KARST DEVELOPMENT IN ORDOVICIAN CARBONATES:
Western Platform of Newfoundland

by
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KARST DEVELOPMENT IN ORDOVICIAN CARBONATES:

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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 inaccessibly 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.
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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.
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1a. 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 Köppen-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.
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 (01220 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.
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

- TUNDRA
- BOREAL FOREST
- OPEN WOODLAND

0 100 km.

b) AVERAGE ANNUAL PRECIPITATION (cm)

0 200 km.

c) FROST FREE PERIOD (days)

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d) AVERAGE DAILY TEMPERATURE (°C)

Fig. 3  THE CLIMATE OF NEWFOUNDLAND  (Nat. Atl. of Canada 1974)
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 branch 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 absence 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, 1972a; 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.

Id-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 really 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

GEOLaGy, 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 overlies 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.

11b. 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 Peninsula (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,
### TABLE I

Comparative stratigraphic chart, Cambro-Ordovician of the Great Northern Peninsula and Port au Port Peninsula.

<table>
<thead>
<tr>
<th>LOGAN (1863) RICHARDSON (division)</th>
<th>SCHUCERT AND DUNBAR (1934)</th>
<th>WHITTINGTON, KINDLE (1968)</th>
<th>KLUIJVER (1975)</th>
</tr>
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<tbody>
<tr>
<td>MIDDLE</td>
<td>TABLEHEAD FORMATION DISCONFORMITY</td>
<td></td>
<td></td>
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<tr>
<td>St.</td>
<td>St.</td>
<td>Port au Choix Formation</td>
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<tr>
<td>Catoche Formation</td>
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<tr>
<td>Barbaco Point Formation</td>
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<tr>
<td>LOWER</td>
<td>FORMATION</td>
<td></td>
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<tr>
<td>A</td>
<td>Labrador ser.</td>
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<tr>
<td>B</td>
<td>Labrador Bay Fm.</td>
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<tr>
<td>C</td>
<td>Forteau Fm.</td>
<td></td>
<td></td>
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<tr>
<td>Lower St. George Group</td>
<td></td>
<td></td>
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<tr>
<td>C</td>
<td>Cabrian dolomite Fm.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>Micrite Fm.</td>
<td></td>
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</tr>
<tr>
<td>A</td>
<td>Hawkes Bay Quartzite</td>
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<td></td>
</tr>
<tr>
<td></td>
<td>Forteau Fm.</td>
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</tbody>
</table>

**TABLE HEAD FORMATION CONFORMITY**

- Siliceous dol. Fm.
- Diagenetic carbonates
- Autochthon
- Catoche Fm.
- Condensed red bed
- Fault

**LOWER ST. GEORGE GROUP**

- Cabrian dolomite Fm.
- Micrite Fm.
- Hawkes Bay Quartzite
- Forteau Fm.

**LOWER CANARIAN**

- Labrador ser.
- Labrador Bay Fm.
- Forteau Fm.

**BEAM (1972)**

- White Hills U.
- Pine Tree U.
- Pigeon Head U.
- Lower Cove U.

**ST. GEORGE GROUP**

- Port au Choix Formation
- Table Head Formation
- St. George Gr.
- Petit Jardin Fm.
- March Point Fm.
- Kippens Fm.
6. Hubbly, blue-black limestone (previously mapped as Table Head Fm.)

LOWER ORDOVICIAN St. GEORGE GROUP

7. Cristalline, vaggy, siliceous, light grey dolomite, restricted fauna.

CATOCHE FORMATION

WATTS BIGHT FORMATION

UNFORTUNATE COVE FORMATION

Geological boundary (approximate)

Fault
Beddings
Anticline
Syncline

GEOLOGICAL BOUNDARY (APPROXIMATE)

CAMBRIAN
DOLOMITE FORMATION
3c. Predominantly dolostone
3b. Stromatolites, intraformational conglomerates
3a. Thin bedded dolostone, some micrite
2. MICRITE FORMATION
1. HAWKES BAY QUARTZITE FORMATION

(Fore more detailed information and descriptions see Knight 1977)

FIG. 8. STRATIGRAPHIC SUBLDIVISIONS 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. - St. George Group

The St. George Group on the Great Northern Peninsula 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 Peninsula or Port au Port Peninsula, see: (Schuchert and Dunbar, 1934; Whittington and Kindle, 1963; 1968; Kluver, 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.
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.
In the North Lake and Bonne Bay Big Pond area the rocks are shallow water intertidal deposits. The lower dolomite 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 12,000 to 14,000 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, 1959) 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\textsubscript{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...
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 CO₂ 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 accommodate karren forms. Dolomites (CaMg(CO₃)₂) with high magnesium content are generally held to restrict karren forms, because magnesium in large quantities 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 kamenitas, 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 studied 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 (i.e. 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.
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 CO₂ 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 developmental 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
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).
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 CO₂ from the nearby soil and vegetation.
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.
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 (Bogl, 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 CO₂ given off lowers the pH and enhances the solubility of water, so more CaCO₃ 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 channeled 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.
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\textsubscript{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).

Arealy, 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 stüds area. These features are found on sloping surfaces. Locality Pond R2.
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).
IIIb 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 m².

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.

IIib 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 center; 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 Sual 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 into 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
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).

IIIb 5 - Summary & Discussion

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

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 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).
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.
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 caves 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 R2, 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.
FIGURE 7B. Sink points and spring locations in Long Pond - Round Pond area.
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.
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 inundated. 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.
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.
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 2 m 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 its 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. 24B). 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 Goose 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.

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

In Model No. 1 a fluvial 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 Cove where two
<table>
<thead>
<tr>
<th>Name</th>
<th>Hydraulic Gradient</th>
<th>Length of Flow-Line (m)</th>
<th>Sink Point</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nameless Pond to the spring</td>
<td>0.011</td>
<td>2720 m</td>
<td>C</td>
</tr>
<tr>
<td>Browns Pond #2 to #1</td>
<td>0.036</td>
<td>250 m</td>
<td>A</td>
</tr>
<tr>
<td>Browns Pond #1 to North L.</td>
<td>0.09</td>
<td>500 m</td>
<td>D</td>
</tr>
<tr>
<td>&quot; to Bonne Bay</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Big Pond</td>
<td>0.017</td>
<td>2830 m</td>
<td>A</td>
</tr>
<tr>
<td>Bottomless Pond to Bear L.</td>
<td>0.015</td>
<td>1000 m</td>
<td>A</td>
</tr>
<tr>
<td>&quot; to Bonne Bay Big Pond</td>
<td>0.067</td>
<td>2080 m</td>
<td>A</td>
</tr>
<tr>
<td>&quot; to Island Pond</td>
<td>0.021</td>
<td>1500 m</td>
<td>A</td>
</tr>
<tr>
<td>Pond Troy to Bonne Bay Big</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pond</td>
<td>0.21</td>
<td>300 m</td>
<td>D</td>
</tr>
<tr>
<td>Fold Lake to Snake Pond</td>
<td>0.026</td>
<td>1300 m</td>
<td>A</td>
</tr>
<tr>
<td>&quot; to Bottomless P</td>
<td>0.092</td>
<td>1000 m</td>
<td>A</td>
</tr>
<tr>
<td>Pond4 to Sandbar Pond</td>
<td>0.058</td>
<td>550 m</td>
<td>A</td>
</tr>
<tr>
<td>Pond 2 to Pond 4</td>
<td>0.05</td>
<td>250 m</td>
<td>A</td>
</tr>
<tr>
<td>Pond 3 to Sandbar Pond</td>
<td>0.048</td>
<td>250 m</td>
<td>A</td>
</tr>
<tr>
<td>Pond S2 to Spring north of</td>
<td>0.20</td>
<td>300 m</td>
<td>A</td>
</tr>
<tr>
<td>Bear Lake</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mud Pond to Spring</td>
<td>0.44</td>
<td>900 m</td>
<td>A</td>
</tr>
<tr>
<td>Long Pond to Round Pond</td>
<td>0.142</td>
<td>350 m</td>
<td>D</td>
</tr>
<tr>
<td>Round Pond to Spring</td>
<td>0.100</td>
<td>300 m</td>
<td>B</td>
</tr>
<tr>
<td>Pond R1 to R2</td>
<td>0.20</td>
<td>250 m</td>
<td>A</td>
</tr>
<tr>
<td>Pond R2 to Spring</td>
<td>0.30</td>
<td>300 m</td>
<td>B</td>
</tr>
<tr>
<td>Bear Paw Lake to L1</td>
<td>0.061</td>
<td>300 m</td>
<td>A</td>
</tr>
<tr>
<td>Fox Pond to Grindstone</td>
<td>0.14</td>
<td>500 m</td>
<td>A</td>
</tr>
<tr>
<td>Grindstone P. to Bonne Bay</td>
<td>0.05</td>
<td>400 m</td>
<td>A</td>
</tr>
<tr>
<td>Big Pond</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Jack Sink to Keats P2</td>
<td>0.14</td>
<td>350 m</td>
<td>A</td>
</tr>
<tr>
<td>Snafu Sink to Goose Arm P.</td>
<td>0.148</td>
<td>350 m</td>
<td>B</td>
</tr>
<tr>
<td>Pond B to Spring</td>
<td>0.053</td>
<td>340 m</td>
<td>A</td>
</tr>
<tr>
<td>Seal P. to Goose Arm Brook</td>
<td>0.040</td>
<td>2200 m</td>
<td>D</td>
</tr>
<tr>
<td>NAME</td>
<td>HYDRAULIC H/L</td>
<td>LENGTH OF FLOW LINES (m)</td>
<td>SINK POINT</td>
</tr>
<tr>
<td>------------------------------------------</td>
<td>---------------</td>
<td>--------------------------</td>
<td>------------</td>
</tr>
<tr>
<td>Pond N to Goose Arm Brook</td>
<td>0.153</td>
<td>900</td>
<td>A</td>
</tr>
<tr>
<td>Canal Pond to Spring</td>
<td>0.06</td>
<td>1100</td>
<td>D</td>
</tr>
<tr>
<td>Pond Tub to Seal Pond</td>
<td>0.079</td>
<td>500</td>
<td>A</td>
</tr>
<tr>
<td>Pond S1 to South Pond</td>
<td>0.092</td>
<td>200</td>
<td>A</td>
</tr>
<tr>
<td>Pond S1 to a NW stream</td>
<td>0.122</td>
<td>450</td>
<td>A</td>
</tr>
<tr>
<td>Pond S1 to a south lake</td>
<td>0.095</td>
<td>800</td>
<td>A</td>
</tr>
<tr>
<td>Jaw Sink to lake</td>
<td>0.130</td>
<td>350</td>
<td>A</td>
</tr>
<tr>
<td>Lake 1 to Lost Pond</td>
<td>0.073</td>
<td>750</td>
<td>A</td>
</tr>
<tr>
<td>Lost Pond to Moose Spring</td>
<td>0.134</td>
<td>750</td>
<td>D</td>
</tr>
<tr>
<td>Sophies Pond to Moose S.</td>
<td>0.305</td>
<td>550</td>
<td>D</td>
</tr>
<tr>
<td>Round Pond to Moose S.</td>
<td>0.169</td>
<td>900</td>
<td>B</td>
</tr>
<tr>
<td>Round Pond to Lost P.</td>
<td>0.14</td>
<td>500</td>
<td>B</td>
</tr>
<tr>
<td>Trout Pond to Alder Steady</td>
<td>0.056</td>
<td>1800</td>
<td>A</td>
</tr>
<tr>
<td>M1 to Lake 1</td>
<td>0.22</td>
<td>300</td>
<td>A</td>
</tr>
<tr>
<td>M1 to an eastern stream</td>
<td>0.06</td>
<td>250</td>
<td>A</td>
</tr>
<tr>
<td>Ghost Sink area to Goose</td>
<td>0.1808</td>
<td>1400</td>
<td>A</td>
</tr>
</tbody>
</table>

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 40-300m/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>
<thead>
<tr>
<th>Location</th>
<th>Karst relief</th>
<th>Minimum distance between sinks and springs</th>
<th>Ground water velocity m/hrs</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yorkshire, England</td>
<td>Low</td>
<td></td>
<td>0.03</td>
<td>Ford D.C., pers. comm.</td>
</tr>
<tr>
<td>Vaucluse, France</td>
<td>Medium</td>
<td>1.5 to 2.3 Km</td>
<td>7.0 -8.0</td>
<td>Sweeting, 1973</td>
</tr>
<tr>
<td>Languedoc, France</td>
<td>Medium</td>
<td>22 Km</td>
<td>26.0</td>
<td>Avias, 1972</td>
</tr>
<tr>
<td>Nameless Pond Spring</td>
<td>Medium</td>
<td>5-20 Km</td>
<td>14 - 500</td>
<td>Avias, 1972</td>
</tr>
<tr>
<td>High Pond, Newfoundland</td>
<td>Low</td>
<td>1.8 Km</td>
<td>3000</td>
<td>this report</td>
</tr>
<tr>
<td>Nameless Pond Spring</td>
<td>Medium</td>
<td>1.1 Km</td>
<td>43.2</td>
<td>this report</td>
</tr>
<tr>
<td>High Pond, Newfoundland</td>
<td>Low</td>
<td>0.75 Km</td>
<td>10.8</td>
<td>this report</td>
</tr>
<tr>
<td>Sophies Pond</td>
<td>High</td>
<td>2.72 Km</td>
<td>54.0</td>
<td>this report</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
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 fluvikarst), 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, i.e., 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 geomorphology. 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, $P_{CO_2}$, or on the quantity of dissolved carbonate species.

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

<table>
<thead>
<tr>
<th>Closed System</th>
<th>Open System</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) $H_2O \rightarrow H^+ + OH^-$</td>
<td></td>
</tr>
<tr>
<td>2) $CaCO_3 \rightarrow Ca^{2+} + CO_3^{2-}$</td>
<td></td>
</tr>
<tr>
<td>3) $CaCO_3 + H^+ \rightarrow Ca^{2+} + HCO_3^-$</td>
<td></td>
</tr>
<tr>
<td>4) $H_2O + CO_2 \rightarrow H_2CO_3 \rightarrow H^+ + HCO_3^-$</td>
<td></td>
</tr>
<tr>
<td>5) $HCO_3^- \rightarrow H^+ + CO_3^{2-}$</td>
<td></td>
</tr>
<tr>
<td>6) $CaCO_3 + H^+ \rightarrow Ca^{2+} + HCO_3^-$</td>
<td></td>
</tr>
</tbody>
</table>
In the simplest closed system solution of calcium carbonate in water may be represented by:

7) \[ H_2O \rightarrow H^+ + OH^- \]

8) \[ CaCO_3 + H^+ \rightarrow Ca^{2+} + HCO_3^- \]

The hydrogen ions (H+) produced as H\(_2\)O 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) \[ H_2O + CO_2 \rightarrow H_2CO_3 \rightarrow H^+ + HCO_3^- \]

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

10) \[ CaCO_3 + H_2O + CO_2 \rightarrow Ca^{2+} + 2HCO_3^- \]

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

Reactions 1 to 6 will continue until equilibrium 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 than 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 CO₂ 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 PCO₂ 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 logarithms of IAP/K, where the IAP is the ion activity product of calcite or dolomite 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).
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 uniqueness 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$_3^-$, (a$^{++}$, 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
Figure 34 demonstrates that waters in the study area are of the simple bicarbonate type. The strong correlation ($r = 0.977$) 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 $0.892$. The scatter indicates the presence of cations other than $Ca^{2+}$. 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 $0.978$, $Ca^{2+}/Mg^{2+}$ 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 $\text{HCO}_3^-$ and ionic strength.
216 point plotted
- denotes coincident points

FIG. 35. The graph of $C_{a}^{++}$ and $HCO_{3}^{-}$ (ppm).
216 points
= denotes coincident points

1 = karst sp.
2 = surface streams
$ = small ponds
A = large rivers
B = karst ponds
+ = sinkhole lakes

FIG. 36. The graph of Ca$^{++}$ and ionic strength.
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 CO₂. 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 CO₂ 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 - Behaviour 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.

216 points plotted
- denotes coincident points

- = karst sp.
2 = surf. streams
$ = small ponds
A = large rivers
B = karst ponds
+ = sinkhole lakes
The graph of pH and SIC.

216 points plotted

- denotes coincident points

SATURATED
UNSATURATED

1 = karst sp.
2 = surf. streams
3 = small ponds
A = large rivers
B = karst ponds
+ = sinkhole lakes

FIG. 38
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. Separate graphs of these variables (Figs. 40, 41 and 42) all the sample values are used, because the major factor producing 15% and greater 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 6.2°C in late May to an average high of 19.5°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.

YORK ».

TOTAL HARDSNESS (ppm CaCO)

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 (i.e. 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
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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 ground-
water 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, i.e. perched upon a permafrost body. He called such a system
"karst sous-cutané". 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 CO₂ 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 SIC 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 occurred 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 SIC 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 in terms of their 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 anomalous. 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.
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 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 Camel 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 plateau's 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.
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 aquifer 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 snowmelt 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 explanation 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: Comparative Studies of Canadian Karst Waters

The study area is a temperate forested area with a large number of ponds and lakes. It is comparable to other temperate regions of Canada in vegetation, temperatures and limestone characteristics 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 unique 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 2000 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 Georgian 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 CO₂ 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 are the dominant feature of the waters collected.
SUMMARY OF CHEMICAL DATA FOR NEWFOUNDLAND
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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 characterizes 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 Goslarlos area
   - the sinkholes in gypsum reproduce 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) Roddickton area
   - cave at least 400ft.


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Gulf of St. Lawrence

Cow Head
Boone Bay
Western Brook Pond
St. John's Bay
FIG. 1. LOCATION MAP

CABOT STRAIT
LEGEND

CLOSED DEPRESSION

SMALL COLLAPSE DOLINES

CAVES

UNDERGROUND DRAINAGE

LAKES WITH PERIODIC OVERFLOW

NO SURFACE OVERFLOW

SINKPOINT

SPRING

SURFACE FLOW

PERIODIC SURFACE FLOW

UNDERGROUND DRAINAGE

DIP OF ROCKS

FRACTURES
CAVES
UNDERGROUND DRAINAGE
LAKES WITH PERIODIC OVERFLOW
NO SURFACE OVERFLOW
SINKPOINT
SPRING
SURFACE FLOW
PERIODIC SURFACE FLOW
UNDERGROUND DRAINAGE
DIP OF ROCKS, FRACTURES
LINIATION
FOLD PLUNGE
CONTACT OF CARBONATE AND NON CARBONATE ROCKS

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DRAINAGE BASIN BOUNDARY
DRAINAGE BASIN BOUNDARY FOR
HOLOKARSTIC BASINS AND
PARTLY KARSTIC BASINS

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