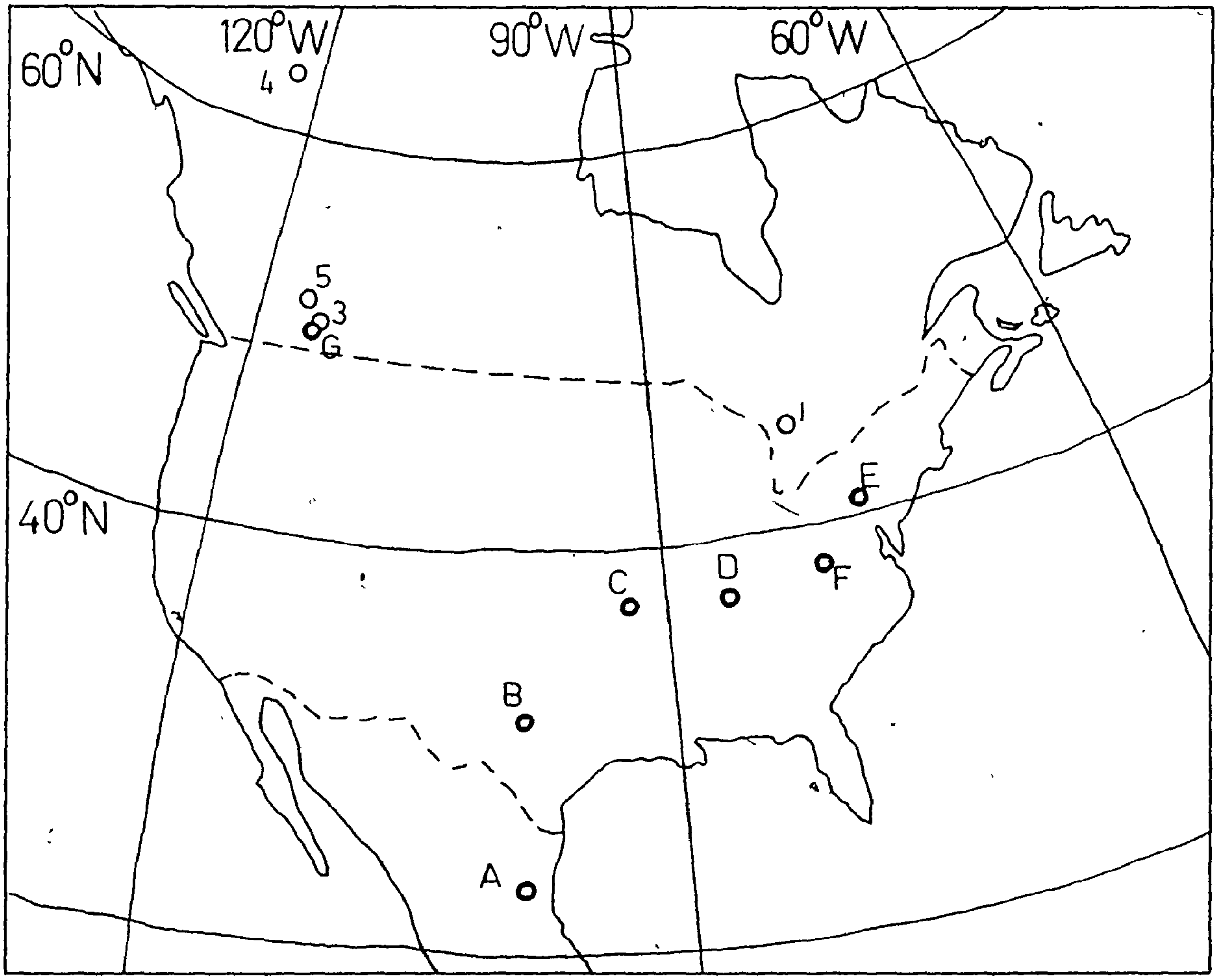

Figure 5.15 Location of sample areas in North America. See Figure 5.16 for place names.

TABLE 5.6

Summary of Bruce Peninsula Spring Analyses

Spring		n	Ca^{++}	Mg^{++}	HCO_2^-	PCO_2	SI_c	T(°C)
Kimberley †	$\bar{x}$	8	57.1	23.6	281.2	2.57	0.23	10.7
	H_i		63.2	32.6	347.7	1.74	0.57	15.5
	L_o		50.4	17.3	237.9	2.93	-0.97	3.2
Talisman †	$\bar{x}$	8	71.8	29.0	367.3	2.08	-0.024	7.95
	H_i		80	33.1	422.1	1.96	0.05	8.2
	L_o		67.2	25.4	326.4	2.19	-0.09	7.5
St. Edmunds resurgence	$\bar{x}$	7	61.8	30.8	339.0	2.77	0.46	6.84
	H_i		70.4	35	375.2	2.12	1.01	8.0
	L_o		52.0	24	301.95	3.36	-0.14	6.0
Dorcas Bay	$\bar{x}$	6	58.3	26	287.58	2.27	0.097	8.83
	H_i		70.4	37.3	303.8	1.33	0.41	10.0
	L_o		47.2	19.7	276.0	2.89	-0.87	7.0
Dyer Bay Fluvio-karst	$\bar{x}$	5	56.0	19.4	247.68	2.28	-0.104	12.7
	H_i		68.0	22.6	303.8	1.77	0.61	14.5
	L_o		49.6	16.3	220.8	2.75	-0.89	7.5
Crane River Spring	$\bar{x}$	3	65.9	26.1	316.2	2.18	-0.1	7.33
	H_i		75.2	31.2	334.3	1.82	0.1	9.0
	L_o		60.0	23.5	295.9	2.43	-0.3	6.0
Marr Lake Diffuse Spring	$\bar{x}$	2	58	20.6	255.6	1.08	-1.33	10.0
	H_i		60	20.6	271.5	0.82	-1.14	10.0
	L_o		56	20.6	239.7	1.33	-1.52	10.0
St. Edmunds closed depression spring	$\bar{x}$	4	66.6	18.3	299.6	2.53	0.263	9.2
	H_i		71.2	20.2	306.8	2.31	0.78	10.8
	L_o		63.2	17.3	283.4	3.03	0.03	7.5
Rocky Bay		1	54.4	36	360.5	3.23	0.9	8.0
Average of means		9	67.14	25.53	306.07	2.33	0.044	9.06
	H_i $\bar{x}$		71.8	36.0	367.3	1.08	0.9	12.7
	L_o $\bar{x}$		54.4	18.3	247.68	3.23	-1.33	6.84

† Cowell and Ford (1975)

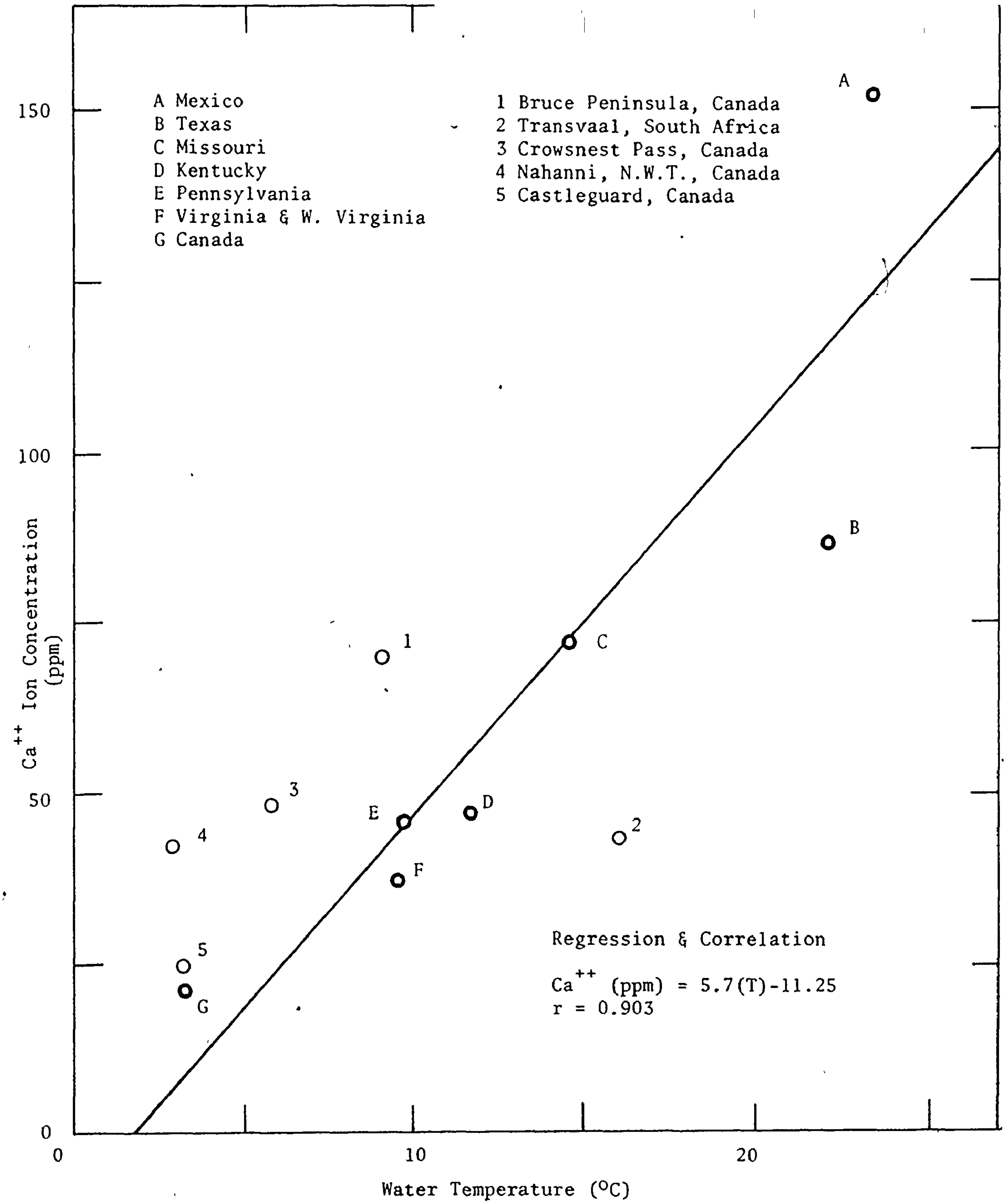

Figure 5.16 Variation in mean Ca^{++} concentration with temperature. The regression line is for Harmon et al 1975 data only. Additional data points have been added, labelled 1 through 5.

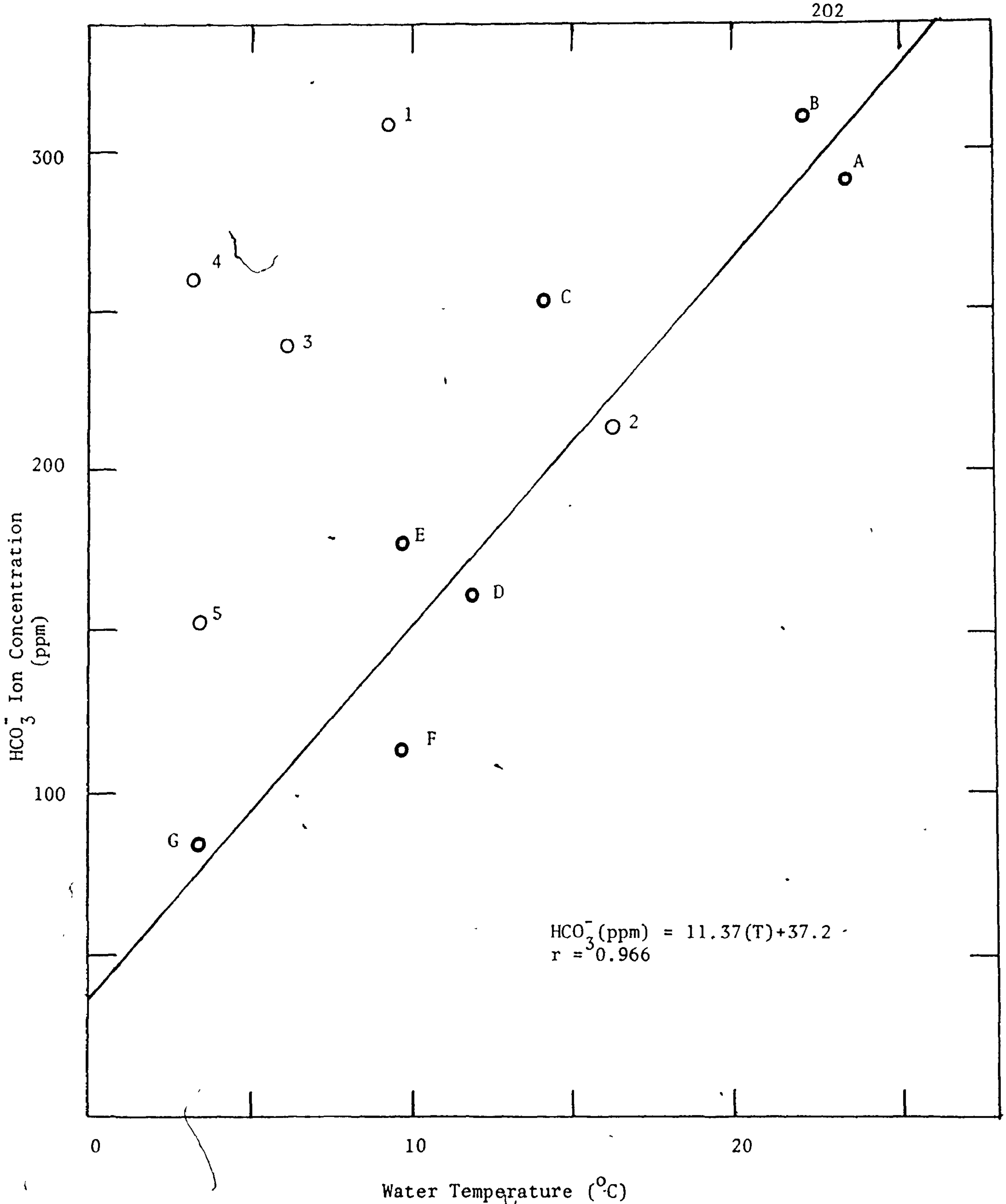

Figure 5.17 Variation in mean HCO_3^- concentration with temperature. Regression line and equation for Harmon et al 1975.

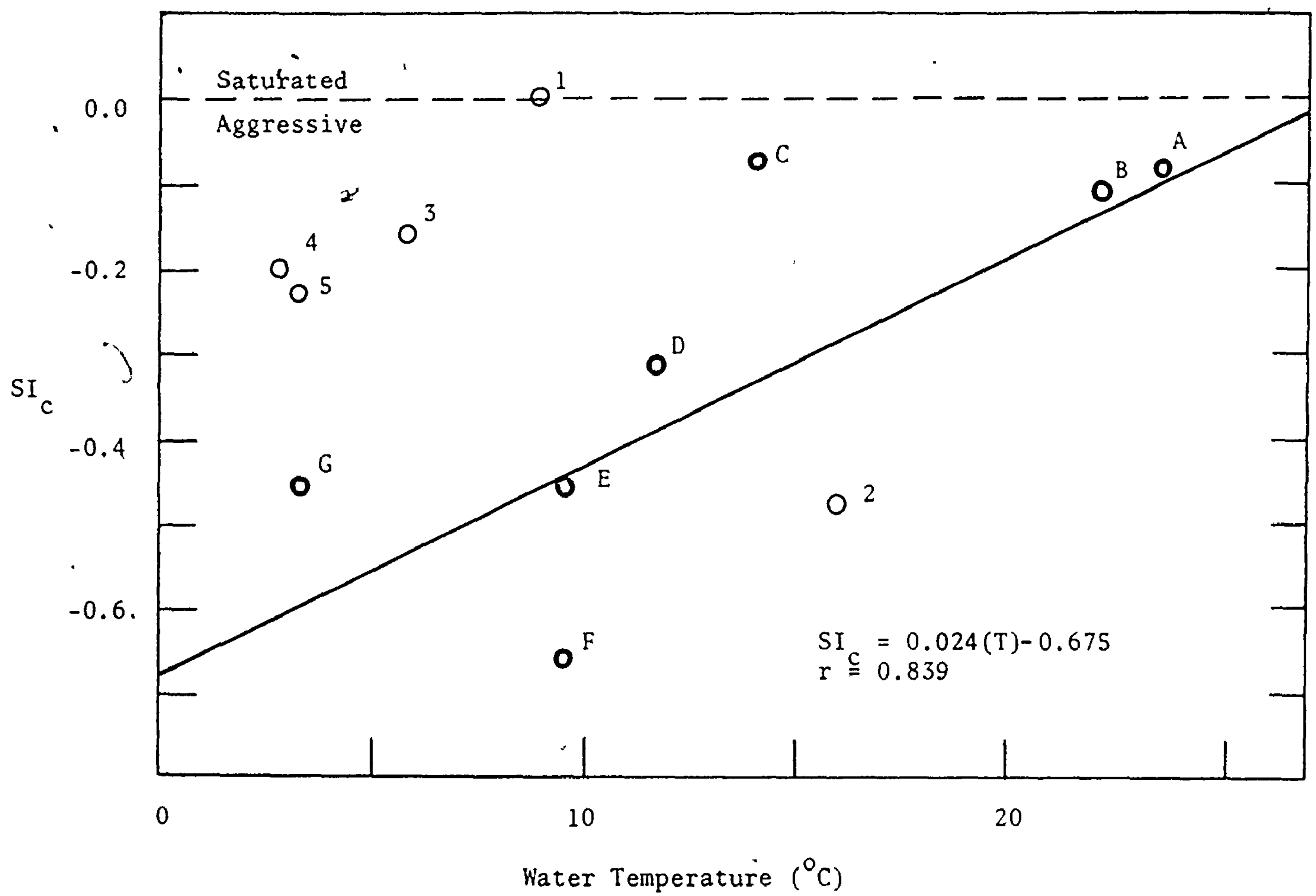

Figure 5.18 Variation in mean SI_c with temperature. Regression equation for Harmon et al 1975.

Harmon et al (1975) did not consider the SI_c regression line significant and with the added data it can be seen that there is no relationship (Figure 5.18). Springs in all climatic regions are undersaturated but local factors, such as hydrogeologic setting and seasonality, overwhelm any major climatic variation.

Ca^{++} ion and HCO_3^- ion also become less significant with the additional data (Figures 5.16 and 5.17). The Nahanni springs have concentrations similar to those of the central United States, as do Texas and the Bruce Peninsula. The high Ca^{++} ion value for Mexico is due mainly to sulphate because its ratio with bicarbonate ion is too high. If it were derived from $CaCO_3$, the HCO_3^- concentration (Figure 5.17) should be over 500 ppm. The comparison of Ca^{++} and HCO_3^- with temperature for samples at different levels of saturation (Fig. 5.18) is pointless. It is possible for a saturated spring in the arctic to have higher concentrations than a spring in the subtropics which is not saturated. These correlations would best be carried out by using only springs which are saturated.

The best correlation is obtained with PCO_2 (Figure 5.19). Harmon et al (1976) obtained a regression line defined by:

$$\text{Log } PCO_2 = -3.33 + 0.881 \,(T°C)$$

with a correlation (r) equal to 0.96. In this model the theoretical equilibrium partial pressure of CO_2 in water at 0°C is $10^{-3.33}$ atm. With the addition of the other five data sets and minus Harmon et.al's Canadian data, the equation becomes:

$$\text{Log } PCO_2 = -2.92 + 0.06 \,(T°C)$$

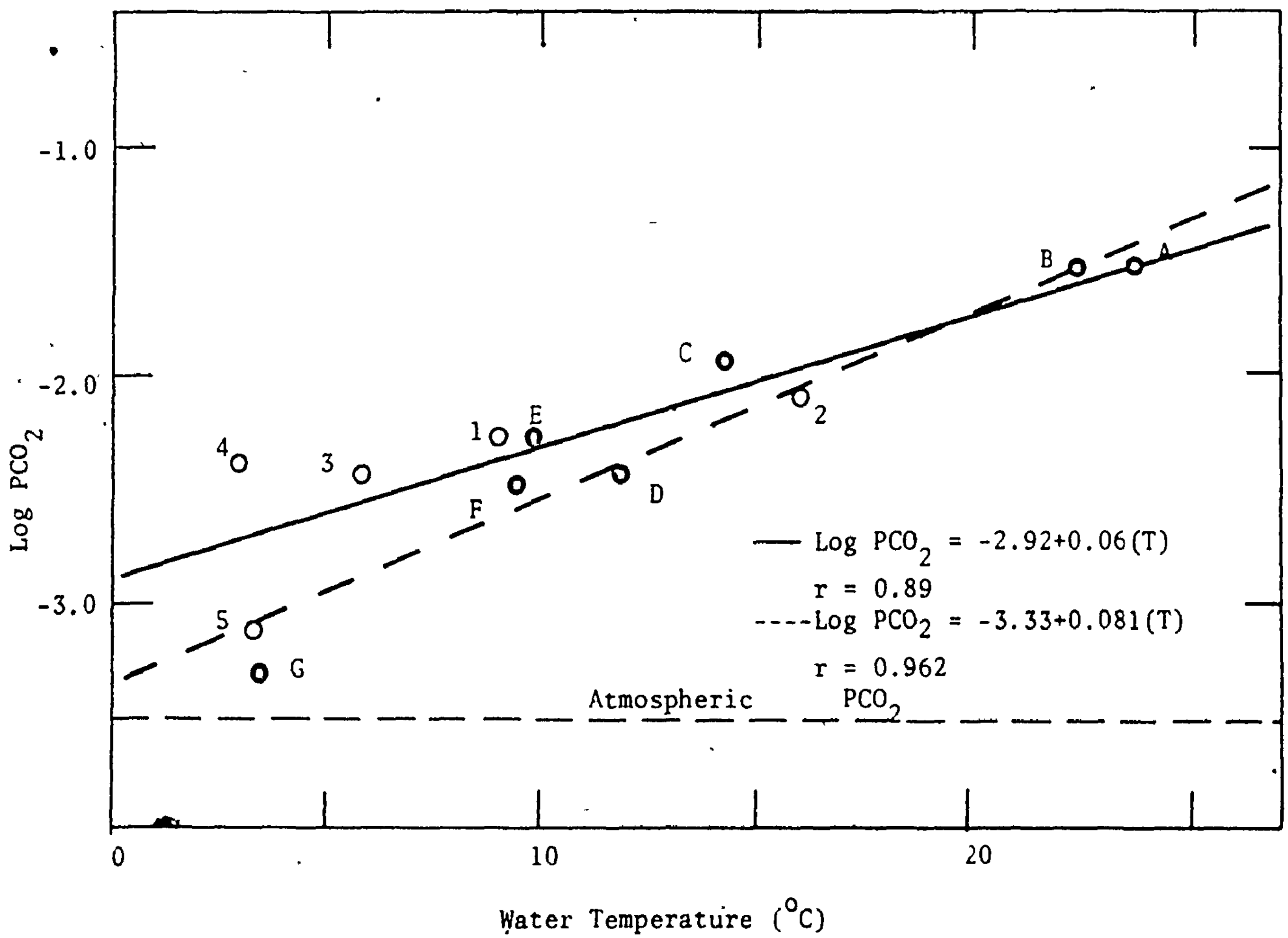

Figure 5.19 Variation in LogPCO_2 with temperature. Dashed line is regression line for Harmon et al 1975, solid line is for all data (minus G).

with a correlation (r) equal to 0.89. This is a good correlation ($r^2 = 0.79$) based on 11 points and covering a substantial latitudinal range. It confirms the result of Section 5.3 which indicated that PCO_2 was the only chemical variable with which carbonate areas could be compared on an inter-regional basis. It is not influenced by SO_4^{--} nor by incongruent solution. Figure 5.19 indicates that the Bruce Peninsula waters have the same potential for solution as those of Pennsylvania and the Virginias. Springs even in the arctic have a PCO_2 well above $10^{-3.0}$ because of soil biotic activity.

The results indicate that the potential for solution is higher in lower latitudes but not by as much as suggested by Harmon et al. Solution intensity cannot be determined as easily. Ionic concentrations tend to be higher in tropical climates (Figures 5.16 and 5.17) but the correlations are not significant. Seasonality and precipitation are two factors not accounted for in any of the correlations. Now that the model for potential solution is known the next step is to add parameters for these two factors. A climatic model of solution rates would also have to consider the chemistry of water leaving carbonate basins rather than just springs.

CHAPTER 6

SUMMARY

The Bruce Peninsula is an abraded, bedrock controlled, dolomite plain bounded by an escarpment. Karst solution is among the most significant of geomorphological processes and has produced excellent dolomite pavement as well as fluvio-karst and holokarst features. These are entirely postglacial and therefore younger than about 13,000 years. Glacial scouring was important in preparing the peninsula for karst processes, particularly pavement development, and most of the karst is closely associated with glacial features. It can thus be considered a'glacio-karst'.

Karst features and drainage, except possibly for the St. Edmunds cave, are young and immature. Few solutional caves are of explorable dimensions, sinkholes are small compared to other karst areas, collapse features scarcely exist, and subsurface drainage tends to be very inefficient during high stage. There are several reasons for this; (1) karst processes have had a relatively short time to develop, (2) dolomite is less soluble than limestone, (3) there is a lack of large surface rivers which might pass underground, (4) pavement favours small inputs rather than concentrated inputs and (5) most recharge waters are hard and already at or near saturation (Table 5.2). The third and fourth are partly related because of the lack of soil or drift but rivers are also kept small because they flow across the peninsula instead of along it and consequently are more restricted. The Niagara Escarpment has enhanced karstification by creating locally high groundwater hydraulic gradients but also inhibits mature, well integrated subsurface drainage. There is a tendency to develop many small springs, rather than only a few major ones characteristic of mature karst areas. This is because of the long linear extent of the escarpment and the presence of numerous large promontories. It is also due to the lack of substantial vertical karstification which is restricted by the thickness of the carbonate units and the presence of shale aquicludes.

The following is a summary of the main points discussed in this thesis:

(A) PAVEMENT

(1) The surfaces of the Guelph Formation and Colpoy Bay - Wiarton member of the Amabel Formation have developed a fine dolomite pavement which is well displayed north and south of the Eastnor Clayplain. It has a variety of karren forms, many of which have been described in the literature for limestone pavements.

(2) The pavement can be separated into three common karren assemblages two of which are controlled by lithology and the third by environmental factors.

(i) The 'Amabel' pavement is found on biohermal ridges (roches moutonnées) of the Amabel Formation and most commonly consists of well developed clint and grike, rundkarren and meanderkarren, kamenitzas, pitkarren and splitkarren. Other types of karren on this pavement include rillenkarren (found at only 2 localities), deckenkarren and hohlkarren.

(ii) The 'Guelph' pavement is found on ridges and on flat surfaces of the Guelph Formation and is characterized by irregular, cavernous weathering. The only well developed recognizable karren are clint and grike, pitkarren and groovekarren. Only one example of deckenkarren was observed but it is likely common in wetland areas. This pavement is best developed on the north Bruce.

(iii) The 'littoral zone' pavement is found along the shore of Lake Huron and continues down into the lake. It consists of distinctive pitting and is best developed on the north Bruce e.g. at Warner Bay, Dorcas Bay, Tobermory and also Marr Lake.

(3) The Amabel and Guelph formations are chemically similar but the latter is more porous and thus forms a more irregular pavement surface. Biological, structural and gravity controls permit the development of more characteristic karren forms on the Amabel. Exceptions do occur which are probably related to zones of greater or lesser porosity in the two formations, respectively.

(4) Littoral zone pitting is probably a result of biologically induced solution by freshwater lichen and algae common to that environment. It is interesting that the largest pits, and thus the most intensive solution, occur on the floor of Lake Huron. It is still not clear whether the pit is initiated by biological activity (e.g. lichen) or is only later occupied and enlarged. This is an area where much more study is required and it would seem that the Bruce Peninsula would be a good place to start.

(5) Nearly all of the karren have smooth lips and bottoms. Sharp crested features (rillenkarren and pitkarren) were observed at only two localities (Rocky Bay and Cave Point). The dominance of smooth forms

and their close association to vegetation, particularly lichens and mosses, suggest that biological factors play a major role in pavement development. Biotic acids help boost solution and vegetation permits greater wetting (i.e. moisture is retained for longer periods after rain) and lowered rainfall intensity. Sweeting (1966 and 1972) considers these factors to be important in the formation of rounded karren.

(6) Glacial deposits inhibit pavement development because aggressive waters are neutralized before reaching bedrock. Thus glacial striae are preserved where located beneath deposits. Root grooves (deckenkarren) are the only forms which are produced beneath soils. These are good examples of biological solution and were well displayed beneath a tree in Cyprus Lake Provincial Park and in a trench at the Dyer Bay outcrop.

(B) KARST HYDROLOGY

(1) Four types of drainage occur on the Bruce Peninsula. These are normal stream runoff, partial underground capture of runoff, underground capture (fluvio-karst), and holokarst (no runoff). These represent stages of karstification ranging from channelized surface flow to complete capture of all runoff and precipitation. Most of the subsurface flow is directed towards the escarpment along prominent joints. Bedding is not as significant because of the biohermal nature of the bedrock.

(2) Holokarst drainage occurs along the brow of the escarpment where groundwater hydraulic gradients are the highest. All water in this zone sinks but the internal drainage is diffuse (non-integrated) as

indicated by the lack of major exsurgences on the escarpment face.

(3) Fluvio-karst drainage is common and occurs next to the holokarst. It includes intermittent and perennial sinking streams as well as at least one lake (Horse Lake). The largest systems are Colpoy Bay Creek east of Wiarton, an unnamed stream west of the village of Dyer Bay, Gillies Lake, Horse Lake and an unnamed stream southeast of Tobermory. The latter is the largest and most mature. It includes the St. Edmunds cave which is the longest active river cave in Ontario (at least 2 km). This cave is the largest single karst feature on the Niagara Escarpment and ranks as one of the top three caves in Ontario, including the Bonnechere Caverns in the Ottawa Valley and Moira Cave southeast of Peterborough.

(4) Partial underground capture is known to be taking place in the Crane River upstream of highway 6. It was discovered by gauging the river at two points. Such drainage is likely very common on the Bruce because of the lack of overburden and high potential for karst capture provided by the presence of the escarpment.

(5) The largest springs are of conduit flow type although at least one major diffuse flow exsurgence is known (Cape Dundas). Conduit flow springs are characterized by concentrated input (streamsink) and are chemically similar to the recharge. Diffuse flow springs tend to be harder, more aggressive and cooler. The holokarst is drained by the latter, as would be expected - "Direct infiltration of the rainfall favours diffuse groundwater circulation, and the general enlargement of joints over a wide area."[1]

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1 Sweeting, 1972, p.250.

All springs are stratigraphically above the lower shale member of the Cabot Head Formation.

(6) Karst drainage is quantitatively second to runoff but will eventually capture most of the surface flow. Karstification will proceed via expansion of the holokarst into basin headwaters and increased capture of stream channels. Eventually only the area next to Lake Huron (below about 650' a.s.l.) and the thick deposits, such as the Eastnor Clayplain, will maintain surface networks.

(7) Most caves in the face of the escarpment on the Bruce are predominantly the product of wave action. They were initiated by (1) solutional cave development following the main stage of glacial Lake Algonquin, (2) solution along joints from the surface downward, or (3) wave exploitation of weak zones, such as thin bedded strata next to massive strata. In all cases their greatest enlargement was by wave action. The caves occur at various levels including the present shore and even below the surface of Georgian Bay, and are especially well displayed on Bears Rump Island.

(8) Cave precipitates are rare although a few small, well decorated caves are known. One of these, the upper chamber of Hope Bay Cave, has been severely vandalized.

(C) WATER CHEMISTRY

(1) The seasonal chemistry of the Bruce Peninsula displays a late summer, early fall maximum which corresponds to biological activity and CO_2 production in soils (and in grikes). A great deal of rock is carried away each year by streams and springs. Their dissolved load ranges between 150 and 326 ppm (Ca + Mg as $CaCO_3$).

(2) Subsurface solution is considerable even though sinking waters are usually at or near saturation. Connecting springs characteristically have harder waters and higher theoretical partial pressures of CO_2. This is attributed to one or all of three conditions, (1) soil CO_2 at the ponor, (2) mixing of chemically distinct waters inside the cave ('mixing corrosion'), and (3) incongruent solution which permits solution of dolomite in the cave following deposition of Ca^{++} from the water. The first two are the main methods by which sinking water can be chemically boosted. The resulting increase in hardness varies from 1 or 2 ppm up to 50 ppm(as $CaCO_3$) as in the case of St. Edmunds cave (Fig. 5.5). Much of the total solution occurs at the surface because water flows on bedrock or calcareous deposits.

(3) The various water types sampled on the Bruce, i.e. streams, inland lakes, Lake Huron and Georgian Bay, swamps, diffuse springs and conduit springs, cannot easily be differentiated by graphical or statistical analyses. Only diffuse flow springs ($\bar{x}$ Ca^{++} = 63.6 ppm, $\bar{x}$ SI_c = -0.08, $\bar{x}$ PCO_2 = $10^{-2.22}$ atm.) and Lake Huron and Georgian Bay ($\bar{x}$ Ca^{++} = 28.2 ppm $\bar{x}$ SI_c = +0.33, $\bar{x}$ PCO_2 = $10^{-3.58}$ atm.) can be separated from the remaining data. This is partly due to the seasonality of the data but primarily reflects the dynamics of this system. The Bruce data are not derived from many distinct environments and recharge water is in contact with dolomite at all times. There are only three distinct groups, (1) waters derived from various sources and equilibriated with the standard atmosphere (Georgian Bay and Lake Huron), (2) waters derived from a high PCO_2 environment and approximating a closed system with it (conduit springs,) and (3) approximating an open system with it

(diffuse springs). The PCO_2 source in each case is the soil atmosphere. Inland lakes are transitional from (1) to (2) and swamps from (2) to (3).

(4) PCO_2 is the only variable which can be used to distinguish and compare carbonate waters given the presence of dolomite and/or within the range of the last major glaciation (assuming calcareous drift). SI_c and Ca^{++} are significant only when considering limestones and if recharge waters are well undersaturated.

(5) Recent models of climatic controls on regional solution rates indicate that Ca^{++}, HCO_3^- and PCO_2 correlate strongly with water temperature (positive slope) which in turn has a high correlation with latitude. These were based on over 300 spring analyses which were heavily biased toward lower latitudes. Ca^{++} and HCO_3^- concentrations are higher on the Bruce Peninsula than predicted by these models. The addition of the Bruce data plus data from the Northwest Territories substantially lowers the correlation of these variables with water temperature. Only PCO_2 maintains a good correlation although the slope is decreased. The PCO_2 indicates the potential for solution in a given region and does not reveal the actual amount of solution. Ca^{++} concentration is a better indicator of rates but the Bruce Peninsula data are in the same range as the central United States, The best model should be multivariate, encompassing PCO_2, Ca^{++} (preferably using waters of equal saturation) and length of season.

APPENDIX 1

CHEMICAL COMPOSITION OF THE

NIAGARAN DOLOMITES

APPENDIX 1: Atomic Absorption Spectrophotometer Analyses of Silurian Dolomites on the Niagara Escarpment

	Sample No.	Formation (Member)	CaO	MgO	Ca/Mg	Notes
a) Bruce Peninsula Area	73-1	Guelph	29.3	20.7	1.41	From weathered, reefal sample on the shore of Cyprus Lake
	73-2	Guelph	28.5	20.4	1.39	Pitted sample from Dorcas Bay shore
	73-3	Guelph	27.5	19.5	1.41	Pitted reefal sample from Marr Lake shore
	73-5	Guelph	28.1	20.2	1.39	Uuggy, reefal material above Driftwood Cove
	73-8	(Eramosa) Amabel	24.2	16.9	1.43	Cherty, well-bedded material on inside of Bears Rump Island
	73-11	Guelph	29.7	21.0	1.42	Fresh sample blasted from reef material at Tobermory for new ferry-dock
	73-S1	Guelph (?)	31.5	22.2	1.42	Deeply pitted sample from 55' below Lake Huron in Big Tub Harbour (Tobermory)
	73-S3	Guelph	29.1	20.6	1.42	Same sample as above only from iron-rich (hematite) zone at base - not pitted
	74-1	Amabel (Wiarton-Colpoy Bay)	31.8	22.6	1.41	From exposed bioherm above Dyer Bay (Dyer Bay karren site)
	74-2	"	30.6	21.6	1.42	Same site as 74-1 but under forest cover and different weathering features
	74-3	Amabel (Eramosa)	29.2	20.7	1.41	Thin bedded, non-pitted material near Stokes Bay

continued over...

APPENDIX 1: (continued)

	Sample No.	Formation (Member)	CaO	MgO	Ca/Mg	Notes
	74-4	Guelph	30.6	21.5	1.43	Vuggy reefal material on highway #6 near Willow C.
	74-5	Amabel (Wiarton-Colpoy Bay)	27.8	19.8	1.40	Fresh sample from inside Hope Bay Quarry (reefal)
	74-10	Amabel (Eramosa)	30.9	21.5	1.43	Fresh sample from Ebel Quarries west of Wiarton
	74-11	Amabel (Wiarton-Colpoy Bay)	30.0	20.9	1.44	Reefal material on road cut on side of spillway near Purple Valley
	74-12	Amabel (Lionshead)	31.9	21.8	1.46	Well bedded material at same place as 74-11
	74-13	Fossil Hill	29.4	19.2	k,53	Highly fossiliferous (pentanerus oblongus) sample from Cape Croker (Jones Bluff)
	74-14	Cabot Head (Dyer Bay)	26.7	18.1	1.47	Fossiliferous, well-bedded material w. of Cape Chin on Georgian Bay shore
b) Manitoulin Island	73-7	Guelph	29.2	20.6	1.42	Pitted material from south Baymouth, Manitoulin Island
c) Beaver † Valley (SE of Owen Sound)	72-1	Amabel (Wiarton-Colpoy Bay)	29.7	21.2	1.40	From the side of a roche moutonnie near a sinking stream-highly weathered
	72-2	Amabel (Lions Head)	30.1	20.6	1.46	Near resurgence to sinking strean noted above (72-1)

continued over ...

	Sample No.	Formation Member	CaO	MgO	Ca/Mg	Notes
	72-3	Amabel (Wiarton-Colpoy Bay)	30.3	20.5	1.48	Side of a rock cliff above Kimberley
	72-4	Manitoulin	29.6	19.1	1.55	Near second set of springs at Talenĩnan Ski Resort
	72-5	Amabel (Wiarton-Colpoy Bay)	30.2	21.1	1.43	Scarp face (reef material) above sample 72-4
d) Eramosa Gorge near Rockwood (NE of Guelph)	72-A	Amabel (Wiarton-Colpoy Bay)	30.2	20.9	1.44	Large Bioherm at entrance to Rockwood cave
	72-B	"	30.5	20.4	1.49	Inter-reefal material on rockface above Eramosa R.
	72-C	"	29.1	20.6	1.44	Inter-reefal material near entrance to Porcupine Cave
	72-D	"	30.1	21.0	1.43	Biohermal material from stack beside Eramosa R.
	72-E	"	30.8	20.2	1.52	Inter-reefal material below entrance to Rockwood Cave.

† Cowell 1973

APPENDIX 2A

ALKALINITY TITRATION PROCEDURE
(after Barnes 1964)

1) Calibrate pH meter with pH 4 buffer

2) Pipet 25 ml sample into conical flask

3) Insert pH probe

4) Run in HCl (approximately 0.003N) until the pH meter shows a stable reading of between pH 3 & 4

5) Read final pH and amount of acid used

6) Calculate alkalinity by -

$$Alk(eq/l) = \frac{VaCa - Hf(VaVs)}{Vs}$$

where Va = vol. acid used (ml)
ca = conc. acid used (eq/l)
Hf = final H^+ conc. of solution in flask (i.e. $Hf = 10^{**}$, final pH)
Vs = sample volume (ml)

7) A check can be performed by adding a small amount more acid, reading the final pH again and recalculating

APPENDIX 2B

DETERMINATION OF CALCIUM AND MAGNESIUM
By the Schwarzenbach Method

i) Total Hardness (Mg and Ca)

1. Pipet 50 ml ofthe sample into a conical flask.

2. Add 1 ml of the ammonia buffer solution and one crushed total hardness indicator tablet.

3. Titrate with N/50 EDTA from the buret until the solution in the conical flask has lost all traces of red colour. Read the buret before and after this step and subtract to get the volume of acid (EDTA) used.

Then: Total hardness = acid used (ml) · 20
This answer is in equivalent ppm $CaCO_3$

ii) Calcium Hardness

1. As above

2. Add 0.5 ml sodium hydroxide buffer and one crushed calcium indicator tablet.

3. Titrate with EDTA until the solution becomes violet. The end-point is reached when the addition of 0.1 ml of EDTA produces no further colour change.

Then: Calcium = acid used (ml) . 20

iii) Magnesium Hardness

Magnesium = Total hardness - calcium hardness.

APPENDIX 3

COMPUTER PROGRAM FOR THE DETERMINATION

OF SI_c, SI_d and PCO_2

```
      PROGRAM TOMCHEM(INPUT,OUTPUT)
C   CHEMICAL ANALYSIS OF WATER SAMPLES ALLOWING FOR ION PAIRING.
C   TOM WIGLEY, DEPT. OF MECHANICAL ENGINEERING, UNIV. OF WATERLOO.
C   THIS PROGRAMME IS AN EXTENSION OF A PREVIOUS PROGRAMME (WIGLEY,
C  AUG. 1970) WHICH INCORPORATES SODIUM, POTASSIUM, NITRATE AND
C  CHLORIDE IONS AND ADDITIONAL ION PAIRS.  THE PROGRAMME HAS BEEN
C  IMPROVED, BUT EXECUTION TIME IS LONGER THAN FOR THE PREVIOUS
C  PROGRAMME BECAUSE OF THE EXTRA CONSTITUENTS AND BECAUSE
C  OF AN INPUT UNITS OPTION.
C   THE PROGRAMME COMPUTES THE IONIC COMPOSITION OF WATER SAMPLES,
C  SATURATION INDICES WITH RESPECT TO CALCITE, DOLOMITE AND GYPSUM,
C  CARBON DIOXIDE CONTENT IN LOGARITHMIC FORM (PPCO2) OR IN PARTS
C  PER MILLION (CO2), CA++/MG++ RATIO (WW),AND CA++/SO4-- RATIO (W).
C   THE INPUTS ARE AS FOLLOWS.  ON THE FIRST DATA CARD THE NUMBER OF
C  SAMPLES TO BE ANALYSED.  ON THE SECOND DATA CARD THE UNITS USED,
C  K(I)=1 MEANS MOLES PER 1000 GMS OF SOLUTION, K(I)=2 MEANS PARTS
C  PER MILLION OF THE APPROPRIATE ION, K(I)=3 MEANS EQUIVALENT CACO3
C  CONTRATION IN PARTS PER MILLION. THE CORRECT K(I) SHOULD BE SPECIFIED
C  FOR EACH OF THE 8 INPUT CONSTITUENTS. K(9) IS A PRINTOUT OPTION
C  WHICH TAKES THE VALUE 1 OR 2 DEPENDING ON WHAT INFORMATION IS
C  REQUIRED IN THE OUTPUT.  K(10) IS AN OPTION TO USE DIFF EQUIL
C  CONSTS.  IF K(10) = 1 PROGRAMME USES LANGMUIRS CONSTS FOR CALCITE
C  AND DOLOMITE AND IGNORES THE ION PAIRS CAHCO3+ AND
C   CACO3 UNDISSOC. FORMAT IS (10I2)
C   K(I)=4 MEANS MILLIMOLES PER LITER
C   THE THIRD DATA CARD HAS THE FIELD NO. OF THE INPUT IONS
C   FROM YOUR CARDS, KK(1) = FILD FOR TEMP, THEN PH, CA, MG, HCO3, SO4,
C   NA, K, CL, NO3, ID OF SAMPLE. FORMAT IS (11I2)
C   AND THE K(I) ON THE PRECEEDING CARD ARE IN THE ORDER JUST GIVEN HERE
C   EXCLUDING TEMP AND PH
C   THE FOURTH CARD SPECIFIES AN INPUT FORMAT WHICH MUST GIVE 10 FIELDS
C   PLUS ONE FOR THE SAMPLE ID WHICH MUST HAVE AN A SPECIFICATION
C   SUBSEQUENT DATA CARDS ARE THE INPUT, IONS IN THE ORDER YOU HAVE
C   SPECIFIED IN DATA CARD 3.
C   IN THE BODY OF THE PROGRAMME X(I) ARE THE IONIC CONSTITUENTS IN
C  THE ORDER, CA++, MG++, HCO3-, SO4--, NA+, K+, CL-, NO3-, CAHCO3+,
C  MGHCO3+, CO3--, NACO3-, NASO4-, KSO4-, NAHCO3, MGSO4, CACO3,
C  MGCO3, CASO4.  ANY OTHER ION PAIRS WILL ALWAYS BE PRESENT IN SUCH
C  SMALL QUANTITIES THAT THEY CAN BE IGNORED EXCEPT IN BRINES.
C   R(I) ARE EFFECTIVE ION RADII, M(I) ARE MOLECULAR WEIGHTS,
C  AX(I) ARE ACTIVITIES AND FX(I) ARE ACTIVITY COEFFICIENTS.
C   ACKNOWLEDGEMENT OF THIS PROGRAMME BY USERS WOULD BE APPRECIATED.
      REAL M, MGTOT,KTOT,NATOT
      DIMENSION FMT(8)
      DIMENSION R(19),FX(19),AX(19),Z(8)
      DIMENSION KK(11),ZZ(11)
      COMMON/TOMZ/B1,B2,C1,C2,C3,C4,C5,C6,C7,C8,C9,C10,C11,C12,C13,C14,
     1K(10),X(19),M(8),T,TT,TDS
      DATA (M(I),I=1,8)/40080.,24312.,61018.,96062.,23000.,39000.,
     162000.,35500./
      DATA (R(I),I=1,15)/6.,8.,3*4.25,3*3.,2*4.25,4.5,4*4.25/,E/.0001/
      READ 100,N,(K(I),I=1,10),(KK(I),I=1,11),FMT
  100 FORMAT(I5/10I2/11I2/8A10)
      IF (K(9).EQ.1) PRINT 10
   10 FORMAT (*1*,*  CATOT   CA++  MGTOT MG++  NATOT  NA+  KTOT  ALK  HC
```

```
 103- SULF  SO4--  CL-  NO3-        SAMPLE ID*)
  IF (K(9).EQ.2) PRINT 11
11 FORMAT(*1*,* TEMP   PH   STCAL  STDOL  STGYP  PPCO2 CO2PPM  ERROR
 1   W       WW    IONSTR          SAMPLE ID*)
  DO 4 J=1,N
  READ FMT,(ZZ(I),I=1,11)
  K1=KK(1)  $ K2=KK(2)
  T=ZZ(K1)
  PH=ZZ(K2)
  DO 30 I=1,8
  K1=KK(I+2)
30 Z(I)=ZZ(K1)
  K1=KK(11)
  SEQ=ZZ(K1)
  TDS=0.
  DO 9 L=1,19
 9 X(L)=0.
  DO 7 L=1,8
 7 X(L)=Z(L)
  CALL UNITS
  DO31 I=1,8
31 Z(I)=X(I)
  A=.4921+(T-5.)*.00079
  B=.3249+(T-5.)*.00016
  TT=T+273.15
  H=10.**(-PH)
  CALL EQUCON
 5 U=(4.*(X(1)+X(2)+X(4)+X(11))+(X(3)+X(5)+X(6)+X(7)+X(8)+X(9)+
 1X(10)+X(12)+X(13)+X(14)+X(15)))/2.
  DO 2 I=1,15
 2 FX(I)=10.**(-A*(U**(.5))/(1.+B*(U**(.5))*R(I)))
  FX(1)=FX(1)**4.
  FX(2)=FX(2)**4.
  FX(4)=FX(4)**4.
  FX(11)=FX(11)**4.
  DO 3 I=1,15
 3 AX(I)=X(I)*FX(I)
  S=X(1)
  X(1)=Z(1)/(1.+FX(1)*(AX(3)/(FX(9)*C3)+AX(3)*C2/(H*C4)+AX(4)/C5))
  IF(ABS((X(1)-S)/X(1)).LT.E) GO TO 6
  AX(1)=X(1)*FX(1)
  X(2)=Z(2)/(1.+FX(2)*(AX(3)/(FX(10)*C6)+AX(3)*C2/(H*C7)+AX(4)/C8))
  AX(2)=X(2)*FX(2)
  X(3)=Z(3)/(1.+FX(3)*(AX(1)/(FX(9)*C3)+AX(2)/(FX(10)*C6)+AX(5)/
 1(C14*FX(15))+2.*C2*(1./FX(11)+AX(1)/C4+AX(2)/C7+AX(5)/(FX(12)*C11
 2))/H))
  AX(3)=X(3)*FX(3)
  X(4)=Z(4)/(1.+FX(4)*(AX(1)/C5+AX(2)/C8+AX(5)/(FX(13)*C12)+AX(6)/
 1(FX(14)*C13)))
  AX(4)=X(4)*FX(4)
  X(5)=Z(5)/(1.+FX(5)*(C2*AX(2)/(FX(12)*C11*H)+AX(4)/(FX(13)*C12)+
 1AX(3)/(FX(15)*C14)))
  X(6)=Z(6)/(1.+FX(6)*AX(4)/(FX(14)*C13))
  X(9)=AX(1)*AX(3)/(FX(9)*C3)
  X(10)=AX(2)*AX(3)/(FX(10)*C6)
  X(11)=C2*AX(3)/(FX(11)*H)
  X(12)=X(5)*FX(5)*X(11)*FX(11)/(C11*FX(12))
  X(13)=X(5)*FX(5)*AX(4)/(FX(13)*C12)
```

```
      X(14)=X(6)*FX(6)*AX(4)/(FX(14)*C13)
      X(15)=X(5)*FX(5)*AX(3)/(FX(15)*C14)
      X(16)=AX(2)*AX(4)/C8
      X(17)=AX(1)*X(11)*FX(11)/C4
      X(18)=AX(2)*X(11)*FX(11)/C7
      X(19)=AX(1)*AX(4)/C5
      GO TO 5
    6 SUMCAT=2.*(X(1)+X(2))+X(5)+X(6)+X(9)+X(10)+X(15)
      SUMAN=2.*(X(4)+X(11))+X(3)+X(7)+X(8)+X(12)+X(13)+X(14)
      ERROR=100.*(SUMCAT-SUMAN)/(SUMCAT+SUMAN)
      W=999.
      IF(X(4).NE.0.) W=X(1)/X(4)
      WW=999.
      IF(X(2).NE.0.) WW=X(1)/X(2)
      C=ALOG10(AX(1)*AX(3)*C2/(C1*H))
      D=-9.99
      IF(X(2).NE.0.)D=ALOG10(AX(1)*AX(2)*AX(3)*AX(3)*C2*C2/(C9*H*H))
      G=-9.99
      IF(X(4).NE.0.) G=ALOG10(AX(1)*AX(4)/C10)
      PPCO2=-ALOG10(H*AX(3)/(10.**(-B1-B2)))
      CO2=44010.*(10.**(-PPCO2-B1))
      DO 1  I=1,19
    1 X(I)=X(I)*1000.
       DO  8 I=1,8
    8 Z(I)=Z(I)*1000.
      IF (K(9).EQ.1) PRINT 12,Z(1),X(1),Z(2),X(2),Z(5),X(5),Z(7),
     1Z(3),X(3),Z(4),X(4),X(7),X(8),SEQ
   12 FORMAT(* *,2F7.2,11F6.2,7X,A10)
      IF (K(9).EQ.2) PRINT 13,T,PH,C,D,G,PPCO2,CO2,ERROR,W,WW,U,SEQ
   13 FORMAT(* *,F5.1,F6.2,5F7.2,F7.1,2F7.2,F9.5,7X,A10)
      IF(K(9).EQ.3) PRINT 300,SEQ,C,U,Z(1),Z(2),Z(5),Z(6),Z(3),Z(4),Z(8)
     1,Z(7),D,X(1),X(2),X(5),X(6),X(3),X(11),X(4),X(8),X(7),G,X(19),X(16
     2),X(13),X(14),PPCO2,X(9),X(10),X(15),T,WW,CO2,X(17),X(18),X(12),ER
     3ROR,W,PH
  300 FORMAT(//10X*SAMPLE IDENTIFICATION  *A10//9X*I*12X*C A T I O N S*1
     14X*I*12X*A N I O N S*27X*I*/10X*CALCIUM   MAGNESIUM SODIUM    POTA
     2SSIUM BICARB    CARBONATE SULFATE   NITRATE   CHLORIDE  I SATCAL
     3=*F6.2* IONSTR =*F6.5/1X*TOTAL     *4(F8.3,2X)*(ALKALINITY =*F6.2*)
     4*3(F8.3,2X)*I SATDOL  =*F6.2/1X*FREE       *9(F8.3,2X)*I SATGYP  =*F
     56.2/1X*SULFATE  *4(F8.3,2X)*I*16(3H  -)* I PCO2     =*F6.2/1X*BICAR
     6B    *3(F8.3,2X)*  NEGLECT I     TEMP   = *F6.2* DEG C    I    CA/MG
     7= *F6.2*  I CO2 PPM =*F6.2/1X*CARB      *3(F8.3,2X)*  NEGLECT I
     8ERROR = *F6.2* PERCENT I    CA/SO4 = *F6.2*  I PH       =*F6.2///1X
     9,44(3H* ))
      IF(K(9).EQ.3.AND.((J/4)*4-J).EQ.0) PRINT 301
  301 FORMAT(1H1)
    4 CONTINUE
      STOP
      END
```

```
      SUBROUTINE UNITS
      REAL M
      COMMON/TOMZ/B1,B2,C1,C2,C3,C4,C5,C6,C7,C8,C9,C10,C11,C12,C13,C14,
     1K(10),X(19),M(8),T,TT,TDS
      DO 1 J=1,8
      IF(K(J).EQ.2) X(J)=X(J)/M(J)
      IF(K(J).EQ.3) X(J)=X(J)/100098.
      IF(K(J).EQ.4) X(J)=X(J)/1000.
    1 TDS=TDS+X(J)*M(J)/1000.
      DO 2 J=1,8
    2 X(J)=X(J)*1000./(1000.+TDS)
      RETURN
      END


      SUBROUTINE EQUCON
C   IN THIS SUBROUTINE B1 IS THE HENRYS LAW CONSTANT, B2 IS THE
C  EQUIL CONST FOR (CO2 + H2CO3).   C1 TO C14 ARE EQUIL CONSTS IN THE
C  O-DER 9  CALCITE, HCO3-, CAHCO3+, CACO3 UNDISSOC, CASO4 UNDISSOC,
C  MGHCO3+, MGCO3 UNDISSOC, MGSO4 UNDISSOC, DOLOMITE, GYPSUM,
C  NACO3-, NASO4-, KSO4-, AND NAHCO3.
      COMMON/TOMZ/B1,B2,C1,C2,C3,C4,C5,C6,C7,C8,C9,C10,C11,C12,C13,C14,
     1K(10),X(19),M(8),T,TT,TDS
      C1=10.**(-8.0797997-.013328484*T+.25490188*T*T*10.**(-4.))
      C2=EXP(-(1000./(1.98719*TT))*(-3.596025*TT*TT/(10.**4.)
     1+5.35355*TT*TT*TT/(10.**7.)+.106897*TT))
      C5=10.**(-2.2-.0025166*T-.0000433*T*T)
      C8=10.**(-160.46267+62.90562*ALOG10(TT)+4871.03/TT-.046721*TT)
      DELF=-10.5304-.047122*TT*ALOG(TT)+1.94848*TT*TT/(10.**(4.))
     1-2.75001*TT*TT*TT/(10.**(9.))+620./TT+.3158096*TT
      C9=10.**(-1000.*DELF/(TT*4.575673))
      C10=10.**(-4.6406896+.00248775*T-.592158*T*T*10.**(-4.))
      C3 = 10.**(-1.26)
      C4 = 10.**(-3.1)
      C6 = 10.**(-.95)
      C7 = 4.0*(10.**(-4.))
      C11=10.**(-1.27)
      C12=10.**(-.72)
      C13=10.**(-.96)
      C14=10.**(.25)
      B1=1.12+.014*T
      B2=6.577-.01264*T+.144*T*T/1000.
      IF(K(10).NE.1) RETURN
      C3=10000.
      C1=10.**(-8.3389285-.0012357*T-.00005*T*T)
      C9=10.**(-16.5614285-.0124857*T-.0001999*T*T)
      RETURN
      END
       6400 END OF RECORD
```

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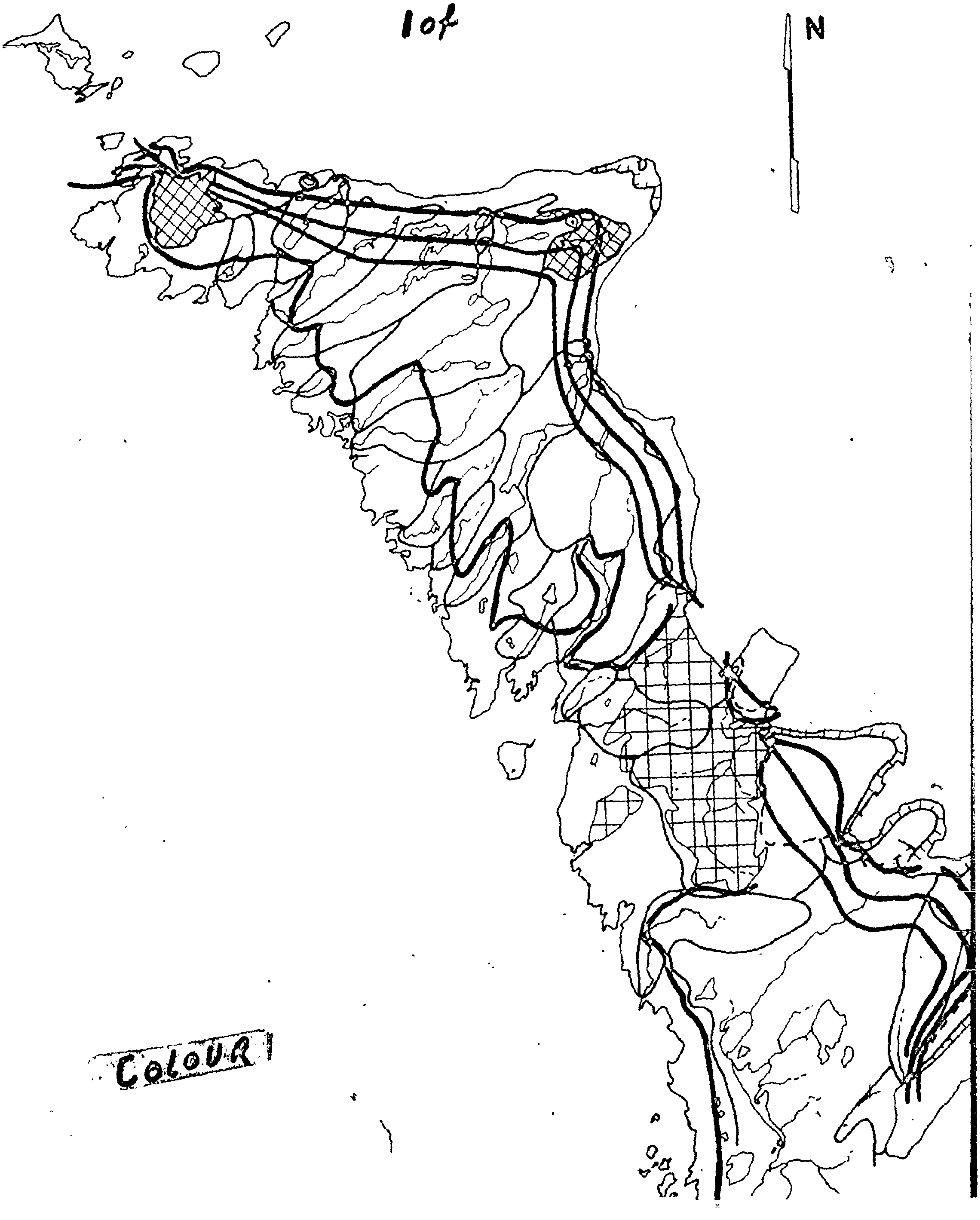

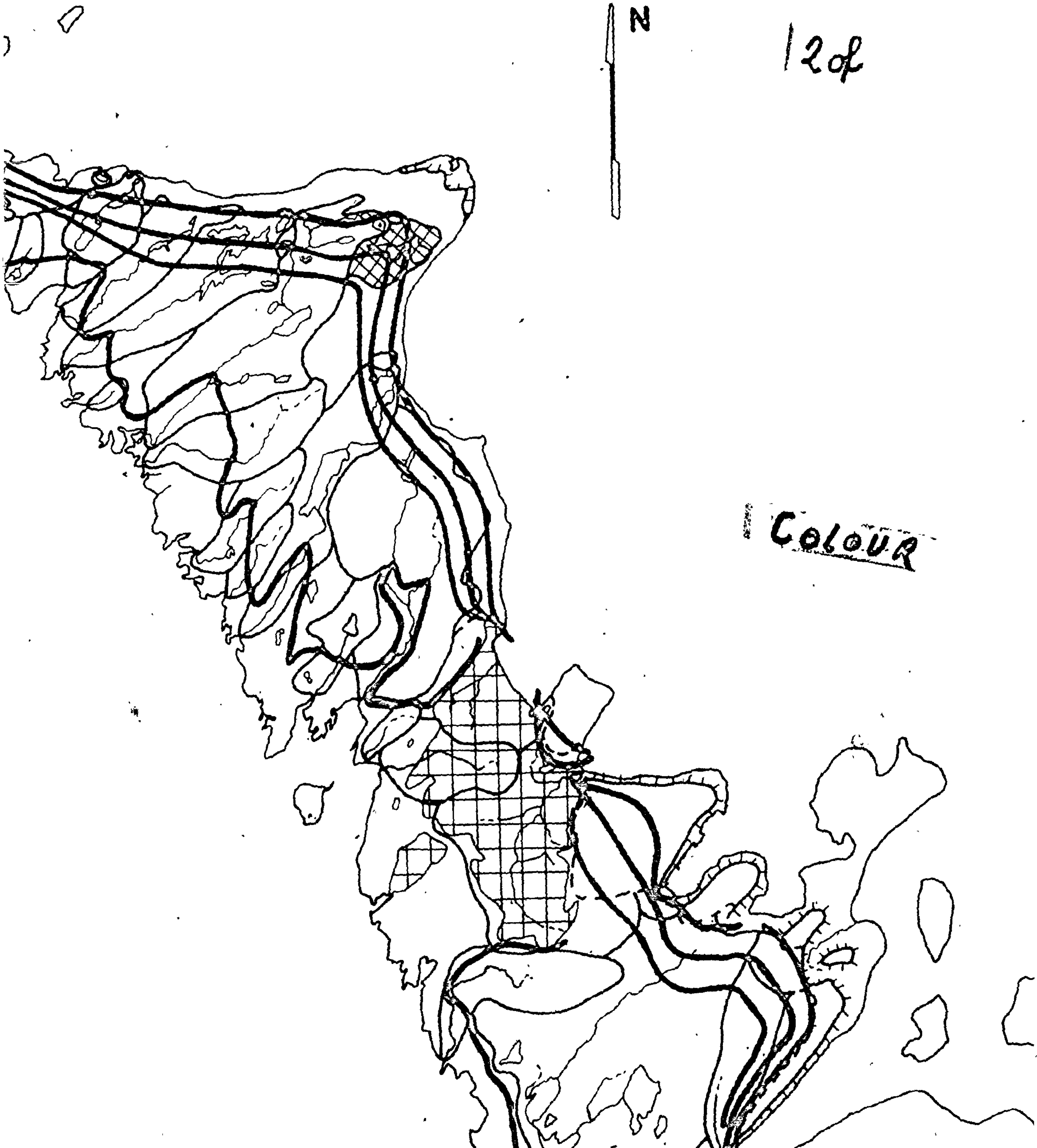

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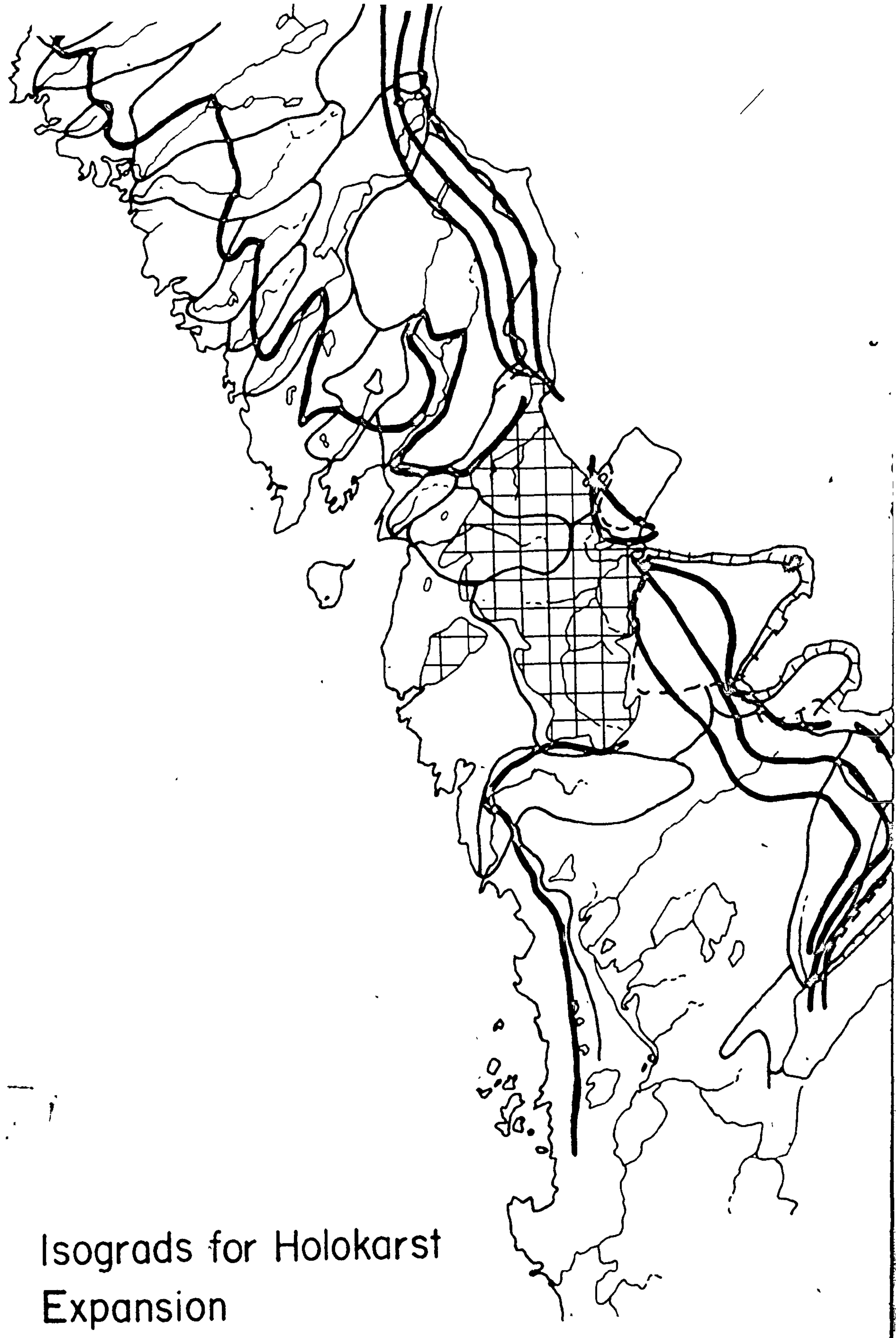

FIGURE 4.5 Isograds for Holokarst Expansion

Scale 1:250,000

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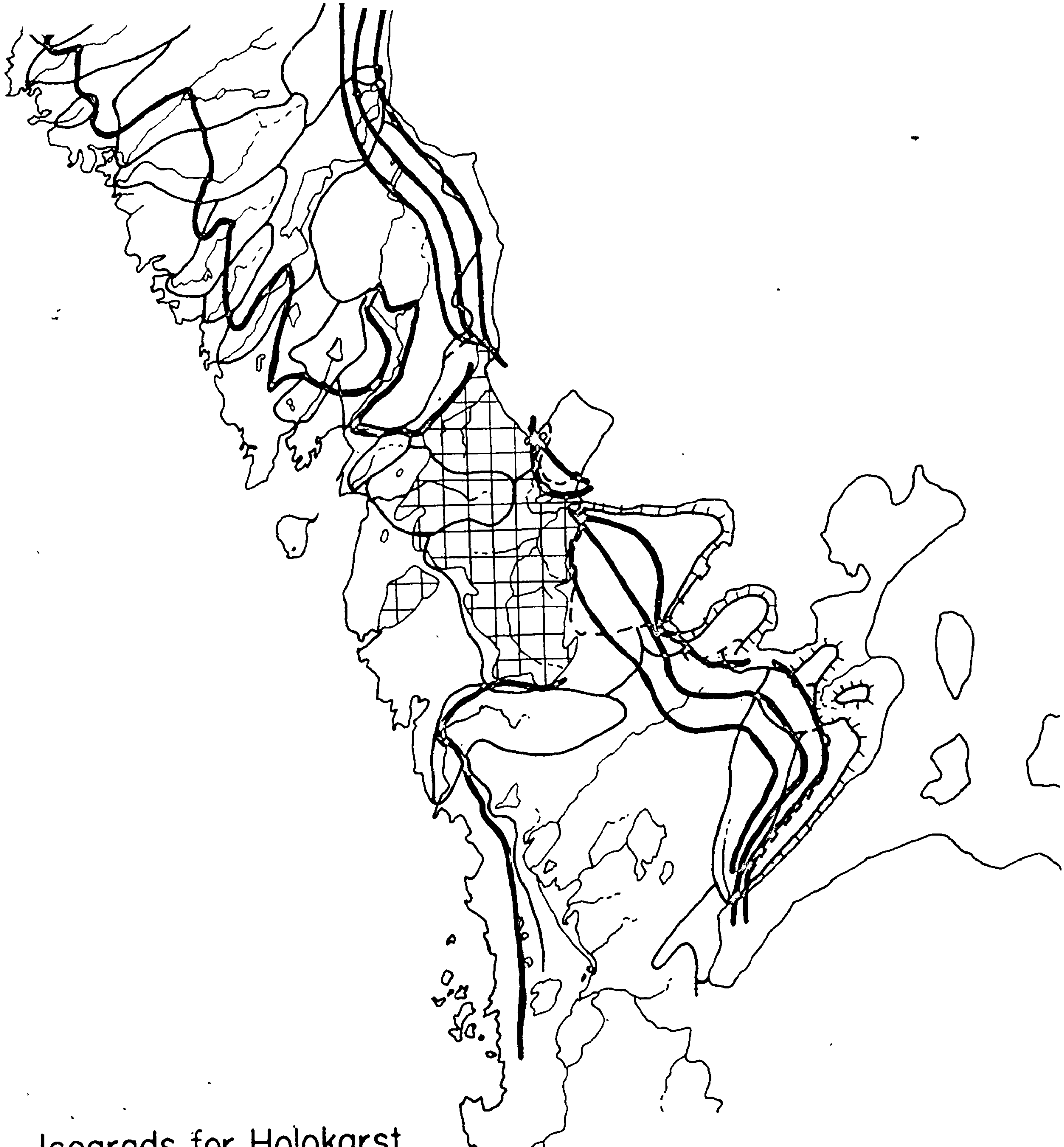

5 Isograds for Holokarst Expansion

Scale 1:250,000

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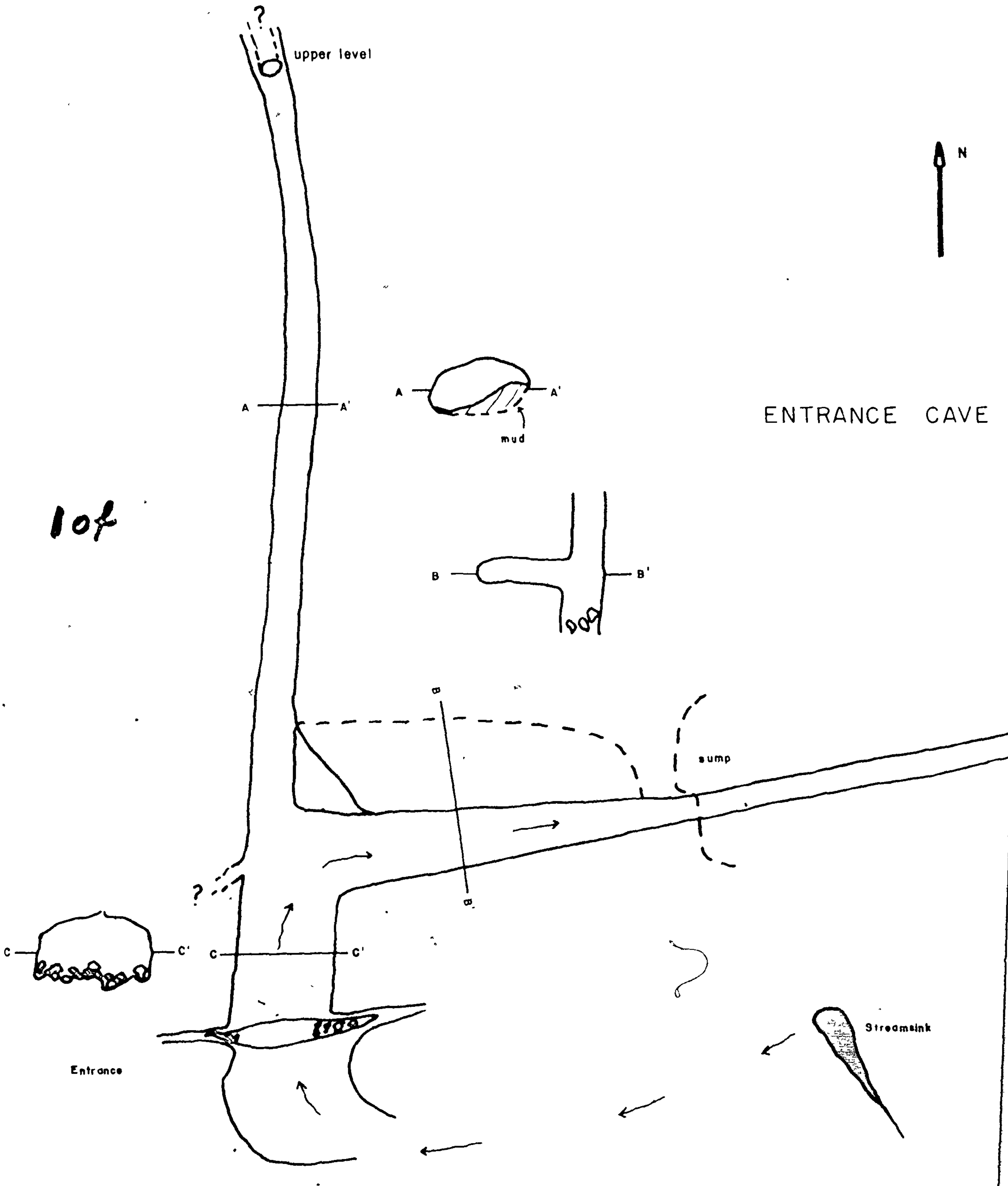
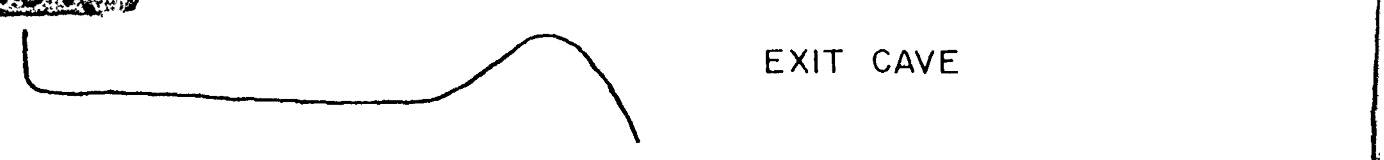
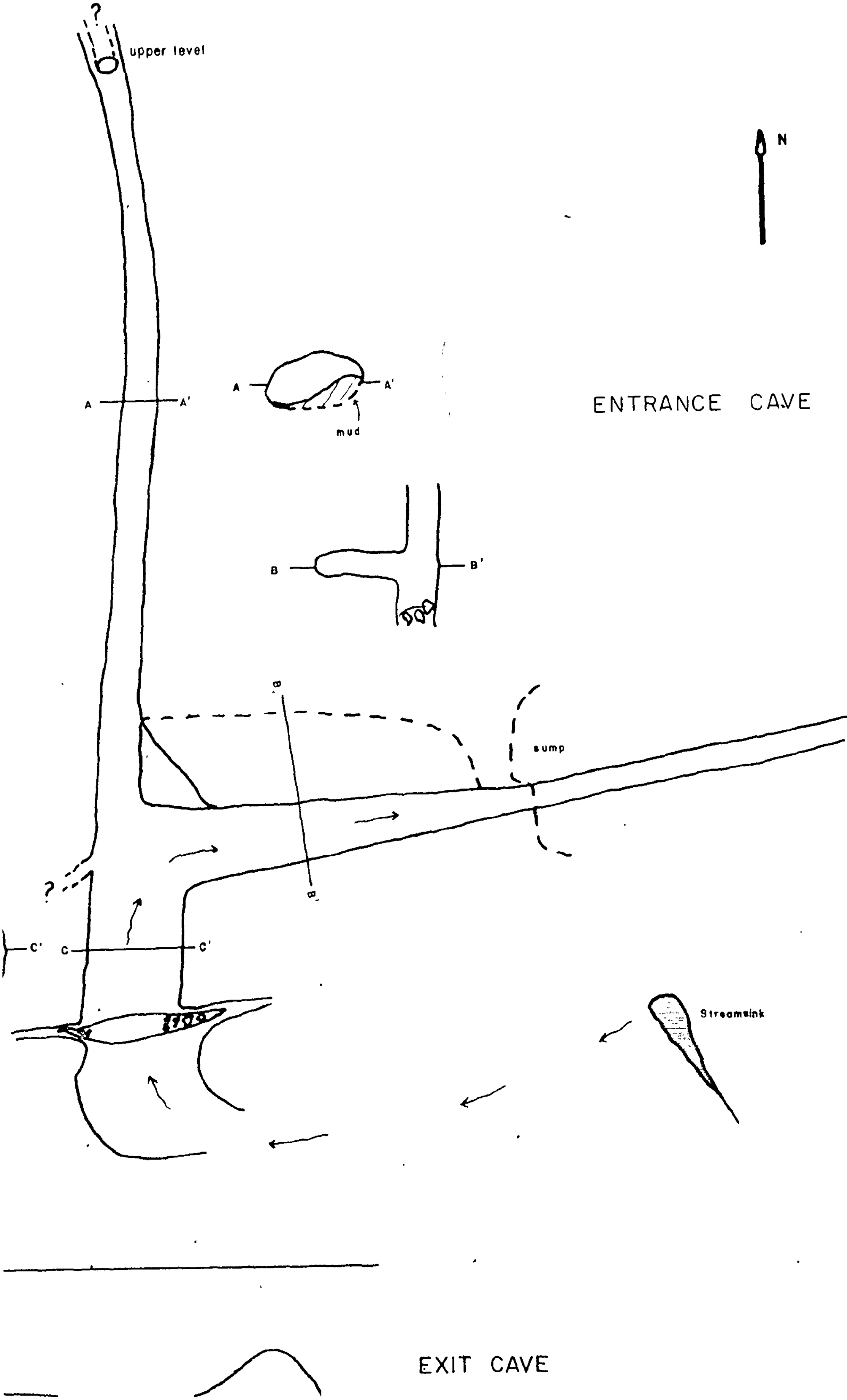
14of4


?
upper level
N
A
A'
mud
ENTRANCE CAVE
1of
B
B'
sump
?
C
C'
Entrance
Streamsink


EXIT CAVE


?
upper level
N
A
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mud
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B
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sump
?
C'
C
Streamsink
EXIT CAVE

12of

Colour

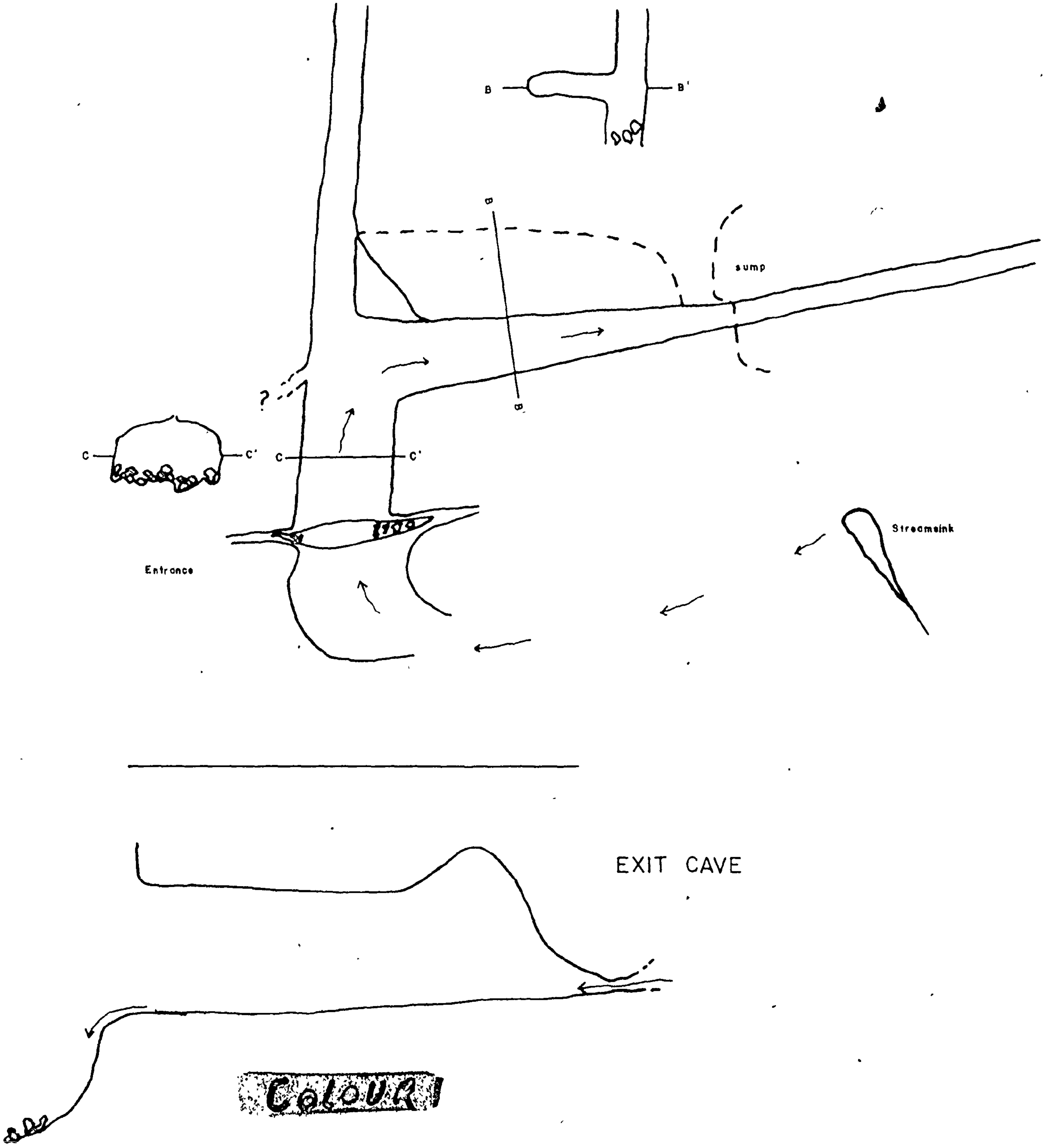


FIGURE 4.4 ST. Edmunds Cave, Bruce Count

Scale 1cm = 1.2m

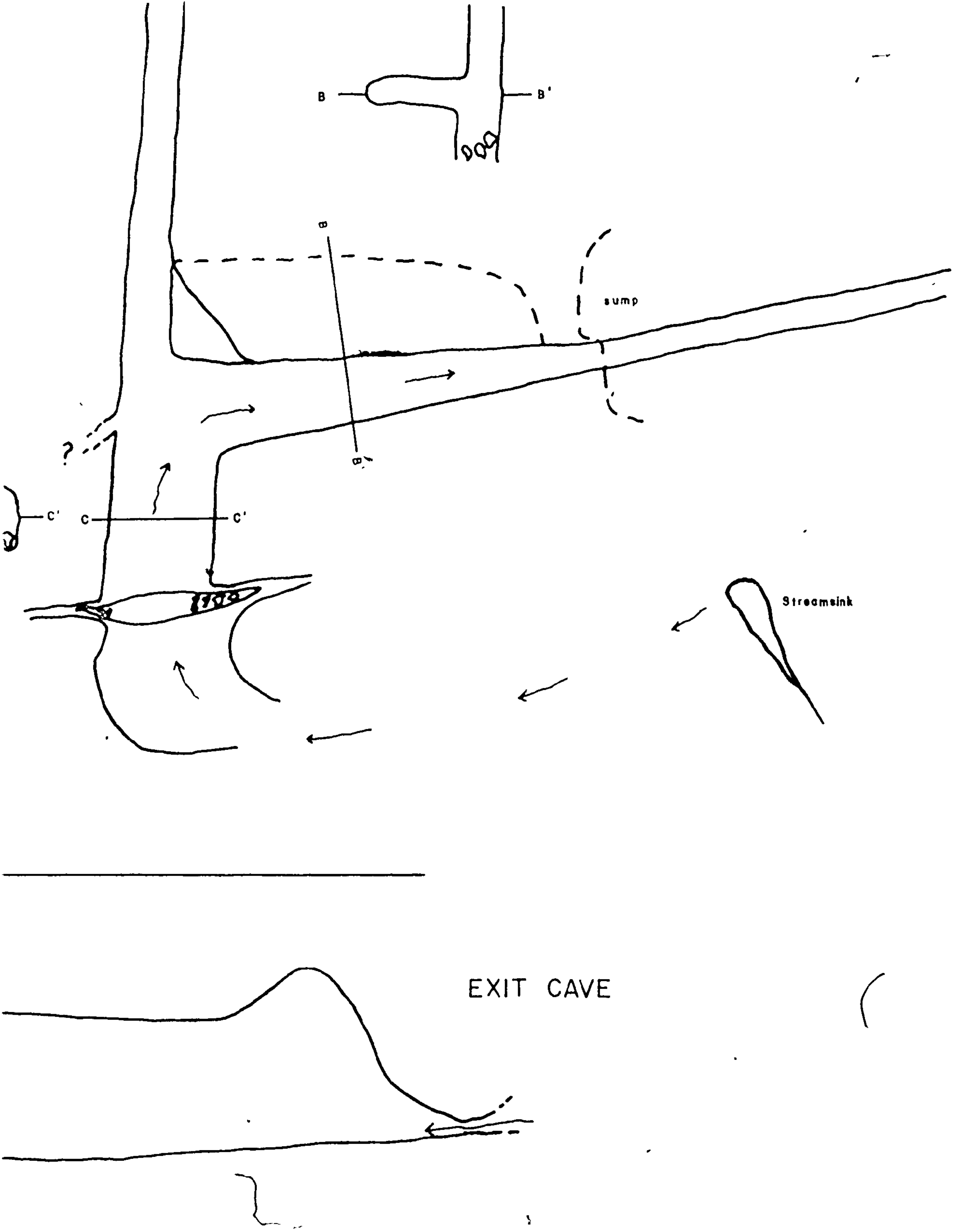
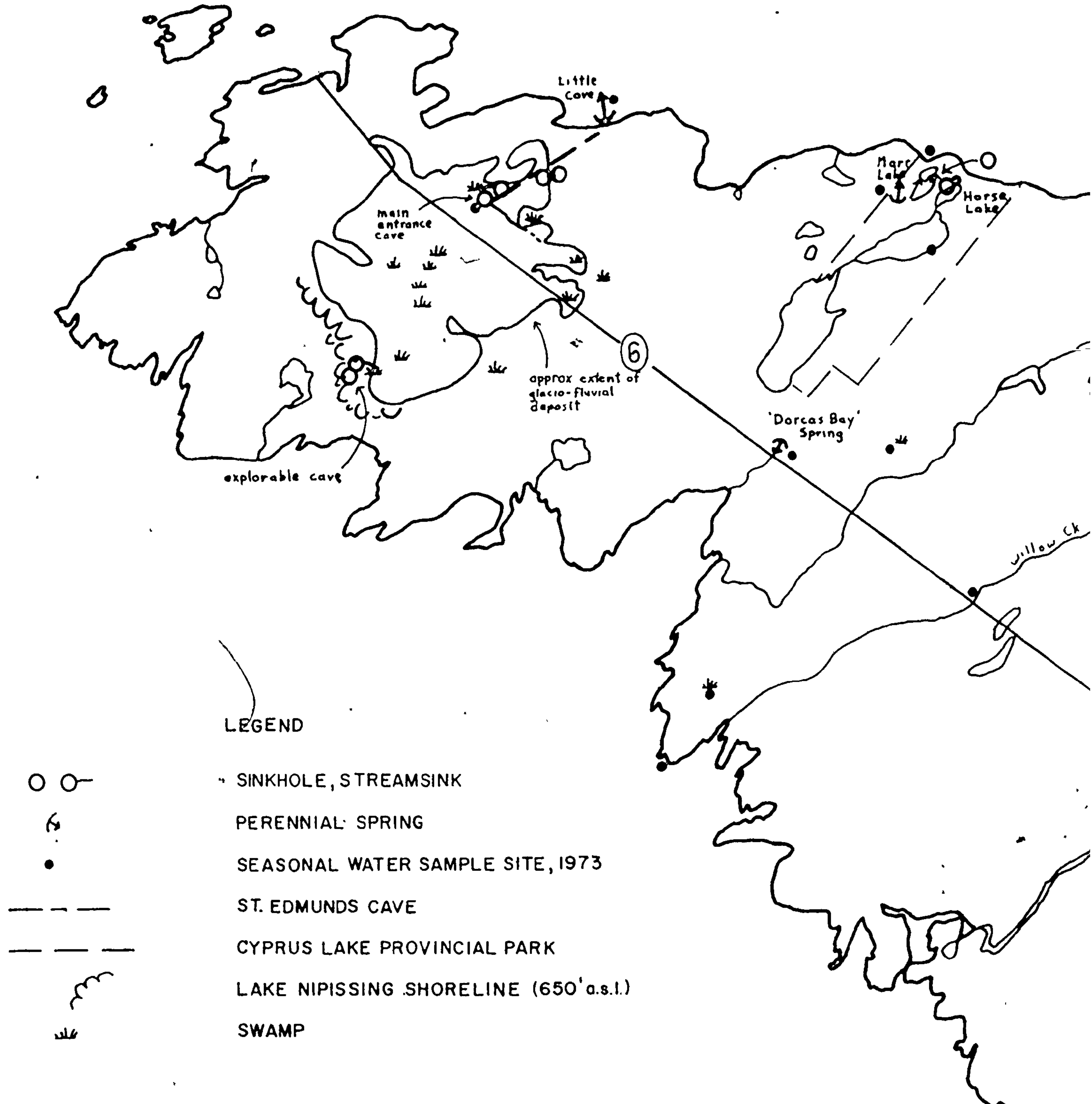


FIGURE 4.4 ST. Edmunds Cave, Bruce County

Scale 1cm = 1.2m


Little cave
Marr Lake
Horse Lake
main entrance cave
approx extent of glacio-fluvial deposit
6
'Dorcas Bay' Spring
explorable cave
Willow Ck
LEGEND
SINKHOLE, STREAMSINK
PERENNIAL SPRING
SEASONAL WATER SAMPLE SITE, 1973
ST. EDMUNDS CAVE
CYPRUS LAKE PROVINCIAL PARK
LAKE NIPISSING SHORELINE (650' a.s.l.)
SWAMP

1of

COLOUR

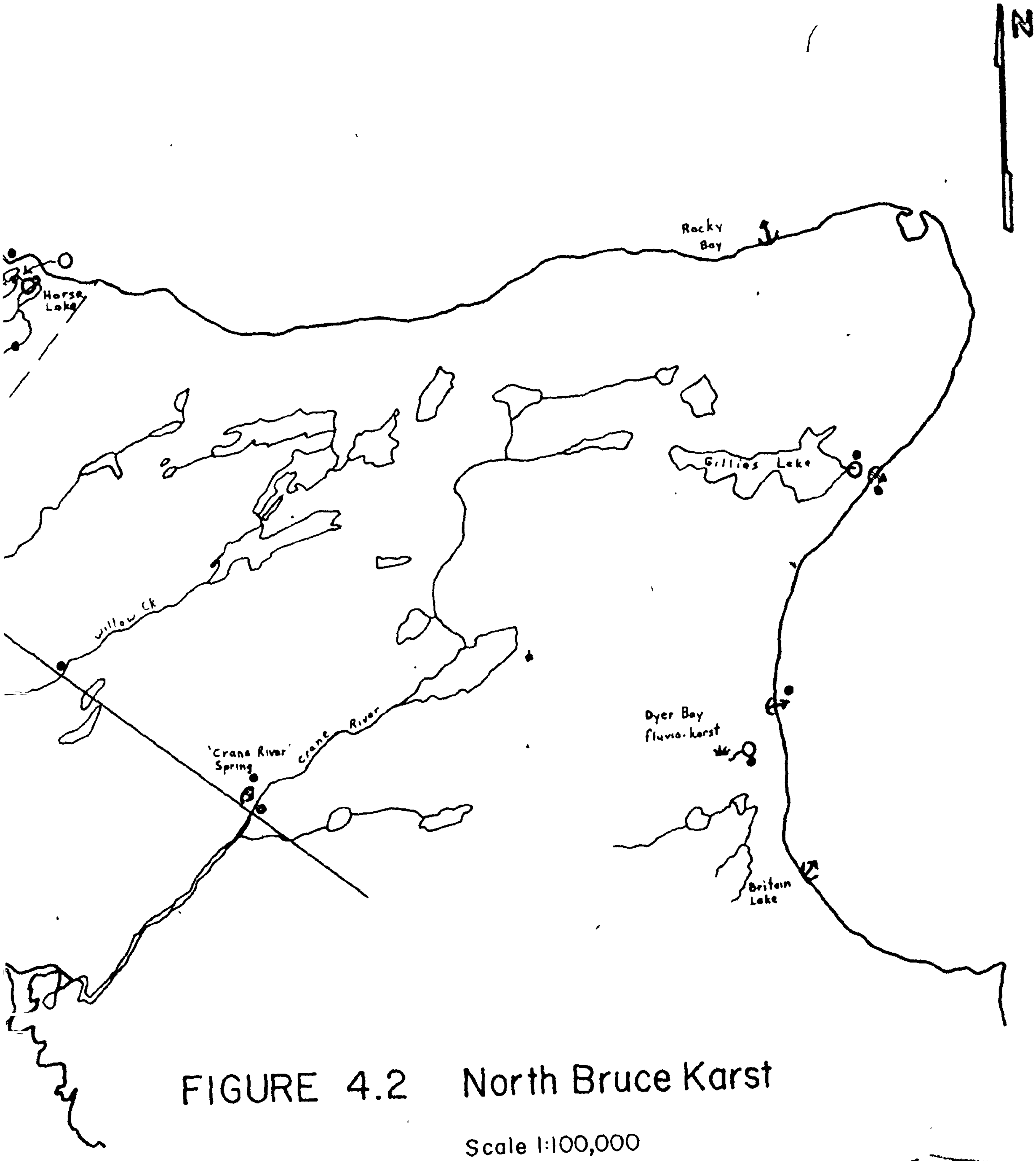


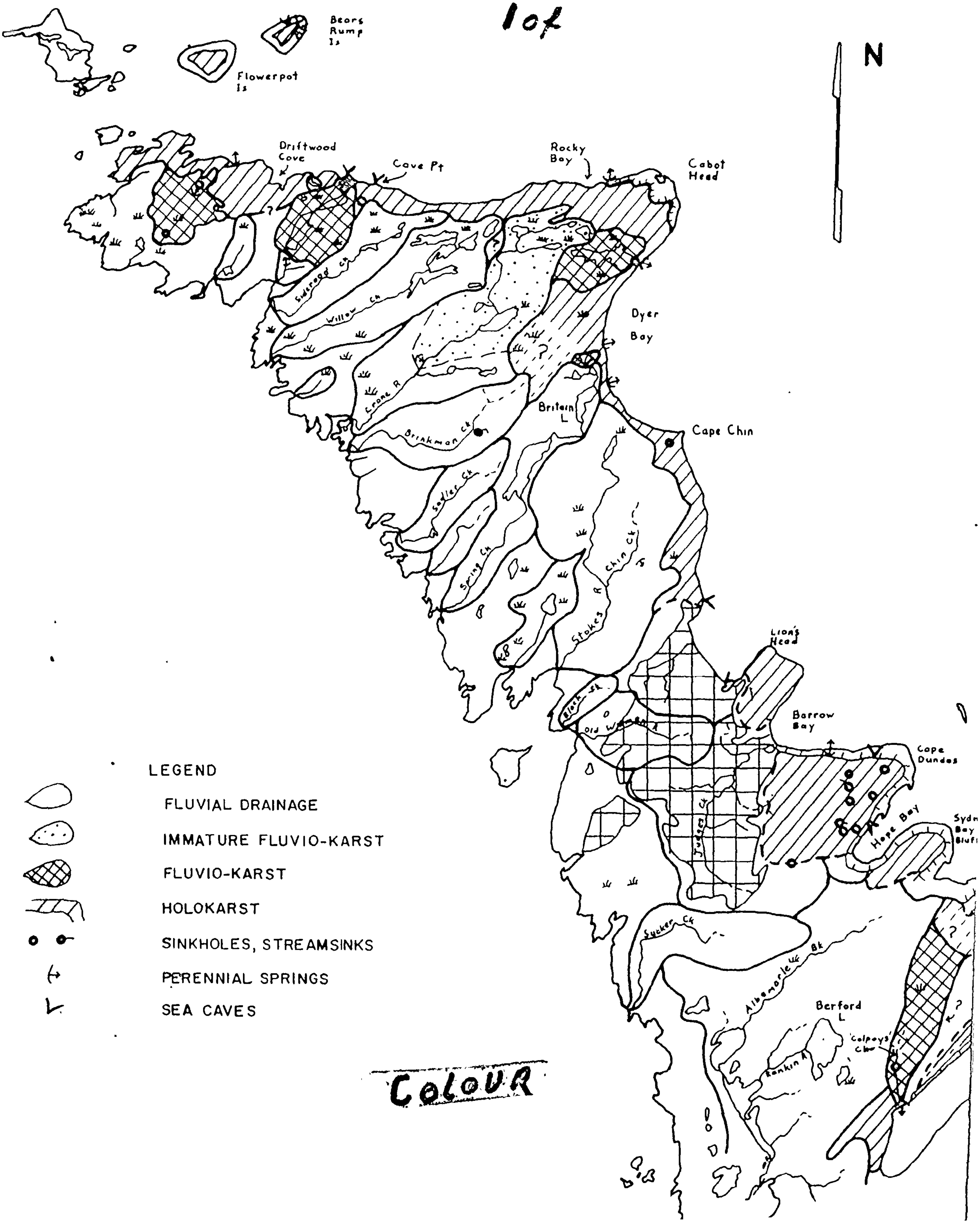
FIGURE 4.2 North Bruce Karst

Scale 1:100,000

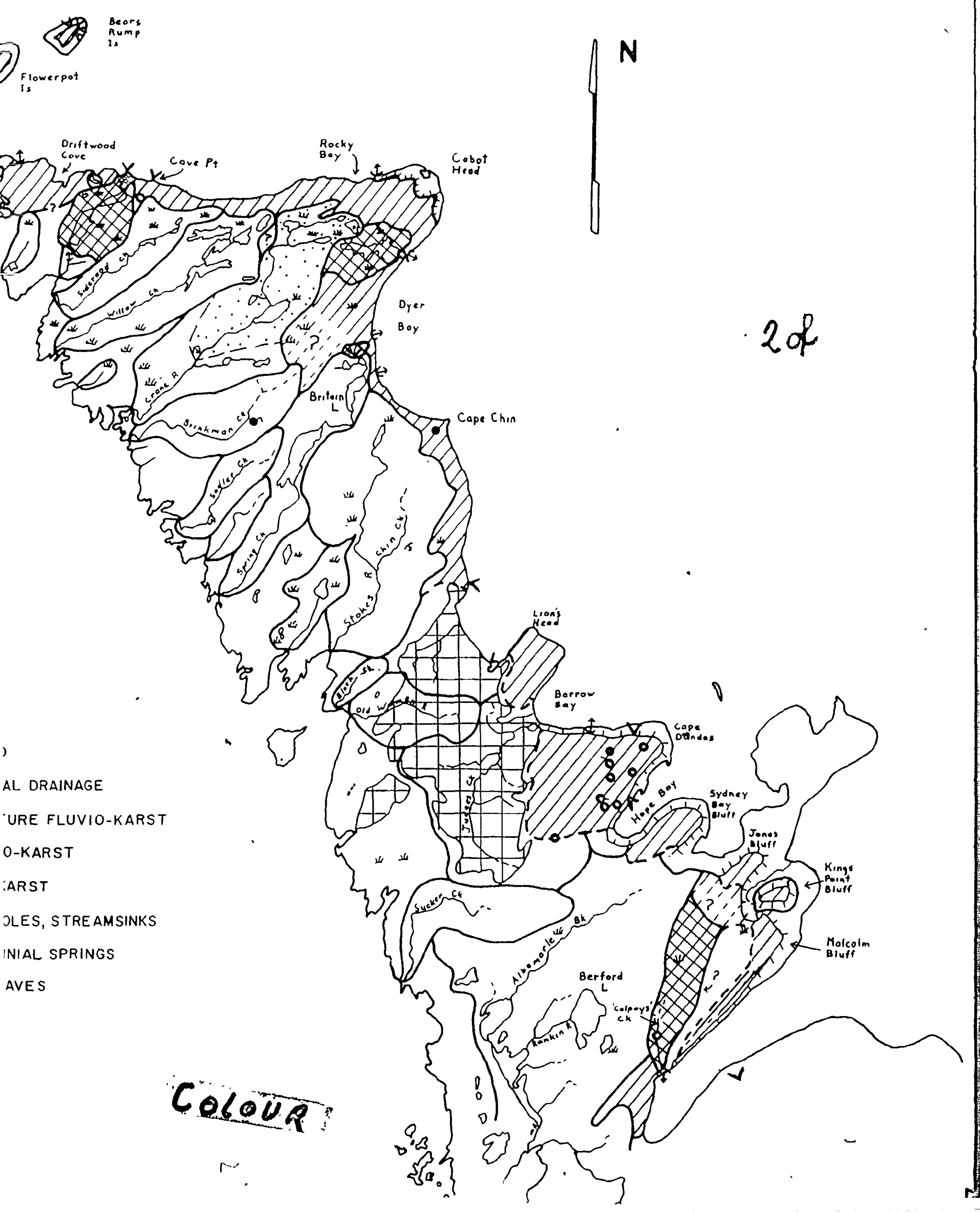
2 of 2

COLOUR

1of


N
Bears Rump Is
Flowerpot Is
Driftwood Cove
Cave Pt
Rocky Bay
Cabot Head
Willow Ck
Crane R
Brinkman Ck
Dyer Bay
Britain L
Cape Chin
Sadler Ck
Spring Ck
Chin Ck
Stokes R
Lion's Head
Barrow Bay
Cape Dundas
Old Woman R
Judges Ck
Hope Bay
Sucker Ck
Albemarle Bk
Berford L
Colpoys' Ck
Rankin R
LEGEND
FLUVIAL DRAINAGE
IMMATURE FLUVIO-KARST
FLUVIO-KARST
HOLOKARST
SINKHOLES, STREAMSINKS
PERENNIAL SPRINGS
SEA CAVES

COLOUR


Bears Rump Is
Flowerpot Is
N
Driftwood Cove
Cove Pt
Rocky Bay
Cabot Head
Dyer Bay
Sideroad Ck
Willow Ck
Crane R
Brinkman Ck
Britain L
Cape Chin
Sadler Ck
Spring Ck
Chin Ck
Stokes R
Lion's Head
Barrow Bay
Cape Dundas
Hope Bay
Sydney Bay Bluff
Jones Bluff
Kings Point Bluff
Malcolm Bluff
Judges Ck
Sucker Ck
Albemarle Bk
Berford L
Colpoys Ck
Rankin R
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ARST
OLES, STREAMSINKS
INIAL SPRINGS
AVES
2 of
COLOUR

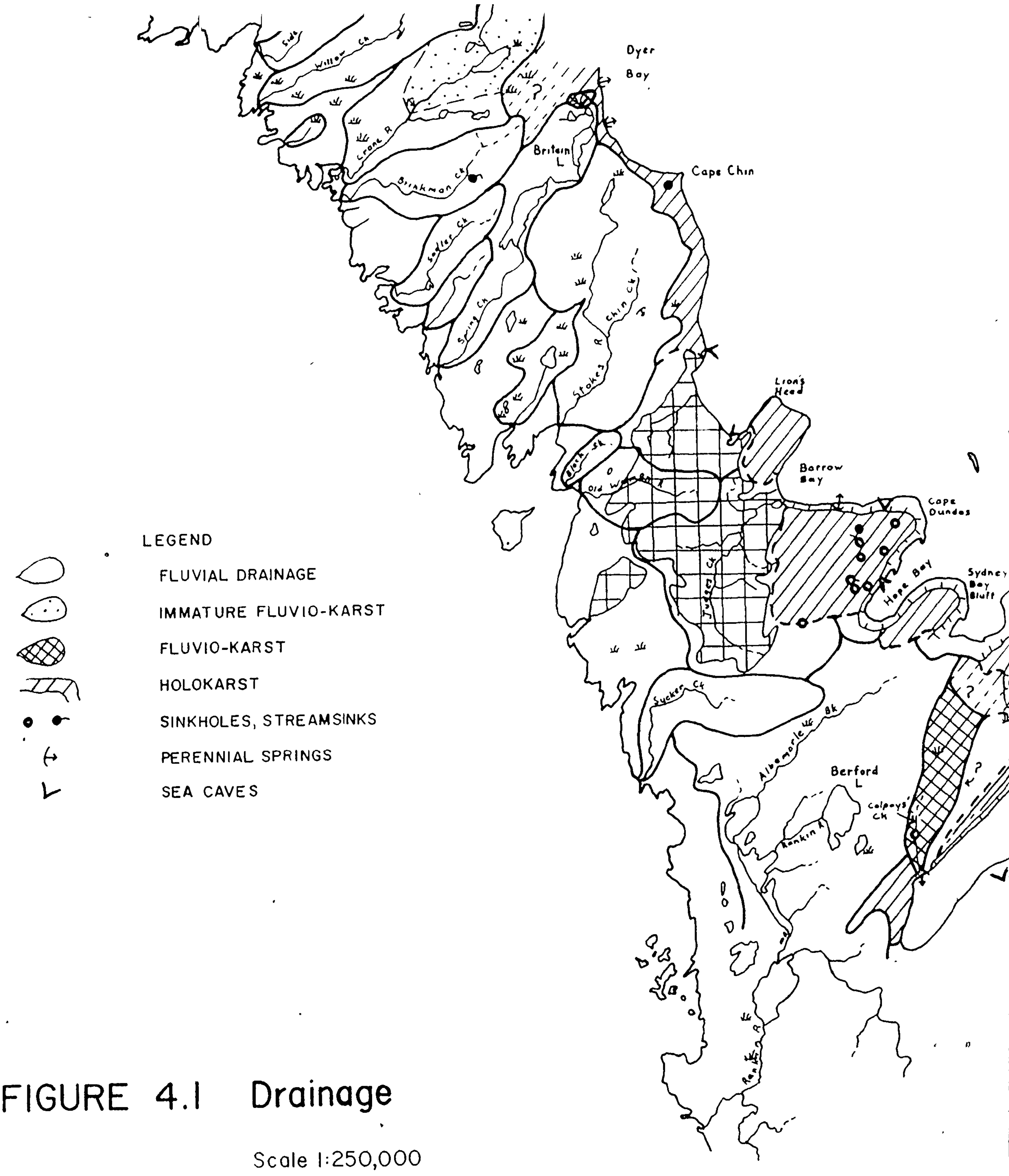
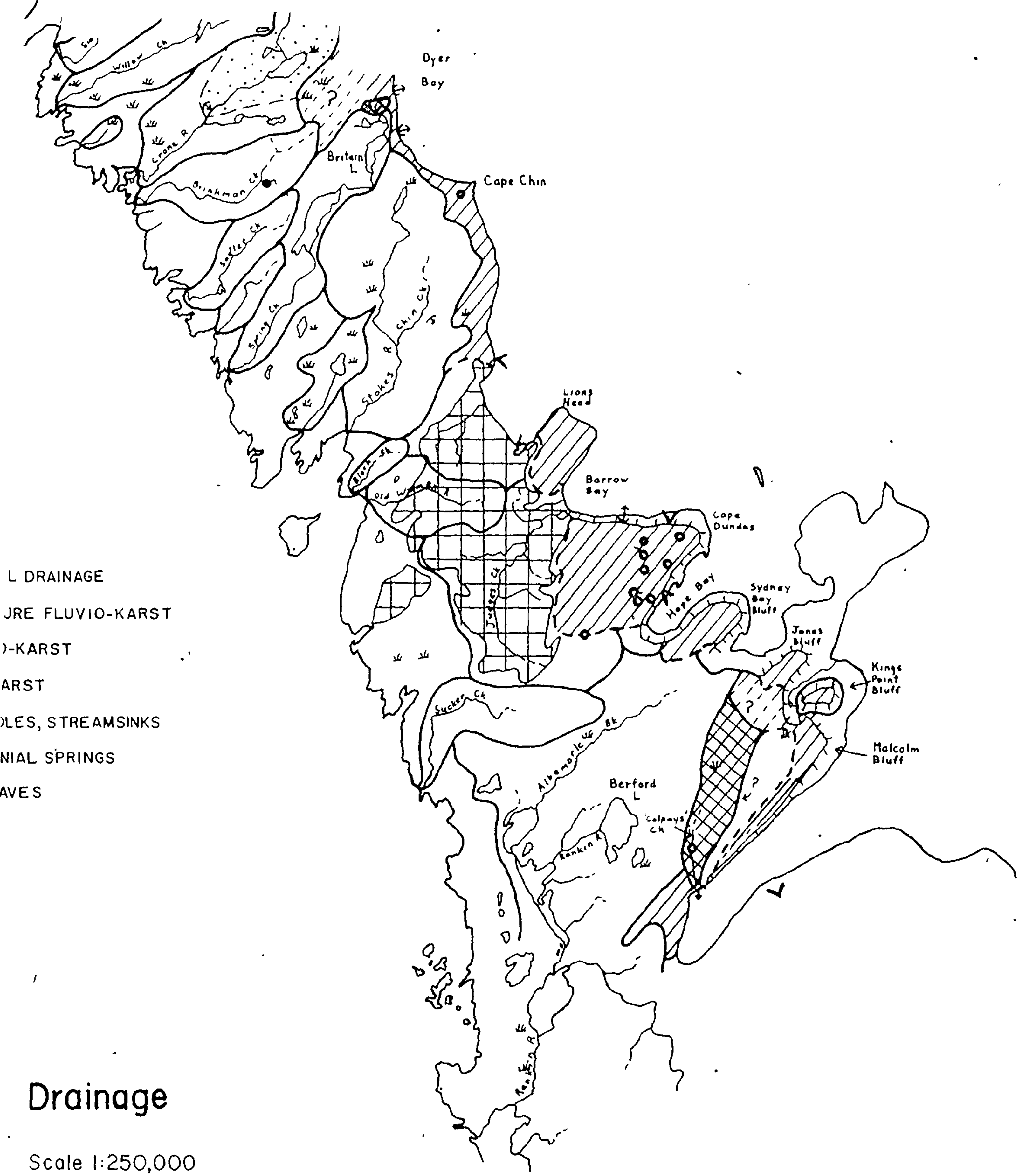


FIGURE 4.1 Drainage

Scale 1:250,000

Colour

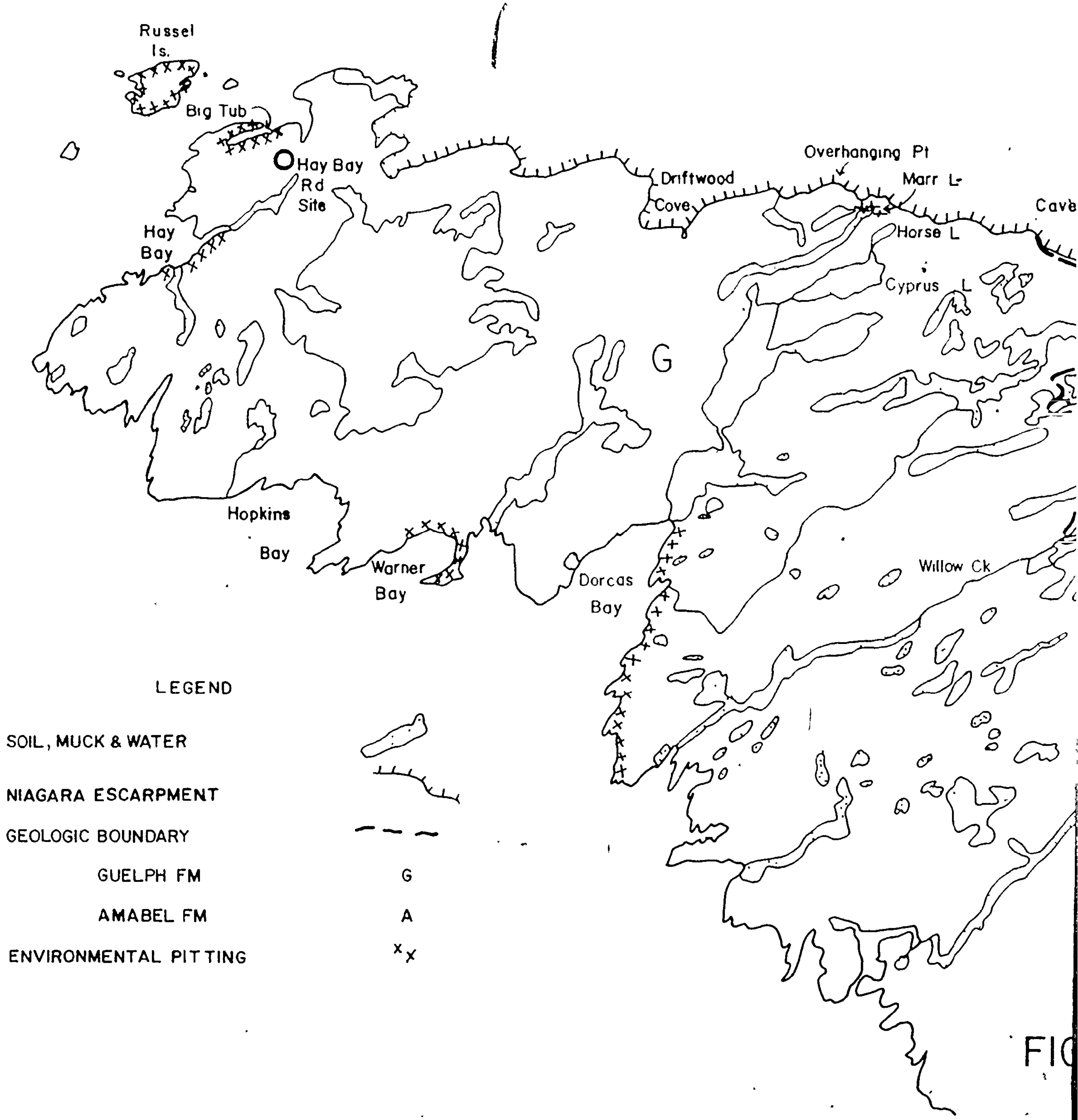


Drainage

Scale 1:250,000

COLOUR

1 of 4



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1 of

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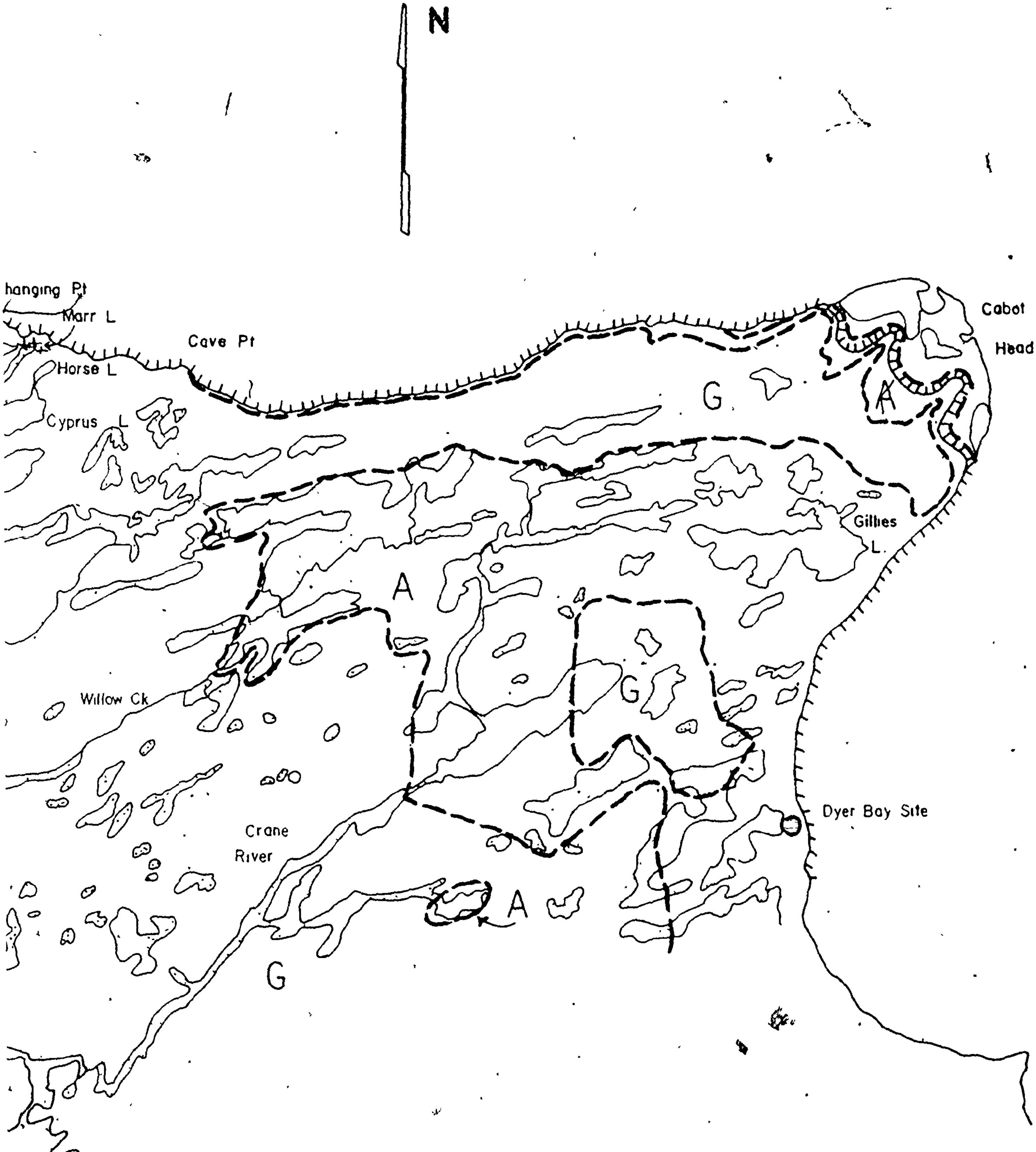
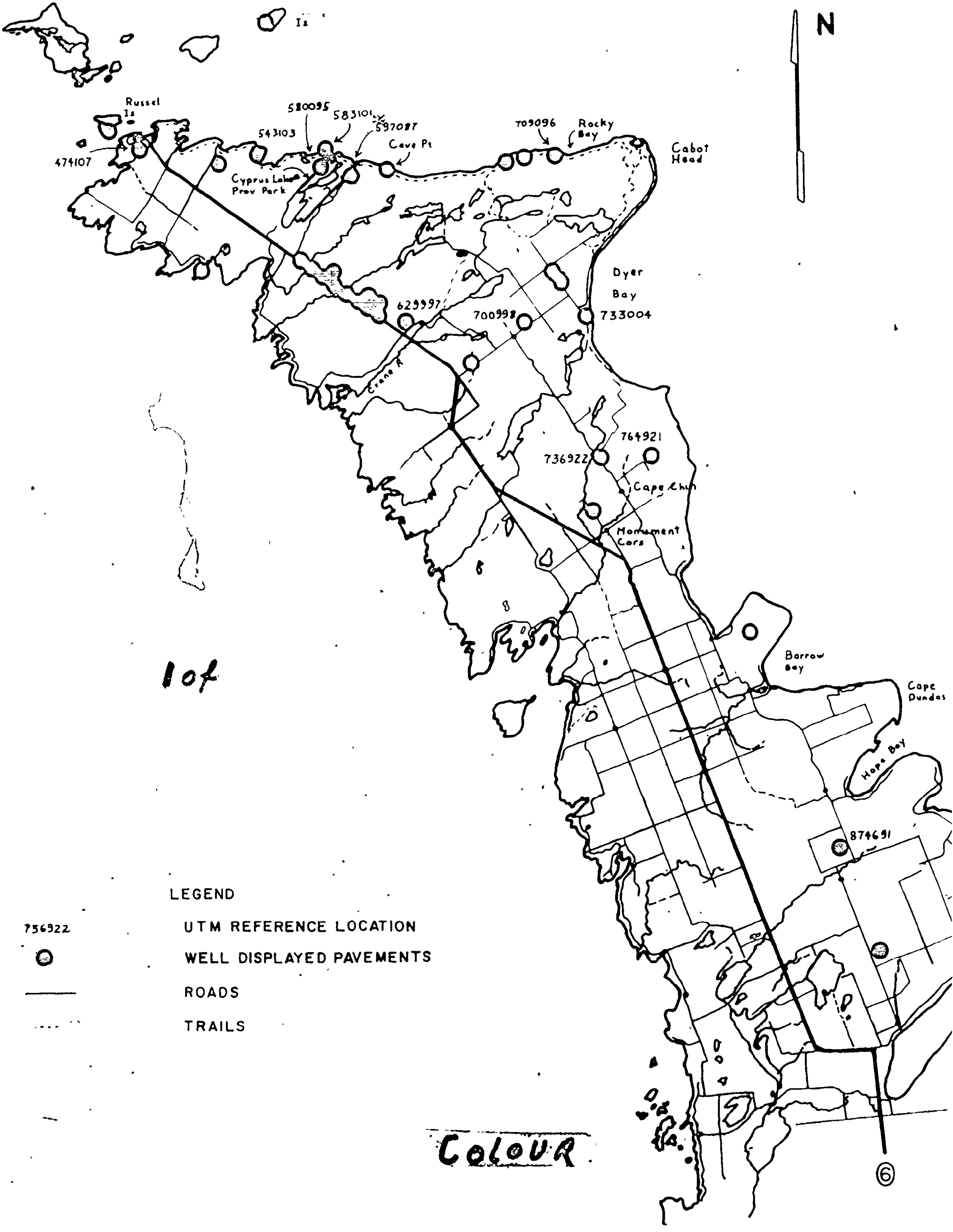
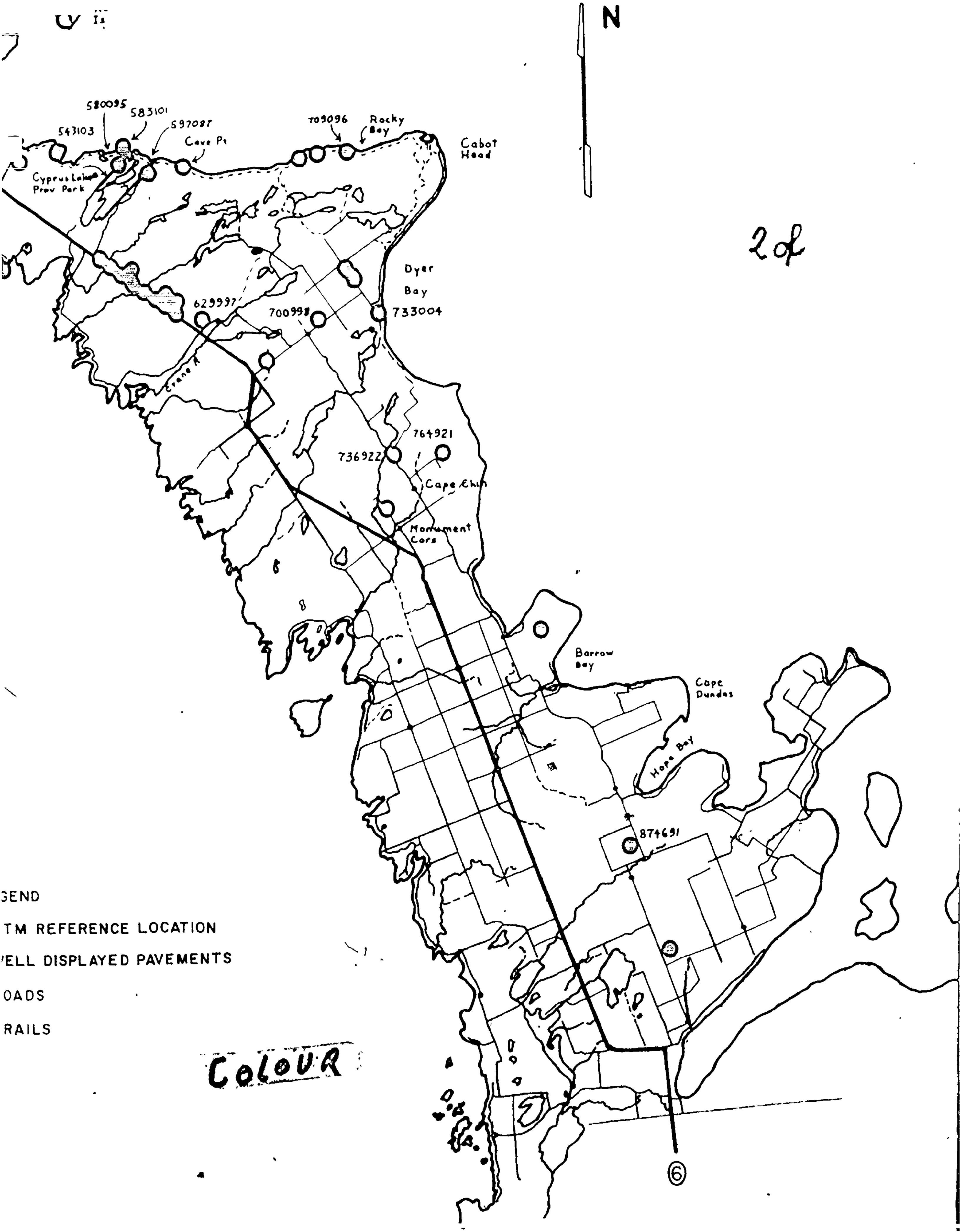


FIGURE 3.2 North Bruce Pavement Distribution

Scale 1:100,000


N
Is
Russel Is
474107
543103
580095
583101
597087
Cave Pt
Cyprus Lake Prov Park
709096
Rocky Bay
Cabot Head
Dyer Bay
733004
700998
629997
Crane R
764921
736922
Cape Chin
Monument Cors
Barrow Bay
Cape Dundas
Hope Bay
874691
6
LEGEND
736922 UTM REFERENCE LOCATION
WELL DISPLAYED PAVEMENTS
ROADS
TRAILS
1 of
COLOUR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Cave Pt
Cyprus Lake Prov Park
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Rocky Bay
Cabot Head
Dyer Bay
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700998
733004
764921
736922
Cape Chin
Monument Cors
Barrow Bay
Cape Dundas
Hope Bay
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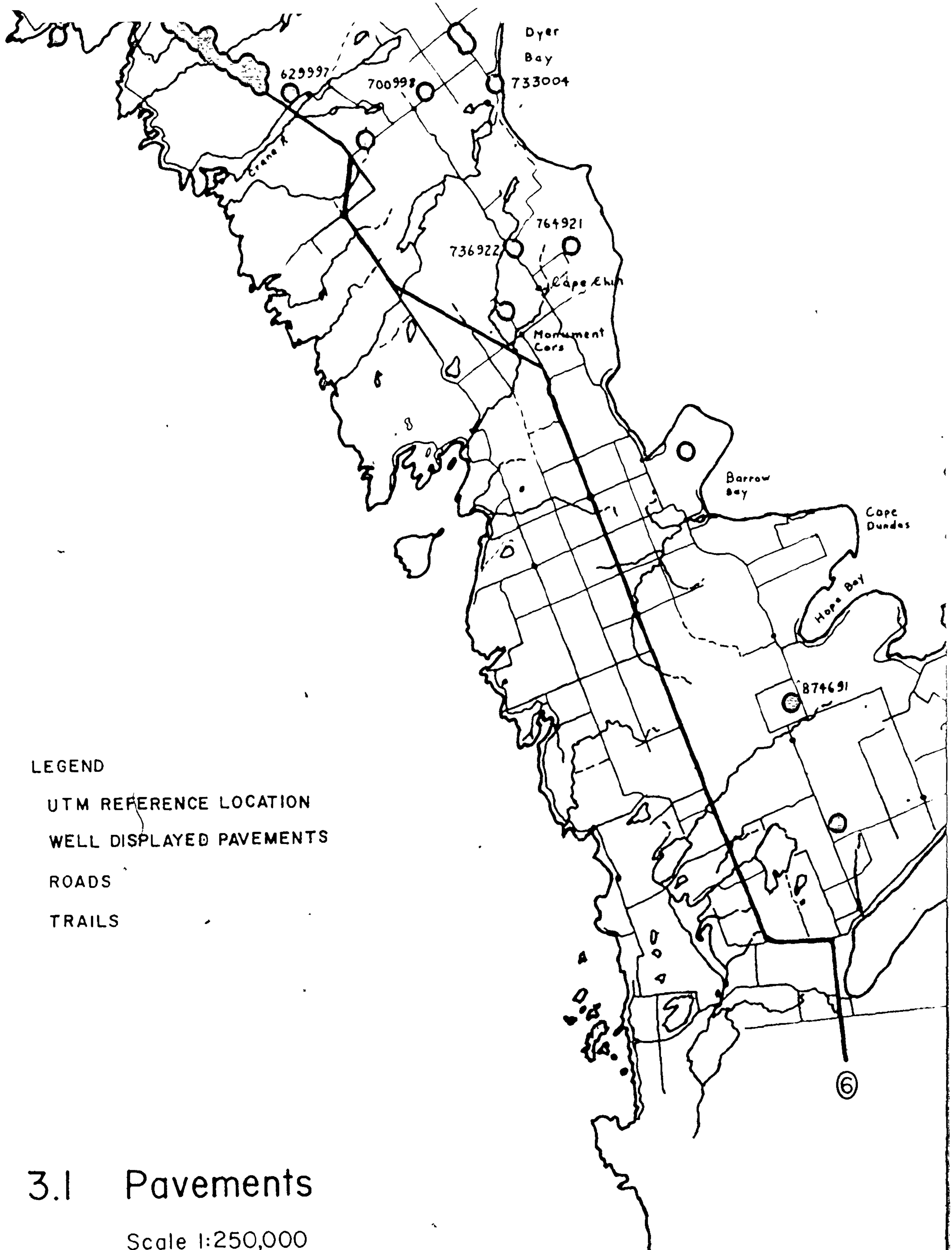
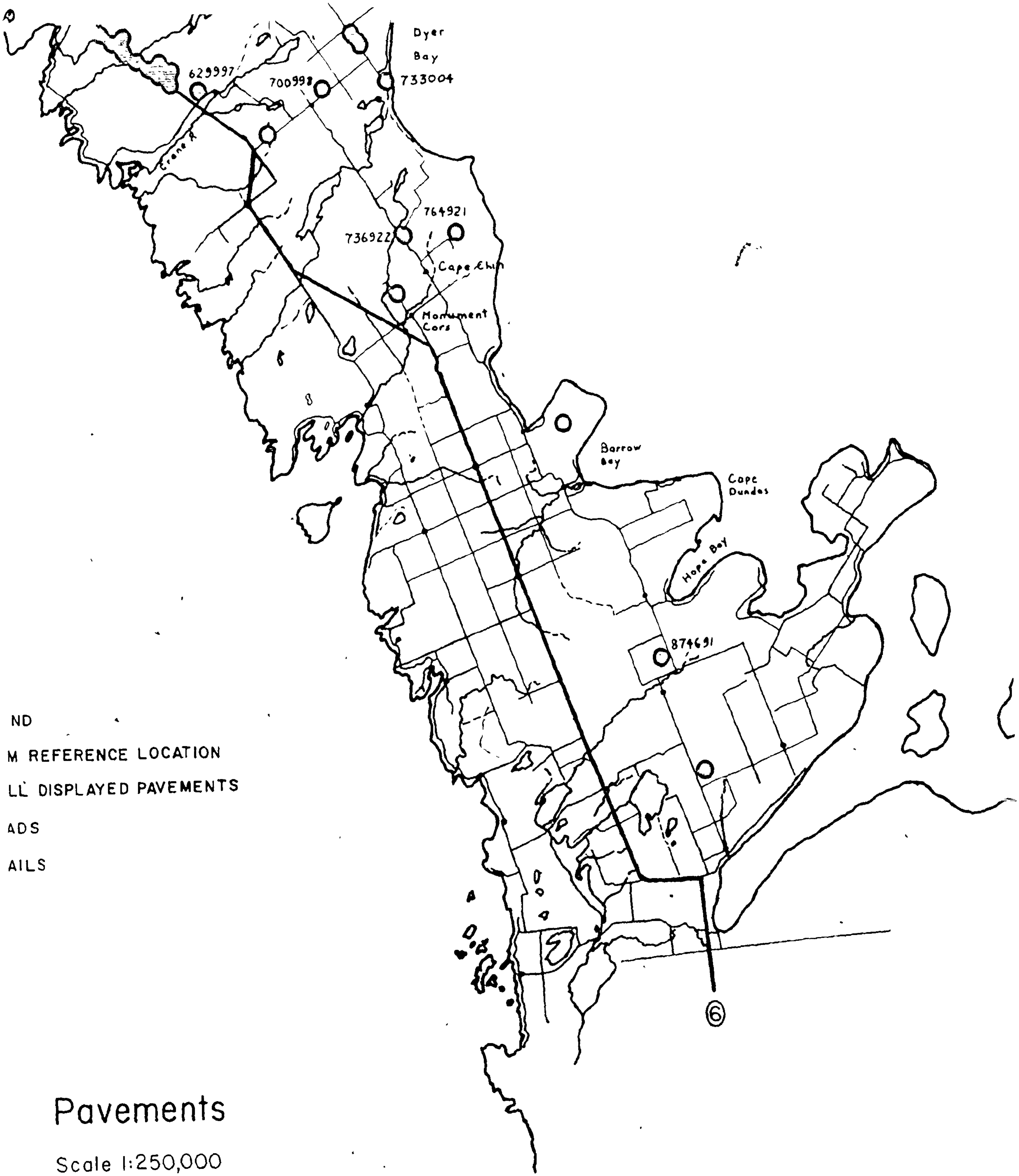


LEGEND

736922	UTM REFERENCE LOCATION
O	WELL DISPLAYED PAVEMENTS
———	ROADS
- - - -	TRAILS

FIGURE 3.1 Pavements

Scale 1:250,000



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M REFERENCE LOCATION

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Pavements

Scale 1:250,000

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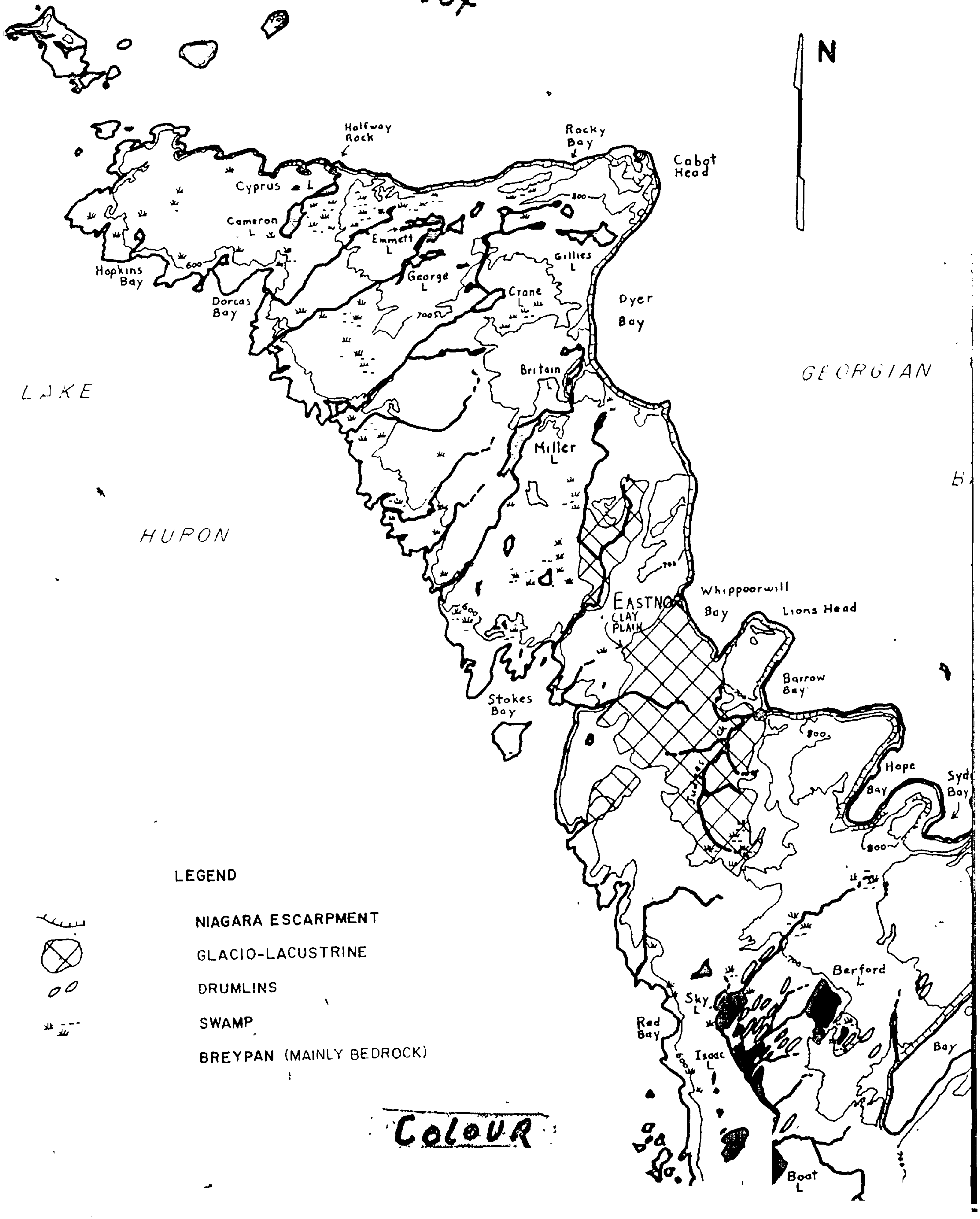
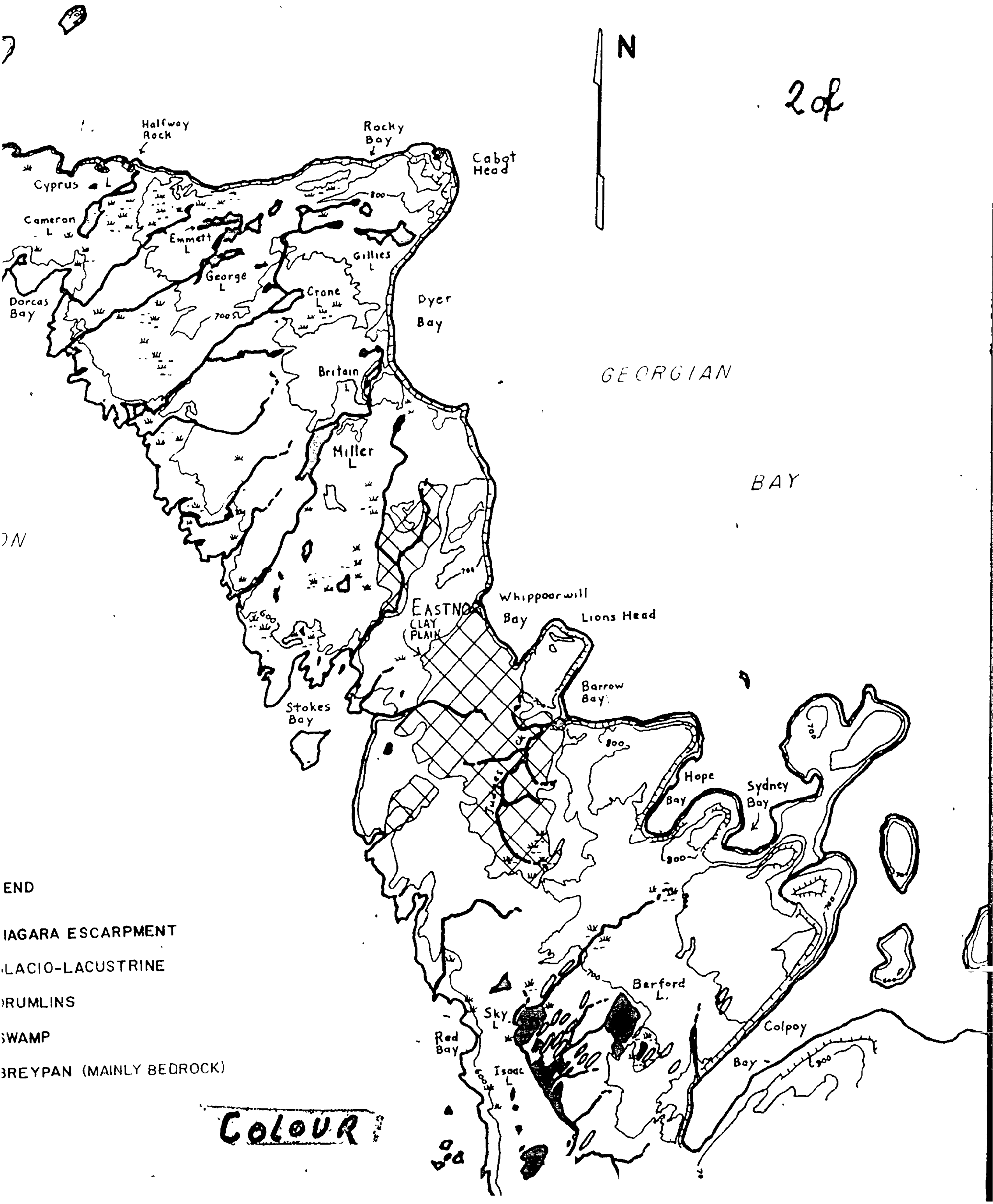
COLOUR

1 of


N
Halfway Rock
Rocky Bay
Cabot Head
Cyprus L
Cameron L
Emmett L
Gillies L
Hopkins Bay
Dorcas Bay
George L
Crane L
Dyer Bay
GEORGIAN
LAKE
Britain L
Miller L
HURON
Whippoorwill Bay
Lions Head
EASTNOR CLAY PLAIN
Barrow Bay
Stokes Bay
Hope Bay
Berford L
Sky L
Red Bay
Isaac L
Boat L
Bay
LEGEND
NIAGARA ESCARPMENT
GLACIO-LACUSTRINE
DRUMLINS
SWAMP
BREYPAN (MAINLY BEDROCK)

COLOUR

2 of


N
Halfway Rock
Rocky Bay
Cabot Head
Cyprus L
Cameron L
Emmett L
George L
Gillies L
Crane L
Dorcas Bay
Dyer Bay
Britain L
GEORGIAN
BAY
Miller L
ON
Whippoorwill Bay
Lions Head
EASTNOR CLAY PLAIN
Barrow Bay
Stokes Bay
Hope Bay
Sydney Bay
Berford L.
Sky L.
Red Bay
Isaac L.
Colpoy Bay
800
700
600
END
IAGARA ESCARPMENT
LACIO-LACUSTRINE
RUMLINS
SWAMP
BREYPAN (MAINLY BEDROCK)

COLOUR

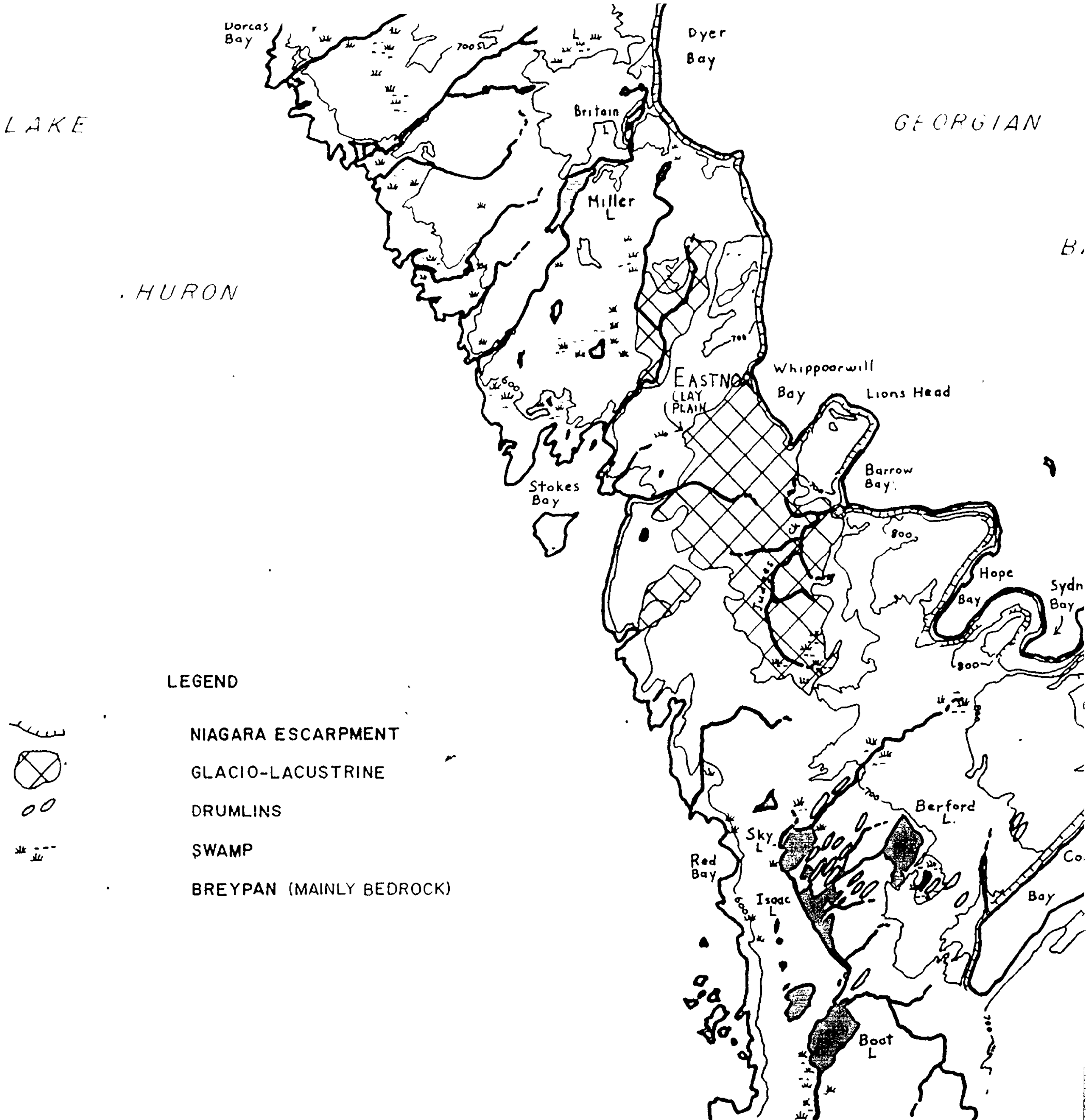
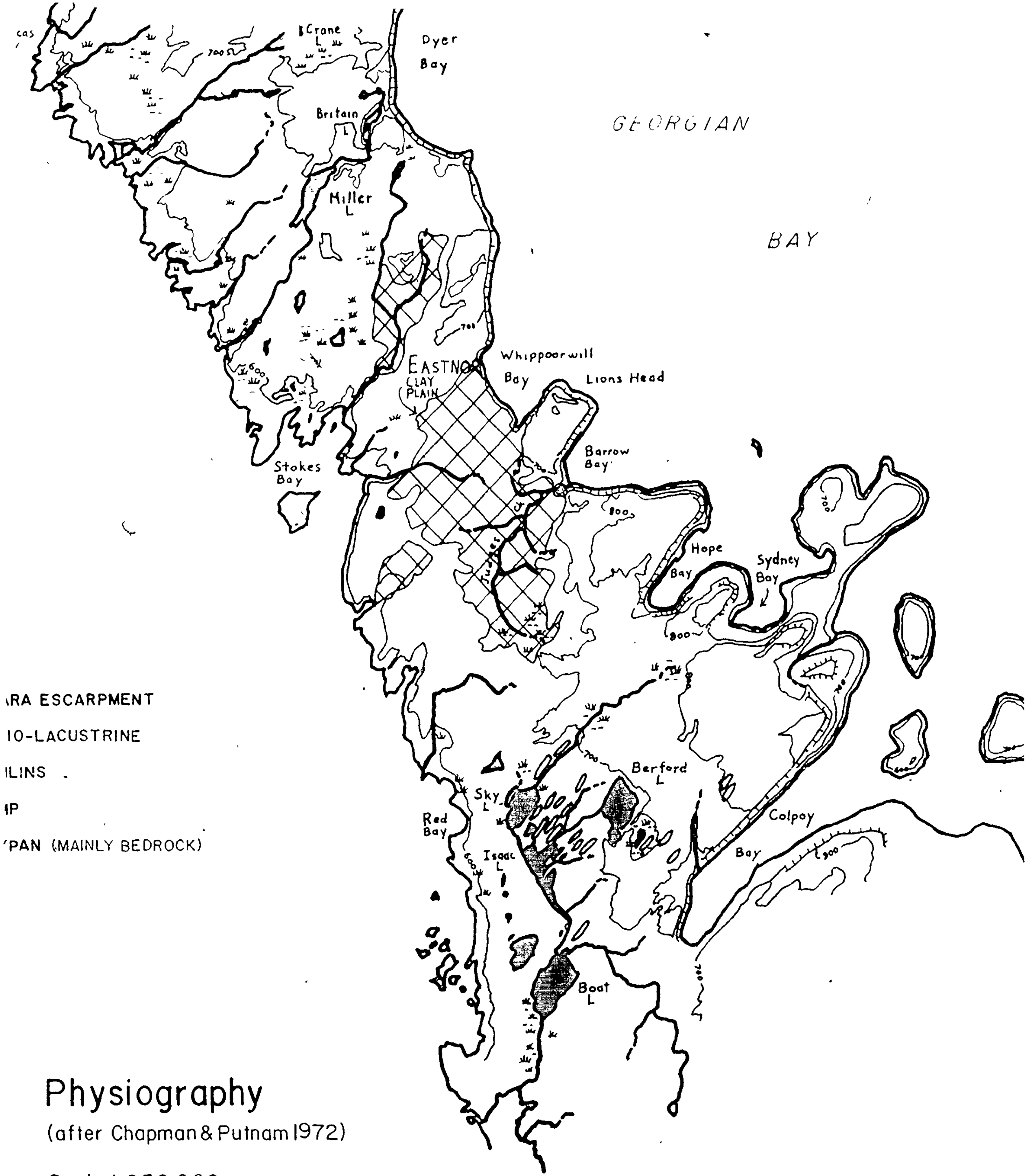


FIGURE 2.4 Physiography

(after Chapman & Putnam 1972)

Scale 1:250,000

COLOUR



Physiography

(after Chapman & Putnam 1972)

Scale 1:250,000

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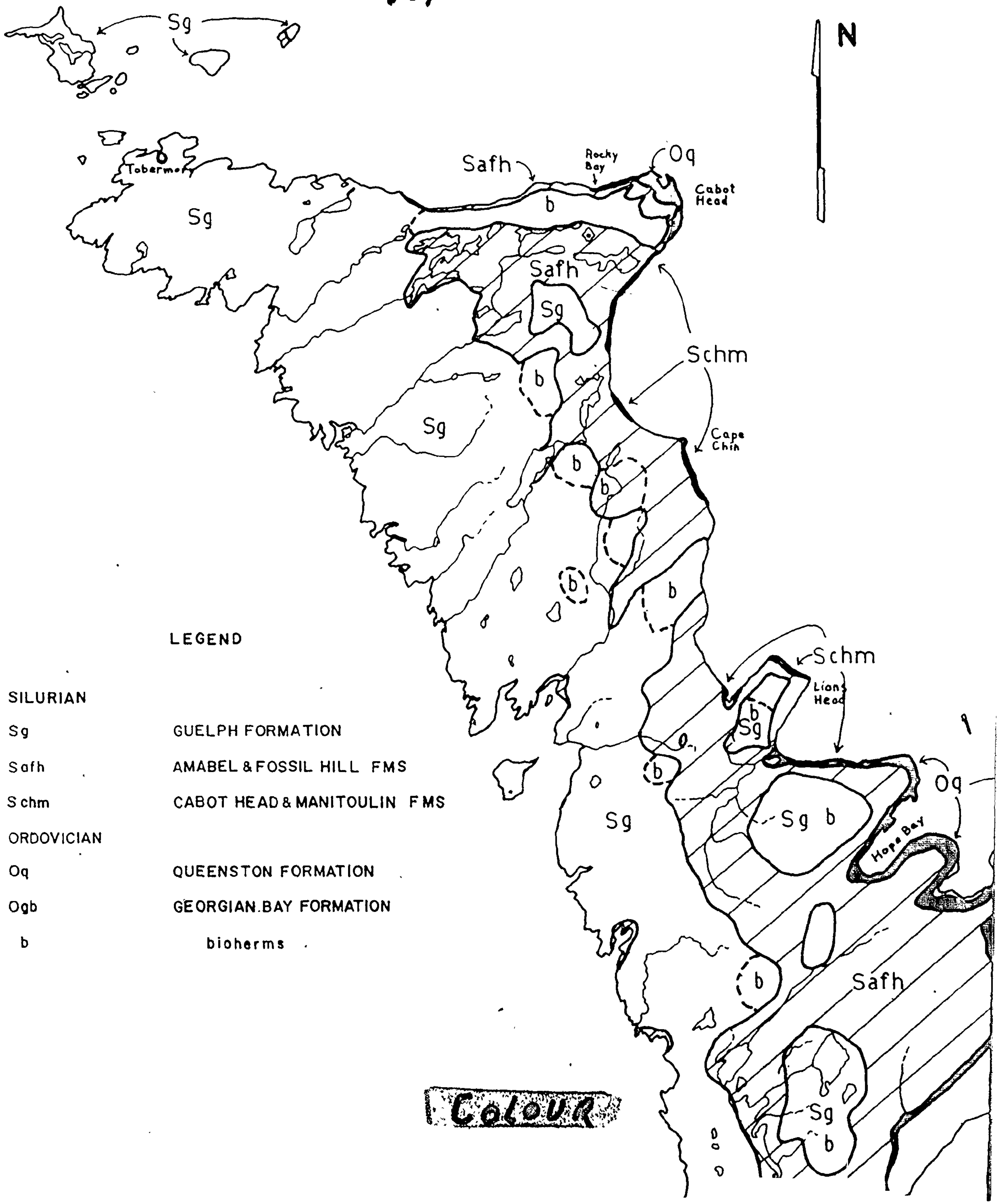
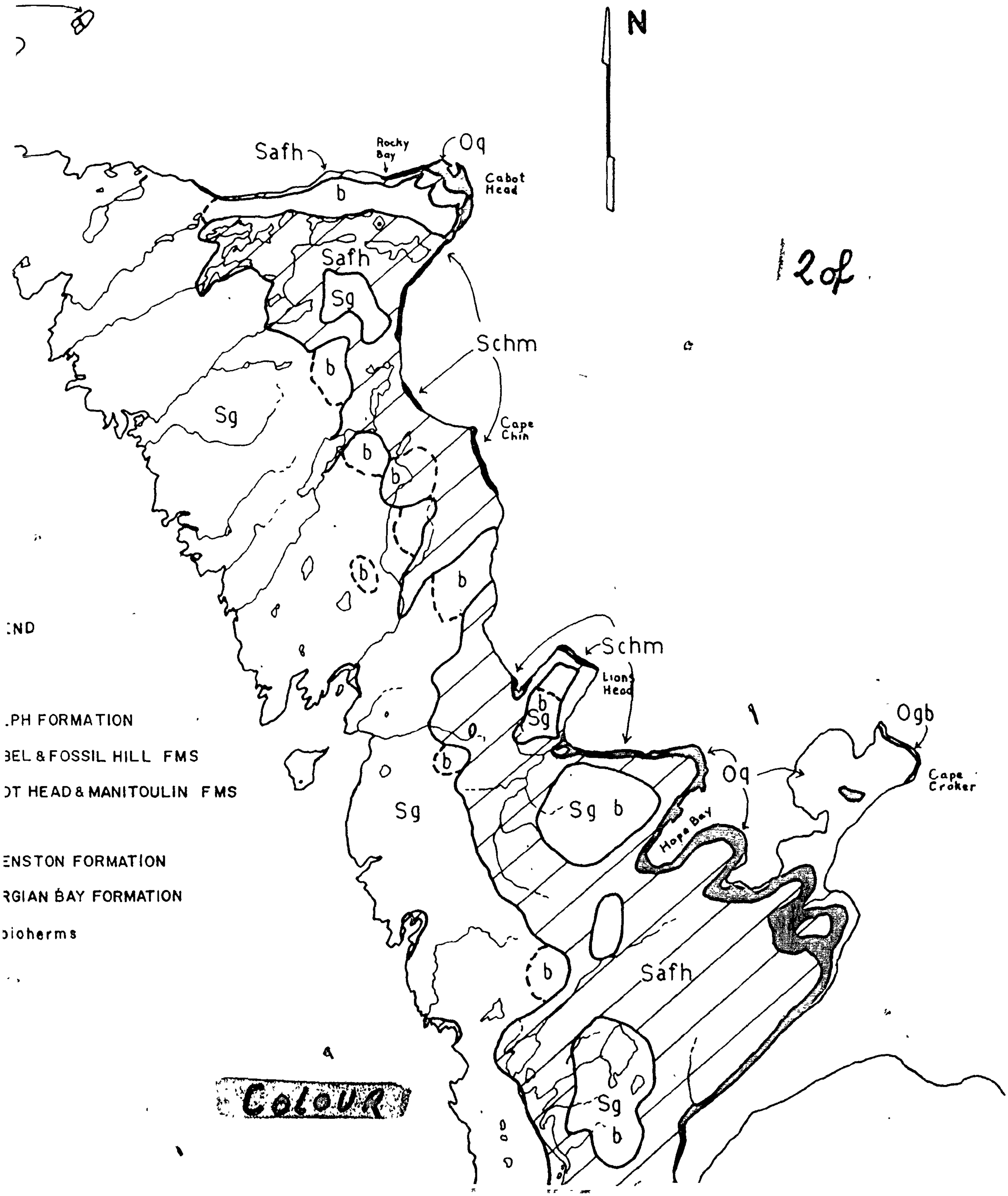
1 of


N
Sg
Tobermory
Safh
Rocky Bay
Oq
Cabot Head
b
Safh
Sg
Schm
b
Sg
Cape Chin
b
b
b
b
Schm
Lions Head
b
Sg
Oq
b
Sg
Sg b
Hope Bay
Safh
b
Sg
b
LEGEND
SILURIAN
Sg GUELPH FORMATION
Safh AMABEL & FOSSIL HILL FMS
Schm CABOT HEAD & MANITOULIN FMS
ORDOVICIAN
Oq QUEENSTON FORMATION
Ogb GEORGIAN BAY FORMATION
b bioherms

COLOUR


N
Safh
Rocky Bay
Oq
Cabot Head
b
Safh
Sg
Schm
b
Sg
Cape Chin
b
b
b
b
Schm
Lions Head
b
Sg
b
Oq
Ogb
Cape Croker
Sg
Sg b
Hope Bay
b
Safh
Sg
b
:ND
.PH FORMATION
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)T HEAD & MANITOULIN FMS
ENSTON FORMATION
RGIAN BAY FORMATION
bioherms

2 of

COLOUR

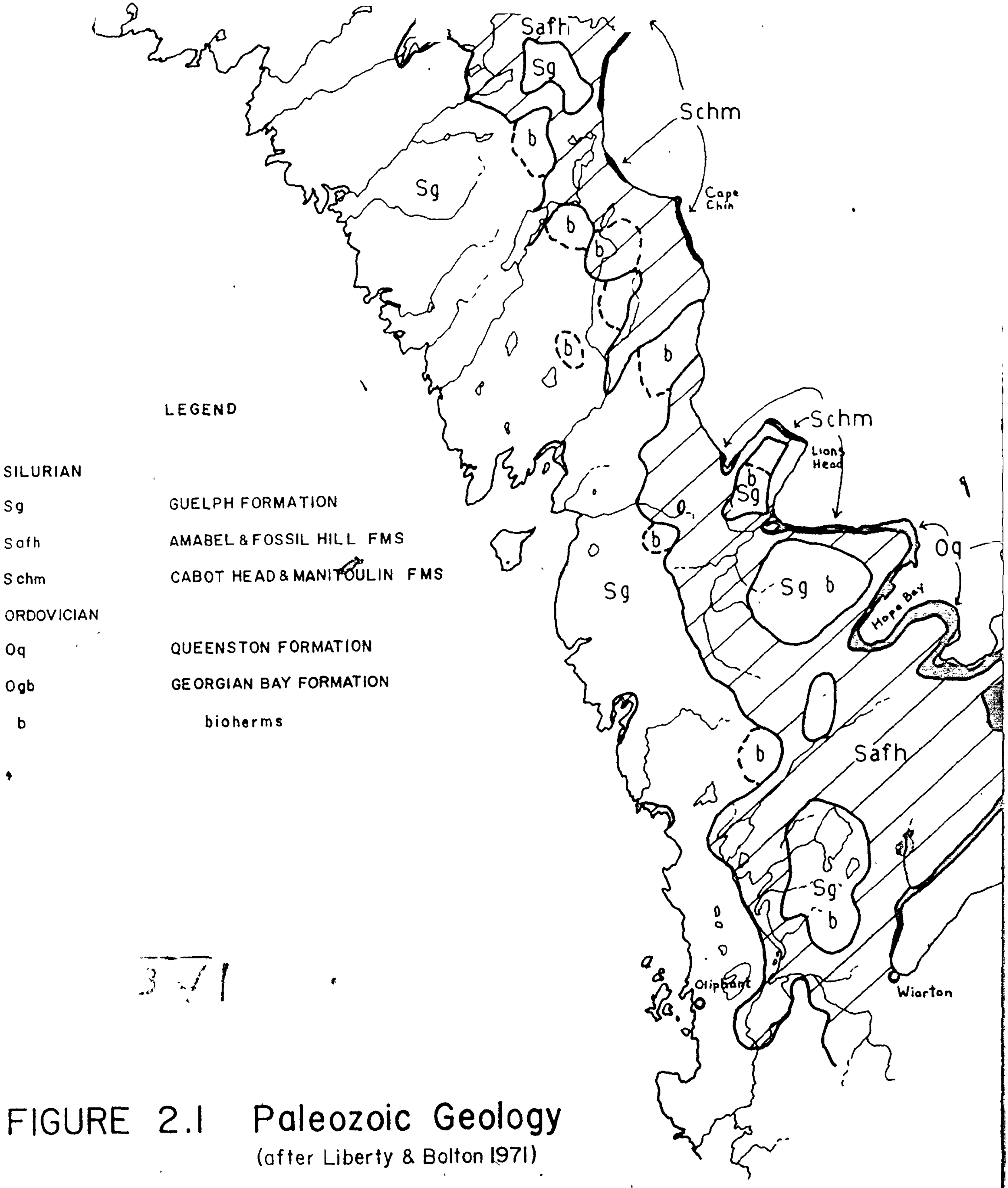
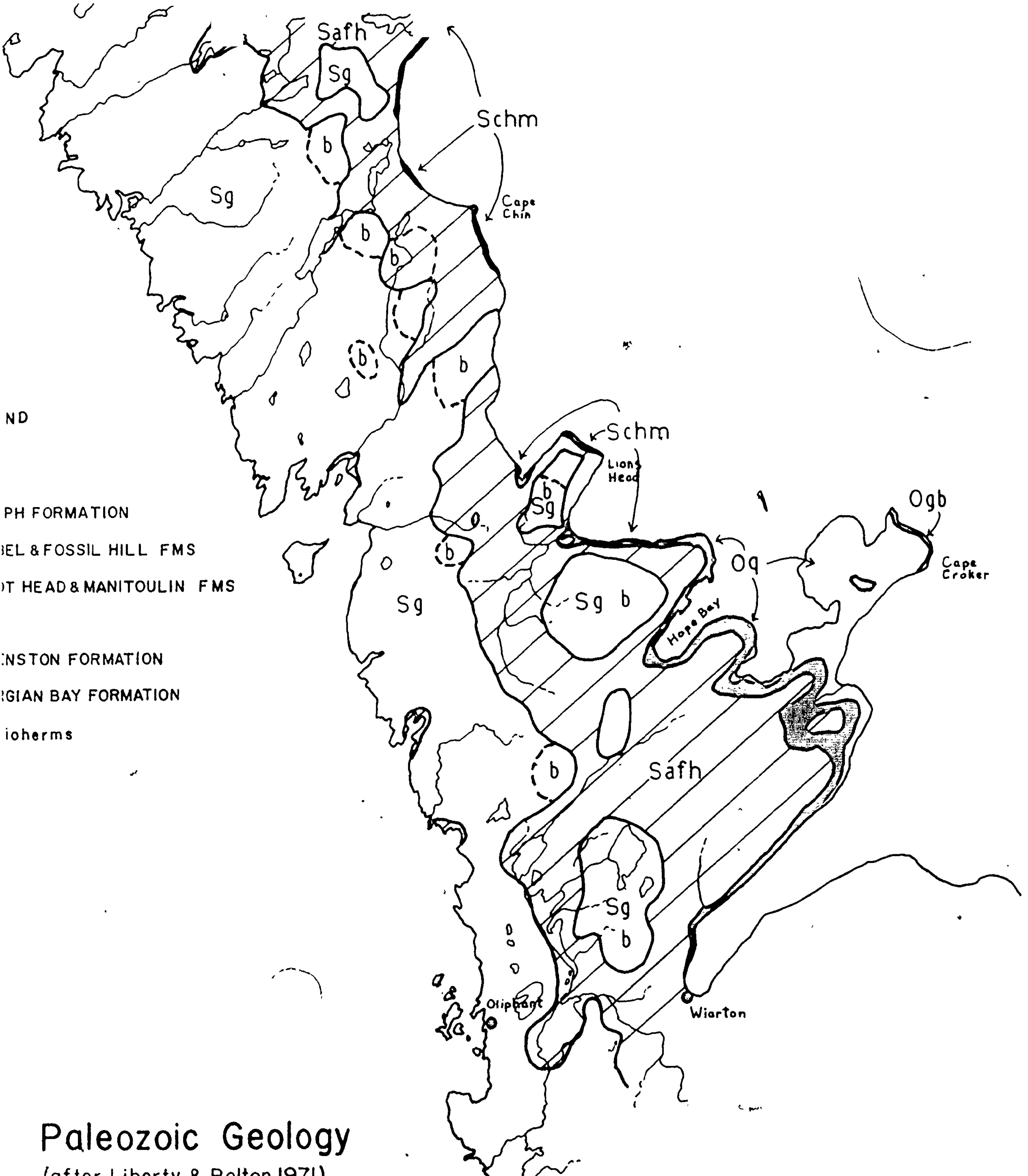


FIGURE 2.1 Paleozoic Geology
(after Liberty & Bolton 1971)

Scale 1:250,000



Paleozoic Geology

(after Liberty & Bolton 1971)

Scale 1:250,000

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