KARST DEVELOPMENT IN ORDOVICIAN CARBONATES:

Western Platform of Newfoundland

by

Marika Sarolta Karolyi, BSc.

A Thesis

Submitted to the Faculty of Graduate Studies in Partial

Fulfilment of the Requirements for the Degree

Master of Science

McMaster University

December 1978.

KARST DEVELOPMENT IN ORDOVICIAN CARBONATES:

Western Platform of Newfoundland

MASTER OF SCIENCE (1979) McMASTER UNIVERSITY

(Geography) Hamilton, Ontario

TITLE: Karst development in Ordovician carbonates: Western Platform of Newfoundland

AUTHOR: Marika Karolyi (BSc. McMaster University)

SUPERVISOR: D.C. Ford
Professor of Geography

NUMBER OF PAGES: VIII, 171

ABSTRACT

The Appalachian fold belt system in Newfoundland is divided into three tectonic divisions: Western Platform; Central Mobile Belt; Avalon Platform. Rocks of the Western Platform range in age from Precambrian to Carboniferous. Major karst areas are found there in Ordovician and Carboniferous rocks. Karst features of the study area(Goose Arm to Bonne Bay Big Pond) are in the Ordovician carbonates of the undivided St. George and Table Head Formations, covering a few hundred square kilometers. Features include karren, sinkholes, sinking streams, and karst springs, caves and other solutional and collapse features.

In the study area multiple fold and faulting episodes complicate the geology. Extensive and probably repeated glaciations have produced rugged terrane with U-shaped valleys and as much as 300m relief on the carbonates. There is variable but thick till cover. A class or classes of ice-scoured closed depressions with internal drainage are recognized. Postglacial karst forms are limited to varieties of karren (mainly littoral), small sinkholes, and cave systems that are inaccessively small in most instances. Distribution of all karst features is highly irregular.

Hydrologic patterns follow fluvial, fluviokarstic and holokarstic drainage. Large number of sinking ponds have seasonal overflow channels. The ground water drainage routes are generally short and shallow, with varied hydraulic gradients. Few instances of ground water route integration to regional springs is found.

The water chemistry of the area displays a tight normal distribution of hardness. This is attributed to the ponding effect. Seasonal trends show an overall increase in total hardness and other parameters, with

some ponds showing linear increases and others cyclic variations.

Karst type and distribution is complex and irregular, but both glaciokarstic and karstiglacial development is present. The majority of karst forms point to karstiglacial development where previous karst forms have been modified by ice. Karstification is controlled by geology, rock lithology, hydraulic gradients and glacial scour and infill. Karstic processes continue to operate today, modifying the scoured basins and creating new karst forms.

ACKNOWLEDGEMENTS

Many special thanks are extended to Dr. Derek C. Ford, my supervisor, for his advice, suggestions and encouragements throughout this study.

I owe many thanks to Dr. David Kobluk who in Dr. D.C. Ford's absence for a year, has provided encouragements and help in sections of the thesis, and who provided geologic advice during the field season of 1977.

Appreciation and thanks are also extended to Gery Sweet in helping with the 1976 field work, and Doreen Bourque was helpful and persevered the field season of 1977 with long hikes and teadious water sampling proceedures.

Thanks are due to Tom Miller who developed the MILCHEM program, and let me use it for the Newfoundland data. Assistance and cooperation is acknowledged and appreciated from BOWATER of Corner Brook, who allowed access to their land and the use of their air-photographs.

Special thanks are due to my husband, Doug, who gave constant encouragement throughout this study, and for the endurance of the long periods of time I spent away from home in preparation of this thesis. Without his help this work would not have been possible.

TABLE OF CONTENTS

ACKNOWLEDGEMENT -- i

TABLE OF CONTENTS-- ii

LIST OF FIGURES -- iii

LIST OF TABLES -- Vi

ABSTRACT -- Vii

CHAPTER I. INTRODUCTION -- 1

Ia -- Purpose of study -- 1

Ib -- Selection of study area -- 3

Ic -- Physiography of the study area -- 4

Id -- Karst: a review -- 11

Id-1- Karst in glaciated terranes -- 14

CHAPTER II. GEOLOGY, STRATIGRAPHY, AND GLACIATION OF THE WEST COAST OF NEWFOUNDLAND -- 21

IIa -- Geology -- 21

IIb -- Stratigraphy -- 22

IIb-1- Table Head Formation -- 24

IIb-2- St. George Formation -- 28

IIb-3- Study area -- 35

IIc -- Glaciation -- 32

IIc-1- Study area -- 35

CHAPTER III. MODERN KARST DEVELOPMENT IN ORDOVICIAN CARBONATES ---- 38

III -- Introduction -- 38

IIIa -- Small scale karren forms -- 38

IIIa-1- Summary -- 55

IIIb -- Classification and morphology of closed depressions ---- 58

IIIb-1- Post-glacial collapse dolines in till and bedrock ------ 59

IIIb-2- Single solutional dolines in bedrock -------------------- 62
IIIb-3- Elongate, probable ice scoured dolines ------------------ 63
IIIb-4- Complex glaciokarstic forms ----------------------------- 65
IIIb-5- Summary and discussion --------------------------------- 67
IIIc -- Caves -- 71
IIIc-1- Study area --- 71
IIIc-2- Summary -- 75
CHAPTER IV. KARST HYDROLOGY ------------------------------------ 76
IV-1- Introduction -- 76
IV-2- Regional development of karst hydrologic systems -------- 78
IV-3- Groundwater regimes ------------------------------------- 93
IV-4- Analysis -- 98
IV-5- Conclusions --- 107
CHAPTER V. WATER CHEMISTRY ------------------------------------- 109
V-1- Introduction --- 109
V-2- The sampling programme:Design and methods -------------- 112
V-3- Chemical characteristics - Results and discussion ------- 113
V-3-1 Chemical water characteristics of the 1977 data set ----- 114
V-3-2 Behaviour of water over time --------------------------- 118
V-4-1 The problem of Moose Spring ---------------------------- 135
V-5- Modeling the seasonal hydrochemistry of Goose Arm Brook-- 139
V-6- Comparison with other studies of Candian karst waters --- 143
Summary of chemical data for Newfoundland --------------- 145
CHAPTER VI. DISCUSSION AND CONCLUSIONS ------------------------ 155
VI-2- Suggestion for further research ------------------------ 158
APPENDIX A. A SUMMARY OF KNOWN KARST AREAS IN NEWFOUNDLAND ---------- 159
REFERENCES -- 161

LIST OF FIGURES

Figure Number		Subject	Page
1	. . . .	Location Map of the West Coast of Newfoundland ...	(in pocket)
2	. . . .	Topographic Zones of the Western Platform	5
3	. . . .	The Climate of Newfoundland	6
4	. . . .	Long Range Mountain Complex	8
5	. . . .	Pavement Outside the Study Area	19
6	. . . .	Newfoundland Carboniferous Basin	23
7	. . . .	Undivided Cambrian and Ordovician Rocks	26
8	. . . .	Stratigraphic Subdivision of Cambrian and Ordovician Carbonates of the Great Northern Peninsula	27
9	. . . .	Limestone Breccia Units and the Underlying Carbonates	31
10	. . . .	Speculative Ice Marginal Positions During Deglaciation of Southwestern Newfoundland	34
11	. . . .	Circular Depressions with Undercut Surfaces	42
12	. . . .	Pit Development Along Joints and Inclined Surfaces	45
13	. . . .	Pits and Hollows Around Lakes and Streams	48
14	. . . .	Coastal Karren Development	50
16	. . . .	Karren Forms: Trittkarren and Deckenkarren	54
17	. . . .	Rinnenkarren or "drape folds"	56

Figure Number	Subject	Page
18	Collapse Sink of Nameless Pond and The Spring Location of the Pond	61
19	Map of the Study Area	(in pocket)
20	An Example of a Funnel Shaped Sink Such as Round Sink #1	64
21	Map and Cross-Section of Bottomless Pond, Nameless Pond and Brown's Pond	66
22	Canal Pond Area and the Underground Connection	68
23	Modification of the Karst Process By Glacial Scour: A Model	70
24	Bedding-Plane Cave at Brown's Pond	74
25	Sink point of Round Pond	81
26	Sink point and spring Location of Long Pond and Round Pond System, and the Spring Location and Structure of Pond R2..........................	82
27	Overflow Channel and Sink point of Troy Pond and an Overview of Bonne Bay Big Pond	85
28	Bottomless Pond	87
29	Canal Pond and Moose Springs	92
30	Cross Section of the Canal Pond Cave System	95
30A	Stage Record Data of Nameless Pond Spring	97
31	Model 1	100
32	Model 2	103
33	Histogram of Hydraulic Gradients and Flow Path Length	105

Figure Number	Subject	Page
34	The Graph of HCO_3^- and Ionic Strength..................	115
35	The Graph of C_a^{++} and HCO_3^-	116
36	The Graph of and	117
37	The Graph of C_a and SIC	119
38	The Graph of pH and SIC	120
39	Total Hardness Histograms from Several Distinct Environments in Canada.............................	121
40	Graph of Temperature against Time....................	123
41	Graph of Total Hardness against Time.................	124
42	Graph of SIC against Time............................	125
43	Flood Water Effect at Nameless Pond, and Sample site withrespect to the collapse sink	127
44	Groundwater Flow Path and Chemical Characteristics of Long Pond and Round Pond Systems..................	131
45	Possible Drainage Routes and Spring Temperatures......	136
46	Inferred Drainage Routes from Sophies Pond and Lost Pond	137
47	"Holding Tanks" Model.................................	141
48	Flowchart of the Water Movement from the Basin and the Holding Tanks	142

LIST OF TABLES

Table 1 .... Stratigraphic Subdivision, Great Northern Peninsula 25

Table 2 .... Dye Tracing Results 98

Table 3 .... Table of Hydraulic Gradients 102

Table 4 .... Groundwater velocity 106

Table 5 .... Nameless Pond and its Spring Temperatures 129

CHAPTER I

INTRODUCTION

Ia. Purpose of Study

The Paleozoic limestones found on the western Platform of Newfoundland are extensively karstified. Karst landform development and drainage has been modified and controlled by rock lithology, structure and regional Pleistocene glaciation.

The study of karst landforms and their development is important from a number of viewpoints. Karst features divert surface water into complex underground systems; the understanding of hydrological processes, the movement of ground water, and evaluation of a karstified carbonate area as a potential reservoir aquifer therefore requires an understanding of karst forms and their function, and degree of development.

This study represents the first detailed description of karst landforms present on the western platform of Newfoundland, and in particular the Bay of Islands area, between Goose Arm and Bonne Bay Big Pond (Fig. 1). It is a preliminary analysis, because only one full summer (1977) was available to study the existence of karst features and the geochemistry of carbonate-waters. It is a unique area for a regional karst study, because of the area's complex geologic structure and particularly the extensive glacial modification. Newfoundland possesses a cool northern climate; according to a Keoppen-type climatic description it is Dfc. (or humid boreal climate). This study describes the pre-Wisconsinan karst development and preservation, and the extent and degree of development of modern karstification and some of the controlling factors.

Previous reference to the presence of karst features in Newfoundland is fragmentary, and is found in only a few geologic reports where the presence of underground drainage is noted (Weitz, 1953; Cumming, 1968; Lilly, 1963). The purpose of this study is to: 1) identify and describe the existing karst landforms, 2) describe proven and inferred patterns of modern karst ground water drainage, 3) determine the extent to which forms and drainage are controlled by rock lithology, structure and Pleistocene glaciation, and 4) a preliminary analysis of solvent behaviour of the different classes of water present, in comparison with other areas.

Ib. Selection of Study Area

The study area comprises approximately 200 km^2 of carbonate rocks of Ordovician age, found north of Corner Brook, between Goose Arm, Old Mans Pond, and Bonne Bay Big Pond (Fig. 1). The sedimentary sequence within this area is some 1220 m thick, including the Table Head Formation, and the underlying St. George Group (Whittington & Kindle, 1963; 1968; Cummings, 1968; Weitz, 1953; Kluyver, 1975; Schuchert and Dunbar, 1934).

The section of carbonate rock in the Goose Arm and Bonne Bay Big Pond area is well suited for the study of karst development because several major controlling factors are present to modify karst processes: 1) presence of considerable thickness of soluble carbonate rock (@1220 m), 2) complex geologic history, where multiple folding episodes, deformation, joint and fault development, and variable rock lithology exerts a controlling influence on karstification, 3) high topographic relief, providing high hydraulic gradients, 4) extensive Pleistocene glaciation which has modified the topography by eroding, infilling, and deranging drainage.

A considerable thickness of carbonate rock is essential for extensive ground water circulation, and for the development of underground drainage routes and explorable caves. Structural geology is important because fractures, joints, etc. are going to provide the possible drainage routes for water. Other controlling influence is exerted by rock lithology, where impure limestones, shaly seams, insoluble residues etc. will inhibit solution.

Ic. Physiography of the study area

Newfoundland is situated on the extreme east coast of Canada, at the northern extremity of the Appalachian Mountain Belt.

The island may be divided up into three tectonic units; Western Platform, Central Mobile Belt, and the Avalon Platform, of which the Western Platform may be divided further into three main topographic zones: mountains, lowlands and plateaus (Fig. 2).

The west coast of the island supports a thick forest cover; the vegetation ranges from tundra to open woodland type (Fig. 3). Most of the land is unsuitable for agriculture mainly because of the lack of thick soil, thick glacial till deposits and minor amounts of lowlands. The west coast has a cool northern climate, with high annual precipitation, small number of frost free days and low average summer temperatures (Fig. 3).

Mountains

The topography of the west coast is dominated by the Long Range Mountain Complex, which runs the length of the island from north to south. This Mountain system is cut by numerous faults, of which the Long Range Fault is the longest; it forms a prominent scarp margin east of the Codroy Lowlands (Fig 4A,B). The Long Range Mountains rise between 335 m - 807 m to a flat, glaciated surface, which in places is covered with erratics. North of Bonne Bay the Long Range Mountain Complex rises to an elevation of 806 m at Gros Morne. The summit of the mountain is mainly a dissected. plateau, with steep sides. Western Brook Pond, a little to the north exemplifies this, where a spectacular U-shaped valley, now occupied by

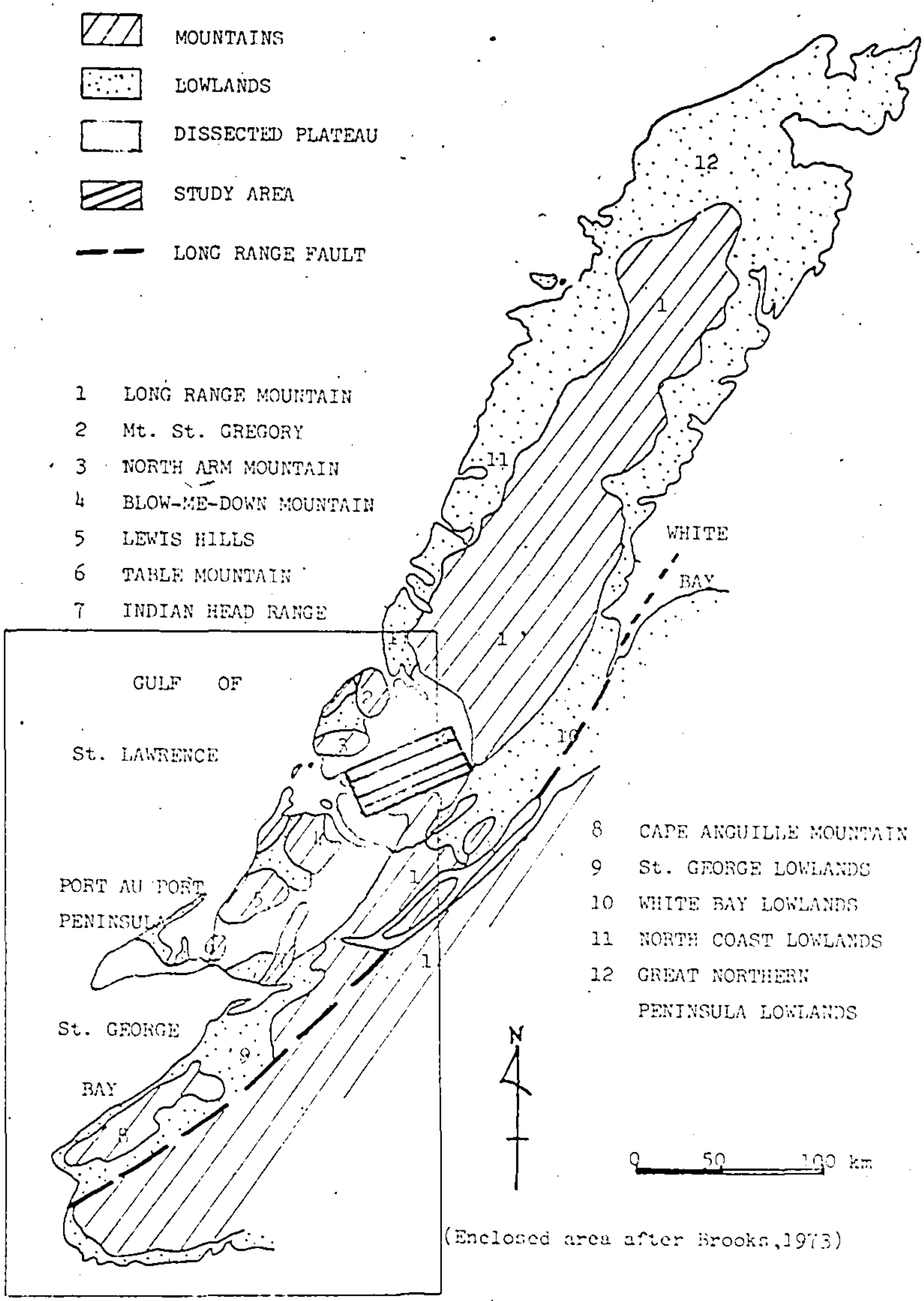
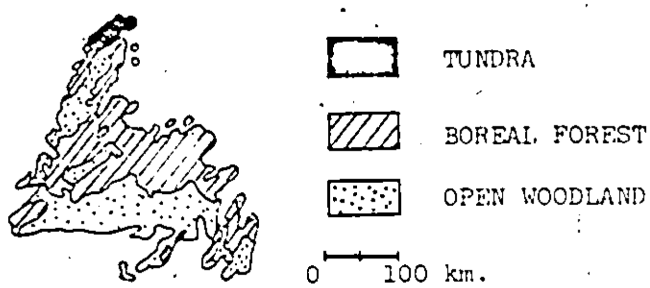
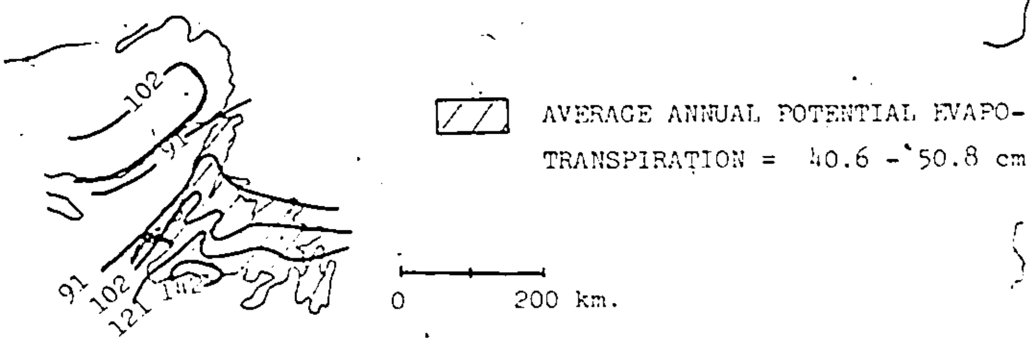


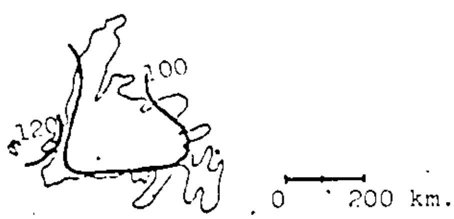
Fig. 2 TOPOGRAPHIC ZONES OF THE WESTERN PLATFORM



a) VEGETATION



b) AVERAGE ANNUAL PRECIPITATION (cm)



c) FROST FREE PERIOD (days)

	MIN.		MAX.			MIN.		MAX.	
DECEMBER	-10	- 5	- 5	0	JUNE	5	10	15	20
JANUARY	-15	- 5	-10	0	JULY	10	15	15	20
FEBRUARY	-15	-10	-10	0	AUGUST	10	15	15	20
MARCH	-10	- 5	- 5	5	SEPTEMBER	5	10	15	20
APRIL	- 5	0	0	5	OCTOBER	0	5	5	12
MAY	- 5	0	5 0	5	NOVEMBER	- 5	0	0	10

d) AVERAGE DAILY TEMPERATURE (°C)

Fig. 3 THE CLIMATE OF NEWFOUNDLAND (Nat. Atl. of Canada 1974)

Fig. 4

A. The Long Range Mountain Complex forms a prominent scarp margin east of the Codroy Lowlands. The mountain chain forms a dissected plateau with steep sided U-shaped valleys.

B. The Long Range Mountain Complex on the Great Northern Peninsula at Western Brook Pond. The lake is bounded by cliffs 610m high above water level. This inlet represents one of the glacially scoured U-shaped valleys.

a lake, is bounded by cliffs that rise 610 m above water level (Fig. 4). All along the western parts of the island impressive mountain fronts and deep glacially scoured valleys are present.

The southwestern coastal areas, between Bonne Bay and Codroy River, have several separate massives such as the Cape Anguille Mountains, Indian Head Range, Table Mountain, Lewis Hills, Blow-me-down Mountain, and North Arm Mountain, all rising to a flat plateau-like surface. Some of these mountains are parts of transported klippen, and are composed of igneous material (Rogers and Neale, 1963; Poole, 1967; Stevens, 1970).

The mountain highlands present a rugged topography with steep slopes and flat plateau surfaces. Glaciation has cut and eroded extensive U-shaped valleys in mountain sides, now occupied by misfit streams. The coastal area shows numerous fiord-like indentations, such as the Bay of Islands area, flanked by steep-sided plateaus.

Lowlands

The lowlands of the Codroy and St. George Bay area consist of a rolling hilly topography, developed in Mississippian and Pennsylvanian sediments (Knight, 1973; Baird & Cote, 1964; Baird, 1959; Baird, 1951). Narrow strips of lowlands are found at several places such as the south coast of the area between Lewis Hills and Blow-me-down Mountain, Port au Port Peninsula, and the northwest coastal lowlands (Fig. 2). Lowlands with larger areal extent are found at White Bay and the Great Northern Peninsula (Fig. 2).

Beaches on the coastal section are limited to narrow gravel or boulder beaches with only small sandy areas. The Western Platform has an extensive stream network development, but only a few large rivers are present, such as the Humber River, Main River, and the Codroy River. Among the largest standing bodies of water are Grand Lake-Sandy Lake, Deer Lake, and Ten Mile Lake.

Plateaus

The plateau area of the Western Platform stretches from southern Port-au-Port Peninsula towards Bonne Bay Big Pond. Elevations in this area vary from 180 - 427 m in a mixture of flat-topped hills and steep-sided valleys.

The study area is situated at the northern end of the plateau subdivision (Fig. 2). It is characterised by a rugged hill and valley topography, with numerous lakes and streams. Elevations range from sea level to 458 m. On the west, the fiord-like arms of the Bay of Islands branches inland into North, Middle and Humber Arms (Fig. 2). The Bay of Islands, like Bonne Bay, is a submerged U-shaped valley, which has been deepened and its sides steepened by glacial erosion. The Arms show a U-shaped cross profile with their upper rims rising about 305 m asl.

The study area is bounded on the west by the Bay of Islands, on the south by Old Mans Pond, and on the north by Bonne Bay Big Pond. The largest river in the area is Goose Arm, draining a major part of the carbonate rocks. Large lakes such as Old Mans Pond, Bonne Bay Big Pond, North Lake, etc. show narrow (.5 - 2.5 meter wide) cobble to boulder beach development with very little or no fine sediments.

Extensive glaciation has produced a rugged topography, with streamlined hills, steep sided U-shaped valleys, hanging valleys, cirques, and large scoured-out depressions among other features. The scoured-out bedrock and transported till has left a deranged drainage with numerous small lakes and streams, and a highly irregular thickness of till cover. Many lakes on the carbonate rocks have no visible outlets and are drained by subterranean courses.

Id. Karst: a review

The word "karst" is German in origin and it comes from the Indo-European word "kar" meaning a rock or a stone, and the Yugoslavian/Slovenian word "kras" referring to a waterless place (Herak and Stringfield, 1972; Jennings, 1971; Sweeting, 1973).

The term "karstification" is used to indicate the process of development of caves, sinkholes or other solutional features. The study of karst includes the circulation of water in joints, fractures and cavities, and the solution of carbonate rocks to produce specific forms on the surface as well as deep underground. The process of karstification starts when aggressive water (ie; water that is capable of carbonate solution) comes in contact with soluble rock. Subsequent circulation of water in fissures leads to the development of complex underground systems. Sinkholes, uvalas, blind valleys, poljes and karren forms are all characteristic features of surficial solution (for definition of terms see Monroe, 1970).

The development of karst features depends on two main factors: 1) the presence of soluble rock at or near the surface, 2) the presence and availability of water. Solution is further dependent on climate, vegetation, and structure and lithology of the soluble rock. For karst landform development adequate solution and circulation of water, sufficient rainfall and relief are required (White, 1977).

Ideal conditions for maximum karstification are the presence of pure and massive limestone with well defined joints, fissures and cracks for effective water circulation. The strength of the limestone along with texture and porosity are also important qualities for effective karst development (Jakucs, 1977). Generally dolomites and impure thin bedded limestones, along with very porous carbonate such as chalk, do not give rise to mature karst forms.

The characteristics of surface and subsurface karst forms and the concept of karst morphology attracted the attention of researchers as far back as the middle of the 19th century. For summary of karst morphology investigations through time see the following for references: (Atkinson & Smith, 1975; Jennings, 1971; Sweeting, 1973; Herak and Stringfield, 1972; Jennings, 1972 (a); Bogli, 1971; Jennings, 1972 (b); LeGrand and Stringfield, 1973; Drake, 1974; Ford 1971 (a); Lowry & Jennings, 1974; Palmer & Palmer, 1975; Miotke, 1974; Sweeting, 1976; Pulina, 1974; Monroe, 1966; Roglic, 1974; Sweeting & Sweeting, 1970' Marker, 1976).

Karst areas around the world are not all like the classical

Dinaric karst (Sweeting, 1973; Jennings, 1971; Jennings, 1972 a; Herak & Stringfield, 1972). Many classifications of different karst types have been proposed. Some of the earliest ones were based on degree of karst development. Cvijic (1893) for example divided karst forms into holokarst (perfectly developed karst), merokarst (imperfectly developed karst), and transitional karst (in-between holokarst and merokarst). Although Grund (1914) has made a similar differentiation, Cvijic's divisions are in more popular use. Gvozdeckij (1965) distinguished different karst forms of the U.S.S.R., and added climatic variations to the classification; he distinguishes between a) covered karst, b) bare karst, c) buried karst, d) tropical karst, e) permafrost karst, f) high mountain karst, g) lowland karst, etc. Jenko (1959) stated however, that climate does not form karst, but rather it gives it specific characteristics. Sweeting (1973) classifies karst on the basis of both process and climate; her classification includes a) true karst, b) fluviokarst, c) glaciokarst, (including both arctic and permafrost karst, d) tropical karst, e) arid and semi-arid karst.

From studying regional characteristics of karst landforms a morphoclimatic theory of karst development has evolved (Lehmann 1964; 1970; Sweeting, 1966). This theory indicates that karst processes and karstic development are most rapid in the tropical hot, wet climates, and diminishes as cooler climates are approached (Balazs, 1971; 1973; Sweeting & Gerstenhauer, 1960). Certain karst forms are associated only with tropical climates such as cockpits, towers, mogotes, and cenotes. These features are not found forming in temperate regions today, and if found they are interpreted as relict features left over from past tropical climates. This prevailing morphoclimatic concept has been questioned recently by many workers (Ford, 1973; Jenning, 1972 a; Sweeting, 1976; Monroe, 1966; Roglic, 1974), and has been strongly disputed by Brooks (1976).

Limestone solution data collected over the world do not indicate such strong climatic differentiation and Sweeting (1976) concludes that "limestone solution is mainly a question of speed and length of contact (of water) with rock" (Sweeting, 1976; Pitty, 1968; Pulina, 1974; Miotke, 1974).

Generally karst areas are classed as tropical, temperate, alpine or arctic karst with typical characteristic features. The Newfoundland karst does not fit well into any one of the above classes. It has a complex glacial history in which glacial erosion played an important role in the development of the present karst features; it does not resemble alpine karst. There are no deep cave systems, elevations are lower, and there is a lack of glacially scoured and rounded pavements. The study area also does not fit the temperate type because the karst development is sporadic and the scale and distribution of closed depressions is quite atypical in characteristics.

1d-1 Karst in glaciated terranes

There is a large amount of published literature discussing karst in glaciated areas. However, most regional studies in such terranes have been limited to alpine situations (Alps, Caucasus, Rockies of Canada and the U.S.A.) to benchlands (Yorkshire, England; Burren, Eire) and scarplands (Bruce Peninsula, Anticosti Island) (Bauer and Zotl, 1972; Bauer, 1964; 1964; 1970; Droppa, 1966; Mazur, 1962; Ford, 1971 (a), Drake, 1974; Cowell, 1976).

The study area is quite unlike other temperate or alpine karst areas. There appear to be no previous studies of areas closely resembling the Newfoundland karst, with its rugged, dissected, intermontane landscape, which has received extensive multidirectional ice scour (from the east - ice was spreading from the center of the island, and from the west - ice invaded the island to some extent from the continent, (Laurentian Ice Sheet)).

Of particular interest to this study are glaciokarst and fluviokarst. Glaciokarst refers to solutional processes acting on a limestone mass which either has been or is being glaciated. Fluviokarst refers to forms that were formed by the combined action of fluvial and karst processes and display a mixture of karst and normal fluvial landforms.

Karst features found in arctic and alpine regions generally consist of bare carbonate rocks, scoured out by glacial ice and at places producing flat pavements. Solution-widened joints and fractures produce deep crevices. Bogli (1964 (a)) divides glaciokarstic surfaces into: Schichtreppenkarst (ie. stepped karst) and Rundhocker karst (ie. rounded karst). Glaciokarstic surfaces are generally described as bare, with pavements where solution has enlarged joints and fissures. Meltwater from the ice and snow may produce shafts and potholes along with enlarged bedding planes that form near-surface caves. Solution is important in the arctic (Woo and Marsh, 1977) as well as Alpine areas, since biogenic CO_2 and cold temperatures increase water aggressivity; in these areas pavements and microkarren may result. Caves may serve as important drainage routes for meltwater, but lakes are generally lacking due to underground drainage, as exemplified in the French Alps; cave development is usually extensive and very deep; 1000 m systems are common (Avias, 1972).

Alpine karst therefore differs markedly from karst in tropical or temperate regions. In tropical climates surface karst tends to be of great relief and density but bare, scoured surfaces are absent. Tower karst forms, mogotes, and cockpit depressions are typical from China, Cuba and Jamaica. In temperate areas, such as Yugoslavia, doline landscapes of lower relief predominate. Poljes are common.

Karst development in Newfoundland is found in gypsum, marble and limestone. The degree of karstification varies from high in gypsum, to moderate or low in marble and limestone. Within the study area the degree of karstification is moderate to low, although areally extensive (Karolyi, 1976 a; 1976 b; 1977).

The carbonate rocks between Goose Arm and Bonne Bay Big Pond show a rugged topography with high hydraulic gradients present. The area has been extensively glaciated, but at present a thick forest cover is found, except for mountain tops where a tundra-like vegetation exists. Bare rock occurs only on cliff faces, some mountain tops, and a few small patches around lakes.

In the study area the glacio-karstic features occur as large closed depressions, harbouring permanent lakes that drain underground. Karren forms are restricted mainly to lake margins where bare limestone is present. Pavements are found outside the study area also at Port au Port Peninsula, Gallants, and along the Great Northern Peninsula (Fig. 5). Blind valleys are not well developed as they are in temperate karsts, although several streams sink in their courses in low water stage. There are several large uvalas or complex coalescent sinkholes; some are dry, others with permanent lakes. There are no poljes. There is an open karst window at Canal Pond cave and several collapse features are also found in the area. Explorable cave passages are few and in the study area are limited to Canal Pond cave. Outside the area caves are found at Corner Brook, Link Pond area, Gallants, Port au Port, Taylors Pond area, Roddicton and the Great Northern Peninsula (Appendix A). Underground drainage within the study area is extensive but the conduit systems appear to be completely full of water and generally too small for exploration. There are large numbers of springs, of which several are of substantial size.

The area may be described as partly glaciokarstic because it has been extensively glaciated; some of the karst features such as sinks and drainage were modified subsequently by glacial erosion. The area has not been thoroughly explored yet, and it is not known if there are preglacial cave systems.

There are several small bedding plane caves which are at the surface and are a meter or two above mean lake water level height. These near-surface bedding plane caves are enlarged by meltwater and rainfall, and are explorable only for two to five meters from the entrance. Generally all underground drainage in the study area is shallow, and the distance from sink point to rising is less than 3 km. This area may

Fig. 5

Pavement development, outside the study area.

A. Extensive joint solution has separated the limestone blocks.

B. The pavement is found on a sloping surface where the overlying soil material has been removed. Frost shattering can be extensive on the exposed limestone surface.

C. Interesting karren forms found on inclined surfaces. (photo courtesy D.C. Ford).

These pavements are found on the Port au Port Peninsula.

also be described as partly fluviokarstic, since major karst forms are due to the sinking of streams and lakes.

CHAPTER II

GEOLOGY, STRATIGRAPHY, AND GLACIATION OF THE WEST COAST OF NEWFOUNDLAND

IIa. Geology

Newfoundland is the northern extension of the Appalachian Mountain Belt which consists of Paleozoic sedimentary, volcanic, metamorphic and plutonic rocks, extending 3300 km along eastern North America from Newfoundland to Alabama (Poole, 1977; Williams et al., 1972; Wilson, 1966; Williams, 1964; Williams, 1971; Williams & York, 1972).

Thick miogeosynclinal sedimentary sequences on the west coast of Newfoundland are overlain by Cambrian and Ordovician sediments. These were deformed, intruded, uplifted and eroded during the Appalachian Orogeny. Several "klippen" transported from the east now overlie younger sedimentary rocks on the Western Platform (Tuke, and Baird, 1967; Kay, 1966; Neale et al., 1974).

The Western Platform is the focus of this study because it contains the bulk of carbonate deposits. It is part of the St. Laurence Platform, which in the Ordovician was the site of continuous shelf carbonate deposition. During the early Ordovician, dolomites were deposited along the northwest margin, such as the St. George area. On the southeast side, which was then oceanward, carbonate breccias were developed, probably as slope deposits (Poole, 1967; 1977; Hubert et al., 1976). In the middle Ordovician, limestones (Table Head Formation) were deposited on an uplifted and karstified topography of lower Ordovician age (Kluyver, 1975; Poole, 1977; Knight, 1976; 1977; Collins, et al., 1973; 1975). The paleokarst surface is of considerable current interest to economic geologists.

The Carboniferous rocks of Newfoundland occur in two depositional basins: the Codroy-Bay St. George Basin at the southwest, and the Deer Lake-White Bay Basin at the northeast (Fig. 6). Karst features are found in the Middle and Upper Mississippian Codroy & Deer Lake Groups. For further discussion of the deposition, structure and stratigraphy of the rocks found in these basins see McArthur & Knight, 1974; Baird & Cote, 1964; Fong, 1974; Knight, 1973; Fong & Douglas, 1975; Knight, 1975; Fong, 1976 (a) & 1976 (b); Knight, 1976. This study only deals with karst landforms found in the Ordovician carbonates.

Limestone deposits in Newfoundland are also found in the eastern and central parts of the island, but it is on the western parts of the island that the largest, most extensive, and commercially attractive deposits occur.

IIb. Stratigraphy

Of the two series of carbonate rocks on the Western Platform, the most extensive are the Cambrian and Ordovician carbonates, of which the Table Head Formation and the St. George Group comprise the thickest section. The Middle Ordovician Table Head Formation and the Lower

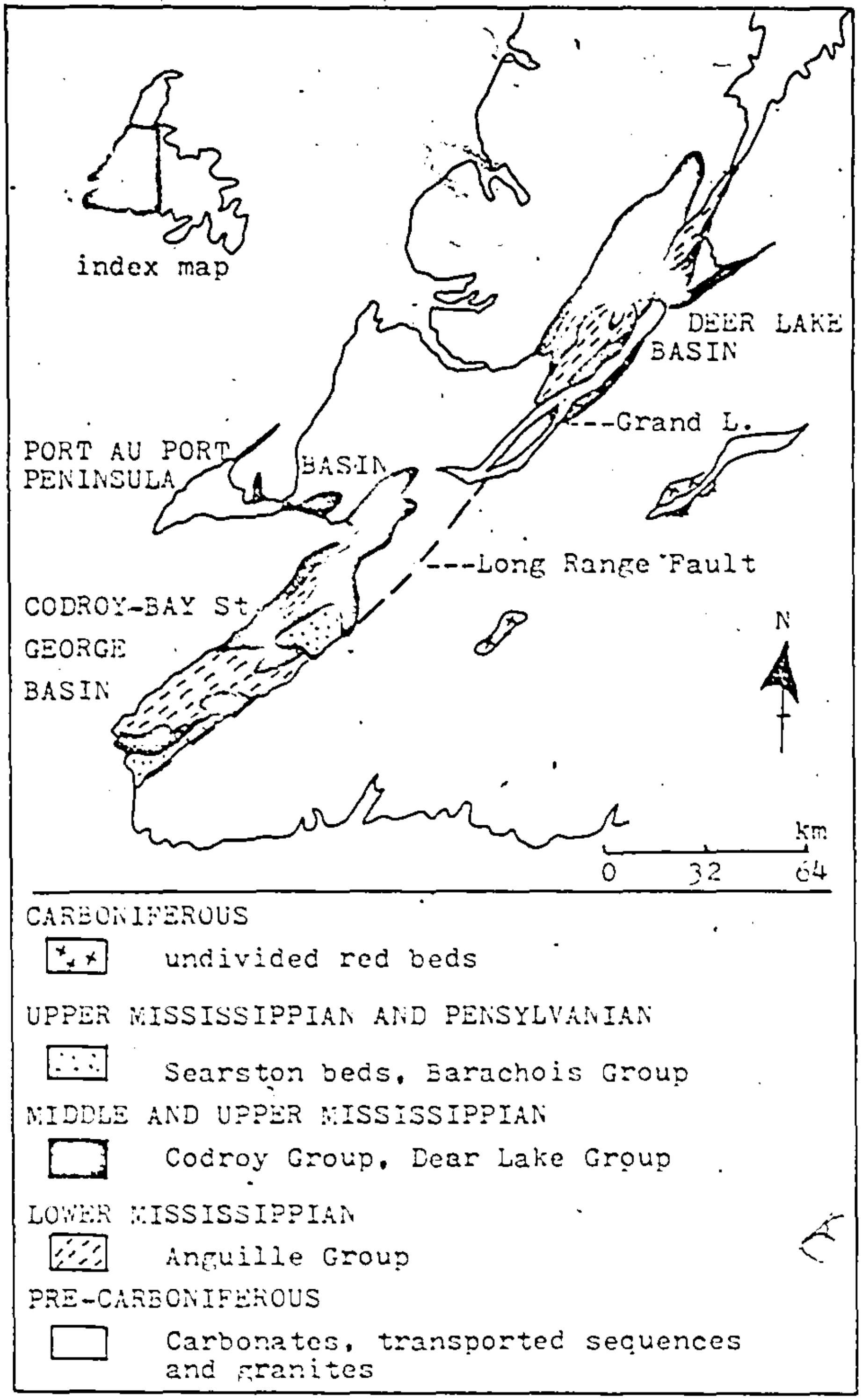


FIG. 6. NEWFOUNDLAND CARBONIFEROUS (After McArthur and Knight, 1974).

Ordovician St. George Group have been recognised for a long time (Table 1); Schuchert and Dunbar (1934) were among the earliest workers to provide a detailed description of these rocks. The Middle and Lower Ordovician carbonates have been described from 2 locations, the Port au Port Peninsula and Great Northern Peninsula. The units have been subdivided several times but there is no present consensus as to the subdivision (Table 1).

The Ordovician carbonates in the Bay of Islands area are 1220 m thick, including the Table Head Formation and the St. George Group. The Table Head Formation consists of grey limestones and black shales, while the St. George Group is marked by light and grey dolomites and limestones with chert beds at the lower contact with the Cambrian (Weitz, 1954).

The Ordovician carbonates within the study area are referred to as the "undivided Table Head and St. George Formations" (Fig. 7) because there has been no detailed stratigraphic study of them.

IIb - 1. Table Head Formation

The Table Head Formation has its type section at Table Point on the Great Northern Peninsual (Fig. 8). The top of the formation consists of about 92 m of black carbonaceous shale, underlain by 72 m of dark grey fossiliferous limestone with minor shale beds. The lower part of the formation comprises about 723 m of massive fossiliferous limestone and dolomitic limestone (Weitz, 1954; Whittington and Kindle,

LOGAN (1863) RICHARDSON (division)		SCHUCERT AND DUNBAR (1934)	WHITTINGTON, KINDLE (1968)	KLUYVER (1975)		KNIGHT (1977)		McARTHUR AND KNIGHT (1974)	BESAW (1972)
N to K	MIDDLE	----- ORDOVICIAN ----- TABLE HEAD FORMATION DISCONFORMITY			MIDDLE	TABLE HEAD FORMATION CONFORMITY	UPPER	Hiatus or condensed red bed sequence	
I	LOWER	St.	St.	Port au Choix Formation	Lower St. George Group	Siliceous dol. Fm	MIDDLE ORDOVICIAN	Long Point Fm.	Table Head Formation
H				Catoche Formation		Diagenetic carbonates Alignet Point mem Catoche Fm.		Humber Humber Arm Arm allochth autochthon	
G		GEORGE	GEORGE	Barbace Point Formation		Watts Bright Fm.		Table Head Fm	St. George Group: Port au Port Unit White Hills U. Pine Tree U.
F						Unfortunate Cove Fm.	LOWER		Pigeon Head U. Lower Cove U.
E		FORMATION	FORMATION			Cabrian dolomite Fm.	CAMBRIAN	St. George Gr.	
D			---- CAMBRIAN ----					Petit Jardin Fm.	
	M. U.	Hiatus Labrador ser				Micrite Fm.		March Point Fm.	
C	LOWER	Hawkes Bay Fm.				Hawkes Bay Quartzite			
B		Forteau Fm.						Kippens Fm.	
A		Bradore Fm.				Forteau Fm.			

TABLE I. Comparative stratigraphic chart, Cabro-Ordovician of the Great Northern Peninsula and Port au Port Peninsula.

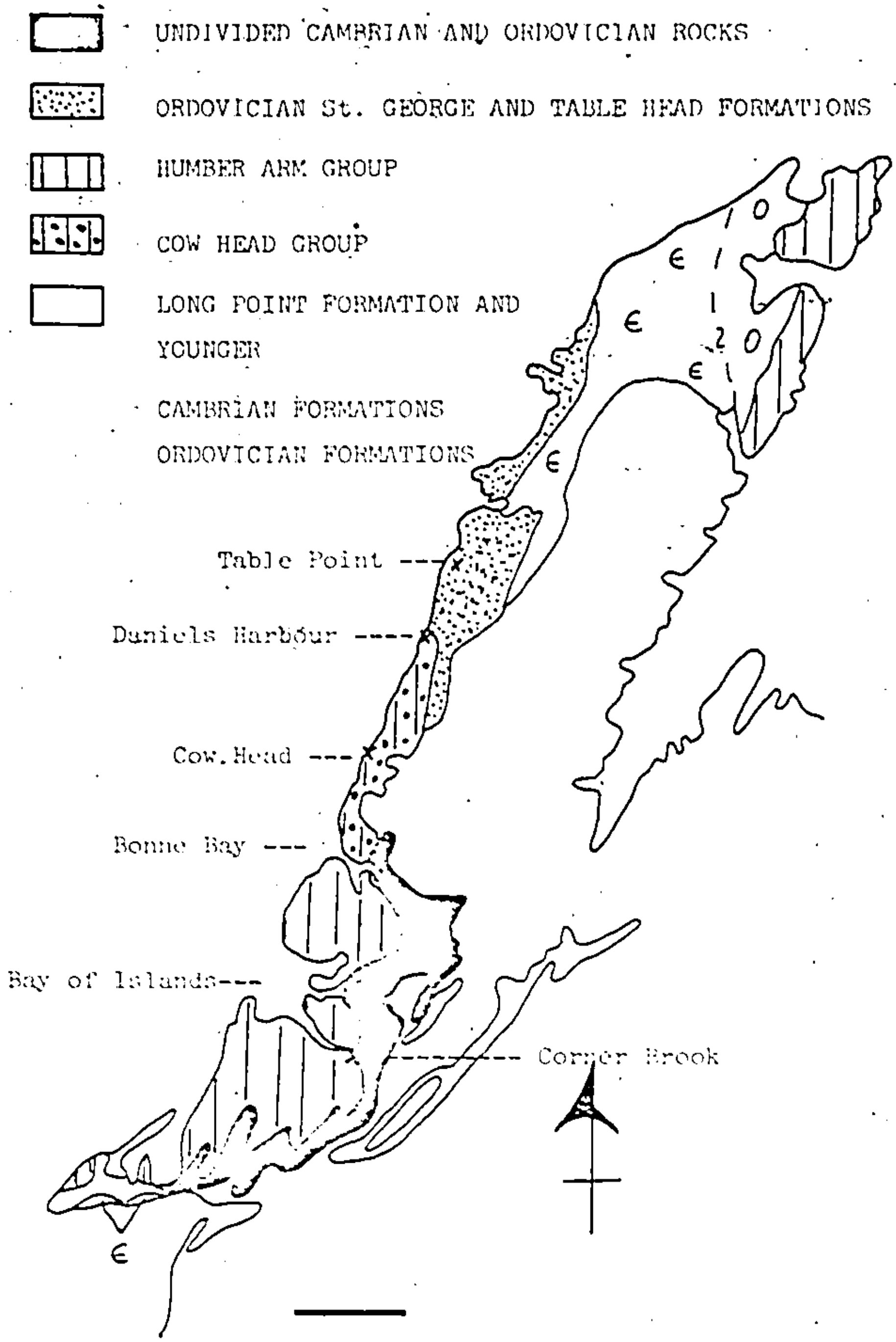


FIG. 7. UNDIVIDED CAMBRIAN AND ORDOVICIAN ROCKS OF THE WESTERN PLATFORM (AFTER CUMMING, 1968).

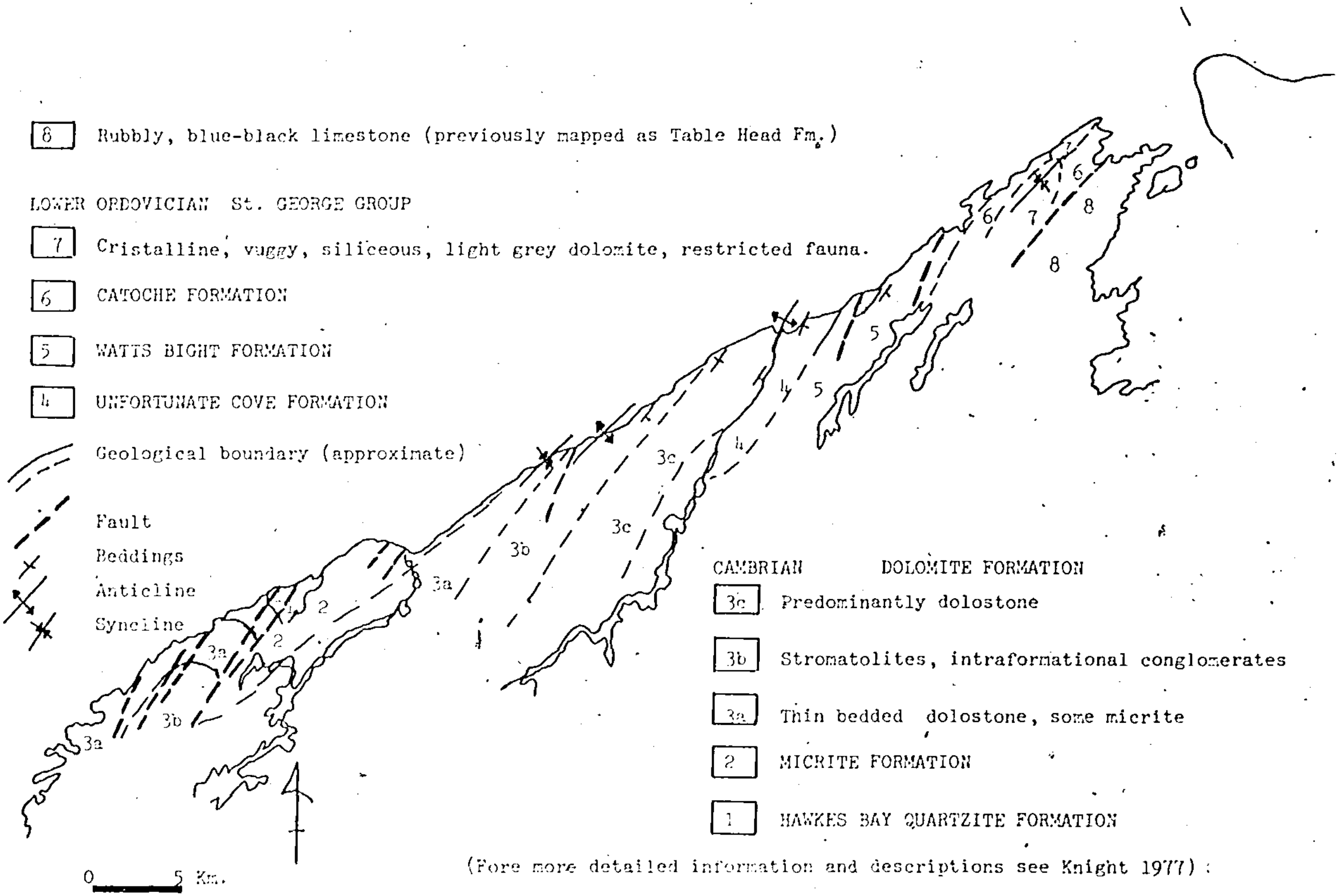


FIG. 8. STRATIGRAPHIC SUBDIVISIONS OF CAMBRIAN AND ORDOVICIAN CARBONATES, GREAT NORTHERN PENINSULA

1963). The Table Head Formation is generally characterized by its rubbly weathering. Whittington and Kindle (1963) divided it into Upper, Middle and Lower; blocks and fragments from the Middle and Lower Table Head Formation are found in the Cow Head conglomerate; this is attributed to contemporaneous deformation of the Middle and Lower parts of the Table Head Formation.

IIb. - 2. St. George Group

The St. George Group on the Great Northern Peninsual has been subdivided by Kluyver (1975) and Knight (1977). Following Knight's subdivisions, there are 4 formations and one diagenetic unit (Table 1).

The lower part, comprising the Unfortunate Cove and Watts Bight Formations, are mostly dolostones and dolomitic limestones, with abundant stromatolites. The Unfortunate Cove Formation also contains black shales and chert. Above these, the Catoche Formation is rubbly weathering micritic limestone rich in fossils. The top diagenetic carbonate unit consists of massive dolostones overlain by very vuggy dolostones rich in sparry dolomite (Knight, 1977).

Kluyver (1975), Cumming (1968), and Collins et al. (1973, 1975), have associated the diagenesis of the upper carbonate unit of Knight (1977) with contemporaneous karstification. This idea and the presence of the disconformity between the Table Head Formation and the St. George Group, has not been accepted by Knight (1977). For a more detailed description of the lithology of the Table Head Formation and the

St. George Group, on the Great Northern Peninsual or Port au Port Peninsula, see: (Schuchert and Dunbar, 1934; Whittington and Kindle, 1963; 1968; Kluyver, 1975; Knight, 1977; McArthur & Knight, 1974; Besaw, 1973; Rodgers, 1965; Fahraeus, 1973; Riley, 1962; Copeland & Bolton, 1977).

IIb-3 Study Area

The stratigraphy of the study area has not been studied in detail, and the Table Head - St. George Formation is undivided. The rock units were only noted in relation to karst development.

The southern limit of the study area from Old Mans Pond towards Canal Pond comprises non-carbonate rocks of the Cambrian Labrador Group (Baird, 1958). North of this contact thick units of limestones and dolomites are found interbedded with varying thickness of shaly beds. Where the shaley beds are extensive and the carbonates are thin, no karst features are found.

Towards the northern boundary around Fox Pond, Long Pond and Round Pond are thick vuggy dolomitic beds and uniform, alternating beds of limestones, siltstones and shales are found. These are overlain by a thick section of limestone breccias. At the contact of the breccias and the underlying beds, strong deformation is evident (Fig. 9). In this area all streams flow on the surface and no karst features are found. Above the breccias are thick shale units marking the northern boundary of the study area.

Fig. 9

A. Within the brecciated unit are sections of the underlying beds which are strongly deformed.

B. Just below the breccia unit the alternating layer of limestone, shales and siltstones show evidence of deformation.

C. Karst features on the breccia material are limited to occasional rough channels on sloping surfaces.


A
B
C

In the North Lake and Bonne Bay Big Pond area the rocks are shallow water intertidal deposits. The lower dolomitic beds have extensive chert nodule deposits, which serve as a marker zone in the area. North of North Lake limestone breccias similar to those at Fox Lake and Long Pond-Round Pond area are found, and again there is no karst development.

From these observations it is tentatively suggested that the northern third of the study area is equivalent of the Table Head Formation and the lower two thirds, of the old St. George Formation.

IIc. Glaciation

General

Newfoundland was extensively glaciated during the Wisconsinan glacial period. There is no record of pre-Wisconsinan glacial activity, but from work elsewhere in North America it can be assumed with confidence that the island was glaciated on several occasions before 100,000 years B.P. Such previous glaciation is probably important in the karst genesis and it is possible that only from the karst records will it be deciphered, if only to a limited extent.

The last of the Wisconsinan ice disappeared from the island between 12000 to 14000 yrs. B.P. (Brooks, 1970; Dyck and Fyles, 1963). Because the topography of the west coast of the island is complex, ice flow directions become difficult to interpret.

Work on the glaciation of Newfoundland has focused on two main topics: 1) postglacial isostatic warping and 2) whether or not the island supported its own ice cap or if it was overridden by the Laurentide ice sheet. Early investigators such as Chamberlain (1805), Bell (1884), Fairchild (1918), Daly (1921), and Coleman (1921) all came to the conclusion that the island supported its own ice cap, although they considered only some of the raised shoreline features and ice flow directions in their assessments. Others (Flint, 1940; MacClintock and Twenhofel, 1940; Grant, 1969) expressed the view that ice from Labrador has invaded Newfoundland at least on the west coast, but probably the whole island. The island's own ice cap existed only after the main ice sheet started to melt (Flint, 1940; MacClintock and Twenhofel, 1940; Grant, 1969; Jenness, 1960; Ludgqvist, 1965). Brooks (1969; 1970; 1973; 1975; 1976 a,b) has shown that there are indications that ice from Labrador did not invade Newfoundland, but that ice flowed from the western mountains of the island into the Gulf of St. Lawrence (Fig. 10).

From raised marine features and their dates an isostatic uplift curve may be constructed, but on the west coast of the island numerous C_{14} dates are still needed to construct a reliable curve. Marine limits varied as deglaciation proceeded. Field evidence indicates that at a deglaciation date of 13700 yrs. B.P. around St. George Bay the marine limit was at 42.7 m - 44.2 m; around the Bay of Islands at the head of the fiords, deglaciation is dated at 12500 yrs. B.P., and the marine limit is at 48.8 m; at Trout River (Bonne Bay) the limit is at 70.2 m but no dates are available; near East Arm, Bonne Bay, the limit is at 35.1 m - 42.7 m; dated at 10500 yrs. B.P. (Brooks, 1973). Figure 10 shows ice flow

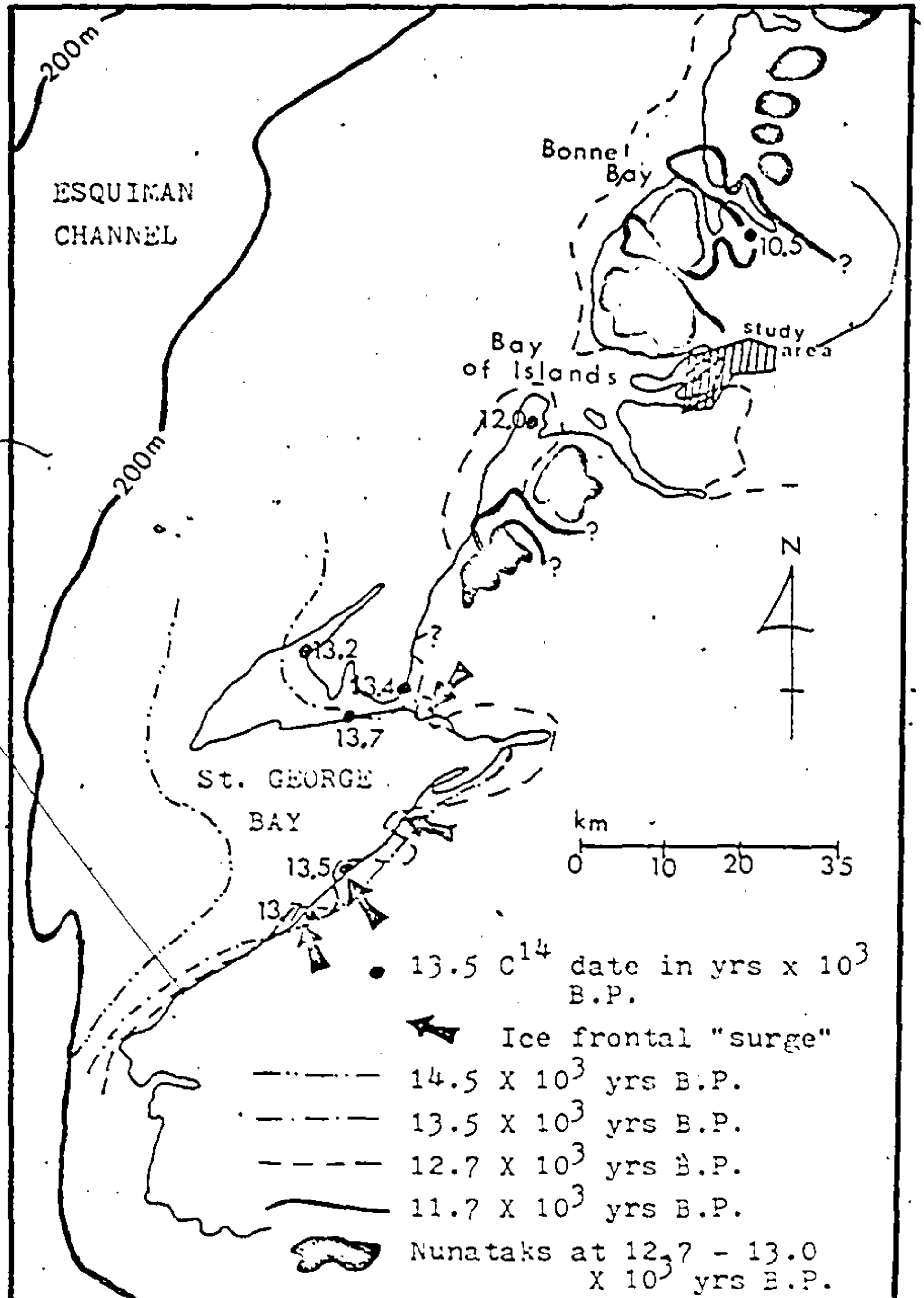


FIG. 10. SPECULATIVE ICE MARGINAL POSITIONS DURING DEGLACIATION OF SOUTHWESTERN NEWFOUNDLAND (After Brooks, 1973).

directions and speculative ice margin positions during deglaciation of southwestern Newfoundland. Brooks (1973) concluded from marine limits and dates, that deglaciation of the west coast took about 13000 years. Conclusions drawn from ice flow directions, erratic boulders, friction cracks, small rock drumlins indicate that ice flowed mainly from the western mountains of the island and the island supported its own ice cap (Brooks, 1970; 1973; 1975; 1976):

IIc - 1 Study Area

Within the study area many features point to extensive and multidirectional glaciation. Among the most conspicuous are the mountain tops and the vertical to steep-sided U shaped valleys. Goose Arm Brook is one of the largest streams draining the area and at places water flow is slow, widening to form ponds and lakes. Drainage has been deranged by glaciation, and many lakes and streams are haphazardly connected forming extensive swampy areas at places before outlets are found. Several lakes are found within large scoured-out closed depressions, draining by underground routes. Small cirques have been transformed into closed depressions and the ponds occupying them drain underground to springs found several hundred meters below in the valleys. Evidence of glacial scouring is seen in striated and polished outcrop surfaces and in abundant stoss - and - lee forms. As the ice melted, scattered deposits of deltaic sediments were emplaced.

Karst development within the study area as well as other areas has been affected by glacial erosion and deposition. No conclusive evidence was found pointing to pre-Wisconsinan karst development. Eventhough more than 1000 m of soluble carbonate rocks with high hydraulic gradients are found in the Goose Arm and Bonne Bay Big Pond area. Several large closed depressions are found that have been scoured by ice; this is indicated by striae, till deposits, non-carbonate erratics, (eg. Bottomless Pond). Underground drainage out of closed depressions containing lakes is slow, and is probably due to till materials and other washed-in fines clogging the underground routes. These observations imply that karst drainage of the depressions may predate Wisconsinan glaciation.

Several areas are found where near-surface collapse has taken place. The areal extent of remnants of cave passages is not known because exploration of these is impossible without the removal of blocks weighing several tons. Due to ice loading near surface collapse features may not necessarily be associated with cave collapse (D.C. Ford, per. comm. 1978). However, it is a possibility, which would indicate glacial disruption of earlier karst development.

Most underground drainage is shallow and short, indicating probably post-Wisconsinan development. It is possible that older routes may have been partly eroded and completely blocked; due to glacial scouring and drainage rerouting, these older routes are now not utilized.

Post-glacial geomorphic features include extensive physical and chemical weathering, mass wasting, stream and river erosion and deposition; most of these processes have not progressed very far in their development. The amount of mechanical sedimentation has been small but bog development in shallow basins is extensive (Bruckner, 1969).

CHAPTER III

MODERN KARST DEVELOPMENT IN ORDOVICIAN CARBONATES

IIIa Introduction

Most karst features in the study area are at the early or youthful stage of development; evidence pointing to karst development prior to the Wisconsinan glaciation is inconclusive. The area supports an extensive surface drainage network of the glacially deranged type, although numerous streams drain underground for short distances. The karst features can be assigned to three main groups: 1) small scale solution features or karren forms, 2) sinkholes or closed depressions, 3) caves.

Karren or lapies are small scale solution features on limestone. These forms can be found on either bare or covered (ie: thin soil or vegetated) surfaces. Karren on bare rock generally have sharp outlines, whereas covered forms show smooth and rounded outlines.

Karren forms are affected by lithology, texture and structure of the rock, the slope of the surface, precipitation and by chemical reactions (ie: amount and availability of water, presence of organic debris and quantity of CO_2 gas). Of fundamental importance are precipitation and limestone texture and composition. The type of limestone whether a micrite, biomicrite, sparry limestone, dolomite etc., will determine to some extent the degree of development and predominant karren forms found (Sweeting, 1973; Williams, 1970; Bogli, 1975; 1961; 1951). Surfaces that have fractures, cracks or joints infilled with precipitates will not accomodate karren forms. Dolomites ($CaMg(CO_3)_2$) with high magnesium content are generally held to restrict karren forms, because magnesium in large quartities has an inhibiting effect on solution (Plummer and MacKenzie, 1974; Rauch and White, 1970; Priesnitz, 1972; Sjoberg, 1976); although Pluhar & Ford (1970), Cowell (1976) have shown that extensive assemblages can occur on dolomite, such as found on the Niagara escarpment.

Generally flat surfaces can have solution pans or kamenitzas, pits and hollows developed, whereas sloping surfaces will commonly have various rills and runnels. Extensive limestone pavements, the result of glacial erosion and subsequent solution can form complex karren assemblages. Clints and grikes are the common names given to the residual blocks and fissures respectively, comprising the pavements. Each block and fissure surface may in turn have its own collection of small scale karren forms.

Sinkholes and dolines are closed depressions of small to large dimensions, with generally bowl, funnel, or well-shapes (Cvijic, 1893; Cramer, 1941; Sweeting, 1973; Jennings, 1971). These forms are found from arctic/alpine to tropical environments and upon a variety of limestone and gypsum surfaces. Genetic classification of these features is difficult because of the complex transition that exists between end members that are of the wholly solutional and wholly collapse type. Most authors hold closed depressions to be the most diagnostic karst feature.

Caves have always been one of the most intensively studies karst features, partly because of the challenge they present to the explorer, and because they represent underground drainage systems, and therefore their formation and function is an important aspect of all large surface karst development. Shapes and form of passages and the presence of cave deposits record episodes and conditions of cave formation, past climates, and surface conditions (Herak and Stringfield, 1972; Sweeting, 1973).

IIIa. Small Scale Karren Forms

Small scale karst forms are found wherever exposed limestone surfaces undergo solution. Karren in the study area have a variety of sizes and shapes, and may be grouped into 3 classes: 1) pits and hollows (size range of a millimeter to over ten centimeters in diameter), 2) solution widened joints (size range of millimeters to decimeters), 3) runnels and rills (size range of millimeters to meters in length).

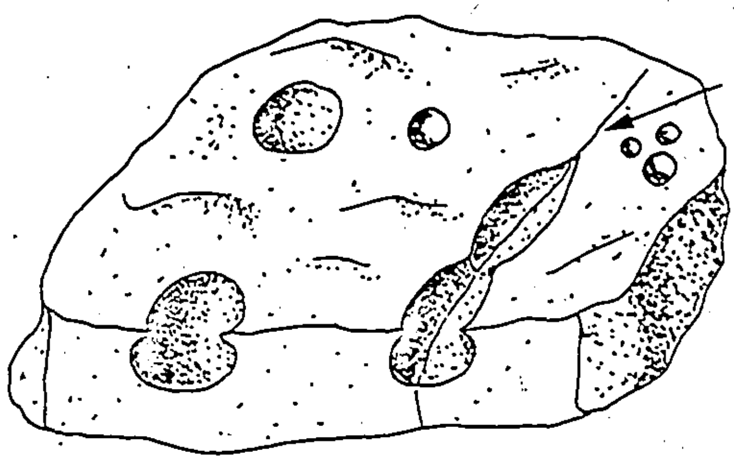
Few forms in these classes can be attributed to immediate glacial scour effect (ie. are solutional adaptions of ice scour forms). There are some instances of "trittkarren" described below. Karstic adaptation of glacial striae, widely reported elsewhere (Cowell, 1976) were not observed. Striae are rare on bare rock exposures, implying that they have been removed by general post-glacial solutional lowering.

(1) Pits and hollows

Pits and hollows are circular to elongate depressions found on carbonate rock surfaces. They are generally smoothly concave in cross section, but in some examples there is a sharp undercutting at the surface boundary (Fig. 11). These depressions may coalesce to form larger, irregular depressions.

Their formation is the result of either purely solutional processes, purely erosional processes or the combination of these two. Some littoral pits that are circular and smooth-sided in cross section are generally the result of mechanical erosion, with only limited solution. The small stone fragments that are found inside the pits are moved around by wave action, and this gives them their smooth polished appearance. Other smooth-sided pits are wholly solutional in origin. Depressions that are undercut just below the surface are due mainly to solution. Water in the hollow becomes isolated from normal circulation, and then becomes stratified with respect to saturation; the top layer will have the highest aggressivity. This stand-still of water in hollows has been observed at several places in the study area, although actual layer by layer saturation measurements were not made. Similar types of saturation layering have been demonstrated in laboratory experiments, and have been associated with bevels found in caves (Mowat, 1962; Lange, 1968a; 1968b; 1968c; Goodman, 1965).

At the bottom of pits and hollows organic debris (plant fragments, roots etc.) may be found which were either blown in or brought in by water. Solution is enhanced by these organic materials because they provide



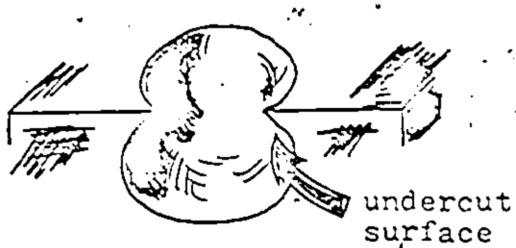


FIG. 11. Circular depressions with sharp undercutting at the surface boundary are common along lakes and streams, on carbonate rock surfaces.

biogenic CO_2 to aid solution. Measurements taken (in the field) in large hollows that had organic debris showed much higher values in SPC, and CA^{+2}, than those that did not have organic materials.

Pits that are in the millimeter size range generally develop where minute, more readily soluble parts are found in the carbonate rock. Overall surface solution will readily pick out variations of solubility, resulting in a rough, etched surface. Water may accumulate in the small irregularities and pinhole sized pits form, which may or may not be enlarged.

A developmentary sequence of these pits may be seen on some bare rock surfaces around lakes. At Pond 4 over a distance extending 3 meters from the water's edge a complete developing section is seen, from a merely etched surface to large hollows and troughs at water level. The etched surface is inclined. General solution has picked out the more readily soluble areas. These small irregular pits increase in size towards the lake, widening to form distinct hollows about 5 to 8 cm in diameter and 3 to 5 cm in depth. The hollows then enlarge and coalesce by first forming tunnels between them. As these are unroofed lines of coalescent hollows form linear troughs.

Ideal sites for pit development are found generally along joint planes or cracks. In this case the pit is not circular but elongate in the direction of the joint (Fig. 12D). Water tends to drain down along the joint plane. Generally these pits do not show any sharp undercutting as described above, although it may occur if water is allowed to stand when drainage is blocked or very slow. As solution progresses several pits may coalesce forming a pinch-and-swell structure (Fig. 12D). As the joint widens the small embayments formed by the coalescent

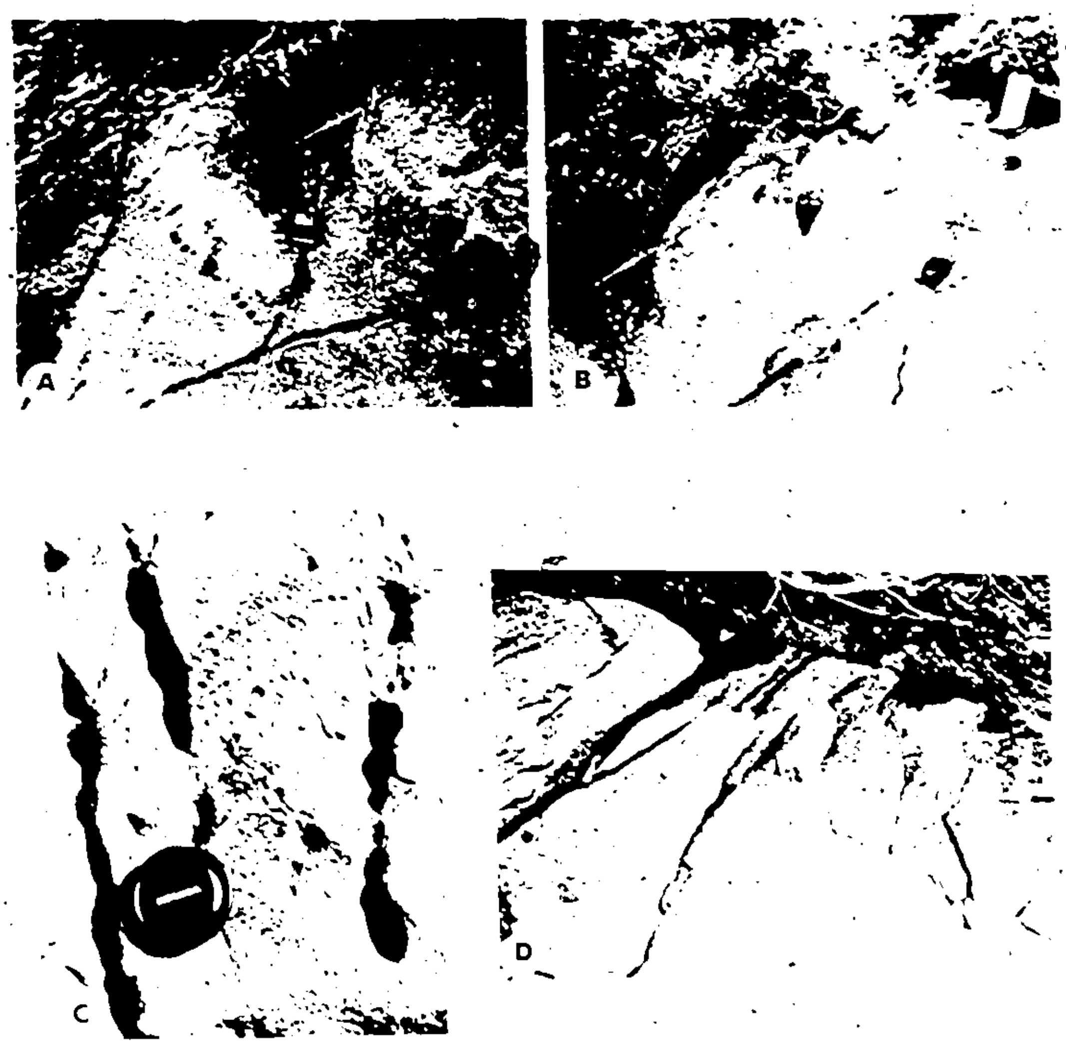
Fig. 12

A. Ideal sites for pit development are found along joints and cracks around Pond 4.

B. Inclined surfaces will drain water along the joints, opening, widening these surfaces into elongate hollows. (Pond 4).

C. Coalescent pits form along hairline joints around Browns Pond.

C. Joints may uniformly widen and open up on inclined rock surfaces without distinct pit development. (Pond 4).


A
B
C
D

pits may be utilised by water and modified into rough rills and channels to drain water down the joint.

Pits and hollows ranging in size from a millimeter to several centimeters are numerous in the study area, and are found mainly around lakes and stream channel sides, and on barren limestone surfaces (Fig. 13). Pits and hollows are not found under thick till or soil cover. This is due to the high carbonate content of the till deposits, and before the bedrock is reached the water becomes saturated. On the Niagara Escarpment dolomites, from 0.6 m to 1.6 m thick till cover is sufficient to prohibit karren development (Pluhar and Ford, 1970). A comparable estimate is not available for the study area.

The development of pits and hollows in coastal areas are generally in the form of smooth circular or elongate shallow depressions, forming coalescent features in cases (Fig. 14).

(2) Solutionally Widened Joints

Joints will be among the first features to be widened by solution. They are found in open environments or under thin soil cover, and are not restricted to horizontal surfaces, as illustrated by solutionally-enlarged joints in steeply inclined rock faces (Fig. 12 A,B,C). Joints and fractures are important in the solution of carbonate rocks because these may serve as routes for underground water circulation, eventually widening to explorable conduit systems.

At the intersection of joints deep funnels may develop, and where the surface has an incomplete soil cover considerable amounts of solution may take place, as percolating waters pick up biogenic CO_2 from the nearby soil and vegetation.

Fig. 13

Pits and hollows of varying sizes are numerous in the study area, generally found around lakes and stream channels.

A. Smooth pits develop around lakes such as Brown's Pond.

B. Rough solution hollows are found at Indian Dock Pond.

C. Karren forms along Goose Arm Brook, exposed in low water stages.

D. Large and partly destroyed solutional hollows found along Goose Arm Brook where swirling waters produce smooth sided pits.

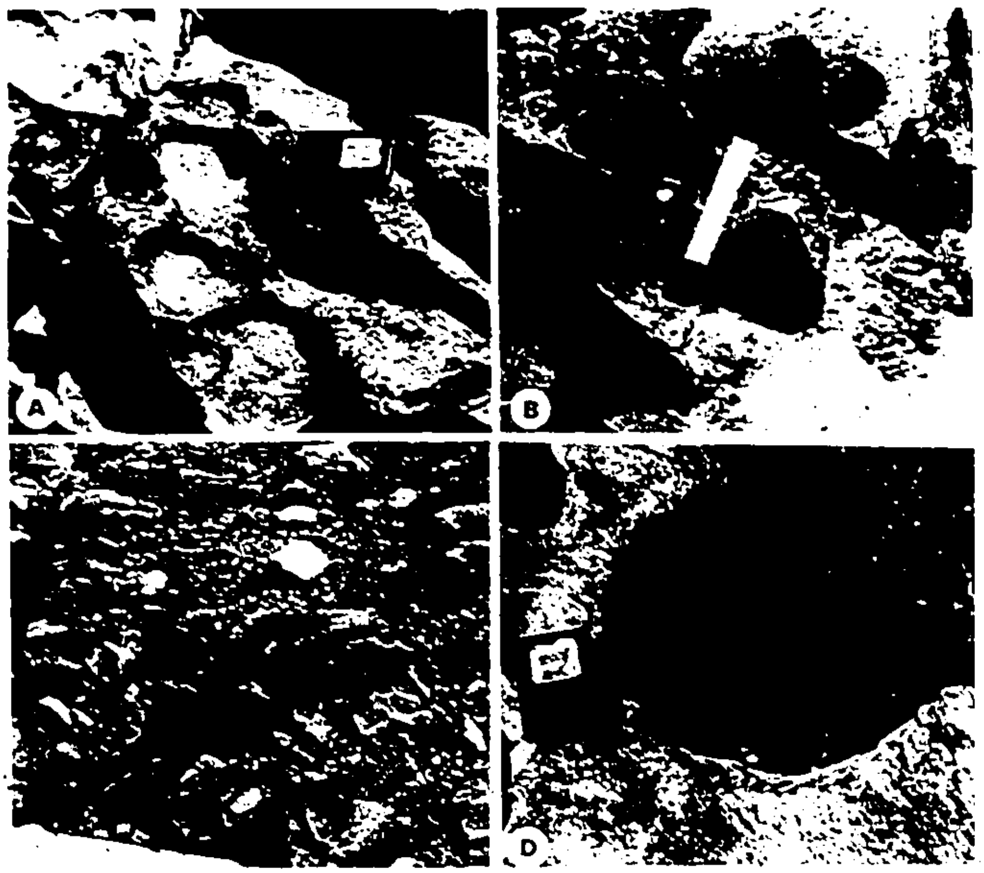
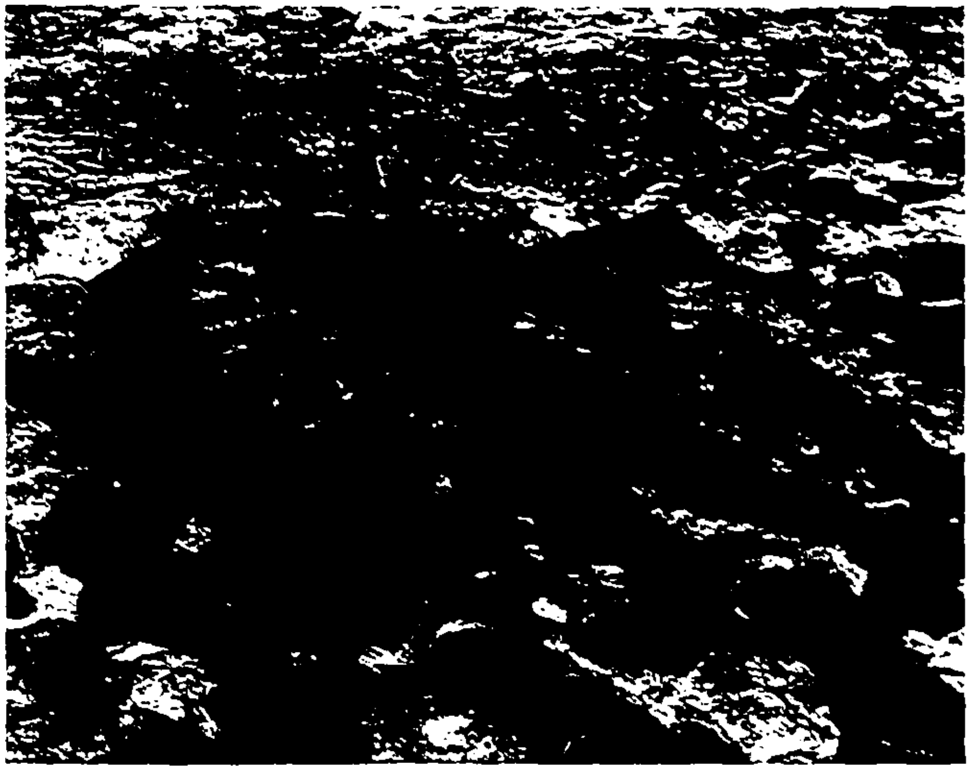

A
B
D

Fig. 14

Coastal karren development. Smooth, shallow depressions are common.

Port au Choix, Newfoundland.



Solution widened joints within the study area generally exhibit smooth sides with no additional small karren forms present. In coastal areas however, (such as the Port au Choix area of the Great Northern Peninsula) constant wave action and water circulation produce wide and deep joints, with numerous small pits and hollows covering not just the surface of the rock between the joints, but the sides of the joints as well. These small pits are in the size range of millimeters to a few centimeters in diameter, and are thought to be due to constant water spray.

(3) Runnels and Rills

Runnels and rills of different types are classified also as karren forms, and are the result of solution on sloping surfaces. The types of rills found in the study area include rillenkarren, trittkarren, and deckenkarren. Outside the study area, inclined pavements are also found, as on Port au Port Peninsula and along the Great Northern Peninsula.

Rillenkarren forms in the Goose Arm and Bonne Bay Big Pond area are usually a few millimeters wide and deep, and several centimeters long. These are finely chiselled runnels with rounded troughs and dominant sharp edges. They are found on open exposed sloping surfaces and form as a result of rain water runoff. They were observed at several different locations, such as mountain tops, lake shores, etc. These rills usually show a deeper trough close to their origin at the top of the slope, and diminish downwards. On exposed mountain tops these small rills are quickly destroyed.

Trittkarren forms are step-like features, crescentic in shape with a steep back wall which may vary in height from a cm. to several decimeters. These features are found on horizontal slightly sloping surfaces (Fig. 16A). Trittkarren are typical of glacially scoured surfaces (Bogli, 1960). Within the study area these features appear to be chattermarks or other glacial scours modified by solution.

Irregular solution basins, with rounded smooth sides, generally with peat soils filling the depressions, are found at a few localities. Within these pans the CO_2 given off lowers the pH and enhances the solubility of water, so more $CaCO_3$ can be taken into solution (Sweeting, 1966; Williams, 1970). These basins are irregular and covered to the top with soil, giving an overall patchy appearance to the exposed limestone surface in between.

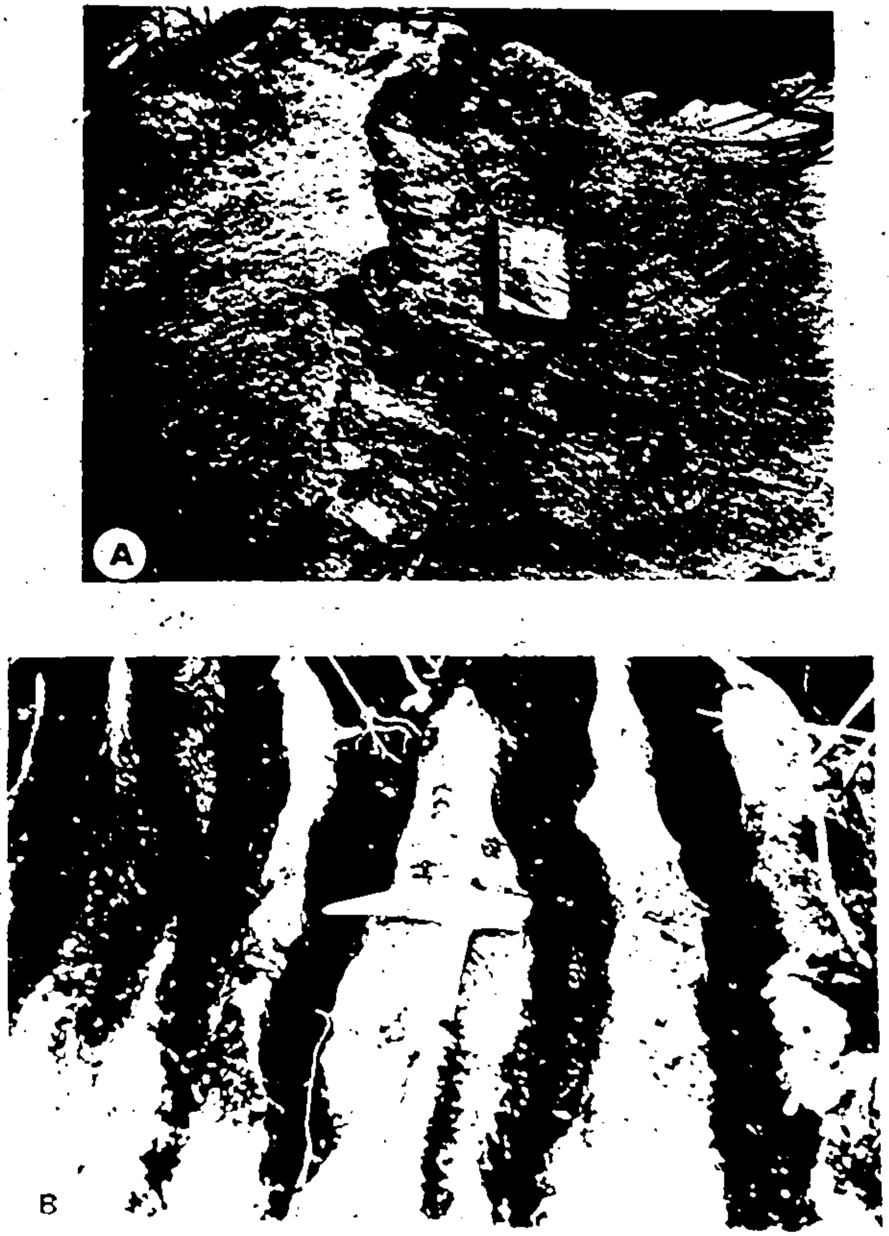
Deckenkarren are among the most common karren forms found in the study area. These are drainage features developed partly under soil and vegetation. They resemble large rillenkarren forms, but are variable in width and depth, and sometimes have a dendritic form. They were seen only on sloping surfaces where water could be channelled from a soil cover to a nearby lake. The runnels begin a short distance under the soil cover and form deepening surrows downslope. Depth may decrease as they reach the lake and a more level surface (Fig. 16B). Similar forms have been found in the Alps, where the name karrenfussnapfe was applied

Fig. 16

Karren Forms

A. Step-like trittkarren found on a slightly sloping surface, near Brown's Pond.

B. Deckenkarren - drainage features found around lakes, where water is channelled from the soil cover to the nearby lake. These features originate under soil and vegetation cover close to the top of the photograph. Found around Frog Pond.


A
B

to them (Bauer, 1961; Haserodt, 1965). These were the result of solution by water issuing from under ice and peaty soil cover. In the study area water issues from under soil and vegetal cover, where its aggressivity evidently is increased by biogenic CO_2 and as a result rills are deepest close to the soil cover.

Rinnenkarren forms are larger solution channels that display network integration. At places in the study area a type of rinnenkarren is found which is fairly regular in width, depth, and in its spacing, and has lengths in order of 2 to 3 meters, and may cover several square meters (Fig. 17). At a first impression they look like "drape folds" because the surface exhibits a distinct convex shape, and the grooves show a certain amount of undercutting, or lateral deepening. This is the result of increased solution in the grooves due to the presence of peat soils.

Summary

The range of karren forms found in the study area is very limited when compared with other areas such as the Niagara Peninsula or the glaciated benchlands of Yorkshire, England; or Burren, Eire, but is comparable to alpine areas such as the Canadian alpine karst of Castleguard (Ford, 1971 a).

Areally, karren forms that are observed on bare rock surfaces are restricted to lake margins. Development of karren forms under till cover appears to be almost non-existent because the high carbonate content of the till has prohibited solutional attack on underlying rock

Fig. 17

Rinnenkarren or "drape folds" are common in some areas in the studs area. These features are found on sloping surfaces. Locality Pond R2:


A

during post glacial time. Because of this the Goose Arm - Bonne Bay Big Pond karst might be called an "armoured karst".

Rock lithology is also a major controlling factor in karren development. In the areas where limestone conglomerates and shaly limestones are found, karren are absent. Dolomites and dolomitic limestones generally show solutionally enlarged joints and pitted surfaces. The best developed karren forms are found on micritic limestones with very little insoluble residue.

IIIb Classification and Morphology of Closed Depressions

Dolines or sinkholes are the simplest kind of closed depression; they may be cylinder, cone-or-bowl-shaped, with circular, elliptical or irregular plan view, and with vegetated or rocky sides. Diameters may vary from a meter to several hundred meters, and depths from a meter to over 100 meters.

Doline formation can be complex but most can be placed into one of the following genetic groups: 1) solutional doline, 2) collapse doline, 3) subsidence doline (alluvial doline), 4) subjacent karst doline (covered karst), 5) streamsink doline in alluvial karst. (Jennings, 1975; Sweeting, 1973).

IIb 1 - Post-glacial Collapse Dolines in Till and Bedrock

Within the study area, dolines of solutional or collapse origin are predominant. Collapse or subsidence dolines are generally small (from 1 m to 3.5 m in diameter and 0.5 m to 3 m in depth). Their shape is typically funnel-like, with soil and vegetation covered sides. Type locality for these is "karst-valley" at the north end of Nameless Pond, where doline expression is entirely in till and their frequency is about 5 per 10 m^2.

The development of these dolines is probably in response to small roof collapses in the underlying, proven and presumed shallow, karst conduit system that transports water from the sink of Nameless Pond to a spring location at Bonne Bay Big Pond. The conduit system is assumed to be shallow because of the presence of these small suffosion or collapse dolines. A collapse sink which takes lake drainage at the northern end of Nameless Pond is the largest of them, with collapsed blocks of bedrock being exposed (Fig. 18).

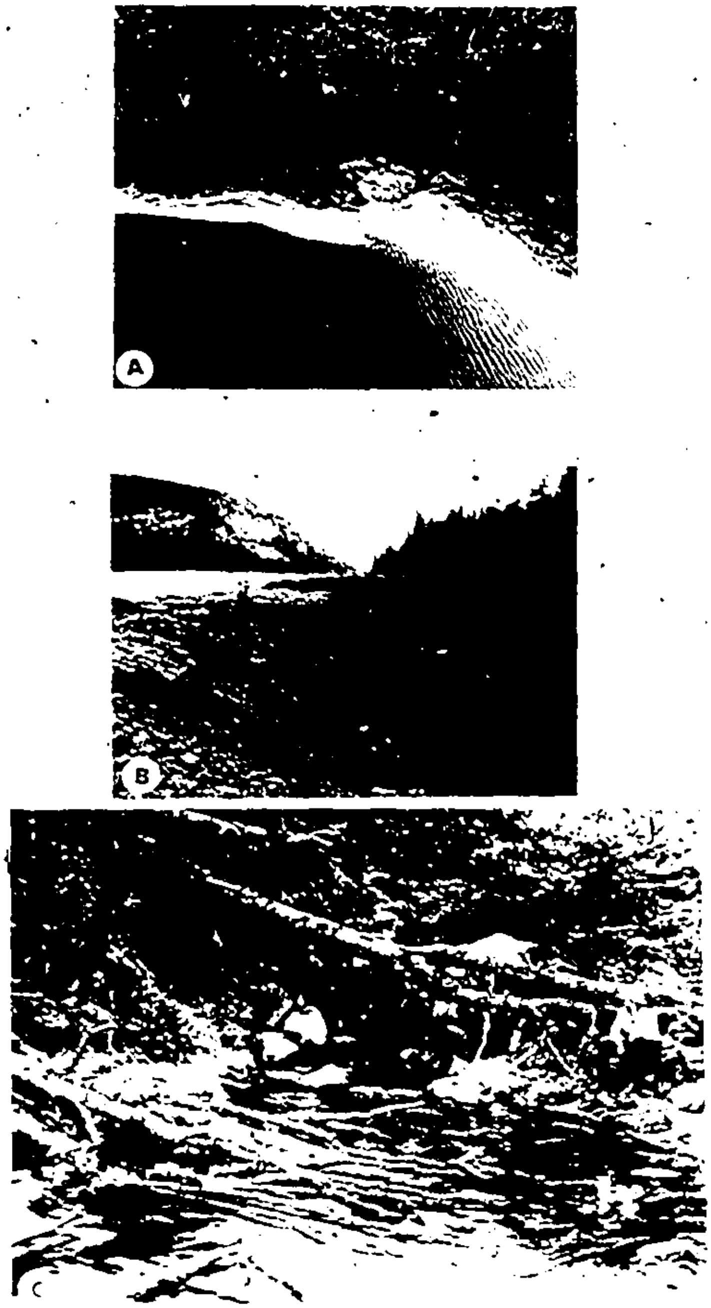
Several valleys adjacent to karst valley are similar in structure, form and dimension but they are without dolines, such as the valleys northeast of karst valley. These are drained underground at their southern ends, opposite to the case at Nameless Pond. Absence of dolines is attributed to lack of local karst drainage, and possibly to thicker till cover. The high carbonate content of the till has an inhibiting effect on solution and therefore, on the indication of karst drainage systems beneath, as with karren forms. Critical depths of till cover inhibiting post-glacial karstification are difficult to estimate, as shown by the above examples.

Fig. 18

A. Collapse sink of Nameless Pond (see arrow) found within the closed depression of Nameless Pond about 10 m away from the lake level. (photo courtesy of D.C. Ford).

B. Close up of the collapse sink. This sink was covered by water in the 1977 field season. (photo courtesy of D.C. Ford).

C. Spring location of Nameless Pond, at Bonne Bay Big Pond.



Several other small collapse sinks were discovered in the vicinity of Goose Plateau and Seal Pond. But frequency and distribution of this class cannot be estimated. Because of their small size they are hard to find in the forest and are rarely distinguished upon air photos.

IIb 2 - Simple Solutional Dolines In Bedrock

Within the map area of Figure 19 there is a total of 37 medium to large sinkholes that are in bedrock and are thought to be of comparatively simple origin (Fig. 20). These sinks are generally circular in plan and exhibit a simple funnel or bowl-shape, comparable to dolines in West Virginia, Kentucky, and other extraglacial karst areas. These sinks may be post-glacial in age because they are very different from the complex, large and scoured depressions such as Bottomless Pond and others considered in the next sections. These dolines also may be wholly karstic in origin; there are no morphological features to suggest glacial effects. However, little or no bedrock is exposed in them to confirm the absence of glacial scour (Fig. 20), and above all, many of them appear to be significantly larger than the class of post-glacial bedrock dolines found elsewhere in Canada (Ford, 1971 a,b; Cowell, 1976).

Round sink #1, on Goose Plateau is a typical example of such a doline (Fig. 19). It is circular in plan view, about 140 m in diameter and about 20 m in depth, with steep, funnel-shaped and vegetated sides.

A small pond periodically occupies its centre; water sinks underground just outside of it (Fig. 20). The sinkhole is close to the edge of Goose Plateau, where a high hydraulic gradient (0.169) is provided. This has enhanced enlargement of this sink, when compared to others further within the plateau, where the lower hydraulic gradients tend to favour shallower and bowl-shaped dolines.

Pond S1, southwest of Seal Pond, is a good example of a shallow bowl-shaped doline. It is circular in plan, about 180 m in diameter and less than 15 m in depth. Underground drainage from the pond appears to be very slow, although the hydraulic gradient is quite high (0.122 to a stream nearby or 0.095 to a lake).

This class of dolines have diameters that are at least twice as great as post-glacial dolines found elsewhere in Canada (Derek Ford, pers. comm.), although their depth is comparable. These features may be post-glacial, but it is possible that they represent a new class of dolines that are older than the last glaciation but have escaped notable glacial modification of their circularity. Examples of this class are widely distributed in the study area, and therefore there is no suggestion that they occur only where ice scour might be limited. The nature and origin of this class remains inadequately known.

IIIb 3 - Elongate, Probably Ice Scoured Dolines

Within this class a comparatively simple morphology exists. The dolines are glacial scour holes adapted to karstic drainage in prevailing post-glacial hydrologic conditions.

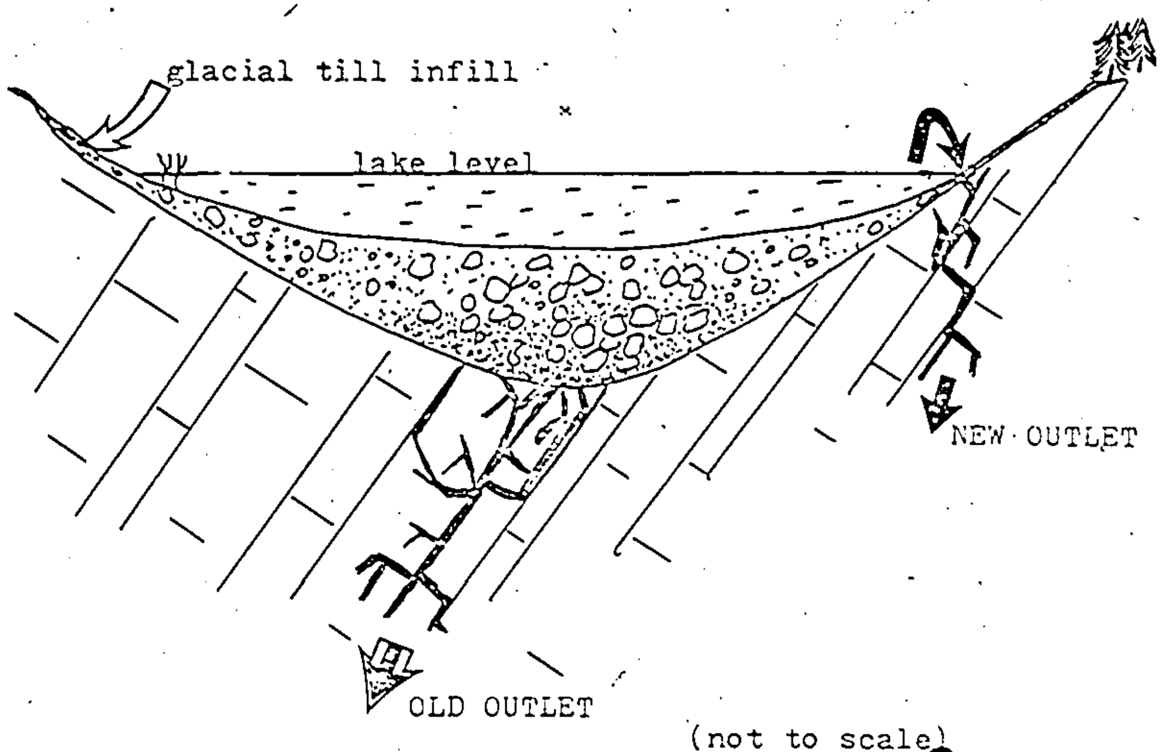


FIG. 20. An example of a funnel shaped sink such as Round Sink No.1. on Moose Plateau, where a possible older route is blocked by glacial till and fines, and a new route is found in a small blind channel off the side.

Snafu Sink is amongst the largest examples. It lies north of Goose Arm Pond and about 30 m above the Pond level. The sink is oriented east-west; 450 m long and about 200 m wide. There are steep sides to a depth of 20 meters, where a permanent lake covers the floor. This is drained somewhere through the bed to an outlet in Goose Arm Pond. The sink may be a feature of glacial overdeepening subsequently adapted to karstic drainage, but no scour forms can be observed because the sides are mantled with soil and forest.

IIIb 4 - Complex Glaciokarstic Forms

Complex depressions believed to be glaciokarstic in origin, are characteristically large in size and show great irregularity of plan form and rim elevation. Such depressions are Bottomless Pond, Nameless Pond, and Canal Pond within the study area and several others just outside of it (Fig. 19).

Bottomless Pond is in a 45 meter deep, highly irregularly shaped, closed depression with varying inside-rim elevations (Fig. 21). The depression is elongated in several directions as a result of small streams flowing in to it. The sinkhole is partly bounded on its northern side by a lineation, a possible fracture. Its southeast side is part of a fold limb, and the shape of the entire sink is also partly controlled by a fold, similar to that which orientates Nameless Pond and several adjacent lakes. The irregularity of the inside rim is clearly a result of differential glacial scour of these structural guides, and there are scoured surfaces within the depression. The central area of the depression is occupied by a filling of till, deltaic and lacustrine deposits in which Bottomless Pond

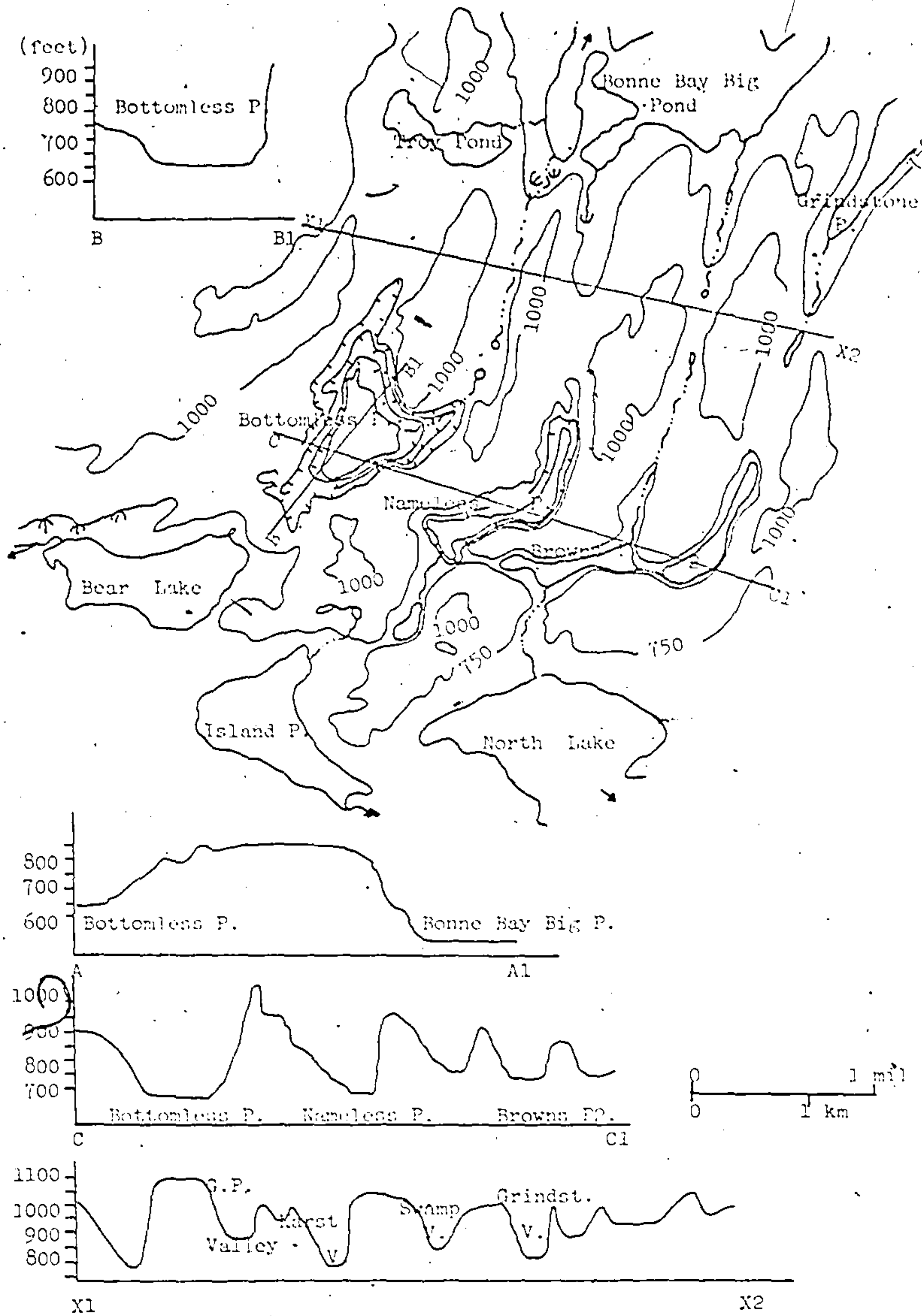


FIG. 21. Map and Cross-section of Bottomless Pond, Nameless Pond, and Browns Pond.

itself rests. Its depth is unknown but unlikely to be great and the Pond bed is almost certainly clastic fill.

Nameless Pond is a simpler form but also glacially scoured (Fig. 21). At present it is not possible to determine whether these two sinks drained karstically before the last glaciation. Modern drainage is slow out of both of them, indicating small and young conduit systems or clogged pre-Wisconsinan systems. The spring outlet of Bottomless Pond has not been found. Waters of Nameless Pond sink just outside the lake in the collapse sink noted, and the dye-traced spring location is found close to Bonne Bay Big Pond.

Canal Pond is a "karst margin" feature, extending across the contact of carbonate and non-carbonate rocks (Fig. 19). This most irregular closed depression appears to be a scoured and drowned karst margin blind valley system (Fig. 22). The valley head is in resistant metamorphic rocks. The carbonate half of the depression is substantially solutional in origin, with several smaller daughter dolines within it. The irregular outline of the sink is due elongation of streams which feed Canal Pond. This irregularity is much more pronounced on the carbonates because of higher solubility. This sinkhole drains underground at its northeastern end into a cave. The spring location is halfway down a dry valley leading to Indian Dock Pond (Fig. 22).

IIb 5 - Summary & Discussion

Within the study area there are a variety of sinkholes ranging from small suffusion or collapse features to small - large, apparently

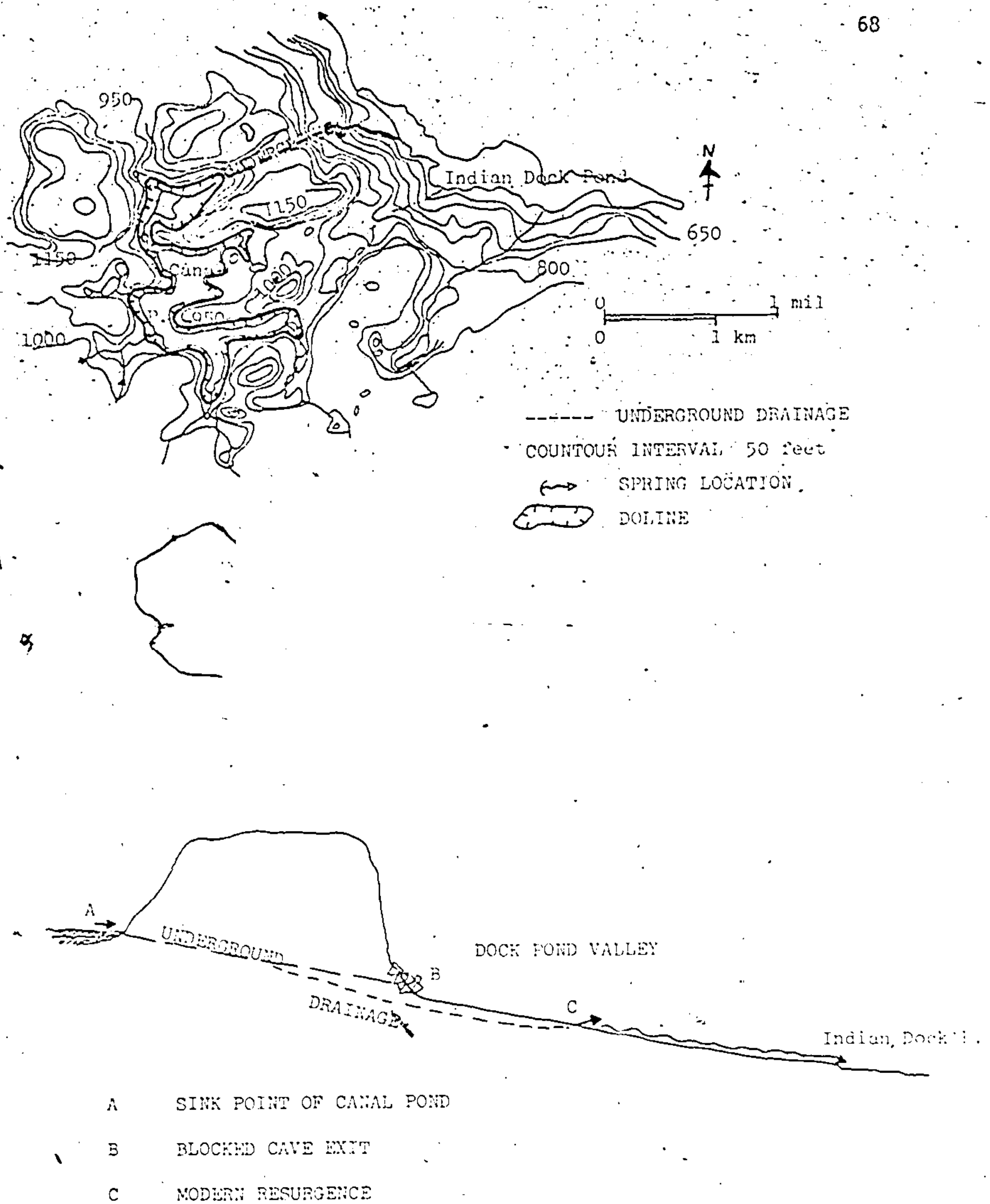


FIG. 22. Canal Pond area and the underground connection.

solutional, dolines, and large complex scoured depressions of pre-Wisconsinan age.

In the case of the modern sinks the shape and depth are controlled by numerous factors. For a shallow sinkhole to originate there must be an underground route present to drain it by conduit flow. If this route is constricted and cannot enlarge at a rate comparable to others (due to rock lithology and or insufficient hydraulic gradient etc.) the sink remains shallow and generally bowl-shaped, with a possible surface overflow channel. If the underground route can enlarge because of high hydraulic gradients and favourable lithologic conditions etc., the sink will tend to deepen and develop a steep funnel shape. This in turn may provide a high local hydraulic gradient locally favorable for the development of "daughter" sinks. This stage is not well developed in the study area, and areas furthest away from zones of high groundwater gradient tend to retain normal surface drainage without dolines..

The large, complex depressions present problems in determining the quantity of ice scour received during the last glaciation, and in determining if these were previously karst sinks (ie. are the features entirely products of glacial overdeepening or are they glacially modified karst precursors (Fig. 23)? Their large and complex form suggests a karst precursor history but no conclusive evidence in the form of infilled paleo-caves or conduit was found, despite careful search.

The spring outlet of Bottomless Pond (the largest of the sinks) has not been established despite several traverses around the sink towards Bear Lake, Island Pond and Bonne Bay Big Pond. Modern discharge

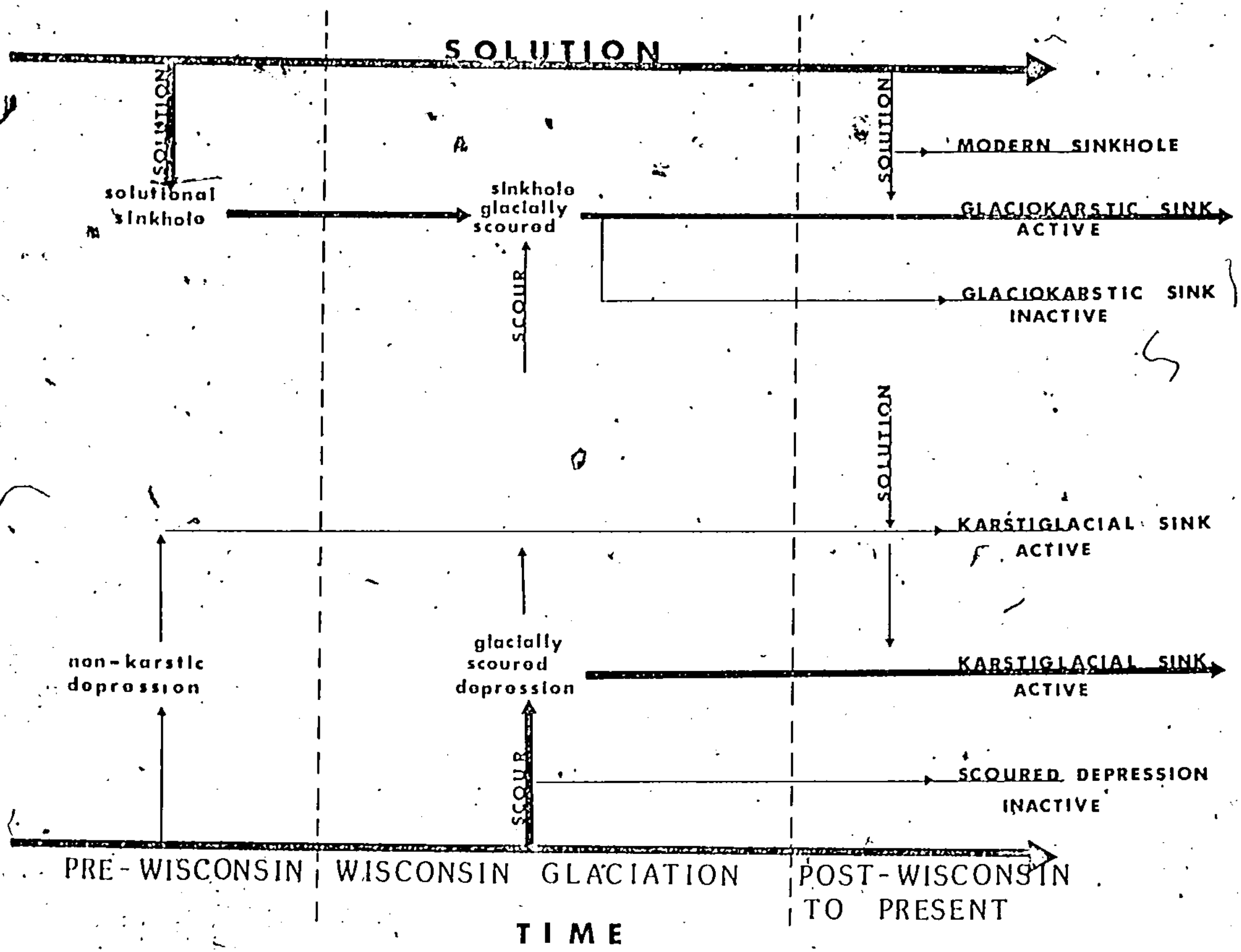


FIG.23. A model for the development of modern, glaciokarstic, and karstiglacial sinkholes.

of the sink is very slow. This would indicate that the conduit system is new and small, and the spring location is small (or under lake level). It is possible that an "old conduit system" (used before the last ice scour) is completely filled, and not utilised any more, and that the "old spring" may be covered under extensive talus deposits.

A model may be derived from the various examples in the area, wherein doline development is controlled by 2 main factors: 1) solution, 2) ice scour (Fig. 23).

In the model, 3 main types of dolines exist over time: a) modern dolines, where the only processes controlling development are solution, collapse etc. b) glaciokarstic dolines, which originated in pre-Wisconsinan time due to solution, then received glacial scour, and continued to function as karstic sinks, c) karstiglacial dolines, where a closed depression is produced entirely by glacial scour. In postglacial time it starts to drain underground producing a karst hydrologic form of scour origin.

IIIc Caves

III c 1 - Study Area

In the study area, with its rugged topography and diversity of type and scale of groundwater sinkhole features, three types of caves were sought: a) relict (or fossil) systems or fragments of systems drained and exposed in cliffs, b) permanent, active, stream or pond sink caves, c) high water overflow caves, intermediate between type a, and b.

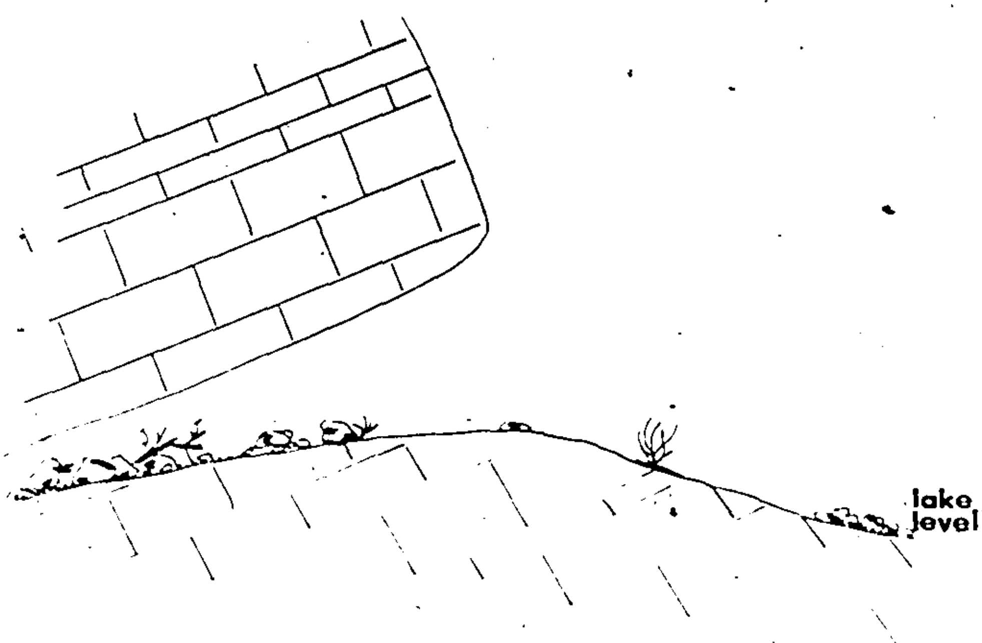
Relict systems are very fragmentary. Generally they are found in exposed cliffs as very small, inactive, open conduits close to present day mountain tops. None were big enough to enter. Other infilled fossil forms are found outside the study area.

Permanent stream or pond sink caves fall into two categories, the inaccessible and the explorable. Inaccessible conduits are channels that are too small or debris-filled or both, suggesting youth or glacial infilling and rerouting. The only accessible stream cave is Canal Pond Cave, about one km long, draining Canal Pond Sink. The cave is air filled in low water stages and ~~is~~ accessible through an "open window" or roof collapse, 50 m east of the modern sink point. This cave could not be explored in the summer of 1977 because of high water conditions. There are no reports of its nature. Water from the cave resurges upwards into a channel halfway down a dry valley leading to Indian Dock Pond (Fig. 22, 29). There is a floodwater exit at the head of the valley; implying an older upper cave route. The modern, low stage, route may be postglacial or older.

Type "c" caves are generally "bedding plane caves", explorable for short distances. Several are found in Browns Pond area, at Seal Pond etc. These caves follow the dip of the bedding and water drains along the solutionally widened planes until they become too constricted to follow (Fig. 24).

Fig. 24

Bedding plane cave at Brown's Pond. In cross-section the cave follows the bedding of the rock, but becomes too small to explore. Water drains along the bedding plane.


lake
level

IIIc 2 - Summary

Within the study area relict caves have not been found (infilled or reopened) to indicate extensive karstification previous to the Wisconsinan glacial period. But this conclusion is only tentative because the area has not been thoroughly explored yet, and there is inconclusive evidence to suggest a long history of cavern genesis and disruption by ice action. Relict features, such as infilled caverns higher than present water levels can well be hidden by the extensive till and talus deposits and/or forest overgrowth.

CHAPTER IV

KARST HYDROLOGY

IV 1 - Introduction

Surface drainage of the study area is through three river basins, draining to Bonne Bay Big Pond in the north, Deer Lake in the south and Goose Arm in the west (Fig. 19). All three basins are above 76 m (m.s.l.) and therefore no marine limit effect is present in the karst drainage. The study area represents a mixed fluvial and fluviokarstic drainage; of the total area of 208 km^2 41% is drained partly underground, 13% is drained wholly underground, and 46% is drained wholly on the surface.

Groundwater drainage may be divided into three distinct zones, northern, eastern, and southern. These differ to some extent from the surface drainage divides (Fig. 19). The extensive northern and southern zones are separated by a wide belt of permanent fluvial drainage containing only scattered, small karst features (Fig. 19). This central belt acts as a "base collector" of water from the southern zone and partly from the northern zone, and drains to Goose Arm. The belt has a low relief, and heavy till and alluvial deposits. Goose Arm Brook is the principal stream. It flows in a meandering channel that widens at places into ponds and swampy areas due to the low gradient.

Several small karst basins are found in this central belt where isolated hills provide sufficient local hydraulic gradient. An example is Snafu Sink where ice scour possibly helped in deepening the feature.

The northern zone comprises the area north of Goose Arm Brook, from Wigwam Lake to Bonne Bay Big Pond. This complex region drains to two major outlets. Bonne Bay Big Pond to the north and Goose Arm to the west. It is a mixture of fluvial, young fluviokarstic, and holokarstic drainage basins. The karstic basins are not integrated with one another, and generally short and shallow connections are found between sink points and spring locations.

The eastern zone drains to Deer Lake. Included in it are Browns Ponds, North Lake and several small tributary lakes. It is mainly a fluvial basin with only minor local karstic features such as the subsurface drainage of Browns Pond #1 and #2, a few post-glacial sinkholes south of North Lake, and a few short bedding-plane caves found at Browns Pond #1. It is possible that some of the tributary lakes northeast of North Lake also drain underground, but with wet period overflows. In 1977 high water level conditions did not allow for their distinction.

The large southern zone is a more complex area that drains to Goose Arm. It is a mixture of fluvial, young fluviokarstic and holokarstic basins. On Moose Plateau, where a holokarstic system is developing, the first stages of an integrated karst system are found. From dye tracing results at least two ponds (Sophies' Pond and Lost Pond) drain underground to the same resurgence point, Moose Spring (Fig. 19). Such elementary integration may also exist in places in the northern zone, but no dye tracing results are available to confirm this.

Basic hydrologic data such as location of sink points, springs, delineation of overflow channels etc., were collected in a preliminary fashion in the summer of 1976 (July-Aug.) and in more detail in 1977

(May-July). In 1976 one gauging station was installed at Moose Spring but the record was fragmentary and without proper rainfall data. In 1977, two stations were set up, one at Goose Spring and one at Nameless Pond Spring. Due to technical difficulties the gauges were not operating and only one week of record is available for Nameless Pond Spring (Fig. 24).

Hydrologic conditions during the summers of 1975, 1976 and 1977 varied a great deal. In 1975 and 1976 the water levels were comparatively low. High winter snowfall and at times heavy spring rainfall provided significant but variable ground-water circulation in spring melt floods. The 1977 Spring conditions were of rapid snow melt, producing torrential streams, very high lake levels and exceptional flooding. Summer water regimes of 1977 continued high, and lake levels did not drop significantly before conclusion of the field season in early August. At the end of July surface overflow channels were still actively utilized in several karstic basins that had been drained entirely underground during the previous two summers. The 1977 high water levels did not allow some of the potential karstic sinks to be distinguished from non-karstic ones. This high ground water level fluctuation in the study area may be indicative of the youthful or deranged karstic development.

IV 2 - Regional Development of the Karst Hydrologic Systems

Groundwater drainage orientation and distribution is mainly determined by rock structure (joints, fractures, dip of beds, etc.), rock lithology (pure soluble limestones, shales, dolomites, etc.), hydraulic gradients, and effects of Quaternary deposits such as till materials inhibiting solutional attack on the bedrock.

Joints and fractures are the commonly utilized structures for underground drainage in the region. In numerous areas water may sink at several points into solutionally widened fractures and resurge at one or more small spring locations, indicating the youthful stage of karstification.

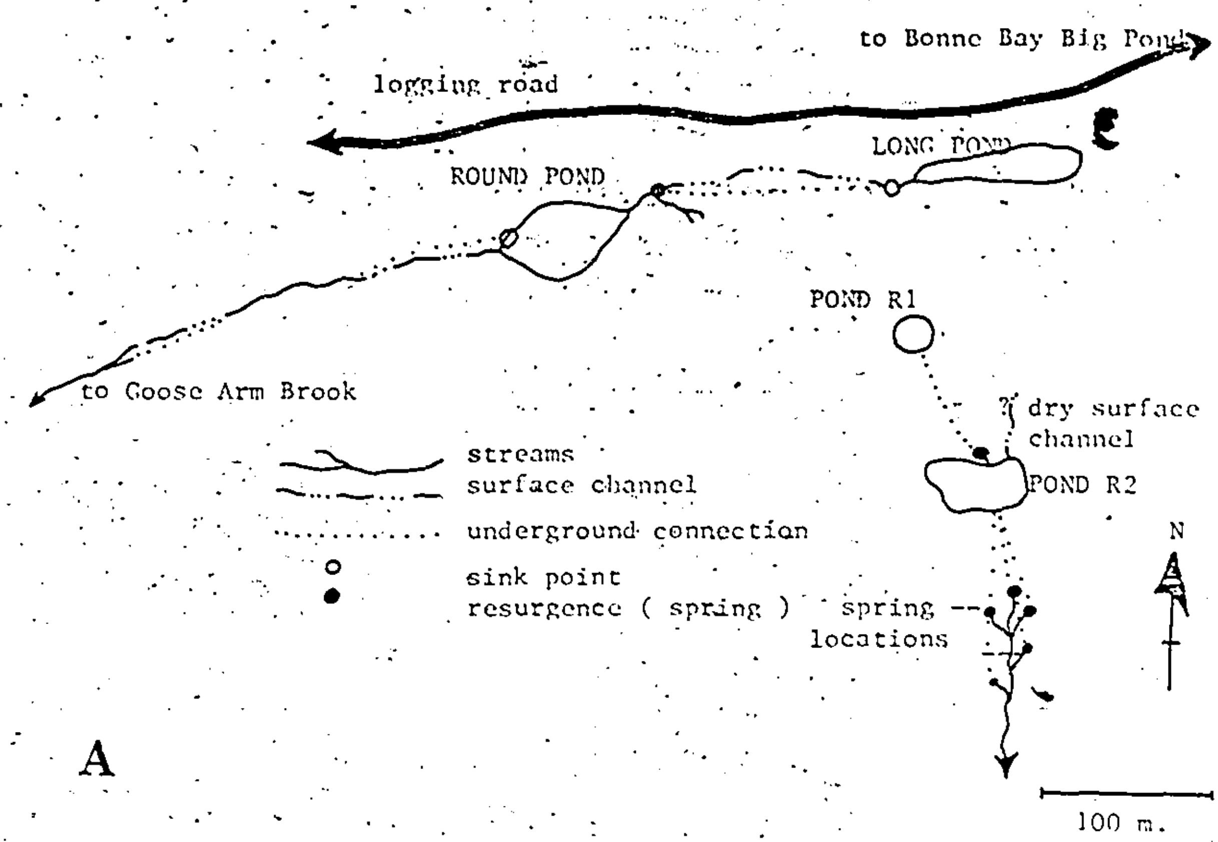
The karst hydrologic systems vary in complexity from one zone to the next: The north region presents a complex sinkhole pattern, where some of the sinkholes are post-glacial in development and others are glacially scoured basins (Fig. 23); but from the characteristic short and shallow underground drainage paths only a karstic groundwater circulation of post-glacial age is indicated.

The Long Pond - Round Pond area is a good example where both hydraulic gradients and structure exert control on subsurface drainage route development (Fig. 26). Long Pond is an elongate lake; water sinks within it's overflow channel through several fractures, and resurges as three small springs at Round Pond, 500 m distant. This pond in turn sinks into a single conduit (0.5 m in diameter), and resurges in the valley at Goose Arm Brook North (Fig. 25) Pond R_2, south of these ponds, drains through fractures and joints, and resurges as numerous springs in the valley to the south (Fig. 26). The bedding at the pond and in the area dips to north but the hydraulic gradient (0.3) created by the steep valley side, favours this southern orientation (Fig. 26).

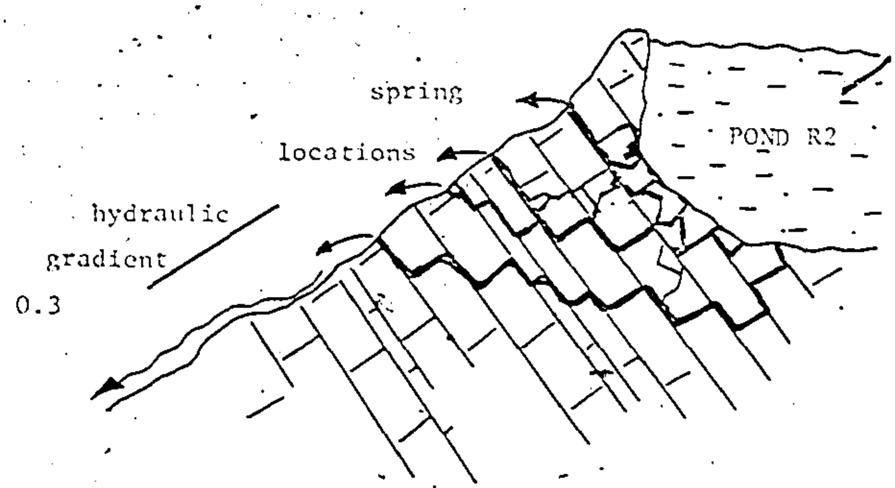
Sinkholes (Pond 1, 2, 3, 4, Frog Pond etc.) found in the area

Fig. 25

Sink point of Round Pond. Water sinks into a circular conduit which is exposed only in low water stages. Surplus water can overflow into a channel leading to Goose Arm Brook North.



A



B

FIG. 26. A) Sink point and spring position of Long Pond – Round Pond [illegible]

[illegible]

between Fold Lake and Sand Bar Pond are large, irregular holokarstic sinks with permanent lakes. There are no surface overflow channels and in spring floods the water level rise is considerable (2 m - 2.5 m at Pond 4). Sink points are within the ponds, and no spring points were found. The structural geology and lithology of this area is complex and spring locations may be either towards Bear Lake or towards Sand Bar Pond. These large sinks could have received ice scour in the last glaciation. Scour marks, if present, are covered by soil and vegetation, for the small exposed patches of bedrock surface have been extensively modified by karren formation.

In the eastern zone the groundwater drainage pattern is more complex due to a number of factors: a) presence of possible pre-glacial or glaciokarstic sinkholes, b) complex structural geology, c) and a varied topography that provides alternative routes of adequate hydraulic gradient for subterranean drainage.

The Troy Pond and Nameless Pond groundwater paths follow the dip of the rocks to the north, where spring locations are at Bonne Bay Big Pond (Fig 27B). Troy Pond is a large, elongate lake with a wide overflow channel about 250 m long that is utilized in Spring floods (Fig. 27A). In low water stages the lake water sinks about 75 m outside the lake in the overflow channel. Water level fluctuation observed at Troy Pond was about 0.75 m. The spring position of the pond is unknown but it is likely in Bonne Bay Big Pond close to the water's edge (Fig. 27B). The estimated hydraulic gradient is 0.21.

Fig. 27A

A. The overflow channel of Troy Pond. Water sinks in the foreground of the picture near (A).

B. Overview of Bonne Bay Big Pond from Troy Pond. Water from the above pond resurges somewhere in Bonne Bay Big Pond.


A

Nameless Pond is a large, irregular, ice-scoured basin with a permanent lake. It is a holokarstic system with no overflow channels. Water sinks into a collapse doline in till that is a few meters away from the lake edge (Fig. 18). The doline base is below the lowest observed lake level but was dry in 1976. In 1977 it was fully innundated. Karst Valley, between Nameless Pond and its rising at Bonne Bay Big Pond, is underdrained (Fig. 21). The length of the flow line is 2.7 km with a hydraulic gradient of 0.011. Dye tracing results were positive,connecting the sink and resurgence points (Table 2).

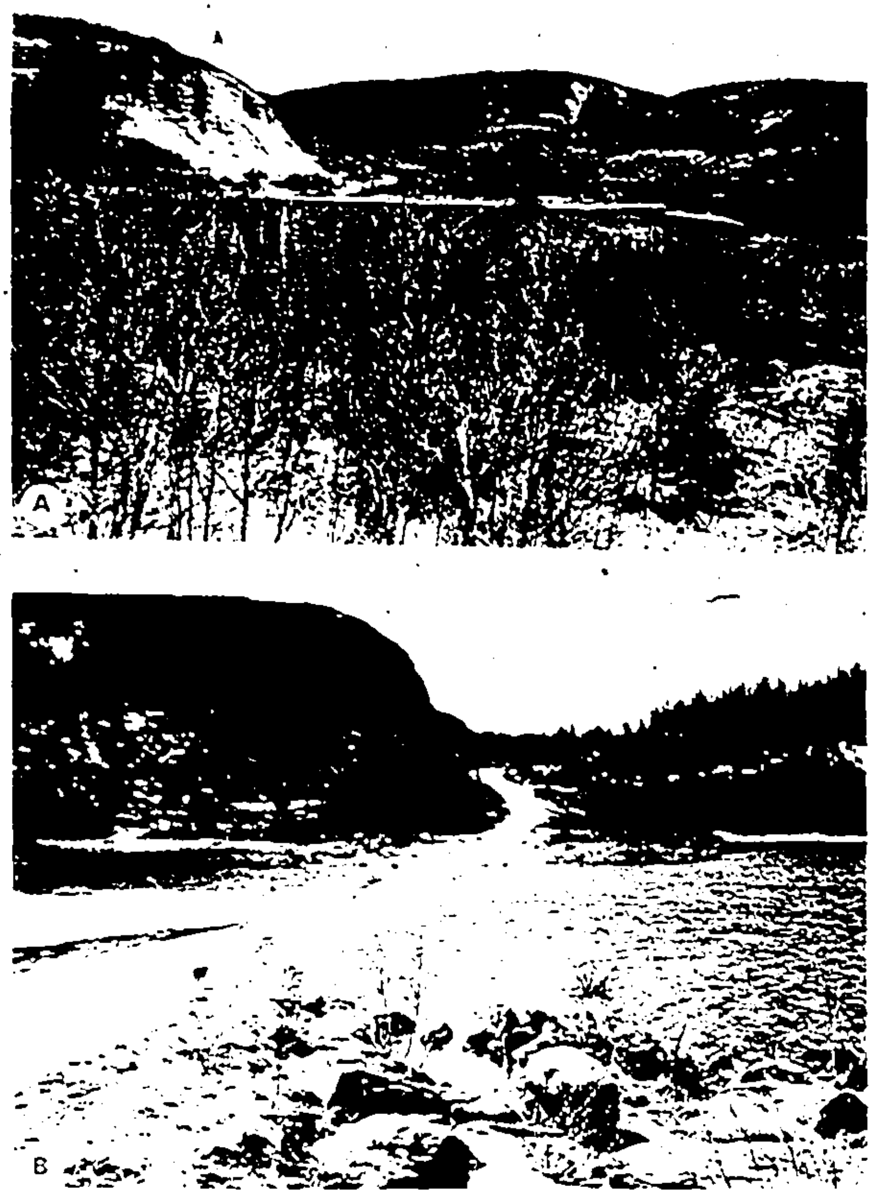
Browns Pond #1, only 200 m east of Nameless Pond and parallel to it, drains in precisely the opposite direction, to the south into North Lake. Browns Pond #2 drains underground to Browns Pond #1 over a distance of 50 m. A valley trending north from the Browns ponds is very similar indeed in structural setting and topography to Karst Valley, although somewhat shallower (Fig. 21). But its drainage is entirely surficial. There are no sinkholes. Browns Pond #1 has an overflow channel which is actively utilized in flood conditions. The sinkpoint is about 50 m outside the lake in the overflow channel where joints and fractures provide the underground route, which is very short (Fig. 19). The adopted hydraulic gradient to North Lake is 0.09, while the alternative to Bonne Bay Big Pond is 0.017.

Bottomless Pond is the largest and most irregular of the ice scoured dolines. It has a permanent lake and several small streams drain to it during heavy rainfall (Fig. 28). There are no overflow channels and water levels can rise 2 meters or more in spring floods and remain high during the summer as in 1977. The sink point is within

Fig. 28

A. Bottomless Pond, looking east.

B. Bottomless Pond, in early spring (June) when water levels started to rise.


A
B

the lake bottom. Despite careful search, the spring position has not been found and dye tracing results were negative to all local springs and streams. This suggests resurgence within one of the lower adjoining lakes. Possible spring locations are in Bonne Bay Big Pond, or Island Pond, or Bear Lake with hydraulic gradients of 0.067, 0.021, and 0.015 respectively.

Small karstic systems in the central fluvial belt exist upon isolated hills. The karst features include small sinkholes, very short underground drainage paths and karren forms. The largest sinkhole, Snafu Sink, has a permanent lake. There are no overflow channels. Water sinks within the lake and resurges at Goose Arm Pond.

In the southern zone the karst hydrologic pattern is also complex. Karst sinks extend from Moose Plateau in the northwest to Indian Dock Pond in the east. Because of the high hydraulic gradient provided by the scarp face of Moose Plateau, and the very steep dip of the strata, several large sinkholes close to the scarp edge are integrated into a holokarstic drainage system. Sophies' Pond is a large lake of irregular shape, sinking in a short, blind, outlet channel at it's northeastern edge to resurge at Moose Spring to the northwest (Fig. 29A). Lost Pond is another large lake that resurges at Moose Spring. It is elongate in shape, belonging to the class of dolines lacking evidence of glacial scour. Dye tracing results for both were positive. Round Pond 1, close by, also sinks. Its resurgence point was not established but is believed to be Moose Spring. There are no overflow channels at these sinks. Further inland on the plateau the dolines are smaller and generally have surface overflow channels which drain their flood water to the scarp edge sinks.

Fig. 29

A. 2nd active spring location of Canal Pond (photo courtesy D.C. Ford).

B. Moose Spring - Draining Moose Plateau.


A


B

Moose Spring is the largest spring in the study area, with measured discharges ranging 0.42 cumec -1 to 0.56 cumec -1 (Fig. 29A). The water resurges amongst boulder debris at the foot of the escarpment and previously at the level of the valley infill, which is of alluvium upon till. There is evidence of overflow discharge through boulders 2m above the spring point, but this has not been observed in active operation. Spring water is drained in a regular channel of 4 m by 0.8 m in dimensions. The channel floor has large numbers of fresh water clam colonies.

Moose Spring is "mature" in that it resurges at the valley floor rather than "hanging" above it as is common in glacially deranged karsts (D.C. Ford, person. comm.). The actual bedrock spring opening is masked by colluvium. It is suspected that it may be buried at depth below the surface of valley infilling, and that the water discharges upwards. This implies that the modern hydraulic gradient is lower than when the spring was first established.

Canal Pond on the eastern side of this zone is a large, irregular sinkhole with a permanent lake and several smaller dolines within it, close to it's northern end. There are no overflow channels and the fluctuations of water level are unknown. Water sinks at the extreme northeastern end via a shaft channel into a cave leading to Indian Dock Pond Valley (Fig. 19). This connection has been confirmed by dye tracing. The hydraulic gradient between sink point and resurgence is 0.06.

This is a very simple and direct connection between an arm of a sinking lake and a valley possessing the same alignment. But the resurgence situation is complex. The limestone bedrock extends to the bottom of

Indian Dock Pond, offering a lowest possible resurgence there. But the main spring is at least 25-30 m higher and 150-200 m nearer to the sink. It is a "hanging" spring position. The main spring is phreatic, and resurges in a small pool close to the left bank of a steep boulder-bed channel (Fig. 29B). Above the spring the channel is normally dry except in spring floods. Upstream from the spring the dry valley terminates abruptly in a major boulder pile at the foot of a steep backwall. Draughts of cold air were blowing from the boulders when visited, indicating a cave conduit behind them.

The spring of Canal Pond is in sharp contrast to Moose Spring. The Canal Pond spring is young and hanging; the main spring position has migrated from the head of the valley (now the overflow point) downstream to an outlet which is still about 25-30 m above the ultimate potential resurgence (Fig. 30). This spring is one of the two largest springs of the region, draining large glaciokarstic features. This may suggest the possibility that glacial derangement has induced a radical shift in the position of the Canal Pond spring.

IV 3 - Groundwater Regimes

The response of spring discharge to melt water floods and heavy rainfall can give an accurate idea of the state of underground conduit systems.

Two stage recorders were set up in the summer of 1977, at Nameless Pond Spring, and at Goose Spring. Due to technical difficulties

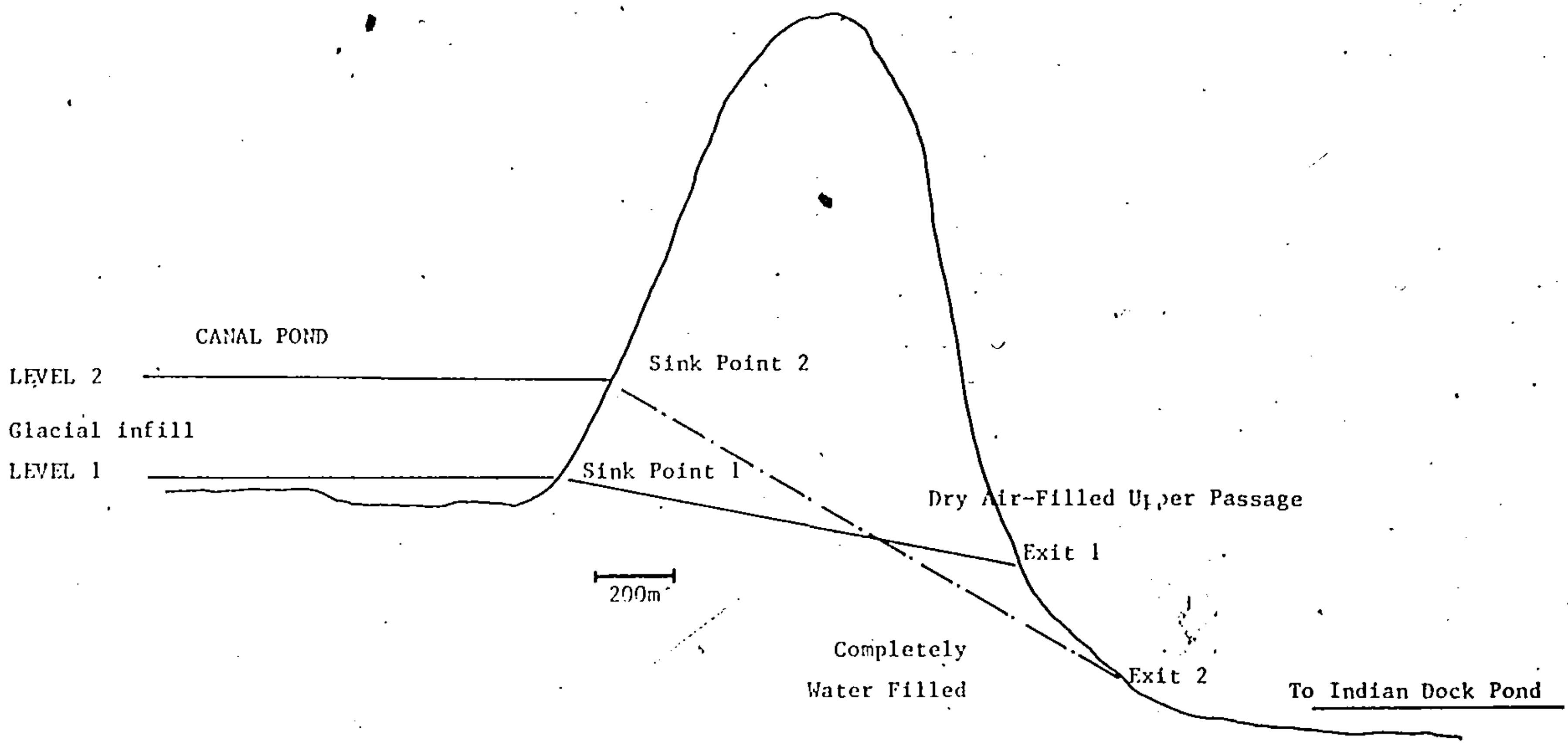


FIG 30 Cross-section of the Canal Pond Cave System.

the recorders were not working and repairs could not be effected in Newfoundland. Only one week of data is available for Nameless Pond Spring (Fig.30A).

The interpretation of such a short record is difficult. Because of flood conditions, the lake level was at least 2 m higher than the previous summer. Small rain pulses during recording period become difficult to interpret and on the trace, very small if any, attributable response was recorded.

Dye tracing was carried out at four localities:

Nameless Pond to its rising.

Lost Pond to Moose Spring.

Canal Pond to its rising.

Bottomless Pond to ? (Table 2)

In 1976 dye tracing on Moose Plateau connected Sophies' Pond to Moose Spring. All dye tracing connections in 1977 were positive except for Bottomless Pond.

In 1977 the discharge of Nameless Pond spring visibly was not very much higher than during 1976. The 2 to 4 days dye travel time from sink to resurgence indicates a young, possibly incompletely connected conduit or a very clogged up older system. Calculated maximum ground water velocities of 0.015 m/sec indicate a flow rate of 1296.0 m/day. Similar results are indicated at Lost Pond, Canal Pond and Sophies' Pond (Table 2).

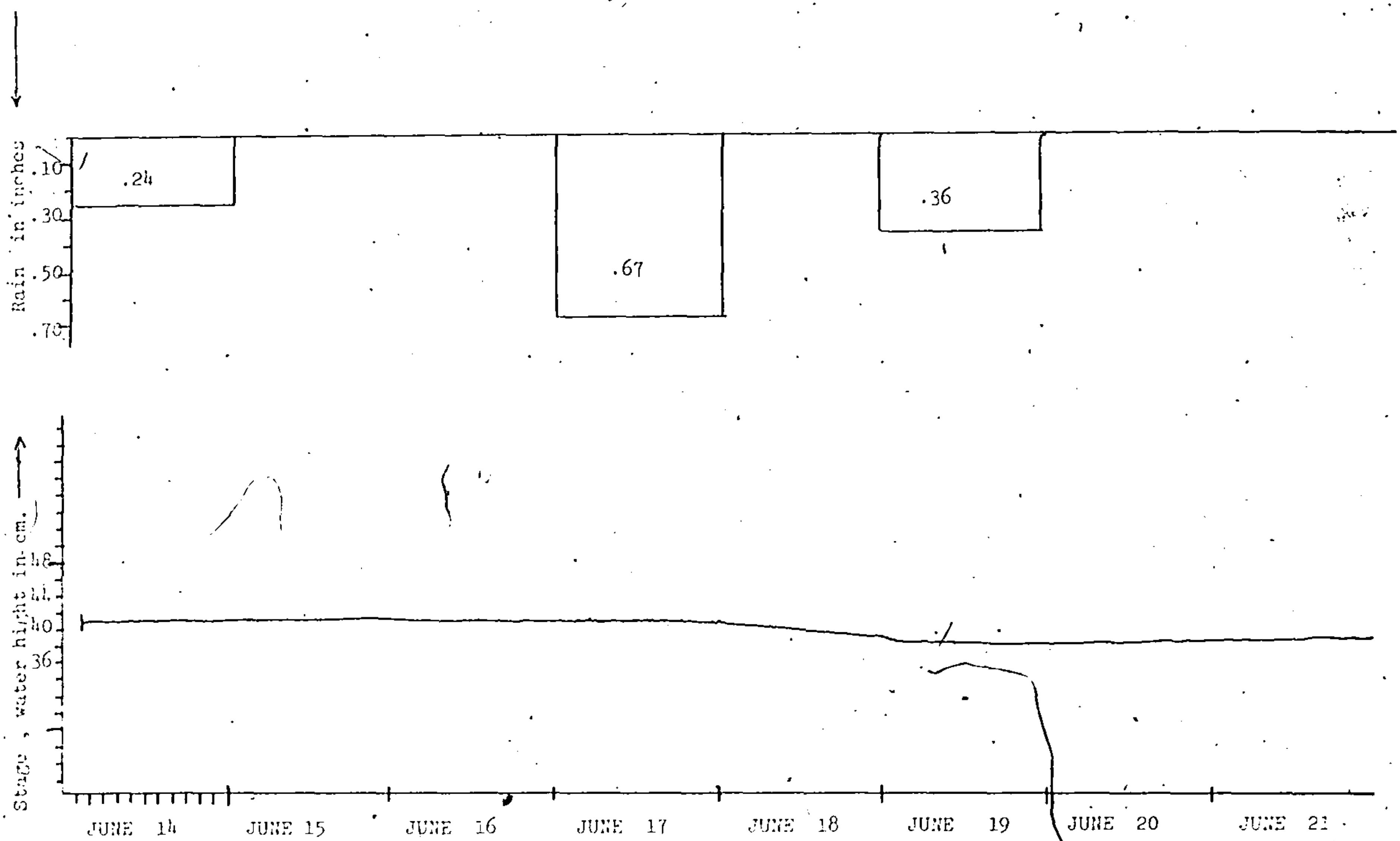


FIG. 30A. Stage record data of Nameless Pond Spring.

TABLE 2 DYE TRACING RESULTS 1976 - 1977

Location	Input date of dye	Dye first detected at spring	No. days dye was noted	Mean Maximum ground water velocity m/sec	Ground water travel, m/day	Length of flow lines (m)
Nameless Pond to spring	1977, June 23, 11:30am	1977, June 25, 9:30 am	2-4 days	0.015	1296.0	2720
Lost Pond to Moose Spring	1977, July 3, 2:15pm	1977, July 6, 10:45am	3-4 days	0.003	259.2	750
Canal Pond to Spring	1977, July 7, 10:30 am	1977, July 8, 2:30 pm	1-2 days	0.012	1036.8	1100
Bottomless Pond to spring	1977, June 2, 7:30am	----------	--------	-------	----------	--------
Sophies Pond to Moose spring	1976, July 31, 11:00am	1976, August 3, 11:00am	3-4 days	0.003	259.2	550

IV 4 - Analysis

The development of the regional hydrologic features are controlled by several factors such as presence of soluble rock, frequency and orientation of fractures and joints, bedding planes etc. for water movement, and complex topography providing varied hydraulic gradients. Additional modifying factors are introduced by glaciation where ice scour and infill has modified existing sinkholes, created new ones, deranging surface and probably subsurface drainage as a result (Fig. 23).

The present groundwater systems tend to indicate post-glacial development because short and shallow flow paths are predominant. But the presence of complex and large scoured basins also indicates the probability of karstification and therefore the existence of groundwater systems in pre-Wisconinan interglacial periods. If these older systems existed, the scour and infill processes have completely blocked and deranged the drainage and the renewed process of karstification had to find new subsurface drainage routes.

Considering the topography, and the distribution and character of the karstic areas a model may be developed, where the development of the karstic systems are the result of hydraulic gradients. In this model it is assumed that lithology and structure would permit karstification.

In a simple form of the model (No. 1, Fig. 31) a flat plateau and cliff combination is used. In the Moose Plateau area, the large and holokarstic sinks are found close to the edge of the Plateau, which provide high hydraulic gradients. Further in from the cliff, doline development becomes shallow and utilization of overflow channels becomes more frequent until a point is reached inland where due to very low

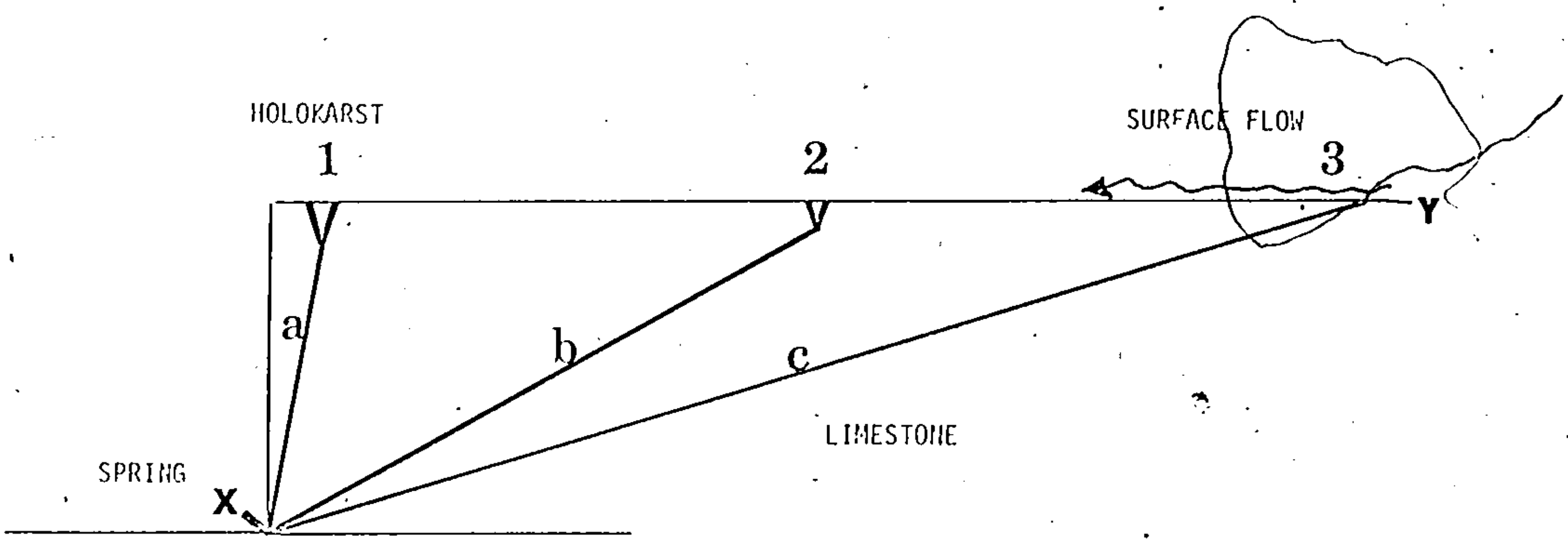


FIG. 31. MODEL 1.

hydraulic gradients only surface flow is present.

In Model No. 1 a fluviokarstic system evolves through time to a holokarstic state at the cliff's edge, where the highest hydraulic gradients are present (1-3 of Fig. 31). Complexities in this case are only introduced by lithology and/or structural variations between points y and x (Fig. 31). This kind of model has been applied to the Niagara Escarpment (Cowell, 1976). In Newfoundland such a simple model cannot be used effectively, mainly because of the rugged topography of the area. Therefore a more complex Model (No. 2) is developed where the topography and, therefore, the local hydraulic gradients can be taken into account (Fig. 32).

Within the study area hydraulic gradients vary a great deal (Table 3). Using the Moose Plateau area again, the shallower and smaller dolies, developed behind the holokarstic sinkholes, periodically, utilize overflow channels. In some cases some of these sinks are present only because of local hydraulic gradients. These dolies are well portrayed in Model 2 (Fig. 32).

The fluvial stage, present where hydraulic gradients low and the quantity of water supplied is large. This stage is generally reached far away from the effects of regional gradients, and where local gradients are not sufficient, or other factors such as lithology or structure are not conducive for sinkhole development (Fig. 32, and 19).

Model 2 may further be modified by changing the regional hydraulic gradient (Fig. 32). This may happen through scour or infill. By changing the regional gradient, the established underground drainage routes may be modified or completely changed. This aspect of the model may be used to explain the development of Canal Pond Cave where two

TABLE 3 · HYDRAULIC GRADIENTS.

NAME	HYDRAULIC GRADIENT H/L	LENGTH OF FLOW-LINE (m)	SINK POINT
Nameless Pond to the spring	0.011	2720 m	C
Browns Pond #2 to #1	0.036	250 m	A
Browns Pond #1 to North L.	0.09	500 m	D
" to Bonne Bay Big Pond -----------------	0.017	2830 m	A
Bottomless Pond to Bear L.	0.015	1000 m	A
" to Bonne Bay Big Pond----------------	0.067	2080 m	A
" to Island Pond	0.021	1500 m	A
Pond Troy to Bonne Bay Big Pond ------------	0.21	300 m	D
Fold Lake to Snake Pond	0.026	1300 m	A
" to Bottomless P	0.092	1000 m	A
Pond4 to Sandbar Pond	0.058	550 m	A
Pond 2 to Pond 4	0.05	250 m	A
Pond 3 to Sandbar Pond	0.048	250 m	A
Pond S2 to Spring north of Bear Lake	0.20	300 m	A
Mud Pond to Spring	0.44	900 m	A
Long Pond to Round Pond	0.142	350 m	D
Round Pond to Spring	0.100	300 m	B
Pond R1 to R2	0.20	250 m	A
Pond R2 to Spring	0.30	300 m	B
Bear Paw Lake to L1	0.061	300 m	A
Fox Pond to Grindstone	0.14	500 m	A
Grindstone P. to Bonne Bay Big Pond	0.05	400 m	A
Jack Sink to Keats P2	0.14	350 m	A
Snafu Sink to Goose Arm P.	0.148	350 m	B
Pond B to Spring	0.053	340 m	A
Seal P. to Goose Arm Brook	0.040	2200 m	D

NAME	HYDRAULIC GRADIENT H/L	LENGTH OF FLOW LINES(m)	SINK POINT
Pond N to Goose Arm Brook	0.153	900 m	A
Canal Pond to Spring	0.06	1100 m	D
Pond Tub to Seal Pond	0.079	500 m	A
" to South Pond	0.092	200 m	A
Pond S1 to a NW stream	0.122	450 m	A
" to a south lake	0.095	800 m	A
Jaw Sink to lake	0.130	350 m	A
Lake 1 to Lost Pond	0.073	750 m	A
Lost Pond to Moose Spring	0.134	750 m	D
Sophies Pond to Moose S.	0.305	550 m	D
Round Pond to Moose S.	0.169	900 m	B
" to Lost P.	0.14	500 m	B
Trout Pond to Alder Steady	0.056	1800 m	A
M1 to Lake 1	0.22	300 m	A
M1 to an eastern stream	0.06	250 m	A
Ghost Sink area to Goose Arm B.	0.1808	1400 m	A

Sink point location symbols :

A unknown

B at edge of pond

C outside pond in a sinkhole

D outside pond in a stream channel

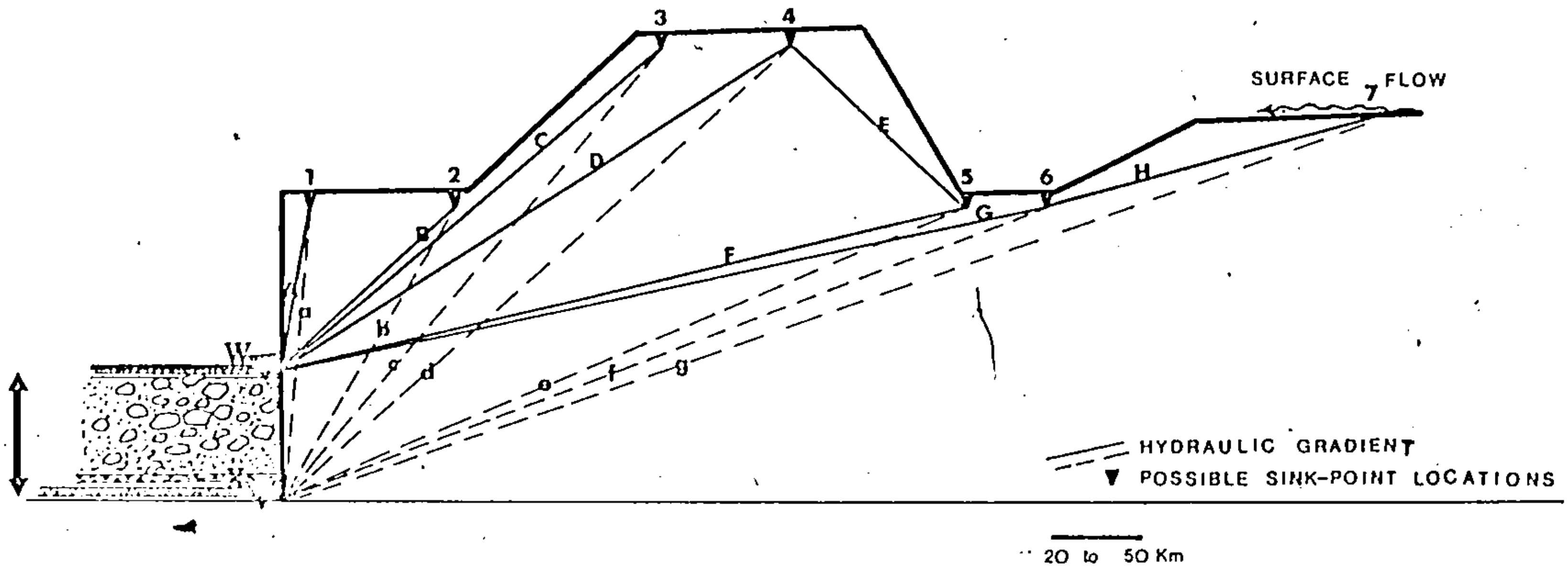


FIG. 32, MODEL 2, REGIONAL AND LOCAL HYDRAULIC GRADIENTS exits are present (Fig. 30). This cave has not been explored and verification of the model's applicability is not possible.

The higher (or first) cave exit of Fig. 30 could have developed before the last glaciation. In the post-glacial period the original sinkpoint has been infilled, and at a new elevation another sinkpoint developed and a new route (2) has been found. It is possible that early in the development of route #2, part of the old route #1 may have been used.

At present the "old upper route" or higher exit is only used in flood conditions. The lower exit point is in a sump and is always active, indicating phreatic conditions. The "hanging" nature of exit 2 is difficult to explain, unless shaley zones in the limestone between the spring and the lake level of Indian Dock Pond forces water to exit at this high point.

Hydraulic gradients in the area vary from a low of 0.011 (Nameless Pond to its spring) to a high of 0/0.44 (Mud Pond to its spring). The distribution of hydraulic gradient values tend to cluster in the low values between 0.0 to 0.20 (Fig. 33A). Generally, with high gradient values short flow path length are associated (Fig. 33B) indicating young and shallow ground water routes. Figure 34 strongly indicates short subsurface routes.

Comparison of mean ground water velocities of the Newfoundland examples with other areas (Table 4) indicates a comparison with Missouri, U.S.A., and the Kentucky Sinkhole Plain where velocities of 13-21 m/hr and 40-80m/hr are found. These results are interesting because the development of both of the above karst areas in the U.S.A. is more mature than the Newfoundland systems.

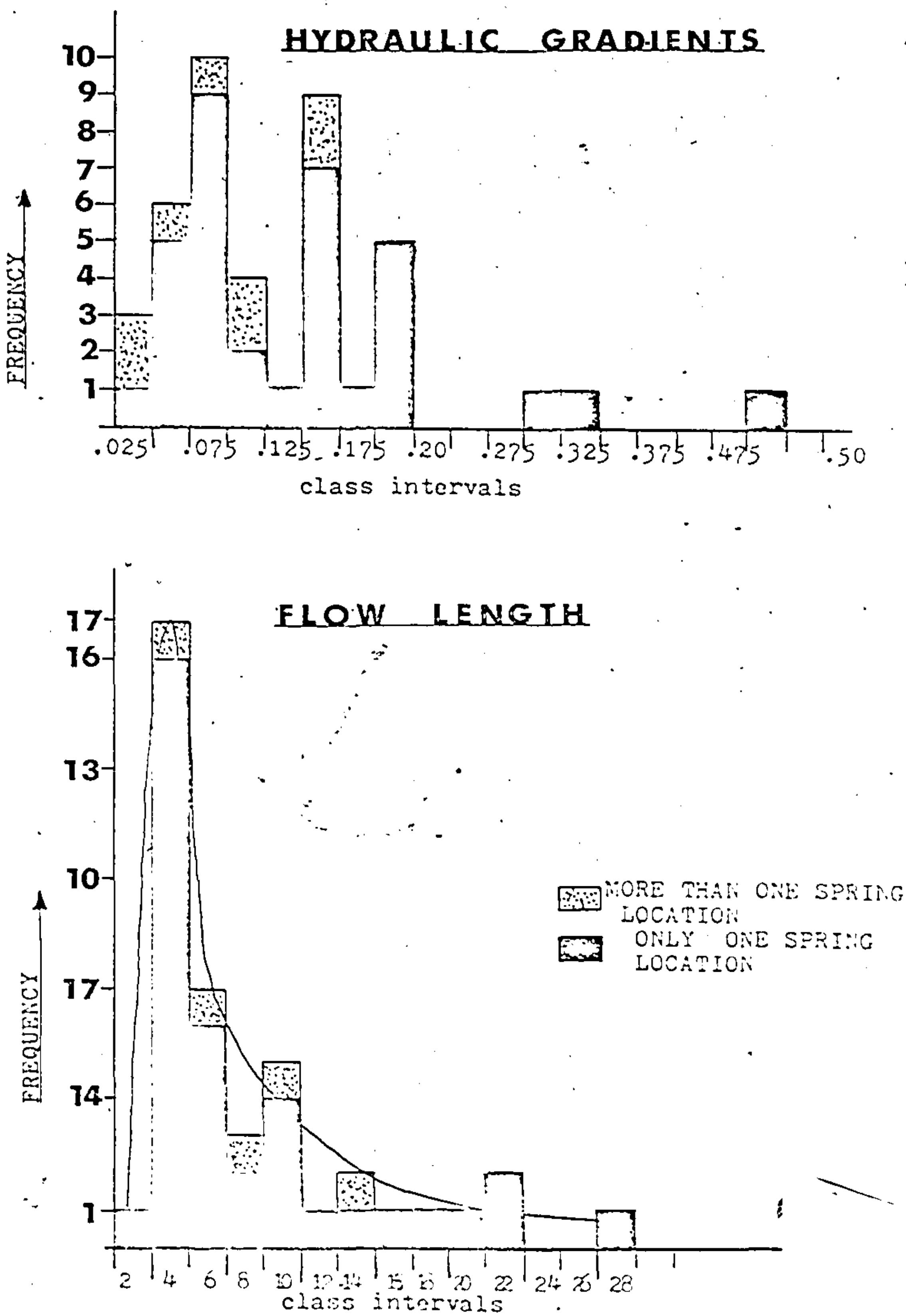


FIG.33. Histogram of hydraulic gradients and flow path length.

TABLE 4 GROUND WATER VELOCITIES

Location	Karst relief	Minimum distance between sinks and springs	Ground water velocity m/hrs	Reference
Theoretical pre-cave flow ,gradient is 1%	low	———	0.03	Ford D.C., pers. comm.
Yorkshire , England	Medium	1.5 to 2.3 Km	7.0 -8.0	Sweeting,1973.
Vaucluse, France	Medium	22 Km	26.0	Avias, 1972.
Languedoc,France	Medium	5-20 Km	14 - 500	Avias, 1972.
Nakimu Cave, Canada	High	1.8 Km	3000	Ford, Unpub.
Canal Pond, Newfoundland	Medium	1.1 Km	43.2	this report
Moose Spring,Newfoundland	High	0.75 Km	10.8	this report
Nameless Pond Spring Newfoundland	Low	2.72 Km	54.0	this report
Sophies Pond	High	0.55 Km	10.8	this report

IV Conclusions

The study area between Goose Arm and Bonne Bay Big Pond is an immature karst region, where not all the discharge from the basins is concentrated at carbonate springs. Subsurface drainage is generally for short distances at shallow depths. The groundwater connections are unintegrated, and some of the flow-through times for dye tracings were 2 - 4 days in distances of less than 2 km.

Drainage within the entire study area can be separated into wholly surface flow (normal fluvial flow), partial underground capture of the surface flow (young fluviokarst), and complete capture of surface flow (holokarst). Surface drainage is extensive (46% of total area); and there are three main basin collectors: Bonne Bay Big Pond on the north, Deer Lake on southeast, and Goose Arm on the west. Few streams flow directly on bedrock because of the alluvial cover present in most valleys. This is a reason why only a small number of streams sink underground. The water becomes saturated as it moves through the carbonate-rich cover. Most of the underground drainage is immature and surface overflow channels are utilised in heavy rain or snow melt.

The karst groundwater systems are not well integrated and their development is largely the result of post-glacial activity. There is inconclusive hydrologic evidence to support pre-glacial development, ie. large, scoured closed depressions such as Bottomless Pond drain through infill in their bases, despite low hydraulic gradients to spring positions.

The study area, therefore, provides substantial difficulties to evaluation of the development of a young karst hydrology, complex topography and high relief, complex structural geology and varied rock lithology are present. Glaciation has provided carbonate-rich till deposits very variable depth deranged drainage, and scoured basins.

The complex topography provides wide variation in hydraulic gradients, and a simple "cliff-plateau" model (No. 1) is not applicable. A more complex model (2) is needed. The main features are the interplay of regional and local hydraulic gradients. Regional gradients are provided by extensive lowlands such as the "base collector" zone, and mountain complexes. High regional gradients product holokarstic zones generally close to the edge of the mountains and plateaus. Smaller sinks with periodic overflow channels are present further inland in response to the lower regional gradient. But high local gradients here may produce local holokarstic areas such as at Pond S (Fig. 19). These are not integrated to the regional springs. Fluvial zones exist where neither local nor regional gradients are favorable for underground drainage or till mantles etc. are too great.

CHAPTER 5

KARST WATER CHEMISTRY

V-1 - Introduction - Solution of Limestone

The dissolution of carbonate rocks by water is fundamental to the karst geomarphology. Solution rates, and the effect of lithology upon these solution rates, are important to the understanding of karst landforms and to the development of underground cave systems.

The ability of water to dissolve calcium carbonate is called the aggressiveness of water towards $CaCO_3$. There are two principal systems that are of interest to karst geomorphologists: open and closed systems (Garrels and Christ, 1965). In an open, or three phase system the water, rock and gas phases are all considered. In a closed, or two phase system only the water and rock phases need be considered. There are no unnatural restrictions placed on the pH, PCO_2, or on the quantity of dissolved carbonate species.

The chemistry of solution of calcium carbonate may be summarised by the following equations:

Closed System:

1) $H_2O \rightleftharpoons H^+ + OH^-$

2) $CaCO_3 \rightleftharpoons Ca^{2+} + CO_3^{2-}$

3) $CaCO_3 + H^+ \rightleftharpoons Ca^{2+} + HCO_3^-$

Open System:

4) $H_2O + CO_2 \rightleftharpoons H_2CO_c \rightleftharpoons H^+ + HCO_3^-$

5) $HCO_3^- \rightleftharpoons H^+ + CO_3^{2-}$

6) $CaCO_3 + H^+ \rightleftharpoons Ca^{2+} + HCO_3^-$

In the simplest closed system solution of calcium carbonate in water may be represented by:

7) $H_2O \rightleftharpoons H^+ + OH^-$

8) $CaCO_3 + H^+ \rightleftharpoons Ca^{2+} + HCO_3^-$

The hydrogen ions (H^+) produced as H_2O dissociates will combine with CO_3^{2-} ion, from $CaCO_3$ dissociation (equ. 3). Because of this, the solution process is going to be strongly pH dependent.

In an open system water is in contact with carbon dioxide gas and reacts to produce:

9) $H_2O + CO_2 \rightleftharpoons H_2CO_3 \rightleftharpoons H^+ + HCO_3^-$

The reaction of water, carbon dioxide, and the carbonate minerals is represented by:

10) $CaCO_3 + H_2O + CO_2 \rightleftharpoons Ca^{2+} + 2HCO_3^-$

(Garrels and Christ, 1965; Drake, 1974; Rauch and White, 1977).

Reactions 1 to 6 will continue until equlibrium concentration of all species is reached, that is no further solution of Ca^{2+} will take place until the PCO_2 is increased. Because of this, the availability of CO_2 is an important control on the open system process described above. In general the greater the PCO_2 the greater the amount of carbonate rock solution.

Generally karst waters are found to have high concentrations of dissolved $CaCO_3$ indicating that the PCO_2 is raised much higher then the global atmospheric mean value of .03%. This excess of PCO_2 comes from the soil and from decaying matter, where organic activity provides high concentrations of carbon dioxide to the percolating waters.

Different quantities of carbon dioxide found in soils at different latitudes are mainly the function of seasonality. In cold regions biological activity producing CO_2 is restricted for the summer months, whereas in tropical areas it operates all through the year at high production rates (Miotke, 1974; Cooke, 1971).

Solution rates, and therefore the attainment of saturation or supersaturation, are dependent on a number of factors such as temperature, pressure conditions and rock lithology. Decreased carbon dioxide pressures or increased temperatures can force water to precipitate calcium carbonate. To increase solution a decrease in temperature and/or an increase in PCO_2 are needed, or there may be mixing of two saturated but quantitatively distinct waters (Bogli, 1964b). According to Bogli (1960) 90% of saturation is achieved in the first 60 seconds that water is in contact with the carbonate rocks.

The chemical characteristics of karst waters may be expressed as a saturation index or in terms of the concentration of the different ions present in solution. To determine the saturation states of water from measured variables, calculations following Langmuir's methods (1971) or others (Drake and Harmon, 1973; Ford, 1971c) are used to arrive at saturation indexes for calcium or dolomite (SIc or SId). The values of SIc or SId are the logarithoms of IAP/K, where the IAP is the ion activity product of calcite or dolimite and K is the theoretical activity product of calcite or dolomite. (Drake, 1974; Langmuir, 1971; Wigley, 1971; Garrels and Christ, 1965; Picknet, 1964). The presence of magnesium in carbonate rocks may have a tendency to lower calcite solubility rates, although small quantities may enhance solution (Plummer, 1972; Picknet, 1972).

V-2 - The Sampling Programme: Design and Methods

The principal sampling programme for the study area was operated from May 1977 to July 1977. During this time 300 water samples were collected from designated lakes, streams, springs, and rivers. Emphasis in the sampling programme was placed upon repeated pond sampling because of the uniqness of the study area "a karst of sinking and overflowing ponds" not found elsewhere in Canada (D.C. Ford pers. comm).

Included within the sampling programme were two "control" waters: Goose Arm Brook North and Corner Brook. Goose Arm Brook North flows on non-karstic rocks partly within the study area, through forested hills and valleys. Corner Brook flows mostly on non-carbonates except for a few miles before 3 Mile Dam, where there is a small artificial lake. Sampling took place at the lake outfall. This site offers a very simple pond situation that may be compared and contrasted with the variety of natural ponds in the study area.

The selection of ponds within the area was aimed at a representative sampling of the range of pond types, with reference to varying size, morphology and hydrology. All karst springs that were accessible were sampled. It was hoped that some of the springs would give insight into the composition of sub soil karst waters etc. which could not be sampled directly.

Goose Arm Brook is the major base collector in the study area, and it was sampled at its mouth. Its behaviour would give insight into the hydrochemical behaviour at the basin scale.

Water samples were collected at frequent intervals between May 25, 1977 and July 29, 1977, a period covering the end of snow-melt to high summer of that year. In addition, a pilot programme was operated in July-August of 1976, when a few water samples were collected. Some sampling sites of 1976, such as Alder Steady, could not be collected in 1977 because of the prevailing higher water stages.

Water samples were taken in capped, 500 ml. polyethylene bottles and at the same time temperature, pH and conductivity were measured. Before each pH measurement, the meter was calibrated with buffers at pH 7.0 and 10.0. All water samples were analysed at a field laboratory within 24 hours of collection. Laboratory analyses were for alkalinity (HCO_3^-) by potentiometric titration with HCl, and for CA^{++} and Mg— by colorimetric titrations. The variables: temperature, pH, HCO_3^-, Ca^{++}, Mg^{++} were then used to calculate saturation states with respect to calcite (SIc) and dolomite (SId), and equilibrium partial pressures of CO_2 (PCO_2). The calculation methods followed those of Drake and Harmon (1973), Langmuir (1971) and Ford (1971c). The computer programme used was Milchem.

When computations were complete, samples with greater than 15% ion balance error were rejected. The remaining samples were grouped into: karst springs, karst ponds, sinkhole lakes, small ponds, surface streams, and large rivers and graphed to see if specific chemical trends may be used to separate the waters into distinct classes.

V-3 - Chemical Characteristics - Results and Discussions

V-3-1 - Chemical Water Characteristics of the 1977 Data Set

Figure 34 demonstrates that waters in the study area are of the simple bicarbonate type. The strong correlation (r+.977) indicates that there are no significant effects of non-carbonate ions such as SO_4^{-2}. Waters collected from terrains with little carbonate present (Corner Brook, Goose Arm Brook North) plot significantly lower and are distinct from the main group. Variation in this tightly correlated data is introduced only by Goose Arm Brook. This is the base collector of the majority of the waters, and other unsampled water types may enter it from marshy sectors where there is a little greater ionic complexity (Fig. 34).

The plot of Ca^{+2} vs. HCO_3^- (Fig. 35) shows a wider scatter than Figure 34, with an r value of .892. The scatter indicates the presence of cations other than Ca^{+2}. It is presumed that these are Mg^{2+}. Corner Brook and Goose Arm Brook North again separate out and plot low on the graph (Fig. 35). There is a wider scatter in the carbonate waters, but without the symbols, separation of karst ponds, streams, etc. would not be possible. The general increasing trend reflects the increase in certain Ca^{+2} and HCO_3^- values over time.

Figure 36 again illustrates the simple composition of these waters. Saturation with respect to dolomite occurs, suggesting the presence of significant quantities of dolomitic beds throughout the regional stratigraphic section. However, there is no incongruent solution of dolomite, such as Cowell (1976) reports from the Bruce Peninsula, which is composed wholly of dolomites. With a correlation coefficient of .978, Ca^{+2}/Mg^{+2} ratio will not be a significant discriminating variable. These results are quite comparable to other karst areas where there is a mixture of limestone and dolomite eg. Langmuir (1971) in

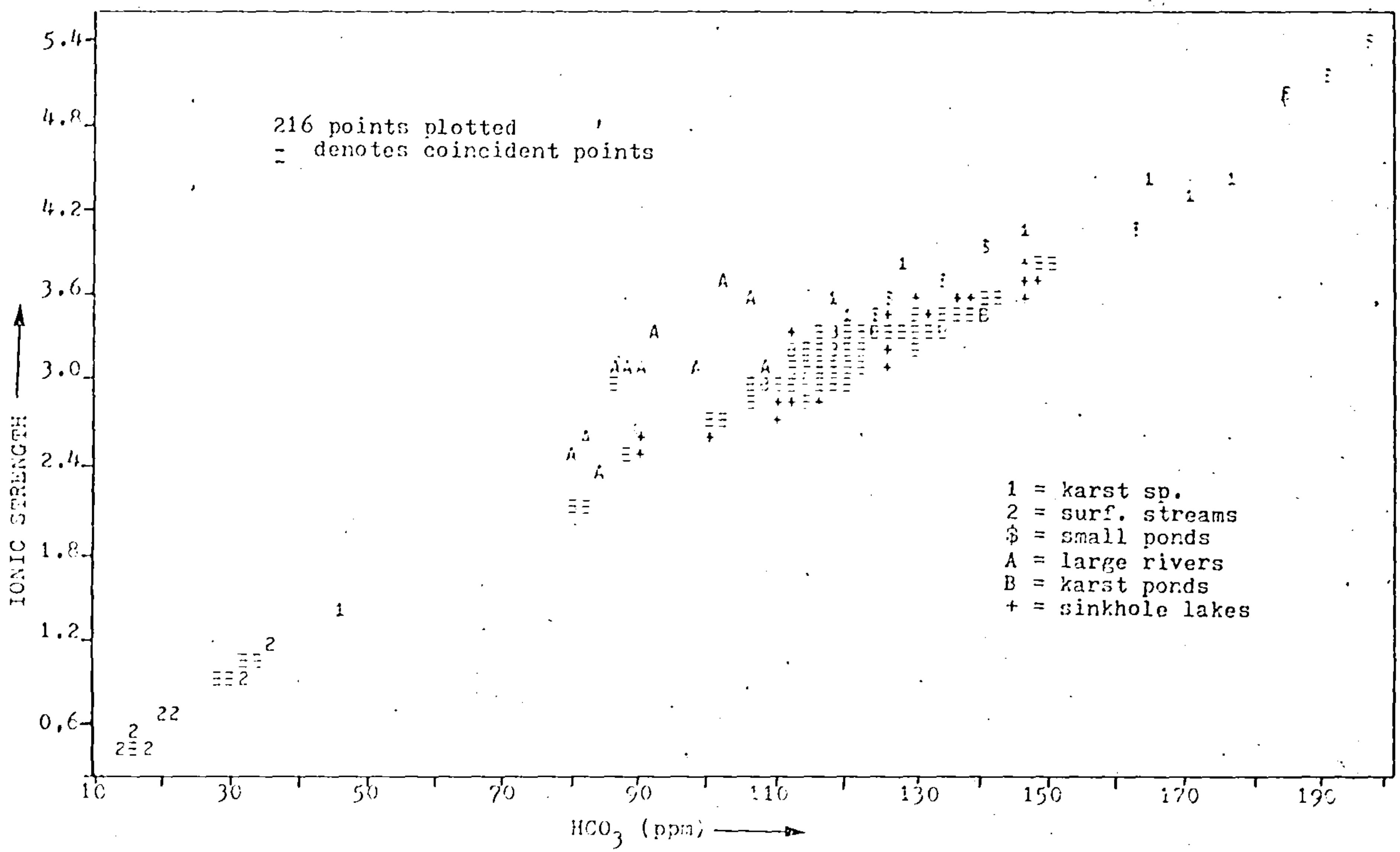


FIG. 34. The graph of HCO_3 and ionic strength.

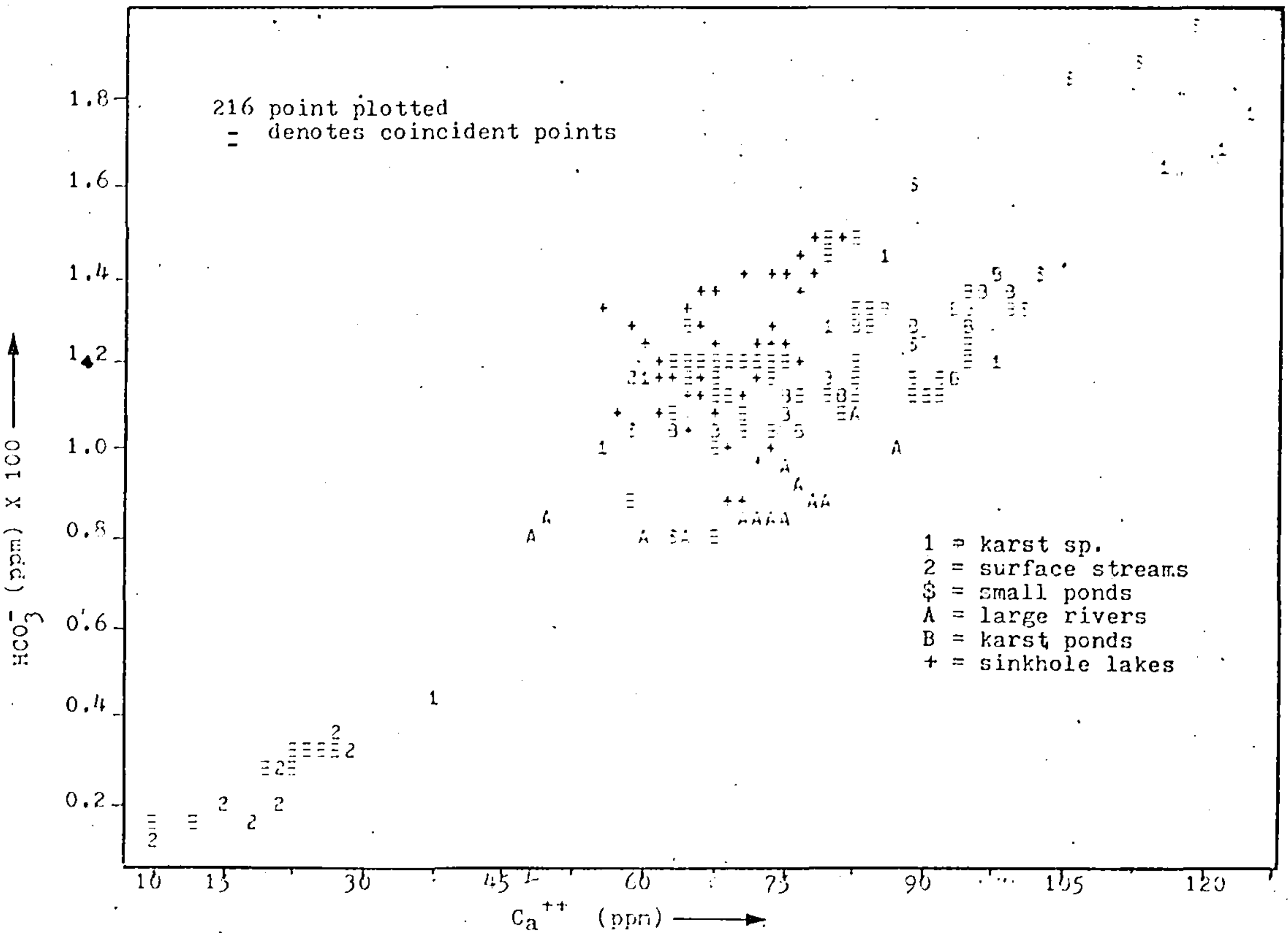


FIG. 35. The graph of Ca^{++} and HCO_3^- (ppm).

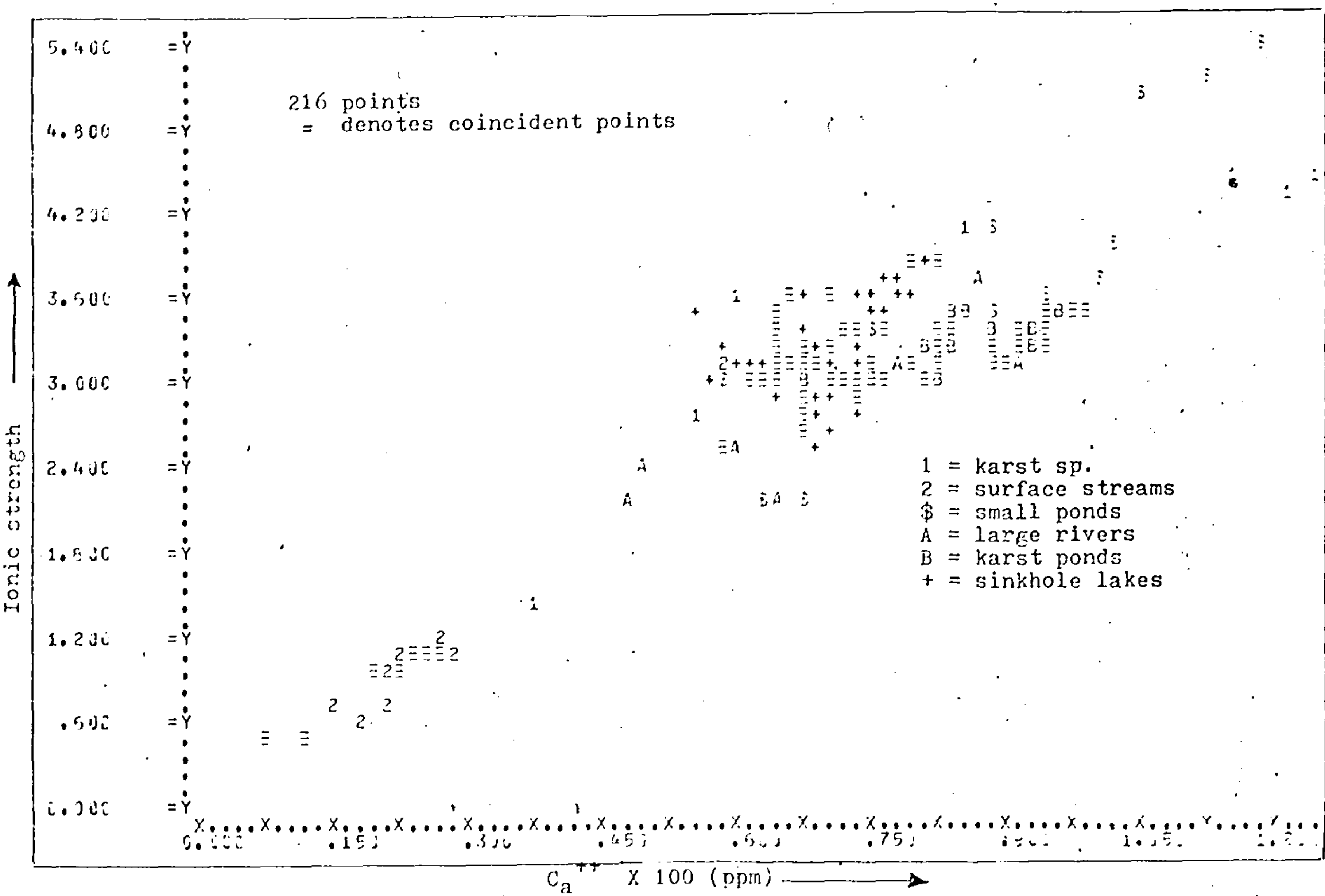


FIG. 36. The graph of Ca^{++} and ionic strength.

central Pennsylvania.

Figures 37 and 38 illustrate the overall chemical evolution of the waters. There are two evolutionary paths, that of the control waters (Corner Brook and Goose Arm Brook North), and that of the main carbonate group of waters. The control waters show a simple, linear path in both graphs. Its trend is towards saturation at a pH of 8.5-8.7, which may be taken to indicate that these waters are equilibrating only with a standard atmospheric concentration of CO_2. The path of the main carbonate group of samples is also simple and linear (Fig. 37). A majority are undersaturated with respect to calcite and only a very few spring and pond samples are super-saturated to the extent that precipitation might occur. Saturation is attained at about pH=7.8, indicating a modest enrichment of CO_2 above standard atmospheric levels. The ranges displayed by the main carbonate group on both graphs reflect a seasonal shift from softer, more acidic waters at the start of the collecting period to harder, more alkaline, waters in July.

V-3-2 - Bahaviour Of Waters Over Time

The conventional geochemical display graphs presented in figures 34-38 suggest that the carbonate waters of the study area are unusually simple and cannot be separated for detailed analysis by standard methods, such as Stepwise Linear Discriminant Function Analysis (Drake & Harmon, 1973). This point is emphasized by Figure 39, a histogram of the total hardness of all fully analyzed waters collected in 1977. The carbonate waters compose a normal

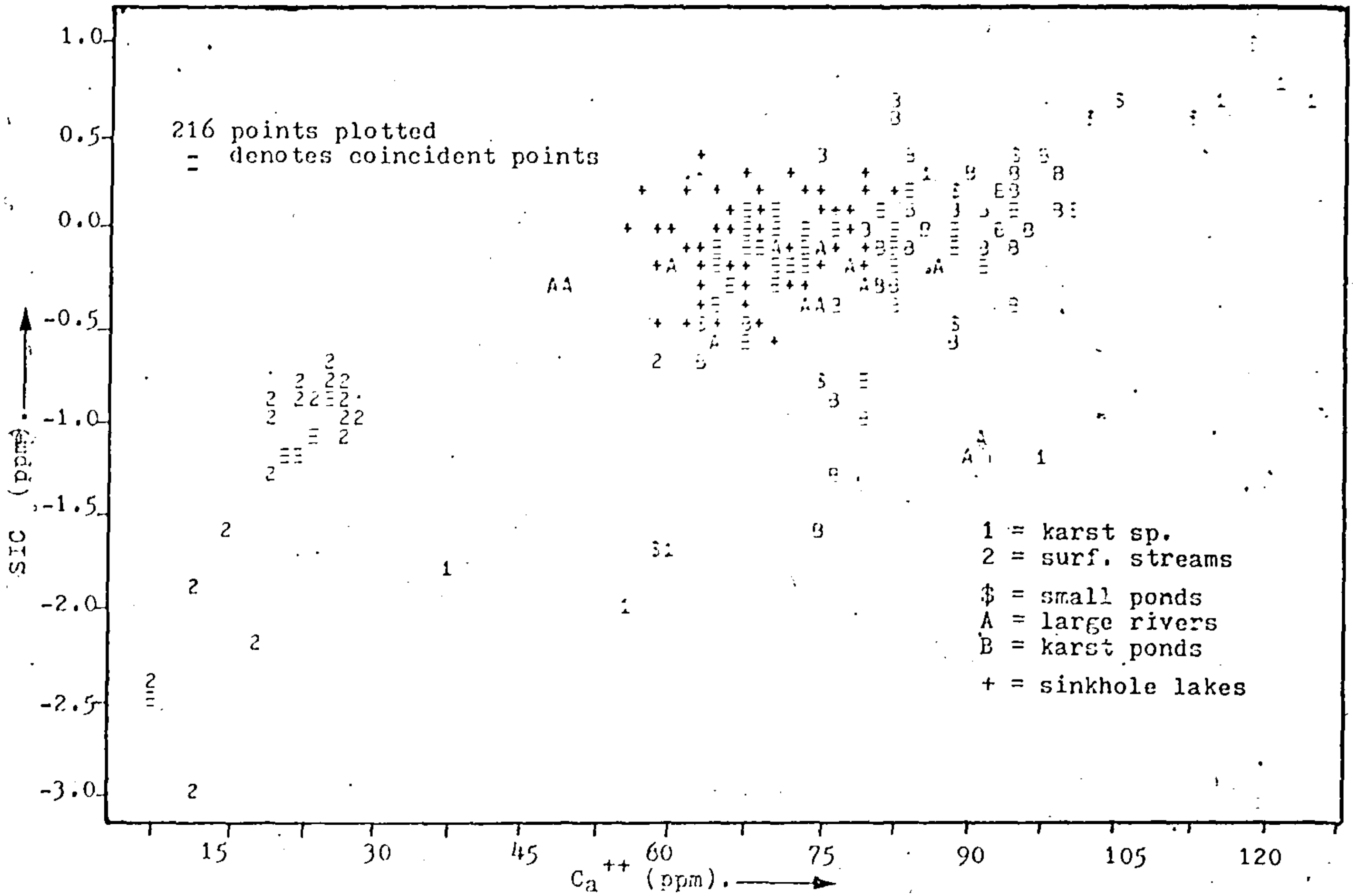


FIG. 37 The graph of Ca^{++} and SIC .

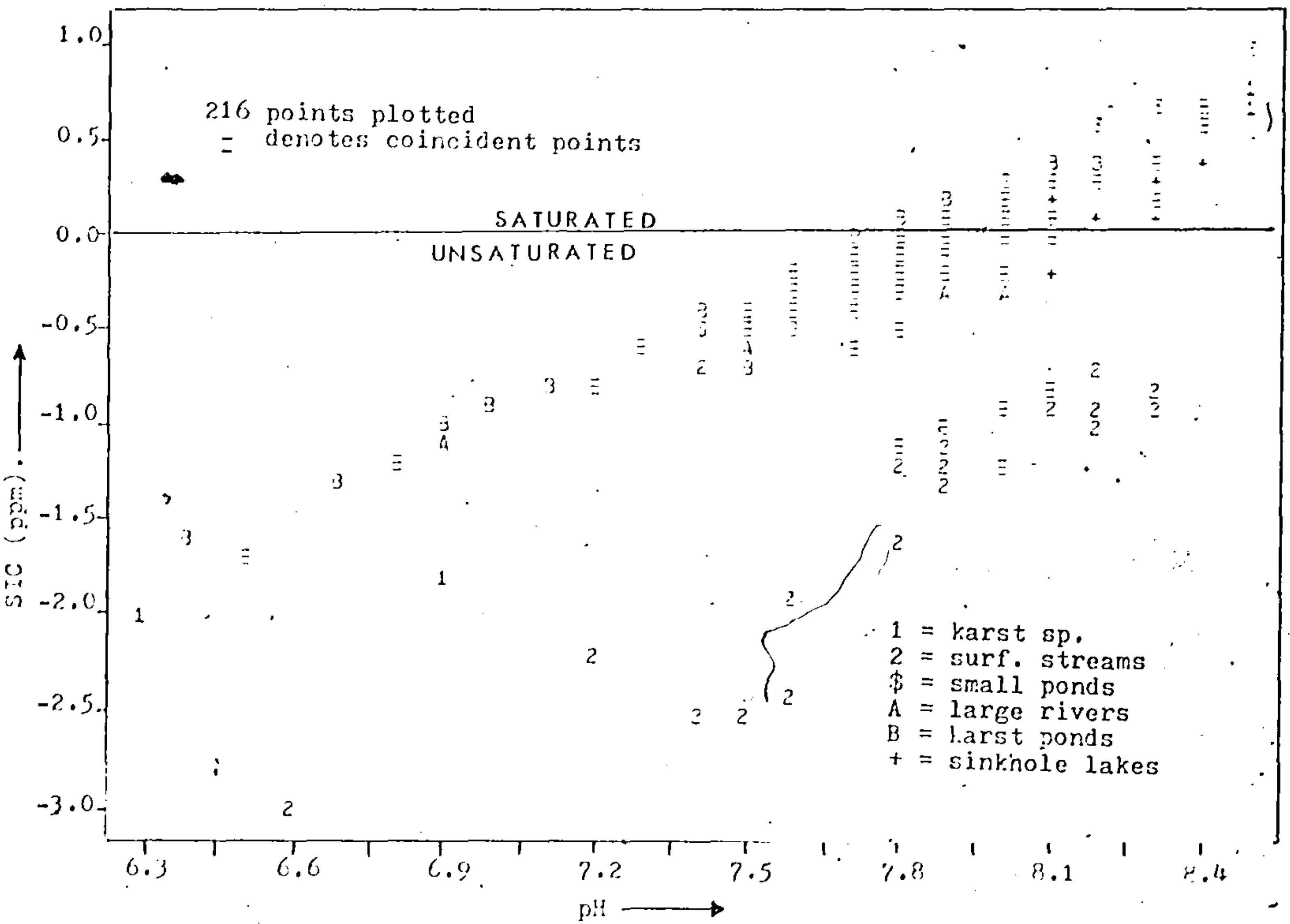


FIG. 38 The graph of pH and SIC.

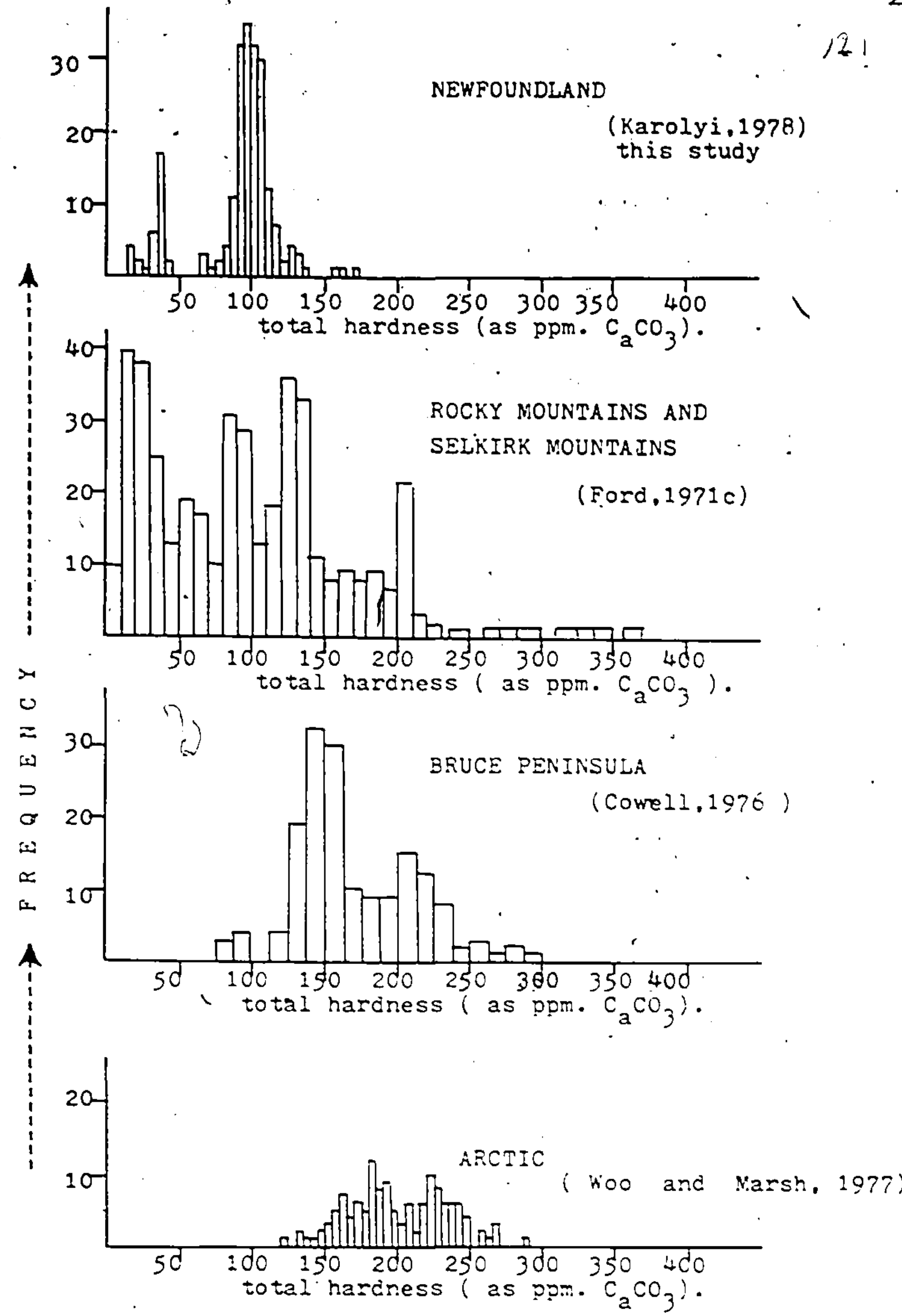


FIG. 39. Total hardness histograms from several distinct environments in Canada.

leptokurtic distribution of quite unusual symmetry. The control waters are completely distinct.

By graphing separate chemical parameters against time, separation within the carbonate group of waters is possible. The behaviour of ponds and streams varied over time with respect to temperature, total hardness and SIc. [redacted]ime graphs of these variables (Fig. 40, 41 and 42) all the sample values are used, because the major factor producing 15% and greater ion balance errors is most likely to be inaccuracy in pH readings; temperature and total hardness are not affected. Certain SIc values in figure 42 are in error, but insufficiently to affect trends displayed there.

Water level conditions in the study area in 1975 and 1976 were low compared to 1977, when lake levels were much higher. At Nameless and Bottomless Ponds the water levels were at least 2 m higher, and in some of the smaller enclosed ponds probably over a meter. Rainfall events in 1977 are noted on Figure 40. These were mostly small, and only the July 5-7 rainstorm of .44" produced a response noticeable on most graphs.

The temperature data of figure 41 indicate an overall increase from the average low of 6.75^{o}C in late May to an average high of 19.5^{o}C at the end of July (not including the springs). Temperature fluctuations are present in almost all water bodies; (they are mainly due to the rapid response of surface waters to daily fluctuations in solar radiation. The July 5-7 rain pulse depressed temperatures for most ponds and lakes, or at least dampened the rate of warming as in the case of Bottomless Pond.

The warming of lakes and ponds is mainly through absorption of heat from solar radiation. The absorption and radiation of heat from bottom sediments is minimal in deep waters, but becomes more significant in shallow (less than 1 m) waters. All water samples in the study area were collected in less than

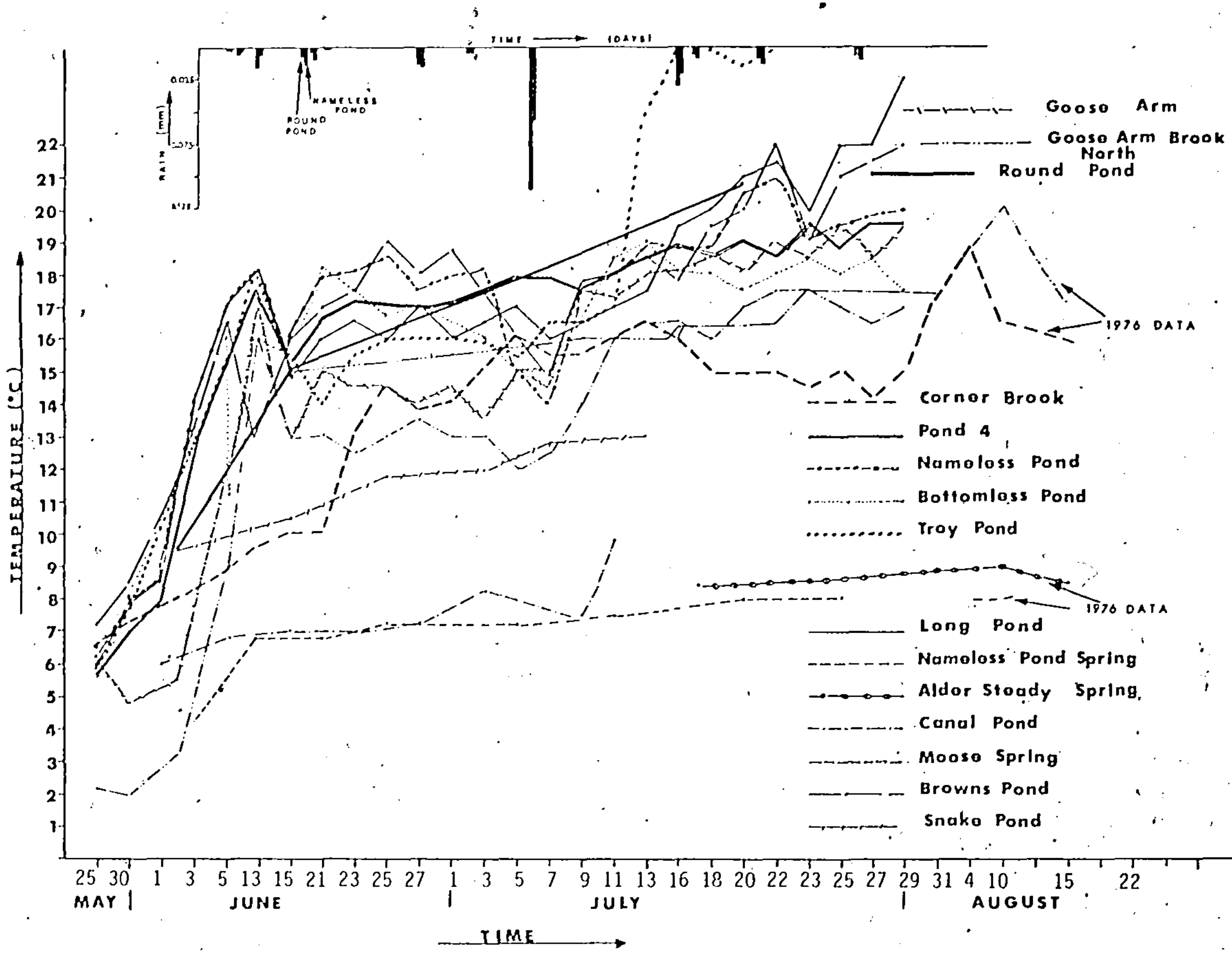


FIG. 40 Graph of temperature against time.

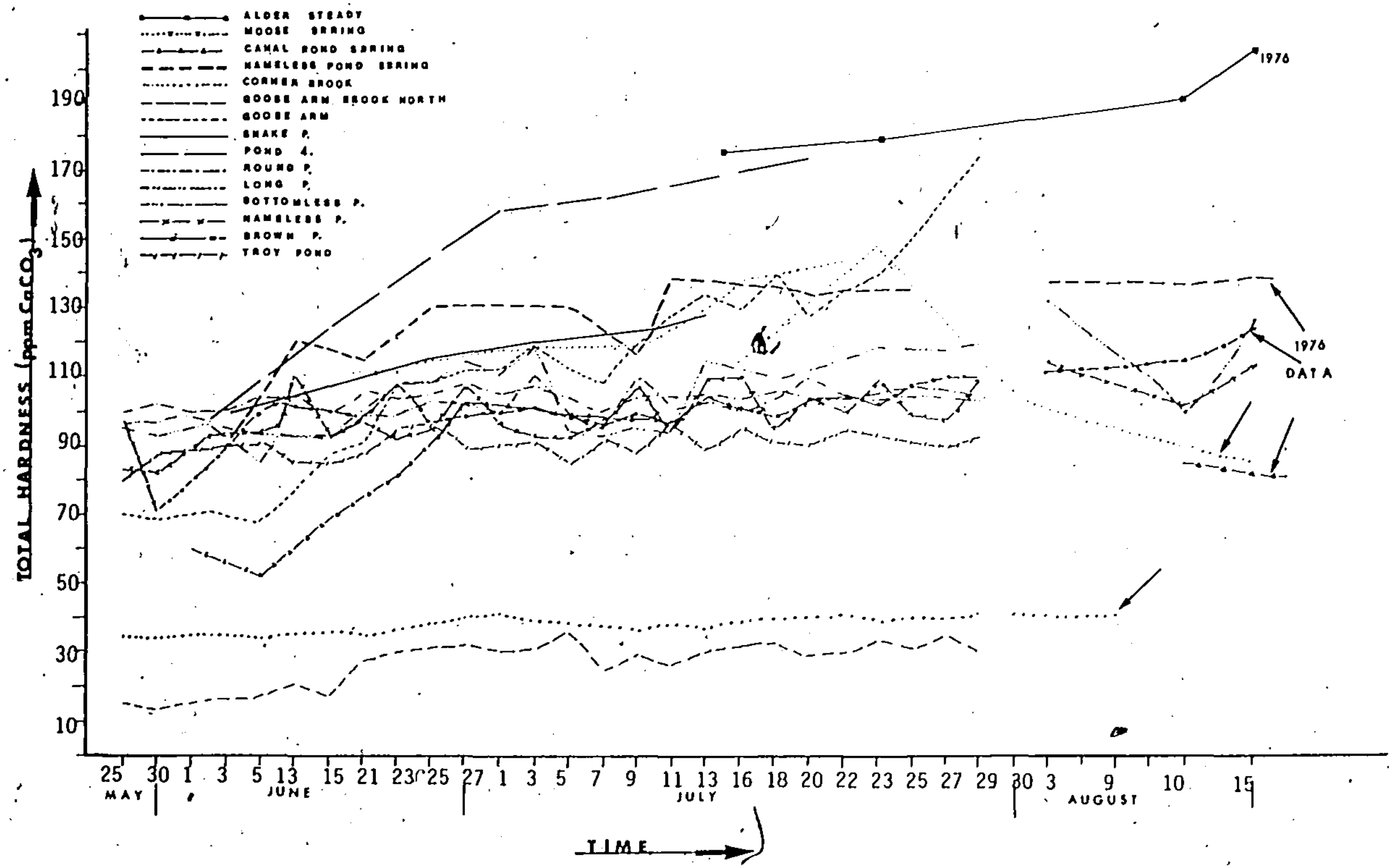


FIG.41. Graph of total hardness against time.

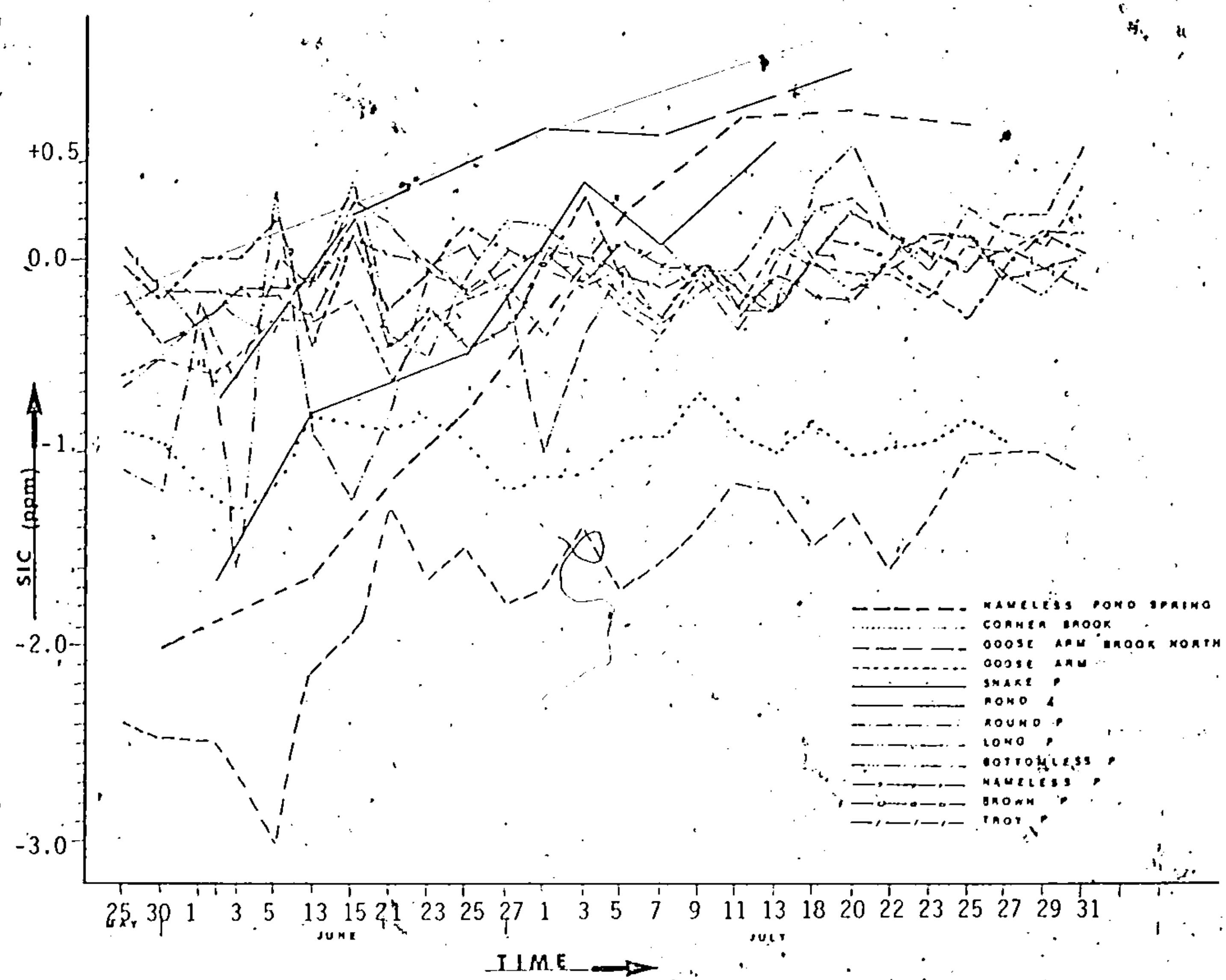


FIG.42. Graph of SIC. against time.

1 m of water. These shallow areas tend to respond to daily temperature variations much faster than the deeper zones. Because of this factor, temperatures may show high short-period fluctuations, as in the cases of Browns Pond, Nameless Pond, etc. In shallow waters temperature changes from early morning to early afternoon may also vary within a few degrees in some cases; therefore variation of the hour of sample collection may also add to the fluctuations seen on the graph.

An interesting feature of the pond and stream temperature behaviour is a contrast between a majority of sites displaying short period fluctuations as they warm up over the season, and sites such as Pond 4 (a small water body) and Troy Pond (of intermediate size) which show a rather steady gain. This cannot be entirely an artifact of the longer sampling interval at the two later sites. Pond 4 has no surface outflow and no observed inputs. Its water drains slowly through the base. In thermal terms it appears to have been fluctuating like a simple evaporating pan, although its waters are not exceptionally warm. Those of Troy Pond are particularly cool. It lacks surface channel inputs, but has an overflow outlet channel that was active in 1977. Its low temperature is taken to indicate a significant input from unknown springs.

In terms of thermal behaviour, the springs may be divided into two classes, the expected and the unexpected. Alder Steady, Canal Pond springs and Nameless Pond spring are the examples of the expected, although they drain very different physical systems; a granular aquifer, a karst conduit with a known and large input passage, and a primitive, probably wholly, phreatic karst drain, respectively. With the exception of an anomalous measurement at Canal Pond on July 11th, they display a slight but steady gain of temperature

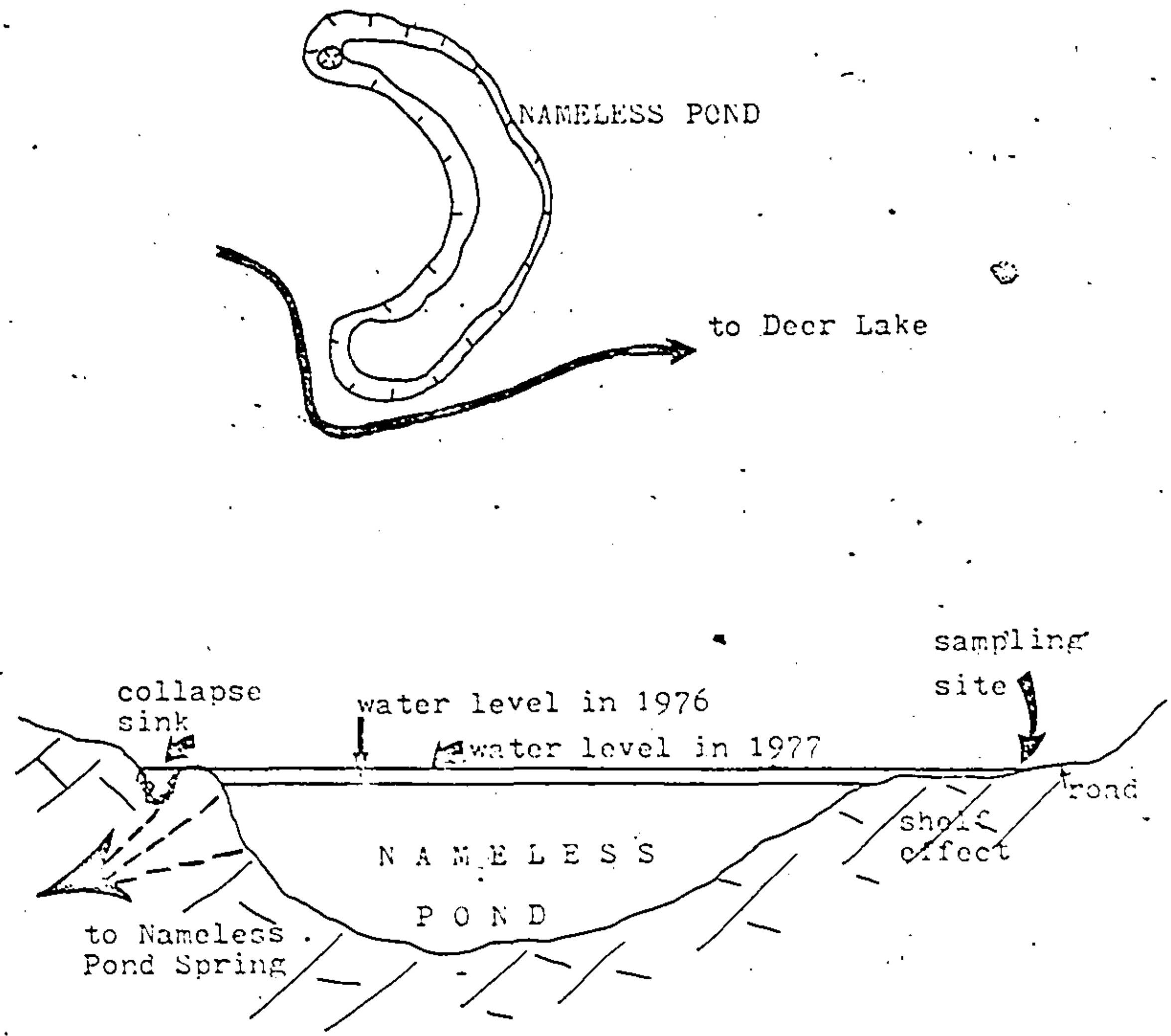


FIG. 43, Flood water effect at Nameless Pond, and sample site with respect to the collapse sink.

to about the mean annual air temperature of the region, 8°C. This is the expected behaviour of groundwater springs in temperate regions of Canada, where Spring flood melt waters depress the output temperatures for a short while and then there is a slow recovery to the ambient temperature of the rock.

Differences between input and spring temperatures can be analysed at the Nameless Pond system. Input temperatures vary from 7.8°C to 19.0°C and output temperatures from 4.2°C to 8.0°C in 1977, indicating a significant cooling effect (Table 5). This is perhaps misleading because the lake level was about 1.5m-2 m higher than in the previous years. The collapse sink where previously water was observed to sink from the lake was completely submerged. Nameless Pond appears to be a deep lake, therefore cold bottom waters will dominate its composition. The water that drains underground may do so by one or both of two means: 1) through the lake bed or 2) by overflow into the collapse sink (Fig. 43). During the high water levels of 1977 the sink point was well under water, therefore cold bottom or cool intermediate waters were sinking through both routes, not the much warmer surface waters. Water sampling was at the pond's southern end where there is a shallow shelf, not at the northern end where the waters sink and a similar "shelf" effect is not found. In sum, it is expected that much of the measured contrast between lakes and spring water temperatures here is due to the inability to measure the lake waters actually sinking.

Round Pond Spring and Moose Spring show unexpected behaviour because their temperatures are very similar to those of the ponds and streams (ie. climb quickly to 15°C or greater). They perhaps display a lesser short term fluctuation. The Moose Spring record of August 1976 plots in the same range

TABLE 5. NAMELESS POND AND ITS SPRING TEMPERATURES

DATE	SINK POINT T°C.	SPRING T°C.	DIFFERENCE T°C.
6/03	10.5	4.2	5.8
6/12	17.0	6.8	10.2
6/21	17.9	6.8	11.1
6/25	18.5	7.2	11.3
7/05	15.0	7.2	7.8
7/11	18.0	7.5	10.5
7/20	20.0	8.0	12.0
7/25	19.5	8.0	11.5

as that of June-July 1977, suggesting that the 1977 results are not the a-typical product of a particularly wet year.

The Long Pond-Round Pond system is shown in figure 44. The groundwater flowpath is only 500 m in length and the gradient is shallow. It is suggested that the explanation of the anomalous maintenance of warmth in the waters is that the flowpath is very shallow, a few meters deep at most, and the input is of warm surface-layer pond water abstracted by a short overflow channel. Ciry (1959) has described such shallow karst groundwater systems in France and interpreted them as developments in a seasonally active layer, ie. perched upon a permafrost body. He called such a system "karst sous-cutanee". However in the Goose Arm study area there is no evidence of a strong periglacial phase.

In chapters 3 and 4 evidence was produced to suggest that Nameless Pond system was shallow. But its thermal behaviour indicates that it is a deeper more "normal" karst system than the subcutaneous type represented by Long Pond-Round Pond.

It appears at first sight that the Moose Spring system cannot be shallow, because there is a headfall of at least 270 m between input and spring, and from the successful dye test, the groundwater flow rate is low. This problem is taken up in a separate section below.

Total hardness values and SIc values plotted over time show trends that are similar to each other, although the population of water characteristics may be better defined in the total hardness graph. In figure 41 it is seen that the control waters are distinct throughout the period. A feature of their behaviour is that there is comparatively little absolute gain in their hardness (to maximum values some 60 mg/l less than the carbonate waters at the end of the collecting season), but as a proportion of their early season hardness

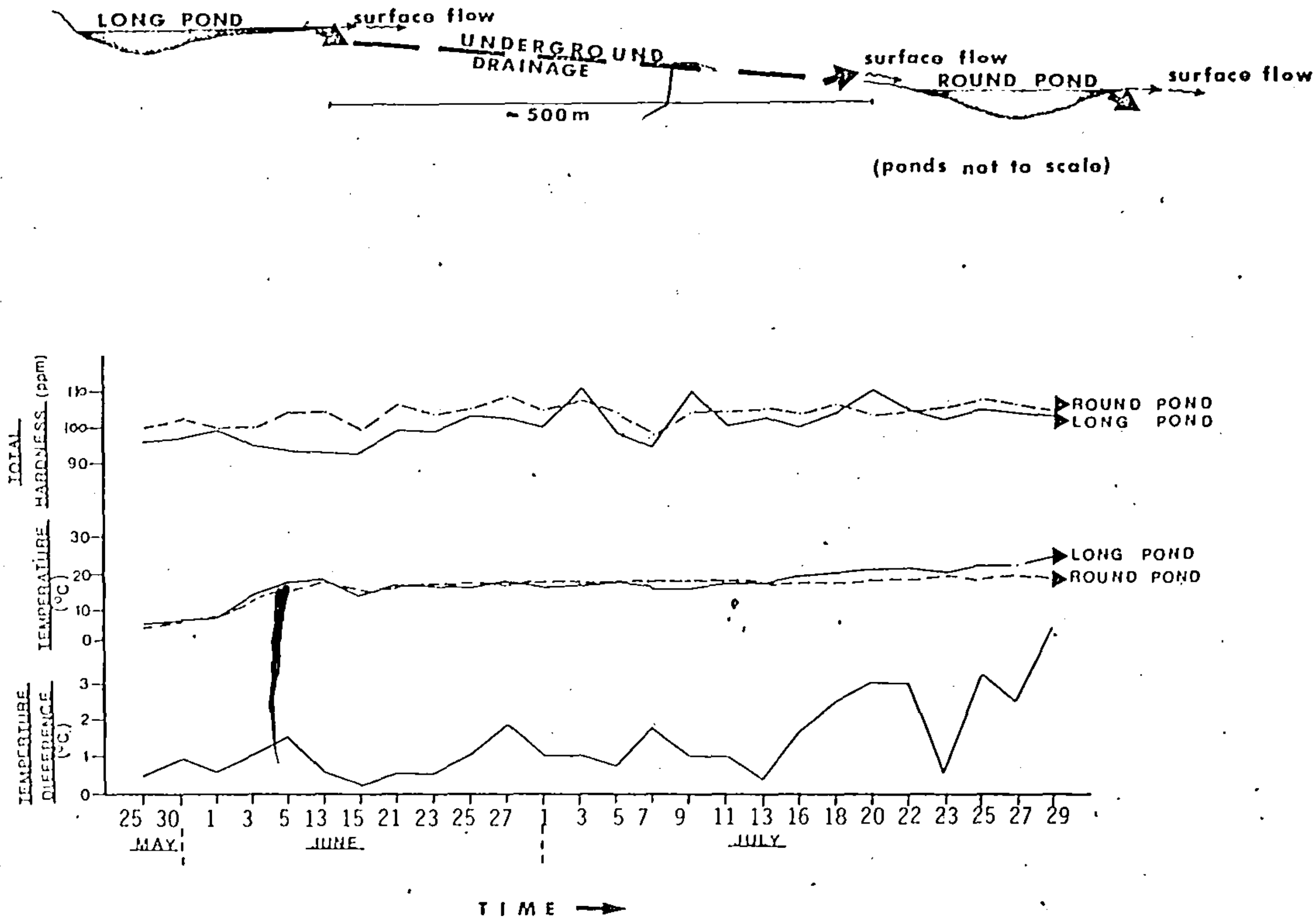


FIG. 44. Ground water flow path and chemical characteristics of Long Pond Round Pond system.

the gain compares to that of most of the karst waters.

A majority of karst pond, stream and spring waters plot in a body and display comparable behaviour in 1976 and 1977. Three are distinct: 1) the Alder Steady Spring functions as an ideal diffuse flow spring in carbonate terrains. It has consistently the greatest hardness, which may be matched with the steady thermal behaviour. It is concluded that it is a true granular aquifer spring draining carbonate-rich valley fill. Its high hardness reflects soil CO_2 enrichment in the region more completely than do any of the other waters. 2) Pond 4 displays high gain rates over time. This is emphasized on the SIc graph, where it appears as a steadily supersaturating water. (Figure 42). As with its thermal behaviour these evidences indicate that it is functioning as a simple evaporating pan, concentrating solutes. Although not as distinct on figure 41, Snake Pond behaves in a similar manner, with rather steady gain of hardness and SI value over the season. It is known to drain to a karst spring, but it appears that the drain is sufficiently obstructed to permit significant concentration of solutes. From their SIc trends up to late July of the 1977 season, it appears that these two ponds belong to the class where seasonal deposition of marl may occur. 3) Goose Arm Brook, the regional river that takes the discharge of the majority of ponds and streams, displays a remarkable pattern of gain across the main body of carbonate results in Figure 41, such that it is amongst the least hard waters at the beginning of the collecting season and converging upon the Alder Steady hardness values by the end of the season. Its gain appears to be a mixture of steps and linear increases, with dilution following the rains of July 5-7, 1977.

This behaviour is considered separately in Section V-5.

Amongst the remaining carbonate waters of Figure 41 it is possible to make a division into those that show notable gain of hardness and those that fluctuate over time with little net gain after mid June. Because the range of hardness involved is comparatively small and the sample is restricted to parts of two seasons, it is not certain that such division is significant and it is not developed further here. Certain ponds display individual cycles of higher and lower hardness. They differ from one another in size, depth, morphometry, water input and output characteristics. Overturn of waters, addition from unknown underwater springs, and differing biological activity in the waters, may each or all contribute to the variation measured at the sampling points. For example, Bottomless Pond records the greatest dilution of hardness following the rains of July 5-7th. It is fed by more short, fast responding, streams than the other ponds.

It is important to note that the karst springs (as opposed to Alder Steady, a granular aquifer spring) do not differ significantly in hardness from the main body of ponds. This emphasises that they are discharging the observed pond waters with little net gain from other sources in most instances. Canal Pond Spring is amongst the least hard waters of the group. This is believed to reflect the fact that the Pond has a large non-carbonate sector in its perimeter. Except at the very start of the season the spring of Nameless Pond was always 10-40 mg/l harder than the sample water taken on the same day in its source pond. This may indicate that the spring was composed of colder bottom waters as explained, or there may be a significant net addition of sub-soil waters from karst valley in this particular instance.

The radical reduction of hardness that occured at Moose Spring after July 23 1976 is believed to be a response to heavy rains on the plateau feeding the spring. Lesser dilution effects were noted at Bottomless Pond and Nameless Pond during the same period, although not at Nameless Pond Spring.

The Slc graph (Fig. 42) discriminates the control waters, and Pond 4 and Snake Pond with their strong gain behaviour. As a class, the remaining waters may be said to have attained the saturated state or close to it, by the first week of June, and thereafter to cluster about it. There was greater fluctuation during the earlier half of the collecting season. Goose Arm Brook is the most distinctive. It approached the saturation line more slowly and did not fully saturate before July 13th.

To conclude, analysis of the thermal and chemical behaviour of the waters over time has distinguished a class of ponds or closed depressions that function like evaporating pans. It is possible that more detailed study would permit differentiation of the remaining ponds ie. into those that gain notably in hardness and those that display shorter-term cyclic behaviour. A majority of karst springs have expected temperature behaviour, one appears to be a good instance of subutaneous karst, and Moose Spring is thermally anamalous. The example of a regional effluent drain, Goose Arm Brook, is found to be distinctive in its hydrochemical behaviour.

It is emphasised that this was a pioneer sampling programme. There are no previous studies of pond-dominated karsts to guide the design. It is suggested that, despite the comparatively narrow range of solute concentrations measured in the area, more than enough interesting features have been discovered to warrant a detailed study limited to the hydrochemistry alone.

V-4-1 - The Problem of Moose Spring

The purpose of this section is to amplify the problem that is posed by the high water temperatures recorded both in 1976 and 1977 at Moose Spring. In the months of June, July and August the temperatures of the spring ranged between 15°C and 20°C on different occasions, where other springs ranged at between 6°C to 9°C. Physiographically, Moose Spring is the most mature of the known karst springs and feeds a large stable channel. Discharge is greater than the others, and may display less variation. Two of the water sources are known by dye trace and their mean flow-through time is slow, 10.8 m/hr.

From the previous discussion (neglecting the minor complications introduced by flushing effects, overturn or high water effects as at Nameless Pond) it appears that the thermal behaviour of the karstic pond waters may be modelled simply, as in Figure 45. A majority of ponds drain through their bases (like Bottomless Pond) where the water is cold, and the spring is cold. Some ponds are drained by a short overflow channel to a sink point. In such systems the warm surface water is preferentially extracted. In Figure 45B, it is routed at shallow depth and emerges as a warm spring. The Long Pond-Round Pond system is the regional example. In Figure 45C, the warm overflow water is routed deep into the rock and cooled to regional ambient temperature to produce a cold spring. This happens at Carl Pond.

Figure 46 illustrates the known behaviour of the water at Moose Spring, between the nearest sink point, Sophies' Pond, and the spring. Warm overflow waters are removed from the pond through a small channel on its southeastern side and directed underground towards the spring to the west. The water may

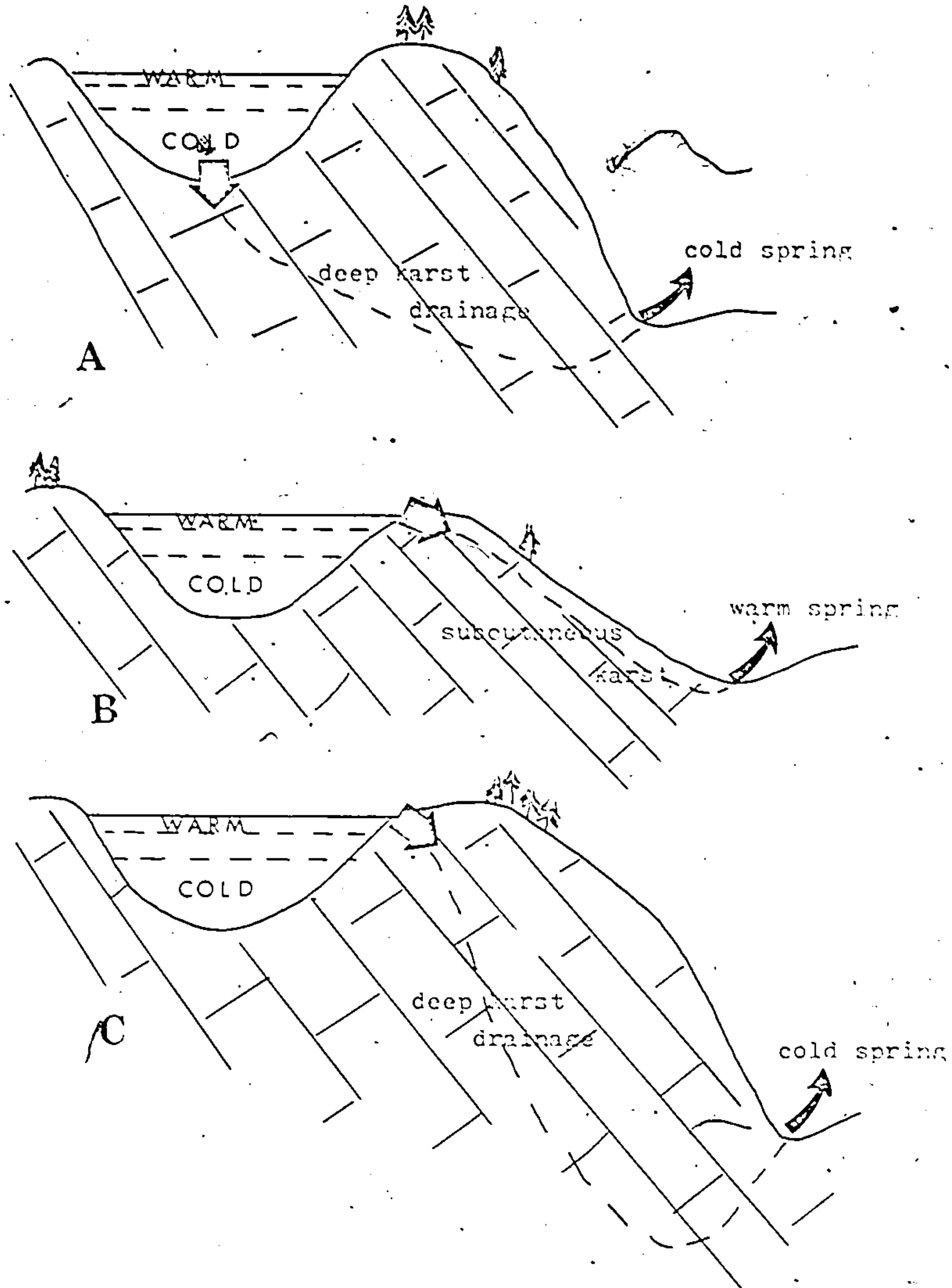


FIG.45. Possible drainage routes and spring temperatures.

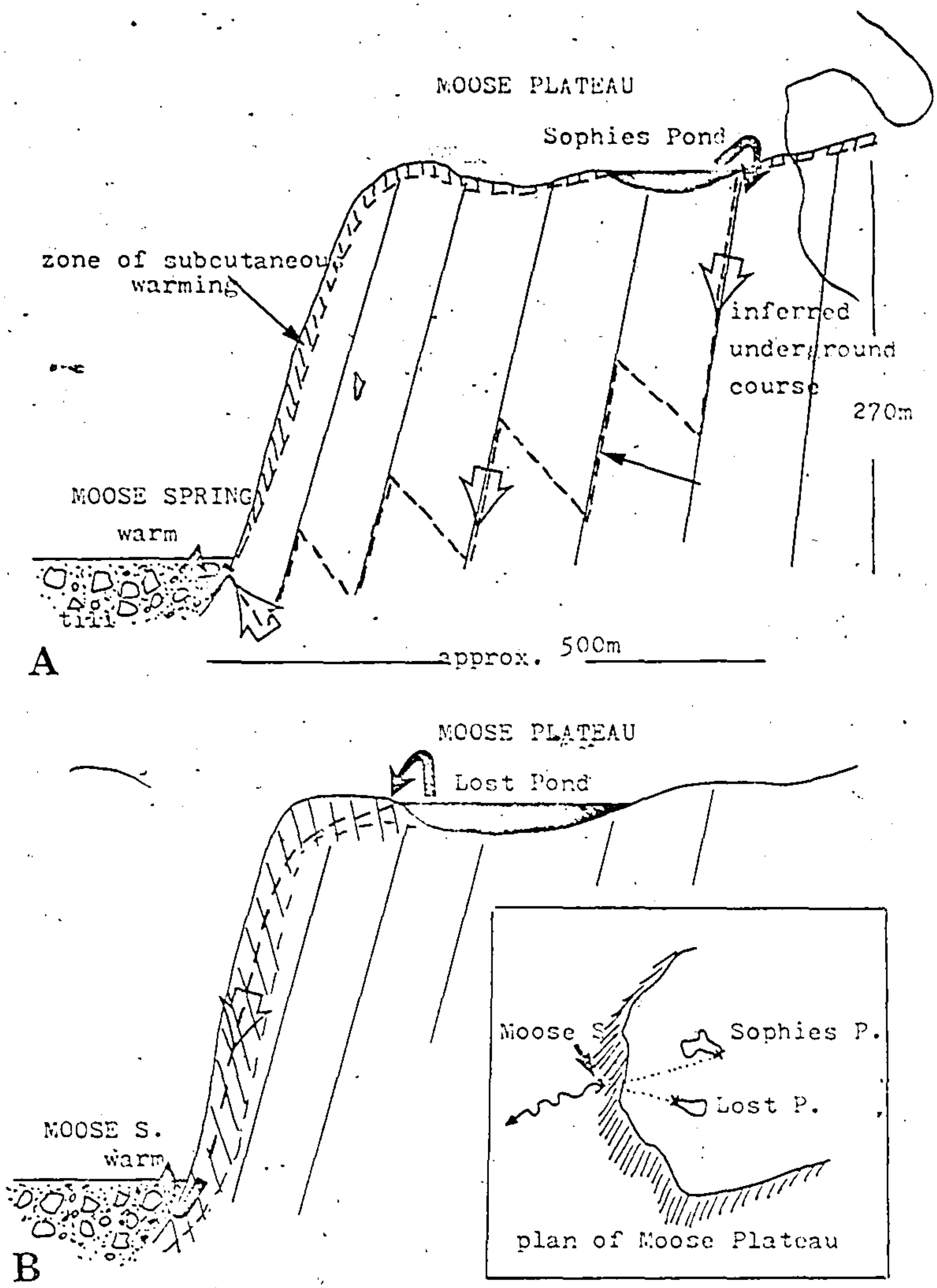


FIG. 46. Inferred drainage routes from Sophies Pond and Lost Pond. A) The inferred underground drainage from the pond may ~~be~~ deep indicating a cold spring BUT it is actually warm. Lost Pond (B) may have a shallow drainage and a warm spring is possible.

be supposed to be routed deep in the rock and it is presumed to rise from depth to the spring point because the spring is of the phreatic type and sited precisely at the junction with the clastic infilling in the valley.

Both Sophies' Pond and Lost Pond feed water from the plateau to Moose Spring, and both these lakes are close to the edge of the plateau. Sophies' Pond drains at its S.E. end and Lost Pond at it southern end close to the plateaus edge. It is possible that both subsurface drainages, and especially Lost Pond have shallow subsurface routes similar to the sub-cutaneous drainage discussed earlier, which would allow the water to be close in temperature to the warm surface lake waters even after the maximum of 2 days travel indicated by the dye tracing. This is illustrated in Figure 46B. Pond temperatures in general are higher than that shown for Moose Spring, and it is assumed that Sophies' Pond and Lost Pond would correspond with other lake temperatures, in which case there is a minor cooling effect before the spring efflux and its presumed shallow subsurface drainage would account for a much smaller cooling effect (from warm input waters) than found at Nameless Pond where cooler water sink.

There is no reason to suppose that these waters alone in the region are warmed by geothermal effect. The geology of the site is inappropriate while the water chemistry suggests nothing except simple bicarbonate waters. The explanatory model of 46B, if correct, is a model of an unusual karst system. There is nothing known in the literature to the writer that can be compared with it, yet there can be no question of the validity of the temperature measurements. The problem of Moose Spring definitely warrants a special investigation.

V-5 - Modelling The Seasonal Hydrochemistry of Goose Arm Brook

Goose Arm Brook is the largest river in the study area, collecting water from parts of the northern, western and southern zones. The catchment comprises uplands drained underground through sinkholes and lakes, and lowlands and valleys drained by streams and springs representing seepage waters. Therefore Goose Arm Brook represents a "base collector" from a wide variety of areas. The sampling locality was at its mouth.

The river's chemical characteristics differ from other carbonate waters of the main group, because over the collecting season its total hardness gains in a stepwise manner across the other carbonate groups, from very low values in May to high values approaching Alder Steady spring in July-August. Alder Steady is a good example of a carbonate-rich, granular quifer of the Goose Arm Basin.

Water draining to Goose Arm Brook comes from numerous karst ponds and lakes. These ponds have the distinct characteristics of slow underground drainage with periodic overflow channel use. The ponds feeding Goose Arm Brook can be regarded as large water storage tanks, as modelled in Figure 47. All these storage tanks will contribute differing amounts of discharge over the season, from heavy snow melt at the start to slow underground drainage later on. Another important contributor is water seepage through the till cover of Goose Arm valley, contributing as springs (like Alder Steady Spring) with high Total Hardness Values, therefore helping to boost the chemical trend of Goose Arm Brook over other karst pond waters.

The seasonal hydrochemistry of Goose Arm Brook may be modelled then by the combined chemical effects of the "holding tanks" and seepage spring waters (Fig. 47). This partial contributing area model has three dominant components: 1) snow melt, 2) ponds, and 3) spring (seepage water in the truck valley).

The regional melt source becomes dominant early in the season and until about mid June. After this, the ponds or holding tanks dominate with their combination of overflow and subsurface flow until late part of July, when seepage water and springs in the valley predominate, helping the chemical increase noted on the graphs (Fig. 48).

The total hardness of Goose Arm Brook at the end of the season approaches the T.H. value of Alder Steady Spring which represents one of the probably many valley springs, representing an important chemical booster for the river.

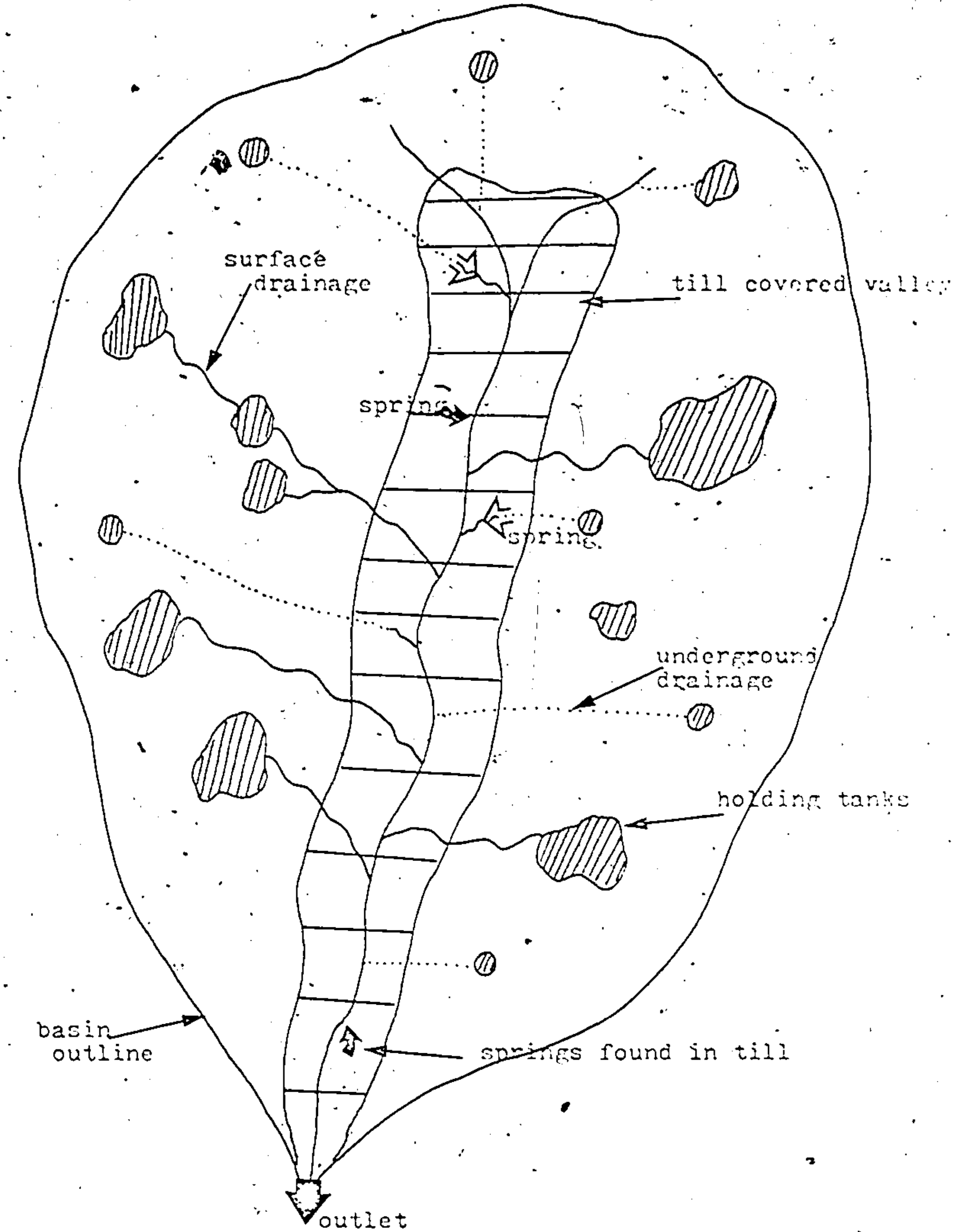


FIG. 47. "Holding Tanks" model for the explonation of the chemical behaviour of Goose Arm Brook, which collects water from a wide variety of zones. High total hardness values are the result of springs found in the carbonate rich till of the inner valley.

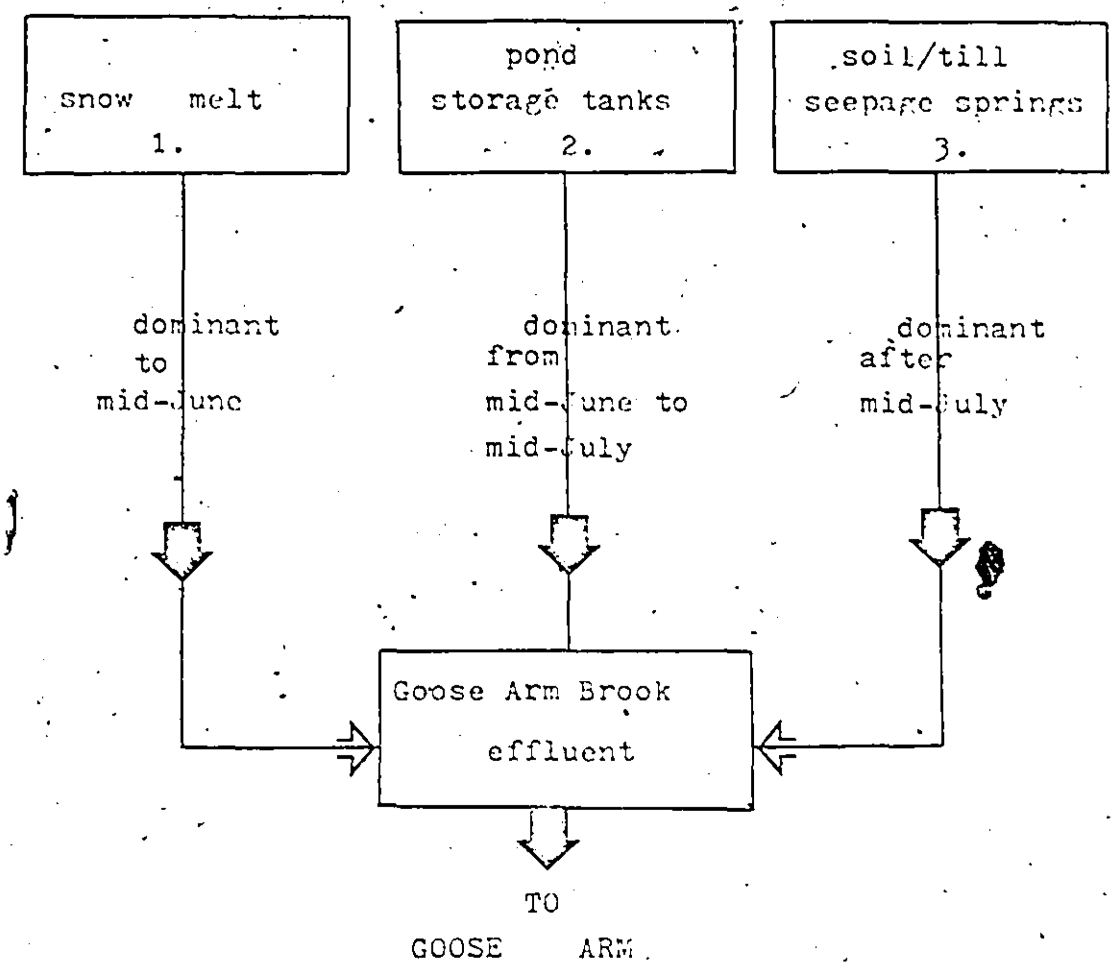


FIG. 48. Flowchart of the water movement from the basin, holding-tanks, etc., to Goose Arm.

V-6.- Comparison With Other Studies of Canadian Karst Waters

The study area is a temperate forested area with large number of ponds and lakes. It is comparable to other temperate regins of Canada in vegetation, temperatures and limestone charcteristics but distinct in its ponded karst nature.Studied karst areas such as the Bruce Peninsula in Ontario (Cowell,1976), the Alpine tundra of western Canada (Ford 1971c), and arctic areas (Woo and Marsh ,1977)are distinct from western Newfoundland. The rugged topography and the ponded karst are characteristics that are uniqe to the study area.

Total hardness histograms for all these areas indicate several obvious differences (Fig. 39). The Rocky Mountain sampling sites varied from glacier margins or snow fields, tundras into forest zones, at elevations ranging from 1010 m to 2600 m (Ford 1971c).Waters included surface and subsurface samples. The Newfoundland area is vegetation covered, ponded site with elevations well below the Rocky Mountain sampling.

This obvious sampling and site difference is strongly reflected in the histograms, where the Newfoundland examples are tightly clustered and the Rocky Mountain samples are over a much wider spread with peaks characterising certain areas and conditions.

The Bruce Peninsula samples (Cowell, 1976) show a stronger grouping than the Rocky Mountain samples but it is still a wider spread than the Newfoundland examples. The Bruce Peninsula data indicates harder waters mainly because the collection of the bulk of the samples were from swamps, conduit and diffuse springs which are not comparable to the study area. The lower values in the Bruce Peninsula data are from inland lakes, and Lake Huron and Georgan Bay. Diffuse and conduit springs will have a much higher total hardness value than lakes and ponds in general where surface waters are the input sources.

The arctic samples (Woo and Marsh,1977) form a compact group with high total hardness values reflecting the vegetated and cold environment of the sampling. The environment again, like the Rocky Mountain, is not comparable to the study area. High total hardness values reflect the organic or biogenic CO_2 present and the much colder temperatures, therefore enhancing water aggressivity and increasing solution.

In a general comparison the most striking feature is that the Newfoundland waters plot lower than all other samples except the tundra and glacier waters of the Rocky Mountains. The lower values found in the study area emphasise the strong equilibrating effect of the ponds (tank storage) which area the dominant feature of the waters collected.

S U M M A R Y
O F
C H E M I C A L D A T A F O R
N E W F O U N D L A N D

SAMPLE	TEMP	PH	CALC	MAG	HCO3	CA/MG	CAT/AN	ION	SIC	SID	PCO2	LOG	ERROR
CANALR6/07	6.80	6.90	33.	14.	45.	2.71	1.156	1.49	-1.643	-2.073	.573	-3.242	7.216
NAMER 6/30	4.20	6.30	55.	35.	101.	1.57	.891	2.61	-2.008	-2.131	4.895	[illegible]	-5.759
NAMER 6/12	6.80	6.50	60.	60.	112.	1.00	1.017	3.56	-1.673	[illegible]	3.693	-1.433	[illegible]
NAMER 6/21	6.60	6.80	93.	17.	119.	5.76	.966	3.49	-1.154	-1.551	1.668	-1.729	-1.719
NAMER 6/25	7.20	7.20	79.	51.	128.	1.55	1.016	3.86	-.617	-.926	[illegible]	[illegible]	.775
NAMER 7/05	7.20	8.20	85.	45.	145.	1.89	.897	4.05	.266	.114	.091	[illegible]	[illegible]
NAMER 7/11	7.50	8.50	115.	24.	164.	4.79	.648	4.42	.748	.397	.051	-3.239	[illegible]
NAMER 7/20	8.00	8.50	122.	12.	170.	10.17	.736	4.33	.798	.236	.054	-3.271	-11.842
NAMER 7/25	8.00	8.40	125.	10.	175.	12.50	.771	4.45	.720	.163	.069	-3.159	[illegible]
CORNB 5/25	6.50	8.30	20.	14.	30.	1.43	1.133	[illegible]	-.886	[illegible]	.015	-3.816	[illegible]
CORNB 5/30	7.20	8.20	20.	14.	30.	1.43	1.133	.95	-.976	-1.069	.019	-3.713	[illegible]
CORNB 6/02	8.00	8.00	21.	14.	28.	1.50	1.250	.98	-1.173	-1.272	.029	-3.539	11.111
CORNB 6/07	8.90	7.90	20.	14.	27.	1.43	1.259	.95	-1.236	-1.379	.035	-3.450	11.475
CORNB 6/12	9.50	7.90	23.	12.	30.	1.92	1.167	1.00	-1.183	-1.326	.040	[illegible]	7.390
CORNB 6/15	10.00	8.30	22.	14.	29.	1.57	1.241	1.01	[illegible]	-.917	.015	-3.914	[illegible]
CORNB 6/21	10.00	8.20	23.	12.	31.	1.92	1.129	1.01	-.862	[illegible]	.021	-3.635	[illegible]
CORNB 6/23	13.00	8.10	24.	12.	32.	2.00	1.125	1.04	-.885	-1.018	.029	-3.556	5.332
CORNB 6/25	14.50	8.10	25.	13.	33.	1.92	1.152	1.09	-.830	-.950	.029	-3.536	7.042
CORNB 6/27	13.80	8.00	26.	14.	32.	1.86	1.250	1.12	-.945	-1.054	.035	-3.453	11.111
CORNB 7/03	15.00	7.80	23.	16.	31.	1.44	1.253	1.09	-1.194	-1.240	.055	-3.261	11.429
CORNB 7/05	16.00	7.80	24.	14.	33.	1.71	1.152	1.09	-1.134	-1.212	.055	[illegible]	7.042
CORNB 7/07	15.50	7.95	24.	13.	32.	1.85	1.156	1.06	-1.053	-1.151	.045	-3.344	7.246
CORNB 7/09	15.50	8.00	25.	11.	31.	2.27	1.161	1.03	[illegible]	-1.091	.035	[illegible]	[illegible]

CORNB	7/11	16.00	8.00	26.	12.	32.	2.17	1.108	1.08	-.912	-1.041	.035	-3.442	5.571
CORNB	7/13	16.50	8.20	25.	12.	32.	2.06	1.156	1.06	-.721	-.839	.023	-3.639	7.246
CORNB	7/16	16.00	8.00	26.	13.	33.	2.00	1.182	1.11	-.900	-1.012	.037	-3.429	[illegible]
CORNB	7/18	15.00	7.90	27.	13.	34.	2.08	1.176	1.14	-.966	-1.112	.048	-3.321	8.11[illegible]
CORNB	7/20	15.00	8.00	27.	13.	34.	2.08	1.176	1.14	-.866	-1.012	.038	-3.421	8.11[illegible]
CORNB	7/22	15.00	7.80	27.	14.	35.	1.93	1.171	1.17	-1.074	-1.134	.062	-3.209	7.[illegible]
CORNB	7/23	14.50	7.90	23.	11.	34.	2.55	1.147	1.12	-.976	-1.150	.042	-3.323	6.[illegible]
CORNB	7/25	15.00	8.00	25.	15.	32.	1.67	1.250	1.12	-.845	-1.023	.026	-3.447	11.111
CORNB	7/27	14.10	8.10	27.	13.	33.	2.08	1.212	1.13	-.811	-.943	.029	-3.538	9.56[illegible]
CORNB	7/29	15.00	8.00	26.	15.	31.	1.73	1.323	1.13	-.942	-1.029	.035	-3.461	13.[illegible]
GOOSEN	5/25	2.20	7.60	7.	8.	14.	.88	1.071	.44	-2.410	-2.427	.034	-3.464	3.44[illegible]
GOOSEN	5/30	2.30	7.50	7.	7.	15.	1.00	.933	.43	-2.432	-2.529	.046	-3.335	-3.44[illegible]
GOOSEN	6/02	3.20	7.40	8.	8.	15.	1.00	1.067	.47	-2.509	-2.549	.059	-3.230	3.226
GOOSEN	6/07	9.00	6.60	12.	5.	16.	2.40	1.063	.50	-3.024	-3.219	.424	-2.373	3.13[illegible]
GOOSEN	6/13	16.00	7.20	13.	3.	16.	6.00	1.313	.56	-2.152	-2.513	.125	-2.[illegible]	17.514
GOOSEN	6/15	13.00	7.60	12.	5.	17.	2.40	1.000	.51	-1.941	-2.111	.047	-3.327	[illegible]
GOOSEN	7/07	12.50	7.80	15.	9.	23.	1.67	1.200	.68	-1.589	-1.663	.035	-3.46	[illegible]
GOOSEN	7/11	16.00	8.00	21.	5.	22.	4.20	1.132	.74	-1.154	-1.427	.025	-3.6[illegible]	[illegible]
POND4	6/02	9.50	7.40	53.	39.	118.	1.51	.831	3.14	-.734	-.624	.4[illegible]	-2.318	-[illegible]
POND4	6/15	15.00	8.00	83.	35.	162.	2.54	.765	4.10	.243	.075	.175	-2.758	-13.[illegible]7
POND4	7/01	17.00	8.30	105.	54.	163.	1.94	.869	5.01	.632	.535	.101	-2.996	-7.[illegible]
POND4	7/07	18.20	8.20	112.	50.	169.	2.24	.857	5.13	.643	.519	.133	-2.876	-7.[illegible]
POND4	7/20	20.80	8.50	113.	56.	195.	2.11	.892	5.43	1.[illegible]	.917	.071	-[illegible].151	-3.[illegible]
SNAKE	6/02	9.50	6.50	53.	39.	106.	1.51	.925	3.02	-1.673	-1.765	3.433	-1.464	-3.022
SNAKE	6/15	10.50	7.20	75.	33.	120.	2.27	.900	3.36	-.812	-.934	.703	-2.106	-3.36[illegible]
SNAKE	6/25	11.80	7.40	53.	26.	124.	3.42	.327	3.54	-.503	-.761	.517	-2.2[illegible]	-[illegible].766

SNAKE	7/03	12.00	8.30	94.	26.	125.	3.62	.960	3.65	.420	.156	.066	-3.162	-2.[illegible]
SNAKE	7/07	12.80	7.90	101.	21.	134.	4.81	.910	3.76	.090	-.230	.179	-2.74[illegible]	-4.[illegible]
SNAKE	7/13	13.00	8.40	102.	27.	140.	3.78	.921	3.98	.613	.346	.059	-3.229	-[illegible]
GOOSEM	5/25	6.20	7.70	67.	3.	81.	22.33	.864	2.21	-.569	-1.254	.161	-2.794	-7.[illegible]
GOOSEM	5/30	4.80	7.80	63.	6.	[illegible]	10.50	.363	2.19	-.520	-1.[illegible]	.124	-2.[illegible]	-7.[illegible]
GOOSEM	6/02	5.50	7.70	64.	7.	80.	9.14	.[illegible]	2.22	-.605	-1.110	.150	-2.[illegible]	-5.[illegible]
GOOSEM	6/07	12.00	8.00	43.	21.	81.	2.29	.352	2.19	-.331	-.496	.086	-3.165	-[illegible]
GOOSEM	5/13	17.90	7.90	50.	25.	83.	1.73	.340	2.39	-.337	-.417	.117	-2.93[illegible]	-3.[illegible]
GOOSEM	5/15	12.90	8.00	60.	2[illegible].	8[illegible].	2.14	1.[illegible]	2.56	-.235	-.330	.[illegible]	-3.[illegible]67	-[illegible]762
GOOSEM	5/21	15.20	7.50	63.	24.	62.	2.63	1.122	2.66	-.640	-.331	.235	-2.545	5.747
GOOSEM	5/23	14.50	7.80	70.	38.	85.	1.64	1.271	3.01	-.329	-.431	.146	-2.[illegible]35	11.317
GOOSEM	5/25	14.50	7.90	72.	37.	85.	1.95	1.282	3.03	-.217	-.331	.116	-2.[illegible]	12.[illegible]71
GOOSEM	5/27	14.00	7.90	73.	34.	90.	2.29	1.244	3.14	-.166	-.319	.122	-2.[illegible]	[illegible]
GOOSEM	6/01	14.50	7.70	75.	38.	85.	1.97	1.329	3.11	-.401	-.516	.134	-2.735	14.141
GOOSEM	6/05	15.00	7.80	80.	32.	88.	2.50	1.273	3.12	-.251	-.416	.152	-2.[illegible]	12.[illegible]
GOOSEM	6/07	14.50	7.70	74.	35.	85.	2.11	1.282	3.03	-.405	-.537	.134	-2.735	12.371
GOOSEM	6/09	17.50	8.00	76.	44.	91.	1.73	1.319	3.31	-.027	-.[illegible]06	.102	-2.591	13.744
GOOSEM	6/18	18.50	7.90	75.	35.	93.	2.14	1.122	3.13	-.[illegible]83	-.194	.140	-2.[illegible]54	5.769
GOOSEM	6/20	18.00	7.90	70.	58.	105.	1.21	1.219	3.61	-.[illegible]	-.[illegible]7	.149	-2.[illegible]	[illegible]71
GOOSEM	6/22	19.00	7.70	87.	43.	101.	1.81	1.737	3.71	-.219	-.279	.229	-2.64[illegible]	14.[illegible]
ROUND	5/25	5.50	6.90	91.	9.	112.	10.11	.393	3.12	-1.124	-1.651	1.390	-1.[illegible]	-5.[illegible]
ROUND	5/30	6.90	6.80	90.	12.	111.	7.50	.310	3.15	-1.214	-1.667	1.749	-1.757	-4.[illegible]
ROUND	6/01	7.90	7.80	83.	17.	103.	4.63	.926	3.08	-.245	-.6[illegible]	.172	-2.76[illegible]	-3.[illegible]
ROUND	6/03	13.00	7.30	83.	12.	114.	7.35	.577	3.14	-.625	-1.037	.5[illegible]	-2.215	-6.[illegible]
ROUND	6/05	15.50	7.90	83.	16.	116.	5.50	.397	3.24	.016	-.316	.16[illegible]	-1.796	-5.455
ROUND	6/13	17.50	7.70	91.	13.	113.	7.[illegible]	.92[illegible]	3.21	-.153	-.326	.253	-2.517	-[illegible]

ROUND	6/15	15.00	8.20	93.	9.	112.	10.90	.934	3.10	.306	-.161	.077	-7.117	-6.161
ROUND	6/21	16.50	8.00	83.	17.	112.	5.24	.946	3.24	.11[illegible]	-.137	.124	-2.9[illegible]	-2.752
ROUND	6/23	17.00	7.80	83.	15.	115.	5.93	.904	3.23	-.062	-.403	.213	-2.692	-5.123
ROUND	6/25	17.00	7.70	91.	14.	115.	6.50	.913	3.25	-.153	-.513	.256	-2.592	-4.545
ROUND	6/27	16.90	7.90	82.	16.	116.	5.75	.931	3.32	.053	-.201	.163	-2.753	-7.771
ROUND	7/01	17.00	7.60	83.	16.	119.	5.56	.593	3.23	-.052	-.379	.2[illegible]	-2.631	-5.131
ROUND	7/03	17.50	7.70	91.	16.	117.	5.69	.915	3.31	-.133	-.465	.262	-2.532	-4.454
ROUND	7/05	17.80	7.80	93.	11.	115.	8.45	.914	3.23	-.031	-.444	.205	-2.66[illegible]	-5.[illegible]23
ROUND	7/07	17.80	7.90	94.	6.	120.	15.67	.533	3.20	.092	-.454	.17[illegible]	-2.769	-[illegible].[illegible]31
ROUND	7/09	17.50	7.70	95.	9.	122.	10.56	.052	3.30	-.102	-.565	.273	-2.564	-7.[illegible]65
ROUND	7/11	18.00	7.40	94.	10.	123.	9.40	.346	3.31	-.396	-.531	.552	-2.25[illegible]	-[illegible].[illegible]7[illegible]
ROUND	7/13	17.90	7.60	83.	16.	130.	5.56	.306	3.40	.[illegible]01	-.320	.232	-2.635	-11.[illegible]
ROUND	7/16	17.30	8.00	93.	11.	133.	8.45	.792	3.41	.220	-.134	.149	-2.[illegible]25	-12.[illegible]36
ROUND	7/19	17.50	9.10	94.	12.	134.	7.63	.791	3.46	.331	-.067	.113	-2.924	-11.667
ROUND	7/20	18.00	7.90	94.	10.	129.	9.40	.806	3.37	.123	-.311	.193	-2.73[illegible]	-11.73[illegible]
ROUND	7/22	16.50	7.70	96.	9.	135.	10.67	.779	3.45	-.342	-.501	.305	-2.516	-12.5[illegible]
ROUND	7/23	19.50	8.00	93.	7.	133.	14.14	.797	3.45	.279	-.245	.152	-2.[illegible]17	-11.[illegible]37
ROUND	7/25	18.80	7.90	94.	14.	135.	6.71	.699	3.51	.152	-.205	.133	-2.714	-11.111
ROUND	7/27	19.50	7.80	93.	8.	133.	12.35	.775	3.52	.094	-.391	.25[illegible]	-2.6[illegible]1	-12.553
ROUND	7/29	19.50	8.10	93.	7.	139.	14.00	.755	3.49	.393	-.119	.126	-2.[illegible]	-13.334
LONGP	5/25	6.00	7.80	82.	14.	111.	5.56	.365	3.[illegible]3	-.265	-.673	.173	-2.761	-7.246
LONGP	5/30	7.60	7.90	81.	16.	112.	5.06	.332	3.[illegible]4	-.149	-.511	.139	-2.[illegible]56	-6.[illegible]
LONGP	6/01	9.50	7.70	76.	23.	105.	3.30	.943	3.03	-.336	-.552	.212	-2.673	-2.[illegible]41
LONGP	6/03	14.00	6.40	75.	20.	137.	3.75	.385	2.97	-1.605	-1.365	4.601	-1.337	-5.341
LONGP	6/05	17.00	8.30	75.	13.	114.	4.17	.916	3.00	.364	.133	.164	-3.135	-11.145
LONGP	6/13	18.10	7.90	77.	16.	112.	4.91	.330	2.95	-.316	-1.214	1.263	-1.[illegible]97	-[illegible].[illegible]

LONGP	6/15	14.80	6.70	77.	15.	112.	5.13	.821	2.95	-1.262	-1.535	2.436	-1.613	[illegible]
LONGP	[illegible]	16.00	7.10	80.	19.	115.	4.21	.661	3.13	[illegible]	[illegible]	[illegible]	-1.397	-7.477
LONGP	6/23	16.50	7.90	83.	16.	114.	5.19	.663	3.12	-.101	-.316	.159	[illegible]	[illegible]
LONGP	6/25	16.00	8.00	81.	22.	113.	3.68	.912	3.19	.076	-.167	.125	[illegible]	[illegible]
LONGP	6/27	17.00	7.70	82.	21.	115.	[illegible]	.597	3.19	-.197	-.457	.256	[illegible]	[illegible]
LONGP	7/01	16.00	5.90	80.	20.	114.	4.00	.377	3.14	-1.024	-1.236	[illegible]	[illegible]	-6.542
LONGP	7/03	16.50	7.50	82.	23.	115.	2.93	.957	3.35	-.407	-.597	[illegible]	[illegible]	[illegible]
LONGP	[illegible]	17.00	7.90	80.	19.	114.	4.21	[illegible]	3.12	[illegible]	-.276	.161	-2.795	[illegible]
LONGP	7/07	16.60	7.60	81.	14.	109.	5.79	.572	2.99	-.336	-.577	.303	-2.519	[illegible]
LONGP	7/09	16.50	7.80	82.	23.	120.	2.93	.917	3.40	-.069	[illegible]	.221	-2.677	[illegible]
LONGP	7/11	17.00	7.80	83.	13.	121.	4.61	.535	3.23	[illegible]	-.336	.214	[illegible]	[illegible]
LONGP	7/13	17.50	7.60	83.	20.	123.	4.15	[illegible]	3.34	-.241	[illegible]	[illegible]	[illegible]	[illegible]
LONGP	7/15	19.50	8.20	84.	16.	130.	5.25	.769	3.30	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
LONGP	[illegible]	20.00	8.40	83.	21.	132.	3.95	.735	3.40	.607	.373	.061	[illegible]	[illegible]
LONGP	7/20	21.00	7.90	84.	26.	129.	3.23	.653	3.49	.115	-.069	.159	-2.723	[illegible]
LONGP	7/22	21.50	7.20	85.	20.	134.	4.25	.734	3.44	.044	[illegible]	.249	[illegible]	-12.134
LONGP	7/23	20.00	7.70	84.	21.	130.	4.00	.908	3.40	-.094	-.331	.299	-2.524	[illegible]
LONGP	7/25	22.00	8.00	84.	20.	131.	4.25	.794	3.39	.237	[illegible]	.154	[illegible]	[illegible]
LONGP	7/27	22.00	8.00	84.	21.	131.	4.00	[illegible]	3.41	.237	.013	.154	[illegible]	[illegible]
LONGP	7/29	24.00	8.40	83.	21.	132.	3.95	[illegible]	3.40	.664	.454	.063	[illegible]	[illegible]
BOTTM	5/25	6.50	7.50	63.	32.	105.	1.97	.905	2.95	-.695	-.563	.329	[illegible]	[illegible]
BOTTM	5/30	8.10	7.60	63.	27.	106.	2.52	.396	2.96	-.535	-.744	[illegible]	[illegible]	[illegible]
BOTTM	6/02	11.50	7.80	70.	25.	110.	2.63	[illegible]	[illegible]	-.259	-.462	[illegible]	[illegible]	[illegible]
BOTTM	6/05	16.00	7.60	65.	30.	115.	2.17	[illegible]	[illegible]	[illegible]	-.537	[illegible]	[illegible]	[illegible]
BOTTM	6/07	11.20	7.90	64.	30.	116.	2.13	[illegible]	[illegible]	[illegible]	-.334	.155	[illegible]	[illegible]
BOTTM	6/12	16.00	7.90	63.	29.	122.	2.17	.767	[illegible]	[illegible]	-.233	.167	[illegible]	[illegible]

BOTTM	6/15	15.50	8.40	63.	30.	122.	2.10	.762	3.36	.395	.271	[illegible]	-3.273	[illegible]
BOTTM	6/21	18.20	7.50	64.	36.	130.	1.73	.769	3.30	-.436	[illegible]	.465	-2.333	[illegible]
BOTTM	6/23	17.50	7.30	71.	37.	141.	1.92	.766	3.57	-.571	-.663	[illegible]	-2.112	-13.253
BOTTM	6/25	16.60	7.80	73.	36.	140.	2.03	.773	3.59	-.372	[illegible]	.246	-2.609	[illegible]
BOTTM	6/27	17.00	8.00	82.	33.	150.	2.49	.767	3.60	[illegible]	.056	.167	-2.779	[illegible]
BOTTM	7/01	16.50	9.00	80.	30.	145.	2.67	.759	3.65	.173	[illegible]	[illegible]	-2.735	-13.725
BOTTM	7/03	16.00	7.80	77.	31.	130.	2.48	.783	3.54	-.365	-.223	.241	-2.619	-12.155
BOTTM	7/05	15.00	7.80	64.	30.	118.	2.13	.797	3.56	-.219	-.359	[illegible]	[illegible]	-11.321
BOTTM	7/07	15.00	7.70	63.	30.	110.	2.10	.645	2.96	-.354	-.432	.240	-2.620	[illegible]
BOTTM	7/09	16.50	7.80	66.	29.	118.	2.26	.505	3.06	-.155	[illegible]	[illegible]	-2.633	[illegible]
BOTTM	7/13	19.00	8.10	80.	35.	150.	2.29	.767	[illegible]	.329	[illegible]	.135	[illegible]	[illegible]
BOTTM	7/16	18.20	7.80	76.	37.	145.	2.05	.779	3.71	-.022	-.124	.259	-2.537	-12.412
BOTTM	7/18	18.00	7.60	75.	35.	140.	2.14	.786	3.60	-.243	-.357	.395	-2.403	[illegible]
BOTTM	7/20	17.50	7.80	73.	34.	141.	2.29	.794	3.65	-.031	-.162	[illegible]	[illegible]	-11.462
BOTTM	7/22	18.00	7.90	73.	37.	148.	2.11	.777	3.78	[illegible]	-.015	[illegible]	-2.679	[illegible]
BOTTM	7/23	18.50	7.90	61.	39.	150.	2.33	.609	3.90	.122	.019	.213	-2.671	-11.111
BOTTM	7/25	18.00	7.70	70.	39.	147.	2.03	.303	3.53	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
BOTTM	7/27	18.50	7.60	60.	36.	146.	2.11	[illegible]	3.62	-.194	[illegible]	.414	-2.317	[illegible]
BOTTM	7/29	17.50	7.80	83.	37.	140.	2.24	.811	3.06	.013	-.113	.262	[illegible]	[illegible]
NAMEL	5/25	6.80	8.10	53.	25.	88.	2.32	.943	2.54	-.195	-.394	[illegible]	-3.156	-2.324
NAMEL	5/30	7.90	7.80	59.	23.	67.	2.57	.943	2.51	-.476	[illegible]	[illegible]	[illegible]	[illegible]
NAMEL	6/02	10.00	7.70	65.	26.	106.	2.32	.577	2.92	-.427	[illegible]	[illegible]	[illegible]	[illegible]
NAMEL	6/05	15.80	7.80	63.	31.	109.	2.05	.362	2.37	-.247	-.363	[illegible]	[illegible]	[illegible]
NAMEL	6/07	12.00	8.30	61.	35.	115.	1.74	.873	3.02	.163	.053	[illegible]	-3.235	[illegible]

NAMEL	6/12	17.00	7.90	64.	47.	111.	1.36	1.000	3.33	-.122	-.143	.156	-2.[illegible]	[illegible]
NAMEL	6/15	16.30	8.30	57.	37.	110.	1.54	.855	2.98	.220	.166	.061	-3.214	-7.143
NAMEL	6/21	17.90	7.50	62.	34.	116.	1.82	.823	3.18	-.499	-.579	.414	-2.3[illegible]	-8.436
NAMEL	6/23	18.10	7.70	63.	29.	117.	2.17	.736	3.01	-.235	-.400	.264	-2.570	-11.362
NAMEL	6/25	18.50	7.50	65.	30.	120.	2.17	.792	3.10	-.456	-.569	.431	-2.365	-11.[illegible]
NAMEL	6/27	17.90	7.60	64.	44.	122.	1.45	.805	3.30	-.369	-.399	.345	-2.462	-6.[illegible]
NAMEL	7/01	15.00	8.00	60.	36.	125.	1.67	.763	3.17	.010	-.040	.141	-3.051	-13.122
NAMEL	7/03	16.00	7.90	61.	32.	120.	1.91	.775	3.06	-.113	-.219	.167	-2.773	-12.376
NAMEL	7/07	14.00	8.00	59.	39.	130.	1.51	.754	3.26	-.030	-.092	.140	-2.954	-14.035
NAMEL	7/09	17.50	8.00	55.	53.	131.	1.04	.824	3.47	-.012	.029	.147	-2.934	-9.020
NAMEL	7/13	18.50	7.80	65.	45.	130.	1.44	.846	3.50	-.128	-.153	.273	-2.632	-8.333
NAMEL	7/16	19.00	7.70	65.	45.	133.	1.44	.827	3.53	-.212	-.234	.302	-2.520	-9.465
NAMEL	7/20	20.50	7.90	66.	43.	130.	1.39	.877	3.58	.005	.003	.199	-2.723	-6.557
NAMEL	7/23	19.00	8.00	66.	44.	133.	1.50	.797	3.53	.103	.030	.157	-2.[illegible]	-11.[illegible]
NAMEL	7/29	19.80	7.90	67.	43.	136.	1.56	.869	3.56	.021	-.012	.197	-2.7[illegible]	-1[illegible]
BROWN	5/25	7.20	8.10	65.	32.	117.	2.03	.829	3.11	-.027	-.195	.093	-3.0[illegible]	-9.246
BROWN	6/05	16.50	8.00	63.	32.	113.	2.13	.985	3.13	.036	-.112	.125	-2.912	-6.[illegible]
BROWN	6/07	13.00	8.30	65.	37.	116.	1.76	.879	3.20	.249	.145	.062	-3.2[illegible]	-6.420
BROWN	6/12	16.80	7.50	69.	32.	114.	2.15	.836	3.16	-.473	-.600	.401	-2.396	-6.047
BROWN	6/15	16.00	8.10	66.	32.	115.	2.13	.870	3.15	.109	-.015	.101	-2.997	-6.277
BROWN	6/21	17.00	7.70	66.	32.	120.	2.06	.817	3.16	-.272	-.333	.267	-2.573	-[illegible]
BROWN	6/23	17.50	7.90	63.	40.	121.	1.70	.893	3.37	-.052	-.118	.171	-2.761	-5.677
BROWN	6/25	19.00	8.10	69.	23.	121.	2.46	.802	3.15	.180	.042	.110	-2.[illegible]	-11.[illegible]
BROWN	6/27	18.00	8.00	67.	32.	125.	2.09	.792	3.23	.065	-.043	.141	-2.[illegible]	-11.517
BROWN	7/01	18.80	7.80	69.	31.	119.	2.23	.840	3.19	-.131	-.245	.215	-2.660	-[illegible]
BROWN	7/03	17.50	8.30	63.	33.	120.	2.36	.842	3.22	.347	.239	.067	-3.171	-[illegible]
BROWN	7/05	16.60	7.80	67.	32.	116.	2.[illegible]	.[illegible]	3.14	-.[illegible]	-.115	.2[illegible]	-[illegible]	-7.[illegible]

BROWN	7/07	15.00	7.70	66.	31.	114.	2.13	.851	3.18	-.321	-.451	.243	-2.605	-[illegible].057
BROWN	7/09	17.80	7.90	63.	31.	123.	2.19	.825	3.15	-.045	-.166	-.170	-2.769	-3.559
BROWN	7/11	16.00	7.70	66.	31.	120.	2.13	.833	3.14	-.257	-.369	.27[illegible]	-2.56[illegible]	-1[illegible].59[illegible]
BROWN	7/13	18.50	7.60	72.	32.	125.	2.25	.832	3.33	-.298	-.419	.356	-2.449	-9.17[illegible]
BROWN	7/16	17.60	8.50	70.	31.	119.	2.26	.849	3.21	.06[illegible]	-.066	.134	-2.673	-[illegible].1[illegible]
BROWN	7/18	19.50	7.90	73.	26.	121.	2.81	.816	3.19	.010	-.153	.175	-2.757	-1[illegible]
BROWN	7/20	20.00	7.80	73.	30.	128.	2.43	.905	3.34	-.061	-.190	.234	-2.631	-1[illegible].[illegible]23
BROWN	7/22	22.00	7.70	72.	33.	122.	2.16	.861	3.32	-.159	-.252	.2[illegible]7	-2.542	-7.[illegible]
BROWN	7/23	19.00	7.60	70.	33.	120.	2.12	.859	3.26	-.320	-.425	.344	-2.464	-7.[illegible]
BROWN	7/25	21.00	7.80	74.	34.	126.	2.16	.557	3.42	-.049	-.146	.233	-2.633	-7.692
BROWN	7/27	21.50	8.00	75.	35.	125.	2.14	.85[illegible]	3.45	.150	.068	.146	-2.834	-6.393
BROWN	7/29	22.00	7.90	76.	34.	122.	2.24	.912	3.42	.062	-.036	.1[illegible]1	-2.742	-[illegible].[illegible]72
TROY	5/25	5.90	8.30	69.	11.	89.	6.27	.399	2.49	.074	-.347	.044	-3.355	-5.325
TROY	5/30	7.60	8.00	71.	16.	93.	4.44	.967	2.64	-.188	-.523	.091	-3.[illegible]43	-1[illegible].[illegible]55
TROY	6/02	11.60	7.90	73.	16.	99.	4.56	.599	2.77	-.18[illegible]	-.497	.131	-2.[illegible]	-5.[illegible]1[illegible]
TROY	6/07	15.50	7.80	74.	17.	105.	4.35	.367	2.57	-.196	-.479	.153	-2.737	-7.1[illegible]3
TROY	6/07	15.50	7.80	74.	17.	105.	4.35	.367	2.57	-.196	-.479	.153	-2.737	-7.143
TROY	6/12	18.10	7.60	67.	13.	109.	3.72	.780	2.79	-.334	-.617	.31[illegible]	-2.5[illegible]	-12.[illegible]7[illegible]
TROY	6/15	15.50	8.20	67.	13.	100.	3.72	.553	2.70	.143	-.105	.079	-3.15[illegible]	-[illegible]
TROY	6/21	14.00	8.10	65.	20.	101.	3.40	.571	2.77	.031	-.217	.067	-3.161	-6.[illegible]7[illegible]
TROY	6/23	15.50	8.00	70.	25.	110.	2.60	.864	3.0[illegible]	-.002	-.159	.121	-2.[illegible]	-7.317
TROY	6/25	16.00	7.80	71.	25.	105.	2.84	.914	2.97	-.209	-.396	.164	-2.735	-[illegible].[illegible]47[illegible]
TROY	6/27	16.00	7.90	69.	20.	113.	3.45	.783	2.91	-.085	-.317	.157	-2.[illegible]	-11.[illegible]
TROY	7/01	16.00	8.10	63.	22.	111.	3.09	.311	2.91	.098	-.107	.097	-[illegible]	-1[illegible]
TROY	7/03	15.90	8.00	71.	20.	109.	3.55	.335	2.91	.007	-.229	.120	-[illegible]	-[illegible]
TROY	7/05	15.50	7.90	63.	19.	113.	3.53	.77[illegible]	2.[illegible]7	-.[illegible]1	-.341	.[illegible]56	-2.[illegible]	-1[illegible]

TROY	7/07	16.50	7.80	70.	22.	112.	3.18	.321	2.96	-.179	-.335	.197	-2.705	-9.324
TROY	7/09	16.50	8.00	69.	19.	100.	3.63	.369	2.76	-.031	-.265	.111	-2.950	-6.553
TROY	7/11	17.00	7.70	67.	30.	115.	2.23	.643	3.09	-.232	-.411	.256	-2.591	-[illegible].491
TROY	7/13	23.00	7.60	73.	16.	116.	4.56	.767	2.94	-.254	-.561	.349	-2.457	-13.171
TROY	7/16	26.00	7.90	63.	27.	120.	2.52	.792	3.10	.070	-.033	.127	-2.727	-11.623
TROY	7/18	25.50	8.10	72.	19.	116.	3.79	.794	2.98	.275	.084	.114	-2.945	-12.177
TROY	7/20	24.50	8.00	73.	17.	115.	4.29	.783	2.95	.164	-.061	.140	-2.354	-13.135
TROY	7/22	25.00	7.90	75.	20.	120.	3.75	.792	3.10	.393	-.094	.135	-2.733	-11.921
TROY	7/23	26.15	7.80	70.	23.	122.	3.64	.762	3.03	-.009	-.149	.240	-2.620	-13.435
TROY	7/25	26.00	7.90	71.	20.	119.	3.55	.765	3.01	.057	-.035	.155	-2.732	-12.133
TROY	7/27	26.50	7.70	72.	18.	120.	4.00	.750	3.00	-.096	-.293	.2[illegible]	-2.525	-14.236
TROY	7/29	27.00	7.60	73.	20.	121.	3.65	.763	3.07	-.151	-.355	.321	-2.482	-13.[illegible]4

CHAPTER VI

VI-1 Discussion and Conclusions

Principal karst landforms within the study area are the closed depressions. These fall into three distinct classes: 1) small collapse features in drift, 2) large depressions of simple circular or subcircular forms in bedrock, 3) very large and irregular, ice-scoured depressions. The small collapse features are post-glacial in age and their type locality is found in Karst Valley. These features probably number in the hundreds but their distribution is not known because of dense forest cover and their small size. The simple circular depressions are large and found in bedrock with varying degrees of till and vegetational cover. Many of these depressions contain lakes and drain underground. Glacial scour is not evident in their form, but their scale is greater than that reported from carbonate bedrock-dolines of post-glacial age elsewhere in Canada. The very large sinkholes of irregular shape are obvious ice-scour forms and in most cases such as Nameless Pond, Brown's Pond, Bottomless Pond, erratics and scour marks are found. All of the class 3 closed depressions contain ponds and drain underground either through their bases, or through a short blind outlet channel, or via young sinks in an overflow channel that is seasonally active.

Distribution of the depressions is controlled by several factors: 1) presence of underdrainage routes (such as Karst Valley for the post-glacial collapse sinks), 2) presence of suitable rock lithology and structure, 3) adequate hydraulic gradients, 4) presence or absence of extensive and thick till deposits.

The large irregular dolines are partly the result of glacial scouring and partly of karst processes. If much of the overdeepening is attributed to karst processes then the karstification was aimed into developing groundwater channel systems of substantial dimensions to achieve these large sizes. In Chapter Four it was shown that the present active groundwater systems appear to be short in length and shallow in depth. The range of known hydraulic gradients is considerable but the range of proven groundwater velocities is small. It was found that workable hydrologic model such as Model No. 2 in Chapter 4, must take into consideration local topographic effects and is incomplete because, 1) possibility of surface discharge (ie. the periodic utilization of surface overflow channels) cannot be disregarded at any time, 2) the local geology, rock lithology, structure, etc. is very important in subsurface drainage.

The hydrochemical investigations strongly differentiated bicarbonate waters that were very uniform in their general chemical composition, although interesting variations of regimes are suggested within the detailed analysis of the results. Among the most significant findings are the ponds that function like evaporating pans even in the humid climate of Newfoundland. Pond 4 is an ideal example, where typical doline input hydrodynamics are present (no channelled flow is present because of lack of sufficient catchment area), yet is has not attained the scale of output that will drain it and deepen it effectively.

To characterize the seasonal hydrochemistry at the scale of larger basinal units, a "tank storage" model was found to be the most applicable. This was emphasized by the general lack of chemical contrast between input pond and output spring waters.

The "tank storage" model characterises the style of this karst better than individual explanations of pond and stream behaviour. The karst drainage is a glacially deranged one, derangement here taking the form of infilling largely or entirely obstructing the pre-glacial karst inputs, and of the deposition of blankets of carbonate-rich till which has tended to protect the underlying bedrock from solutional attack throughout the Holocene. The presence of suitable soluble rock, high relief and hydraulic gradients, along with abundant precipitation has permitted the development of only small, young systems amongst some of these large and complex closed depressions during the Holocene.

The study area represents a unique karst terrain, not easily comparable to any other areas found in the literature. Because of its geographical location, the area received net glacial deposition from the surrounding higher noncarbonate areas. It has a very rugged topography with large numbers of ponds and lakes draining underground. The many, varied alpine karst areas are all more closely similar to one another than to the study area because they generally suffered derangement by net glacial erosion. The extensive carbonate lowlands of Hudson Bay also have net deposition of carbonate glacial material similar to the study area, but they lack the ruggedness of Newfoundland.

VI 2 Suggestions for Further Research

This study represents the first detailed work on karst landform development in the Goose Arm area of Newfoundland. All results are new, and cover only a short period of observation, but these results point out interesting and unique features of the area and indicate new avenues of study such as: 1) the strong structural control on karst development 2) working out the complete karst hydrology of the area, which would give more detailed insight into the extent of glacial derangement and lithologic controls, 3) detailed water chemistry of ponds and streams where limnological effects are taken into account. This would be a unique approach to the explanation of hydrochemical results not attempted elsewhere in Canada, 4) detailed study of springs along Goose Arm Valley and the study of the effect of glacial till deposits on spring positions, 5) a more detailed study of the sinkholes and their morphology in relation to the Wisconsinan glaciation and the presence of active or inactive paleokarst systems.

APPENDIX A

KARST AREAS OF WESTERN NEWFOUNDLAND

1) Karst development in gypsum: a) Codroy-Woodville area

- extensive and well developed sinkholes mark the extent of the gypsum deposits
- sinkholes vary in size from less than a meter to several hundred meters, and from solutional to active collapse type.

b) Ship Cove area

- numerous large funnel-shaped and active sinkholes are found along the coastal area
- an ideal "daughter-parent" sinkhole relationship is present.

c) Berry Hill and Boswarlos area

- the sinkholes in gypsum repreduce a tropical cockpit type of development
- karren and pavement development is extensive.

2) Karst development in marble: a) Sops Arm area

- a small, active cave at the north end of taylors Pond is being entrenched along joints
- the cave has 200 m of its passage mapped
- several small caves are found along the cliff face,and numerous small sinkholes on the top (ref. Karolyi, 1976;1977a).

3) Karst development in limestone/dolomite: a) Port au Port Peninsula

- karst features found at several places on the peninsula includes: sinking streams, sinkholes, karren forms, and caves in river valleys which generally follow fault lines.

b) Gallants area

- sinking rivers, collapse features, caves, and karren forms.

c) Corner Brook area

- caves and sinking streams, collapse features

d) Goose Arm area ----this study

e) East Arm- Lomond area

- sinking streams and caves

f) Bonne Bay Big Pond - Wiltondale area .

- sinking streams and caves

g) Daniels Harbour area

- caves

h) Roddicton area

- cave at least 400ft.

(ref. Karolyi, 1977b).

REFERENCE

Atkinson, T.C., Smith D.I., 1975, Speleology: the science of caves. (ed.) T.D. Ford David & Charles, Newton Abbot.

Avias, J., 1972, Karst of France. (ed.) Herak & Stringfield,: Karst; Important karst regions of the Northern Hemisphere, p. 129-188.

Baird, D.M., 1951, Gypsum Deposits of Southwestern Newfoundland. Bull. Can. Inst. Mining, Met. V.44, p. 155.

Baird, D.M., 1959, Development of Gypsum deposits in Southern Newfoundland. Bull. Can. Inst. Mining, Met. V.52, p. 495.

Baird, D.M.; Cote, P.R., 1964, Lower carboniferous sedimentary rocks in South W. Newfoundland and their relations to similar strata in western Cape Breton Island. Bull. Can. Inst. Mining, Met. V.57, p. 509-520.

Balazs, D., 1971, Intensity of the tropical karst development based on caves of Indonesia. Karst es Barlangkut, V.6, p. 33-67.

Bauer, F., 1954, Zur Patashydrographie des Dachsteinstockes. Hohle, 5:46-49.

Bauer, F., 1961, Kalkabsatze unter kalkalpengletschern und ihre Bedeutung fur die Altersbestimmung heute gletscherfrei werdender karrenformen. Z. Gletscherk. Glazialgeol. V.4, p. 215-225.

Bauer, F., 1964, Kalkabtragsmessungen in den Osterreichischen Kalkhochalpen. Erd Kunde, 18: 95-102.

Bauer, F., 1970, Aujgaben der karst hydrologischen Forschung in Osterreich. Osterreichische Wasserwirtschaft, V.22, p. 127-138.

Bauer, F.; Zotl, J., 1972, Karst of Australia. Karst, important karst regions of the Northern Hemisphere. (ed.) Herak M., Stringfield, 1972, Elsevien P. Coy.

Bell, R.A., 1884, Observations on the geology, mineralogy, zoology and botany of the Labrador coast, Hudson Strait and Bay. Geol. Surv. Can. Ann. Rept. 1882-3-4, p. 5DD-62DD.

Bogli, L.A., 1951, Problem der karrenbildung.
Gans Geogr. Helv. VI, p. 191-204.

Bogli, A., 1961, Karrentische ein Beitnag zur karst morphologie.
Z. Geomorph. V.3, p. 185-193.

Bogli, A., 1960, Kalklosung und karrenbildung.
Zeitschr. Geomph. Supp. V.2, p. 4-21.

Bogli, A., 1964(a), Un exemple de complexe glacio-karstique: le Schichthep-penkarst. Rev. Belge Geogr.
(ed.) Soc. Roy Belg Geogr. Spec. Pub. Karst et Climats Froids V.88 (1-2), p. 63-82.

Bogli, A., 1964(b), Mischungskorrosion - Ein Beitnag zum Verkarstungsproblem.
Erdkunde Bd. XVIII, H.2, p.83-92.

Bogli, A., 1971, Corrosion by mixing of karst waters.
Trans. Cave Res. Group of Gr. Brit. V.13/2, p. 109-114.

Bogli, A., 1975, Solution of calcium carbonate and the formation of karren.
Cave Geol. V.1/1, p. 28p.

Brook, G.A., 1976, Geomorphology of the North Karst, South Nahanni River region, Northwest Territories, Canada.
Unpubl. Ph.D. Thesis, McMaster University, p. 627.

Brooks, I.A., 1969, Late glacial marine overlap in Western Newfoundland.
Can. J. Earth Sci. V.6, p. 1397-1404.

Brooks, I.A., 1970, New evidence for an independent Wisconsin-age ice cap over Newfoundland.
Can. J. Earth Sci. V.7, p. 1374-1382.

Brooks, I.A., 1973, Late Wisconsin glaciation of southern Newfoundland with special reference to the Stephenville map area.
G.S.C. 73-40, p. 1-31.

Brooks, I.A., 1976, Late Wisconsin readvance of piedmont glaciers in southwest Newfoundland.
Marit. Sedim. V.11, p. 47-48.

Brooks, I.A., 1976(a), Geomorphology and quaternary geology of Codroy Lowland and adjacent plateaus, southwest Newfoundland.

Brooks, I.A., 1976(b), Radiocarbon age of Robinson's Head moraine, west Newfoundland, and its significance for post glacial sea level changes.
Can. J. Earth Sci., V.14, p. 2121-2126.

Chamberlin, T.C., 1895, Notes on the glaciation of Newfoundland.
J. Geol. V.6, p. 467.

Ciry, R., 1959, Karst cutanes.
Ann. Speleol. V.14, p. 23-30.

Coleman, A.P., 1926, The pleistocene of Newfoundland.
J. Geol. V.34, p. 193-223.

Cooke, H.J., 1971, A study of limestone solution under tropical conditions in North East Tanzania.
Trans. Cave Res. Group G.B., V.13/4, p. 265-276.

Copeland, M.J.; Bolton, T.E., 1977, Additional paleontological observations bearing on the age of the Lourdes Formation (Ordovicion), Port au Port Peninsula, Western Newfoundland.
Rept. of Act. Part B, G.S.C., paper 77-1B, p. 1.

Cowell, D.W., 1976, Karst geomorphology of the Bruce Peninsula, Ontario.
M.Sc. Thesis, McMaster University.

Cummings, L.M., 1968, St. George - Table Head disconformity and zinc mineralization, Western Newfoundland.
C.I.M.M. Bull. 61, p. 721-712.

Cramer, H., 1941, Die systematik der karstdolinen.
Neues Jahrbuch fur Mineralogie, Geologie und Palaontologie Band 85, p. 293-382.

Cvijic, J., 1893, Der karstphanomen.
Geographische Abhandlungen, V.5, p. 217-329.

Daly, R.A., 1921, Post glacial warping of Newfoundland and Nova Scotia.
Amer. J. Science, 5th Ser., V.201, p. 381-391.

Drake, J.J., 1974, Hydrology and karst solution in the Southern Canadian Rockies.
Ph.D. Thesis, McMaster University, Dept. of Geography 1974.

Drake, J.J.; Harmon, R.S., 1973, Hydrochemical environments of carbonate terrains.
Water Resource Res. V.9/4, p. 949-957.

Droppa, A., 1966, Characteristics of the karst regions in the Carpathians.
Probl. Speleol. Res., V.2, p. 23-30.

Dyck, W.; Fyles, J.G., 1963, Geological survey of Canada radiocarbon dates II.
Radiocarbon, V.5, p. 39-55.

Fahraeus, L.E., 1973, Depositional environments and Conodont-based Correlation of the Long Bint Formation (M. Orelov.) Western Newfoundland.
Can. J. Earth Sci., V.10, p. 1822.

Fairchild, H.L., 1918, Postglacial uplift in Northeastern North America.
Bull. Geol. Soc. Amer., V.29, p. 187-238.

Flint, R.F., 1940, Late quaternary changes in level in western and southern Newfoundland.
Bull. Geol. Soc. Amer., V.51, p. 1757-1780.

Fong, C.C.K., 1974, Geological mapping St. George's Bay carboniferous area.
Rep. Act. 1973, Min. Dev. Div. Newf., p. 66-69.

Fong, C.C.K., 1976(a), Geological mapping, Northern half of the St. George's Bay carboniferous basin.
Rept. of Act. 1975, Min. Dev. Div. Report 76-1, p. 2-10.

Fong, C.C.K., 1976(b), Geologic mapping, Deer Lake-White Bay carboniferous basin.
Rept. of Activ. 1975, Min. Dev. Div Rept 76-1, p. 17-25.

Fong, C.; Douglas C., 1975, Geological mapping, Northern part of St. George's Bay carboniferous basin.
Rept. of Act. 1974, Min. Dev. Div. Report 75-1, p. 22-31.

Ford, D.C., 1971(a), Alpine karst in the Mt. Castleguard-Columbia Icefield area, Canadian Rocky Mountains.
Arctic & Alpine Res. V.3, #9 1971, p. 239-252.

Ford, D.C., 1971 (b), Geologic structure and a new explanation of limestone cavern genesis.
Trans. Cave Res. Group of Great Britain, V.13 #2, p. 81-94.

Ford, D.C., 1971(c), Characteristics of limestone solution in the southern Rocky Mountain and Selkirk Mountain, Alberta & British Columbia.
Can. J. Earth Sci. V.8/6, p. 585-609.

Ford, D.C., 1971(d), Alpine karst in the Mt. Castleguard Columbia icefield area, Canadian Rocky Mountains.
Arctic & Alpine Res. V.3/3, p. 239-252.

Ford, T.D., 1971, Structures in limestones affecting the initiation of caves.
Trans. Cave Res. Group of Great Britain, V.13 #2, p. 65-71.

Garrels, R.M.; Christ, C.L., 1965, Solutions, Minerals and Equilibria.
Harper & Row, New York, p. 450.

Goodman, L.R., 1965, Formation of solution bevels at intersections of joints and bedding planes.
Cave Notes (a review of Caves & Karst Research). V.7/4, p. 25-31.

Grant, D.R., 1969, Late Pleistocene readvance of piedmont glaciers in Western Newfoundland.
Maritime Sediments, V.5, p. 126-128.

Grund, A., 1914, Der geographische Zy Khio in karst.
Z. Ges. Erdkunde, 52; p. 621-640.

Gvozdeckij, N.A., 1965, Types of karst in the U.S.S.R.
Separatum, Prob.-Speleol. Res. (Prague), p. 47-54 1965.

Kaserodt, K., 1965, Untersuchungen zur Hohen und Altersgliederung der Karstformen in den nordlichen kalkalpen.
Munchen Geogr. V.27.

Herak, M.; Stringfield, V.T., 1972, Karst: Important karst regions of the Northern hemisphere.
Elsevier Pub. Comp. 1972.

Hubert, J.F.; Suchecki, R.K.; Perry E.A.Jr., 1976, Timing of carbonate and clay diagenesis in Cambrian - Ordovician Cow Head Breccia. Newfl. Eabs.
Am. Ass. Pet. Geol. Bull. V.60/4, p. 682-683.

Jakucs, L.D., 1977, Morphogenetics of karst regions variation of karst evolution.
Akademiai Kiado Budapest 1977, p. 284.

Jenko, F., 1959, Hidrologija in vodno gospodarstvo kras. (Ljubljana).

Jenness, S.E., 1960, Late pleistocene glaciation of eastern Newfoundland.
Bull. Geol. Soc. Am., V.71, p. 161-180.

Jennings, J.N., 1971, Karst
M.I.T. Press. London, England 1971.

Jennings, J.N., 1972(a), The character of tropical humid karst.
Z. Geomorph. V.16, p. 336-341.

Jennings, J.N., 1972(b), The blue waterholes, Cooleman Plain S.W. and the problem of karst derudation rate determination.
Trans. Cave Res. Gr. Gr. Brt. V.14/2, p. 109-117.

Jennings, J.N., 1975, Doline morphometry as a morphogenetic tool - New Zealand Examples.
New Zealand Geographer. V.31, p. 6-28.

Karolyi, S.M., (Bourque), 1976(a), Speleological Reconnaissance in Newfoundland.
The Canadian Caver, V.8/2, p. 42-45.

Karolyi, S.M., (Bourque), 1976(b), Karst of the Western Platform of Newfoundland: Preliminary Observations.
Gol. Ass. Can. (abst.) 1976, V.1, p.61.

Karolyi, S.M., (Bourque), 1977, Glaciokarstic development in Ordovician carbonates - Western Newfoundland.
Proc. 7th Int. Conf. England, p. 252-253.

Kay, G.M., 1966, Newfoundland structures and continental drift.
Bull. Can. Petrol. Geol., V.14, p. 613.

Kluyver, H.M., 1975, Stratigraphy of the Ordovician St. George Gr. in the Port au Choix area, Western Newfoundland.
Can. J. Earth Sci., V.12/4, p. 589-94.

Knight, I., 1973, The Newfoundland carboniferous, an appraisal of the sedimentology and depositional environments and a review of mineralization.
Newfoundland Dept. of Mines Report.

Knight, I., 1975, Geological mapping, carboniferous rocks, Cape Anguille Mountains, Southwest Newfoundland.
Rept. Act. 1974, Min. Dev. Div. Report 75-1, p. 31-42.

Knight, I., 1976, Geology of the carboniferous of the Codroy Valley and Northern Anguille Mountains.
Report of Activities 1975, Min. Dev. Div. Rept. 76-1, p. 10-19.

Lange, L.A., 1968(a), The changing geometry of cave structures, Part 1: The constant solution gradient.
Caves & Karst, V.10/1, p. 1-10.

Lange, L.A., 1968(b), The changing gemoetry of cave structures, Part II: The exporential solution gradient.
Caves & Karst, V.10/2, p. 13-19.

Lange, L.A., 1968(c), The changing geometry of cave structures. Part III: Summary of solution processes. Caves & Karst, V.10/3, p. 29-32.

Langmuir, D., 1971, The geochemistry of some carbonate ground waters in Central Pennsylvania. Geochim. Cosmochim. Acta. V.35, p. 1023-1045.

LeGrand, H.E.; Stringfield, V.T., 1973, Concepts of karst development in relation to interpretation of surface runoff. J. Res. U.S. Geol. Survey, V.1/3, p. 351-360.

Lehmann, H., 1964, States and tasks of research on karst phenomena. Erdkunde V.16, p. 81-38.

Lilly, H.D., 1963, Geology of the Hughes-Brook Goose Arm Area. N. Newf. Unpub. M.Sc. Thesis, Mem. Univ. of Newf., St. John, p. 122.

Lorwy, P.; Jennings, J.N., 1974, The Nullarbor karst Australia. Z. Geomorph. N.F., V.18/1, p. 35-81

Lundqvist, J., 1965, Glacial geology in north eastern Newfoundland. Geol. Foren. Stockholm Forh. V.87, p. 285-306.

MacClintock, P.; Twenhofel, W.H., 1940, Wisconsin glaciation of Newfoundland. Bull. Geol. Soc. Amer. V.51, p. 1729-1756.

Marker, Margaret, E., 1976, Cenotes: a class of enclosed karst hollows. Z. Geomorph. N.F. Suppl. Bd. 26, p. 104-123.

Mazuir, E., 1962, Die Formen des Hochgebirgs-karst in den Cervene vrchy (Westliche Tatra). Geograf. Casopis 2:87-104.

McArthur, J.G.; Knight, I., 1974, Geology and Industrial minerals of the Newfoundland Carboniferous. G.A.C./M.A.C. 1974 Field Trip Manual B-10, p. 23.

Miotke, F.D., 1974, Carbon Dioxide and the soil atmosphere. Abrandl. zur Karst und Hohlenkunde, V.9, p. 1-49 Munchen.

Monroe, W.H., 1966, Formation of tropical karst topography by limestone solution and repercipitation. Caribbean J. Sci. V.6, p. 1-7.

Monroe, W.H., 1970, A glossary of karst terminology. U.S. Geol. Surv. Water Supply Paper, 1899OK, p. 26.

Mowat, D.G., 1962, Progressive changes of shapes by solution in the laboratory.
Cave Notes, V.4/6, p. 45-49.

The National Atlas of Canada, Energy Mines & Resources Canada 1974.

Neale, E.R.W.; Williams, H.; Kennedy, M.J., 1974, The Northwestward termination of the Appalachian Orogen.
Ocean Basin & Margins, V.2, Chapter 4, p. 79-123.
Plenum Press, New York.

Palmer, M.V.; Palmer, A.N., 1975, Landform development in the Mitchell Plain of southern Indiana: origin of a partially karsted plain.
Z. Geomorph. N.F., Bd. 19/1, p. 1-39.

Picknett, R.G., 1972, The pH of calcite solutions with and without magnesium carbonate present, and the implications concerning rejuvenated aggressiveness.
Trans Cave Res. Group of Great Brit. V.14/2, p. 141-150.

Pluhar, A.; Ford, D.C., 1970, Dolomitic karren of the Niagara Escarpment, Ont. Canada.
Z. Geomorph. V.14, p. 392-410.

Plummer, L.N. Jr., 1972, Rates of mineral aqueous solution reactions.
Unpubl. Ph.D. Thesis, N.W. University.

Plummer, L.N.; MacKenzie, F.T., 1974, Predicting mineral solubility from rate data: application to the dissolution of magnesium calcites.
Am. J. Sci. V.274, p. 61-83.

Pilty, A.F., 1968, Calcium carbonate content of karst water in relation to flow through time.
Nature, V.217, p. 939-940.

Poole, N.H., 1967, Tectonic evolution of Appalacian Region of Canada.
Geology of the Atlantic Region
(ed.) E.R.W. Neale & H. Williams.
G.A.S., Spec. Paper, No. A; p. 9-51.

Poole, W.H., 1977, Plate tectonic evolution of the Canadian Appalachian region.
Rept. of Act. G.S.C. Paper 76-1B, p. 113.

Priesnitz, K., 1972, Methods of isolating and quantifying solution factors in the laboratory.
Trans. Cave Res. Group Gt. Brit. V.14, p. 153-158.

Pulina, M., 1974, Chemical denudation on the carbonate karst areas: Polska, Akademia Nauk, Prace Geograf. No. 105, p. 159. Warsaw.

Rauch, H.W.; White, W.B., 1970, Lithologic controls on the development of solution porosity in carbonate aquifers. Water Res., V.6, p. 1175-1192.

Rauch, H.W.; White, B.W., 1977, Dissolution kinetics of carbonate rocks. 1) Effects of lithology on dissolution rate. Water Resources Research, V.13/2, p. 381-394.

Riley, G.C., 1962, Stephenville map area, Newfoundland. Geol. Sur. Can. Mem. 323, p. 72.

Rodgers, J., 1965, Long Point and Clam Bank Formation, Western Newfoundland. Proc. Geol. Ass. Can. V.16, p. 83.

Rodgers, J.; Neale, E.R.W., 1963, Possible Taconic klippen in Western Newfoundland; Amer. Journ. Sci. V.261, p. 713-730.

Roglic, J., 1974, Le characteres Specifques du karst dinarique. C.N.R.S., V.15, Phenomenes Karstiques, II: 269-278.

Schuchert, C.; Dunbar, C.O., 1934, Stratigraphy of western Newfoundland. Geol. Soc. Am. Mem. #1.

Sjoberg, E.L., 1976, A fundamental equation for calcite dissolution kinetics. Geochim. CDS Mochim. Acta. V.30, p. 441-447.

Stevens, R.K., 1970, Cambor-Ordovician Flysch Sedimentation and tectonics in West Newfoundland and their possible bearing on a Proto-Atlantic Ocean. Geol. Asso. Can. Spec. Paper #7, p. 165-177.

Sweeting, M.M., 1960, The weathering of limestones with particular reference to the carboniferous limestones of northern England. Essays in Geomorphology. (ed.) G.H. Dury, p. 177-210.

Sweeting, M.M., 1966, The weathering of limestones with particular reference to the carboniferous limestones of northern England. Essays in Geomorphology (ed.) G.H. Dury, p. 177-210, London.

Sweeting, M.M., 1973, Karst landforms. Columbia Pub. 1973.

Sweeting, M.M., 1976, Present problems in karst geomorphology.
Z. Geomorph. Suppl. 26, p. 1-6.

Sweeting, M.M.; Sweeting, G.S., 1970, Some aspects of the carboniferous limestone in relation to its landforms.
Mediterrance, V.7, p. 201-210.

Tuke, M.F.; Baird, D.M., 1967, Klippen in Northern Newfoundland in Appalachian Tectonics.
Roy. Soc. Canada, Spec. Pub. #10, p. 3-9.

Weitz, J.L., 1953, Geology of the Bay of Islands area. Western Newfoundland.
Unp. Ph.D. Thesis, Yale Univ. p. 140.

White, W., 1977, Geology and biology of Pennsylvania caves.

Whittington, H.B.; Kindle, C.H., 1963, Middle Ordovician Table Head Formation, Western Newfoundland.
G.S.A. Bull. V.74, p. 745-758.

Whittington, H.B.; Kindle, C.H., 1968, Cambrian and Ordovician stratigraphy of western Newfoundland.
Kay M. Ed. North Atlantic Geology and Continental Drift.
Am. Ass. Pet. Geol. Mem. #12, p. 655-664.

Wigley, T.M.L., 1971, Ion paring and water quality measurements.
Can. J. Earth Sci., V.8/4, p. 468-476.

Williams, H., 1964, The Appalachians in Northeastern Newfoundland. A two sided symmetrical system.
Am. J. Sci. V.262, p. 1137.

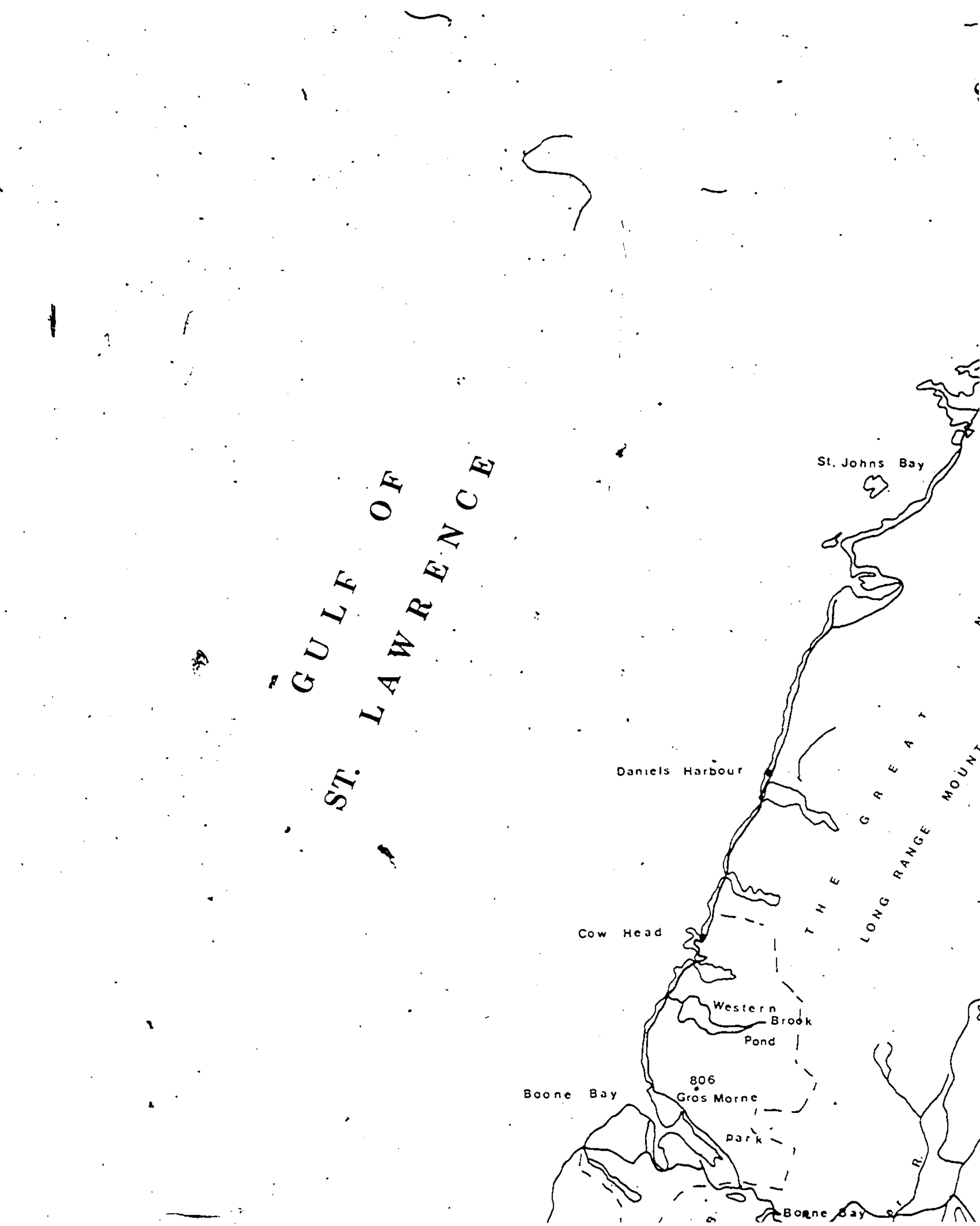
Williams, H., 1971, Mafic ultramafic complexes in western Newfoundland Appalachians and the evidence for their transportation (a rev. & interim rep.)
Geol. Ass. Can. Proc. V.24 #1, p. 9.

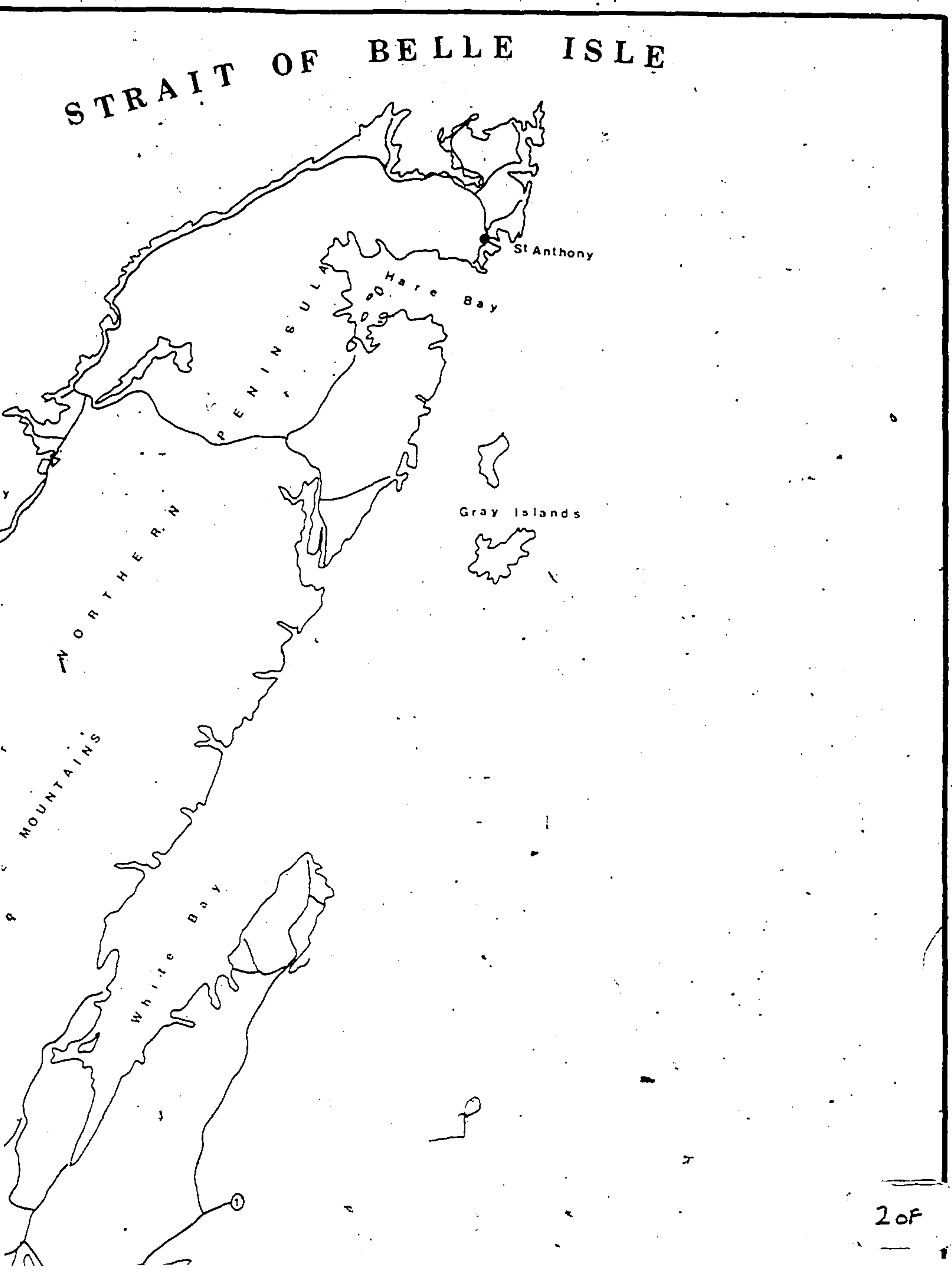
Williams, H.; York, J., 1972, Sheeted dikes and brecciated dike rocks within transported igneous complexes, Bay of Islands, Western Newfoundland.
Can. J. Earth Sci. V.9, p. 1216.

Williams, H.; Kennedy, M.J.; Neale, E.R.W., 1972, The Appalachian structural province.
Variation in Tectonic Styles in Canada.
Geol. Ass. of Canada, Spec. Paper #11, p. 182.

Williams, P.W., 1970, Limestone morphology in Ireland.
Irish Geog. Studies in Honour of E. Estyn Evans.
(ed.) N. Stephens & R.E. Glarrock,
Dept. of Geog. Queen's Univ. of Belfast.

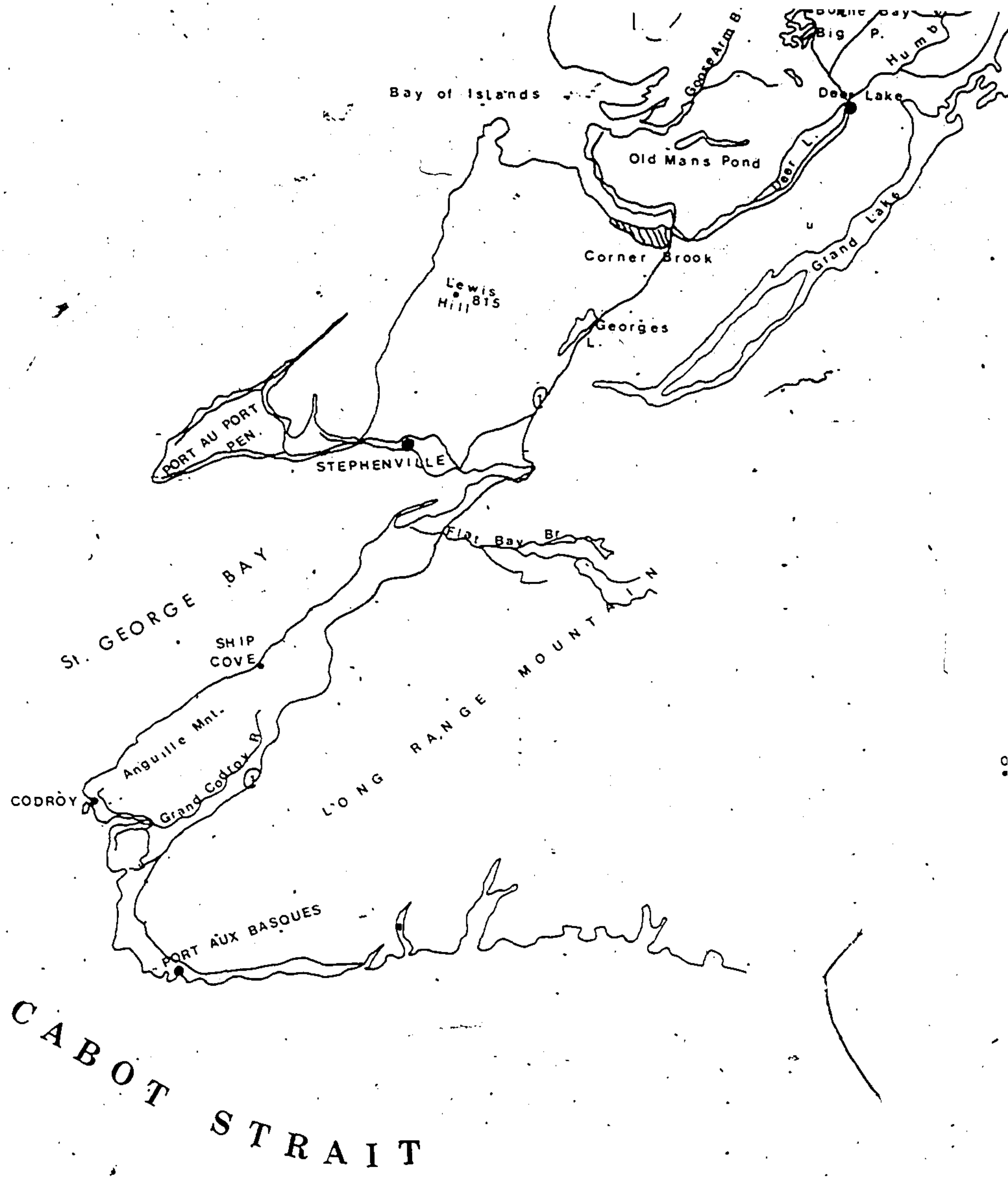
Wilson, J.T., 1966, Mid-Atlantic: Closed and then Re-Opened.
Nature, V.211, p. 676-681.


GULF OF
ST. LAWRENCE
St. Johns Bay
Daniels Harbour
Cow Head
Western Brook Pond
806
Gros Morne
park
Boone Bay
Bonne Bay
THE GREAT
LONG RANGE



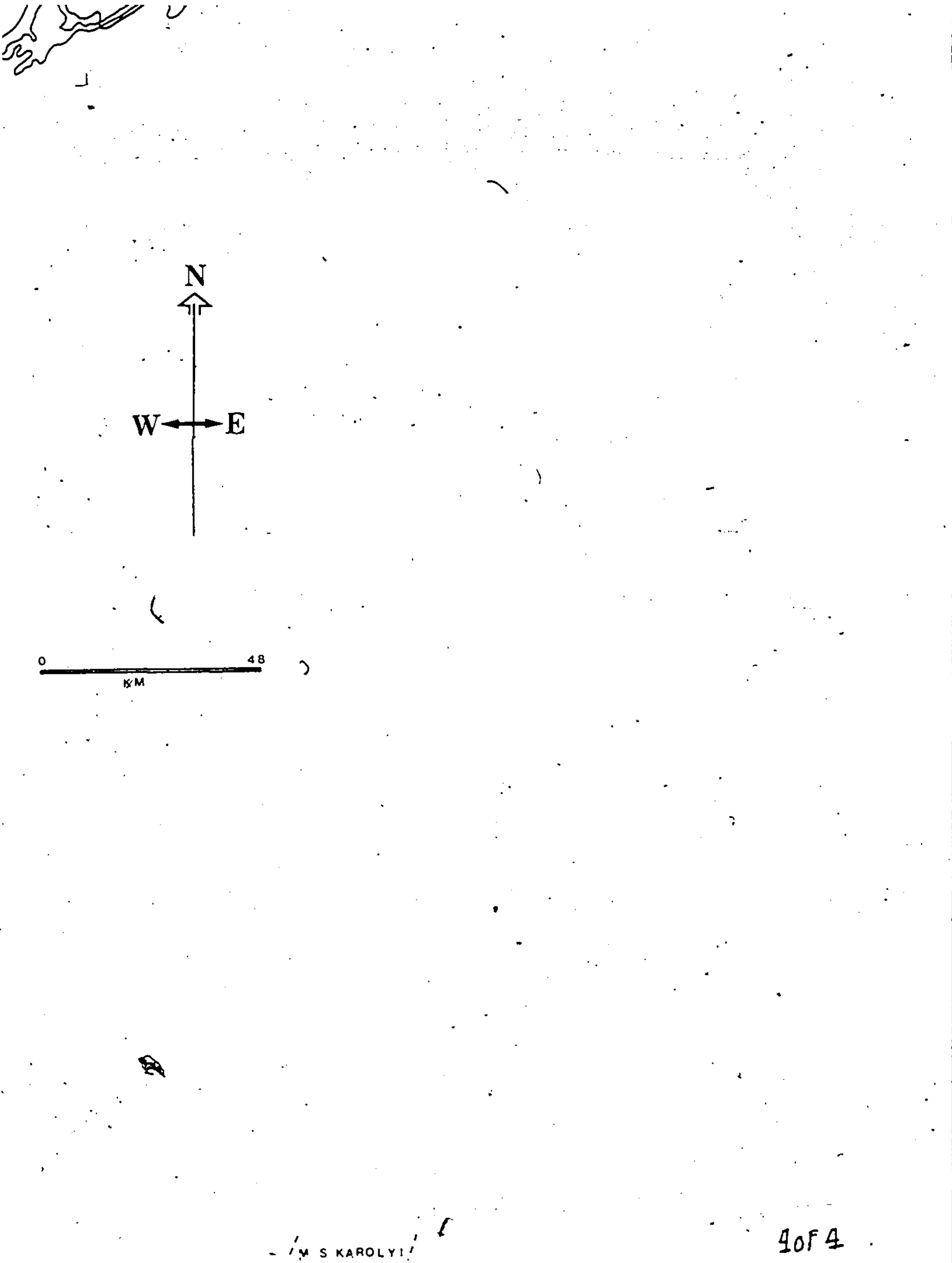
STRAIT OF BELLE ISLE
St Anthony
Hare Bay
PENINSULA
NORTHERN
MOUNTAINS
Gray Islands
White Bay

2 of

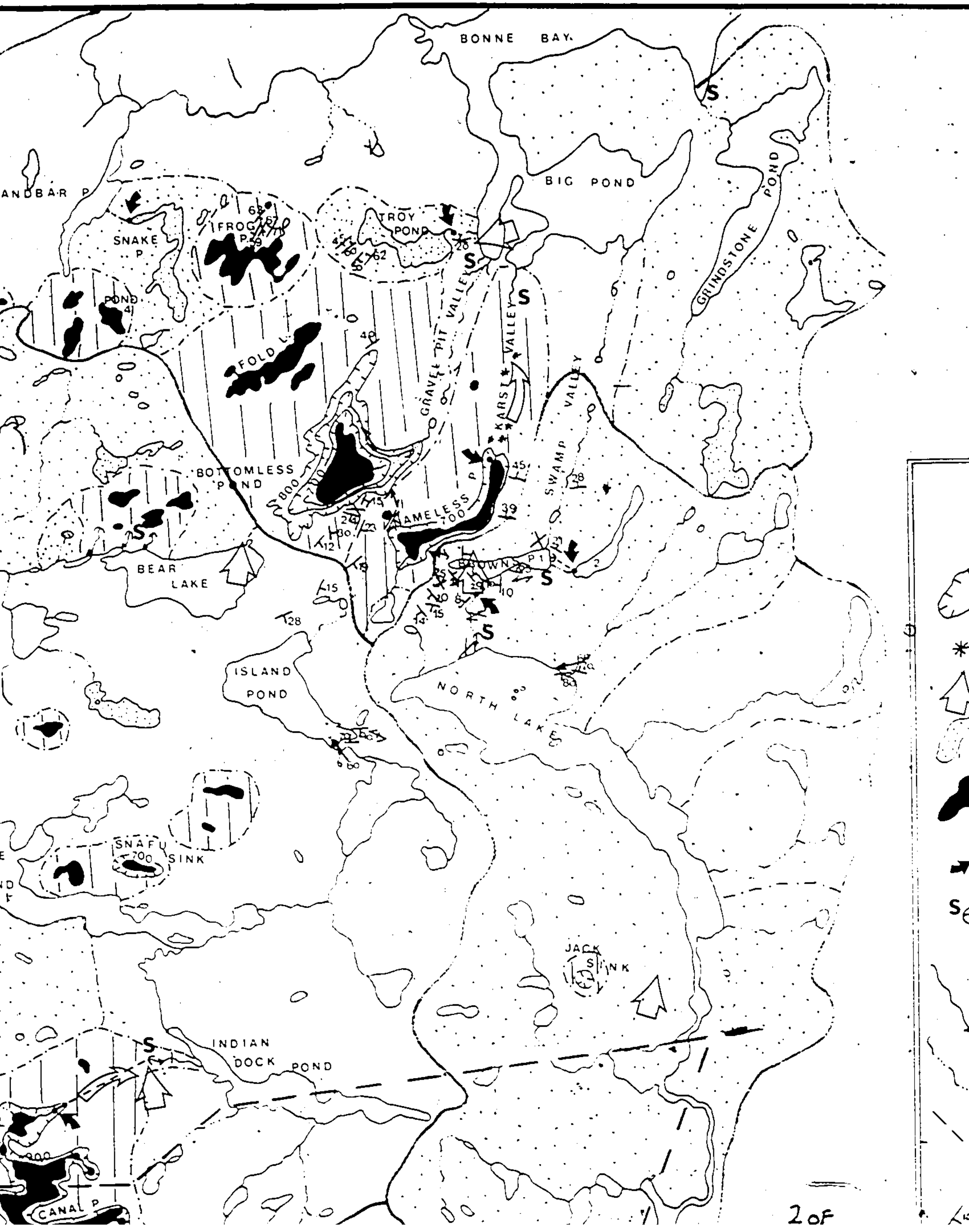


30F

FIG. 1. **LOCATION MAP**

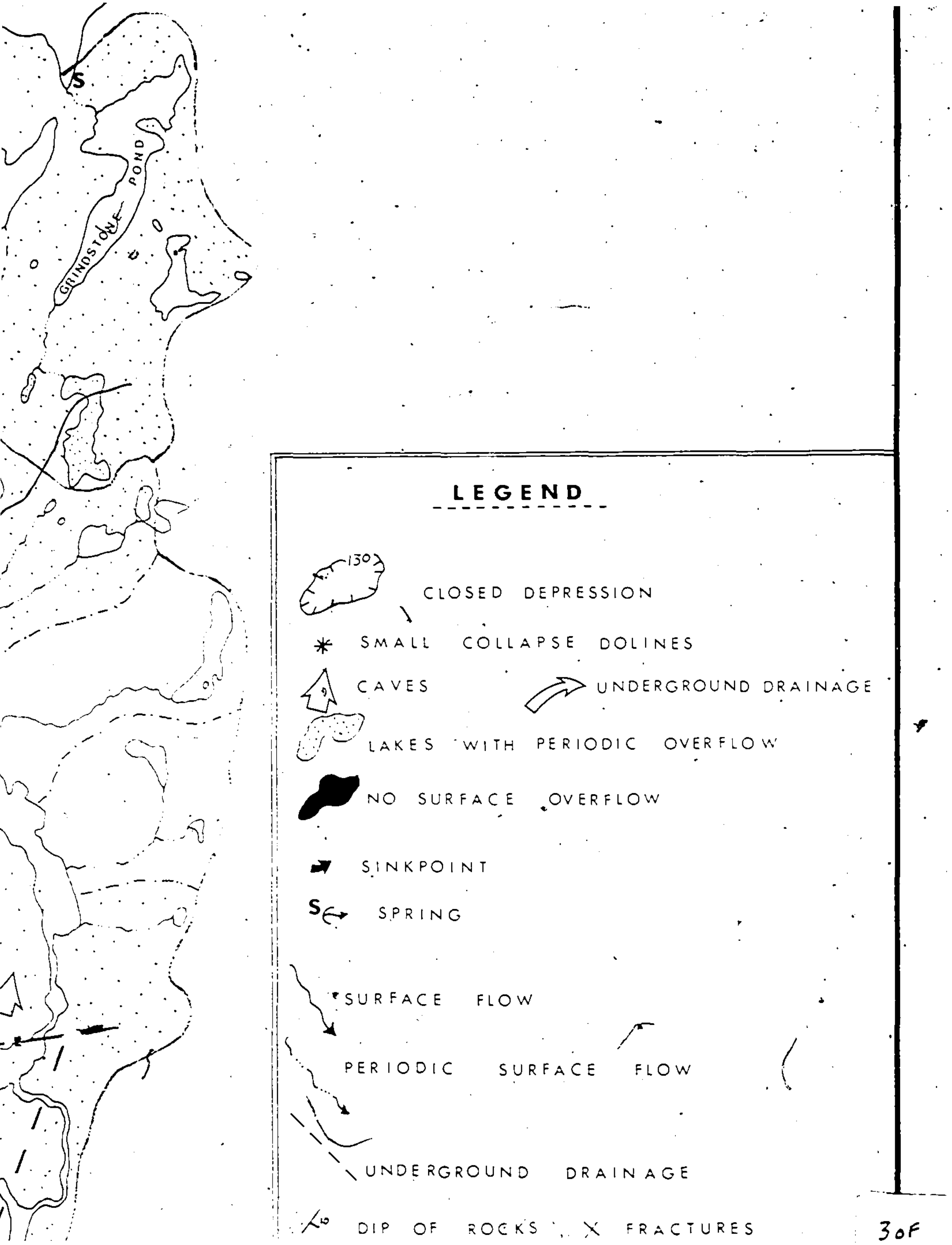

N
W
E
0
48
KM
M S KAROLYI

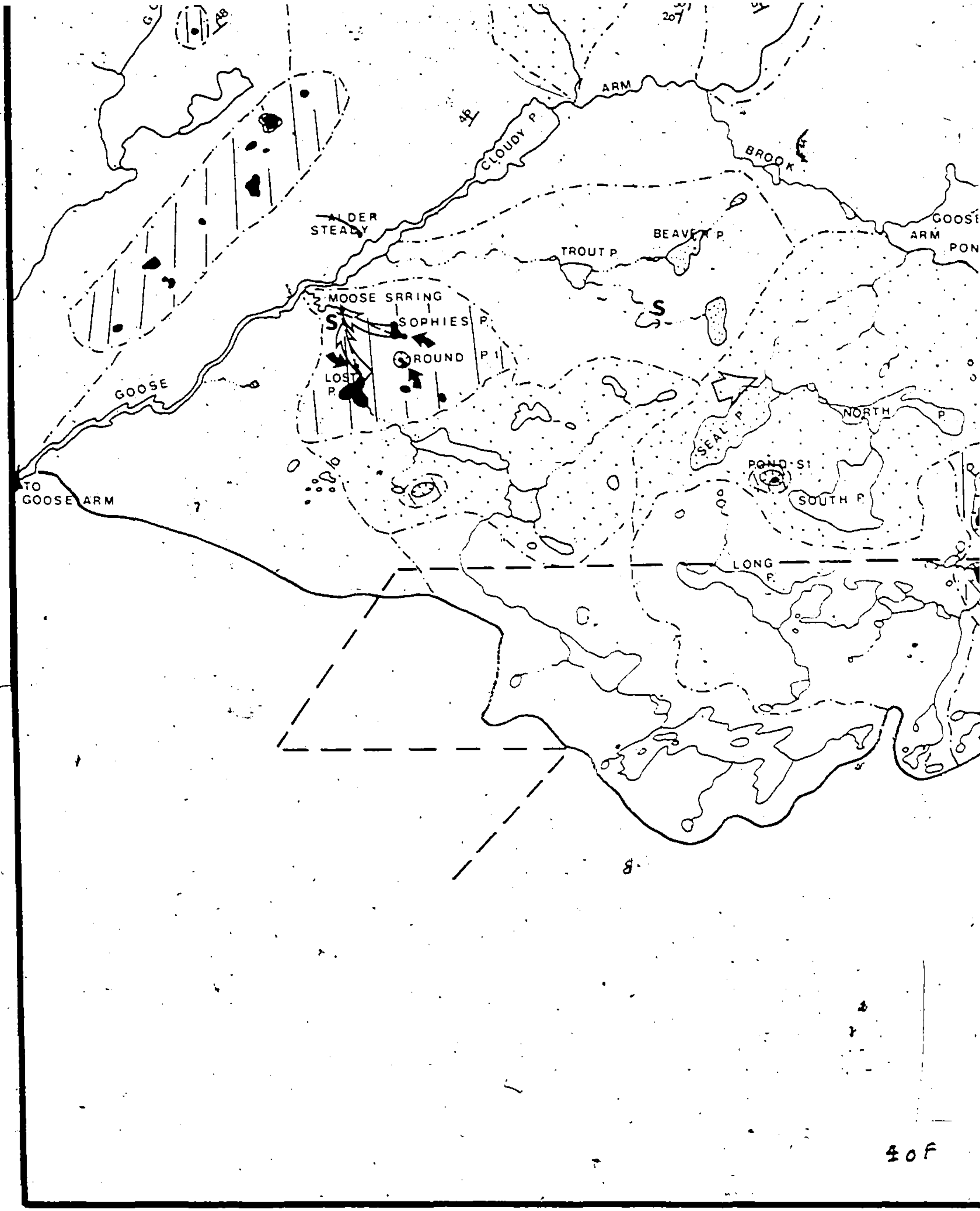

GOOSE ARM BROOK NORTH
ROUND
LONG P
WEASEL PONDS
POND R2
ARM
CLOUDY P
BROOK
ALDER STEADY
BEAVER P
TROUT P
GOOSE ARM POND
MOOSE SPRING
SOPHIES P
ROUND P
LOST P
GOOSE
SEAL P
NORTH P
POND S1
SOUTH P
LONG P.
TO GOOSE ARM
S

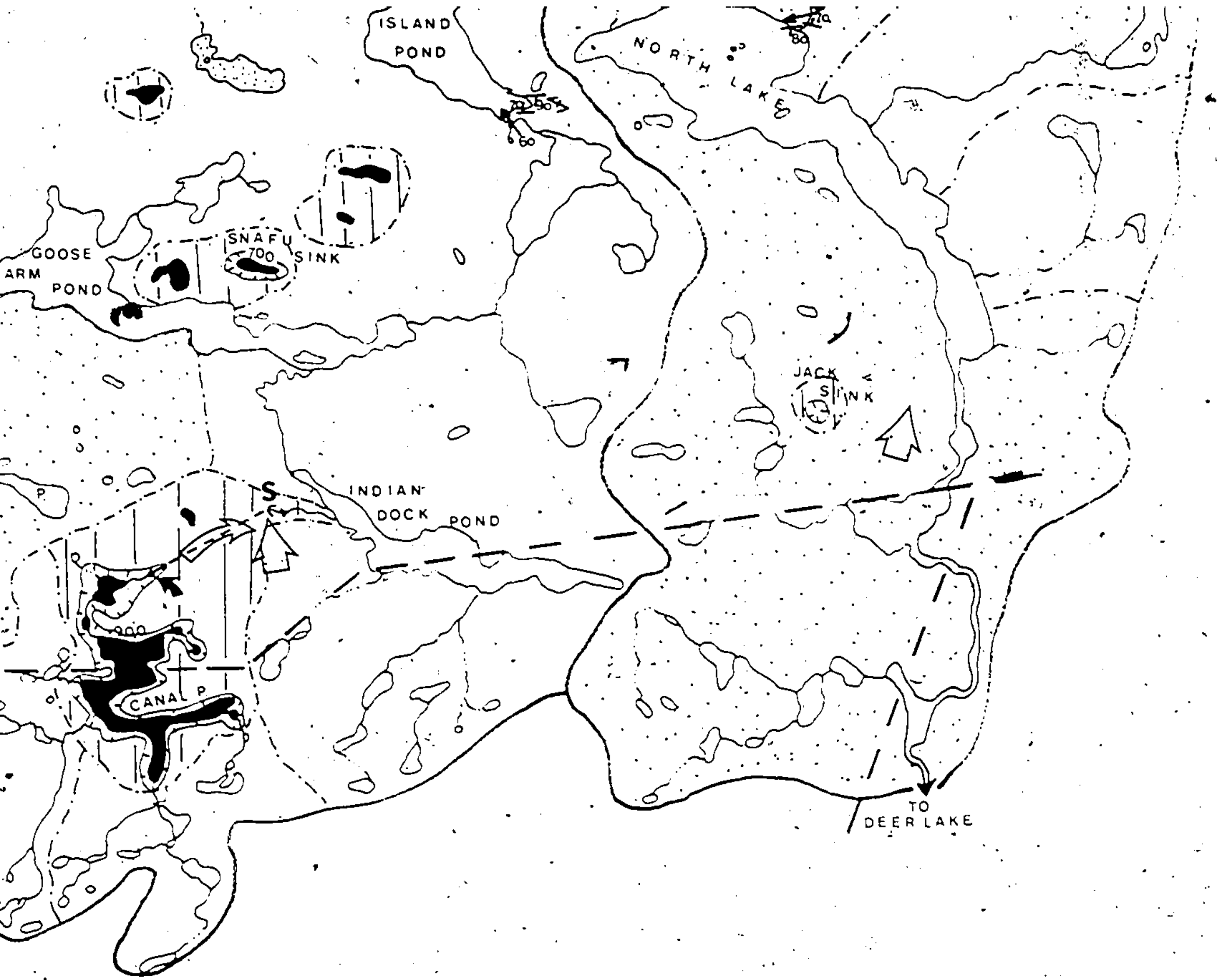


BONNE BAY
BIG POND
GRINDSTONE POND
SANDBAR P
SNAKE P
FROG P
TROY POND
POND 41
FOLD L
GRAVEL PIT VALLEY
KARST VALLEY
VALLEY
BOTTOMLESS POND
NAMELESS P
SWAMP
BROWNS P
BEAR LAKE
ISLAND POND
NORTH LAKE
SNAFU SINK
JACK SINK
INDIAN DOCK POND
CANAL P

2 OF

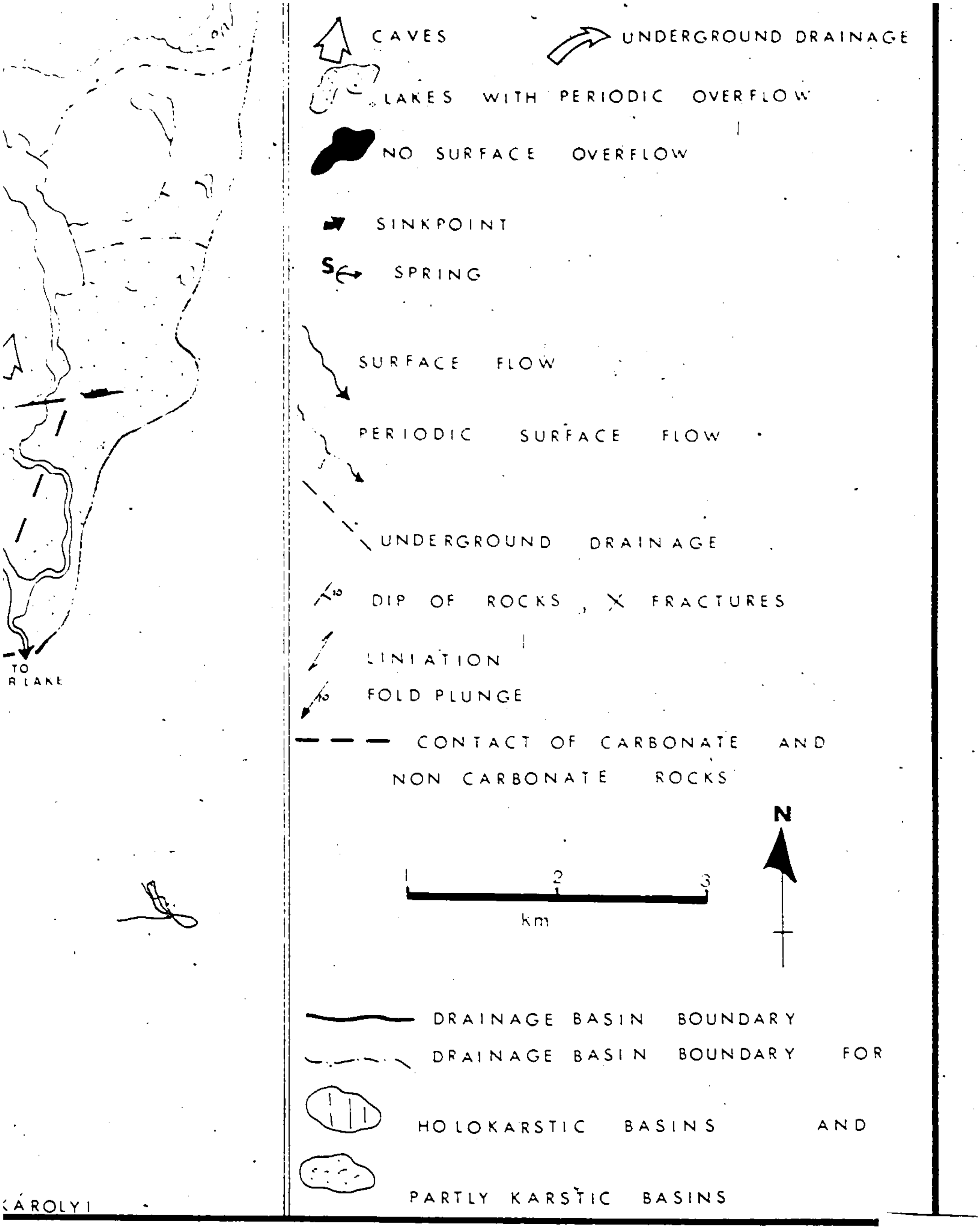

S
GRINDSTONE POND
LEGEND
130
CLOSED DEPRESSION
SMALL COLLAPSE DOLINES
CAVES
UNDERGROUND DRAINAGE
LAKES WITH PERIODIC OVERFLOW
NO SURFACE OVERFLOW
SINKPOINT
S SPRING
SURFACE FLOW
PERIODIC SURFACE FLOW
UNDERGROUND DRAINAGE
DIP OF ROCKS
X FRACTURES


ARM
CLOUDY P
BROOK
GOOSE
ARM
ALDER
STEADY
BEAVER P
TROUT P
MOOSE SRRING
S
SOPHIES P
ROUND
P 1
LOST
P
S
GOOSE
SEAL P
NORTH P
POND S1
SOUTH P
TO
GOOSE ARM
LONG
P
4 OF



M. S. KAROLY

5oF


TO
R LAKE
CAVES
UNDERGROUND DRAINAGE
LAKES WITH PERIODIC OVERFLOW
NO SURFACE OVERFLOW
SINKPOINT
S SPRING
SURFACE FLOW
PERIODIC SURFACE FLOW
UNDERGROUND DRAINAGE
DIP OF ROCKS , X FRACTURES
LINIATION
FOLD PLUNGE
CONTACT OF CARBONATE AND
NON CARBONATE ROCKS
N
1
2
3
km
DRAINAGE BASIN BOUNDARY
DRAINAGE BASIN BOUNDARY FOR
HOLOKARSTIC BASINS AND
PARTLY KARSTIC BASINS