THE GEOMORPHOLOGY AND PERMAFROST CONDITIONS OF
GARRY ISLAND, N.W.T.

by

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A THESIS SUBMITTED IN PARTIAL FULFILMENT OF
THE REQUIREMENTS FOR THE DEGREE OF
DOCTOR OF PHILOSOPHY

in the Department
of
Geography

We accept this thesis as conforming to the
required standard

THE UNIVERSITY OF BRITISH COLUMBIA

August, 1969
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ABSTRACT

Garry Island, approximately 11 kilometres (7 miles) long and 0.8 to 3.2 kilometres (0.5 to 3.2 miles) wide, is located at about latitude $69^\circ\ 28'\ N$ and longitude $135^\circ\ 42'\ W$ in the southern part of the Beaufort Sea.

The stratigraphy consists mainly of unconsolidated sands, silts, clays and stony clays which have been intensively deformed by the thrusting action of glacier-ice moving from the south. The deformed sediments are locally overlain by undisturbed sands and gravels containing marine fossils dated at $>42,000$ years. The absence of any evidence of glacial till on top of the sands suggests that Garry Island lay beyond the northwestern limits of the Laurentide ice sheet during the late-Wisconsin glaciation. Elevated strand-lines, which may be of great antiquity and occur at approximately 7.5 metre (25 feet) intervals to an altitude of almost 46 metres (150 feet), indicate the extent of Pleistocene fluctuations of sea level and the drowning of a pre-existing topography. The development of tundra polygons, in small flats behind sandspits or bars built across the drowned valleys in association with the former sea levels, has imparted a distinctive, stepped longitudinal profile to the stream courses.

The tundra vegetation of Garry Island is classified into ten major habitats which are primarily related to drainage conditions and type of geomorphic activity. The island is underlain by permafrost and the thickness of the active layer is greatest, and ground temperatures in this layer are highest, beneath unvegetated surfaces and where the substrate is composed predominantly of mineral soil.
Stratigraphic, geomorphic and historic evidence indicates considerable recession of the coastline in recent times. Current rates of retreat, reaching maxima of 10.5 metres (35 feet) per annum, are primarily related to the composition of the permafrost, being greatest in areas of fine-grained sediments, containing high ice contents, with a southerly exposure. Thermal erosion of the permafrost is the dominant process influencing cliff retreat and the primary role of wave action, on a short term basis, is in the removal of thawed debris from the base of the cliffs.

Observations of three highly active mudslumps, created by the exposure of segregated ground ice, show that the rate of headwall recession is strongly correlated with ambient air temperatures. Maximum recession occurs where the ice content is high and the slumped debris is frequently removed from the base of the scarp. The cyclic development of a gully system on the ice face is described. The longevity of mudslump activity is prolonged where strong mudflows carry the thawed material away from the foot of the headwall, thus preventing the progressive burial of the scarp face. Mudflow velocities reveal a rhythmic pulsation related to periodic blocking of their channels. Mud levees, bordering the mudflows, result from the progressive bleeding of moisture from, and subsequent stagnation of, the mud rather than as residual features pushed aside by the advancing mudflow.

Patterned ground on Garry Island is primarily restricted to non-sorted types. Angular intersections of thermal contraction cracks, representing the incipient stages of tundra polygons, exhibit a preferred tendency toward slightly-oriented, orthogonal systems. The initial micro-relief of earth hummocks is believed to originate through the accentuation of a miniature desiccation/frost-crack pattern. Following the
establishment of a vegetation cover, their subsequent growth involves further differential frost action and solifluxion. Statistical tests show that the height, size and shape of earth hummocks are closely related to their position on the slope profile.
ACKNOWLEDGMENTS

It is impossible to give full credit to all the people who gave assistance in the preparation of this thesis. Singled out for particular thanks are:—Dr. J. Ross Mackay, my advisor, whose teaching stimulated my interests in the Canadian Arctic and who has been a constant source of inspiration in the classroom and in the field; Dr. J. K. Stager for his assistance in the field and encouragement and advice in the preparation of the text; Dr. H. O. Slaymaker and Dr. W. H. Mathews for their advice and comments on the text; Dr. M. A. Melton and my fellow graduate students for seminar discussions which enabled me to test and clarify my thoughts; Dr. J. D. Ives and the staff of the former Geographical Branch, Ottawa, for the generous support of the field programme through the provision of funds, equipment, laboratory facilities and a base map of Garry Island; Dr. J. G. Fyles, of the Geological Survey of Canada, for advice in the field, radiocarbon dates and, with his colleague Dr. F. J. E. Wagner, identification of the fossil specimens; Dr. E. Hultén and Dr. H. Personn of the Naturhistoriska Riksmusset, Stockholm, for identifications of the plant species; Mr. R. M. Hill and the staff of the Inuvik Research Laboratory for their unfailing support in the field area; Mr. R. Reynolds and the staff of the Print Shop, Brock University, for their assistance in the printing of the thesis; Mr. P. J. Tighe and Mr. W. B. Windjack of the Audio Visual and Photographic Department, Brock University, for their assistance with the photographic illustrations; and last, but by no means least, to my wife, Helen, for the innumerable occasions that I was able to depend on her in the roles of
field assistant, geographer, cartographer and secretary.

August, 1969. 

Denis E. Kerfoot.
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CHAPTER I

INTRODUCTION

The arctic and subarctic regions of Canada have increasingly attracted the attention of scientists in the interval since the end of the Second World War. Prior to 1945, relatively little attention was paid to these remote northern lands, but the post-war realization of their strategic significance and attempts to establish and develop their economic resource potential, have contributed greatly to stimulate all aspects of research in these high latitudes. Much valuable data has been obtained as a 'by-product' of the construction and operation of the military installations and the exploratory surveys seeking to locate potential mineral deposits. One consequence of the availability of this data is that considerable progress has been made in the field of arctic geomorphology during the past few decades.

This same time interval, since 1945, has also witnessed the growth and consolidation of a number of new approaches to the subject of geomorphology. Traditionally, geomorphological studies of landscape development have relied heavily on qualitative description. Such descriptions formed the basis of geomorphology during the 19th century, culminating in the cyclic concepts of William Morris Davis, and most of the studies undertaken during the first half of this century. In the past two to three decades however, attempts have been made to establish the subject on a more precise, objective foundation by substituting quantitative measurements for verbal descriptions. Although the adoption
of this quantitative approach to landform studies is still in its infancy, a number of principal avenues of research can be identified. These include the compilation and tabulation of data relating to the scale and shape of landforms; investigations of the mode of operation and interrelationships between degradational and aggradational forces, including their expression in the forms of models, graphs or formulae; and measurements of the actual rates at which geomorphic processes are operating on various parts of the earth's surface today. To date, most, though not all, of the success achieved by the employment of these methods has been in the humid temperate regions of the world, and in the field of fluvial geomorphology where the drainage basin forms a convenient unit study area.

The adoption of the quantitative approach to geomorphological studies reflected, in part, a growing dissatisfaction with the subjective, genetically-oriented Davisian model of landscape development and the scant attention paid to process studies in this model. Additional reactions against the Davisian approach to the subject have also resulted in increasing attention being paid to alternative theories of landscape development. Thus, objections to the long period of crustal stability required for the production of a peneplain, have led to a revival of the ideas of Penck and an emphasis on the significance of crustal mobility in the formation of landforms. Other geomorphologists have concentrated on the role of climate, and the belief that the rate of operation of geomorphological processes varies considerably from one climatic region to another.

A considerable amount of interest in arctic geomorphology has been generated by the development and elaboration of this concept of
climatic geomorphology. In this concept it is postulated that there is a very close relationship between climate and geomorphology, to the extent that under a given set of climatic conditions certain geomorphic processes will predominate, and these in turn will lead to the development of a characteristic assemblage of landforms. On the basis of these postulates, some proponents of the concept have further suggested that the influence of climate is such that a series of morphogenetic regions can be identified in which the topographic characteristics of an area can be differentiated from those of other areas developed under contrasting climatic regimes.

In North America, the concept of climatic geomorphology was developed by Peltier who tentatively identified nine morphogenetic regions. For one of these regions he adopted the term periglacial, to describe those parts of the earth's surface which have an annual temperature range of 5-30°F and an average annual rainfall range of 5-55 inches, and in which the geomorphic processes are characterized by strong mass movement, moderate to strong wind action and a weak effect of running water. Although the periglacial environment is currently restricted to polar latitudes and high altitudes, it has attracted wide attention because many features, which have been described from more temperate latitudes, have tentatively been interpreted as evidence of a similar, more widespread environment during the Pleistocene period.


3 Ibid., p. 215.
One of the major shortcomings of Peltier's paper was that it was construed within the framework of the traditional Davisian approach to geomorphology. As such, and as Peltier himself realized, it was restricted to qualitative description and was based on inadequate data. Further discussion of the validity and limitations of the concept of morphogenetic regions need not be debated here, save to mention that before it can be given additional credence it will have to be established on a quantitative basis through detailed geomorphic process studies. As yet, however, there has been only limited research into the periglacial processes operating in northern Canada. The number of process studies is steadily increasing, but many more are needed before arctic geomorphology can be fully interpreted, and only as a result of such investigations can the proper role of variations in the climatic regime be evaluated.

The Scope of the Study.

The aims of this thesis are to make a threefold contribution to the general field of arctic geomorphology:

1. To study some of the geomorphic processes currently operating in an arctic environment on Garry Island, N.W.T.

2. To examine the role of permafrost in the operation of these geomorphic processes.

3. To attempt to decipher the complex geomorphological history of the outer Mackenzie Delta area in glacial and post-glacial times.

Current Geomorphic Processes. The specific geomorphic processes investigated were those involved in coastal recession, mudslumps

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and associated mudflows, and the genesis of certain types of patterned ground. This list is by no means exhaustive of all the contemporary processes operating on Garry Island. The most obvious omission is the process of solifluction which is undoubtedly one of the most familiar and widespread agencies moulding the landscape in arctic latitudes and has been more intensively investigated than most of the other geomorphic processes. For this reason, an examination of the comprehensive aspects of solifluction was excluded from the programme of studies on Garry Island.

Observations of the rate of coastal recession were made on approximately 2.5 kilometres (1.5 miles) of coastline along which stakes were installed during the summer of 1964. Most of these stakes were located along the exposed northwest coast of the island, and measurements of the amount of recession that had taken place were made at the beginning and end of each of the field seasons. To supplement these observations, and provide additional data on the processes involved in cliff retreat, four profile stations were established on the prominent sand headlands along the north coast of the island. At each of these stations wooden stakes were driven into the cliff face, normal to the surface, and these were surveyed periodically throughout one of the field seasons to detect profile changes.

Mudslumps are created by the melting out of large bodies of ground ice, and the fine-grained sediments, containing substantial masses of segregated ice, which underlie much of Garry Island provide favourable sites for the development of these features. A series of stakes was installed around three highly active mudslumps, and measurements of the amount of retreat were made throughout each of the field seasons. A programme of ablation studies was also carried out on the ice face
exposed in the headwall of one of the mudslumps. At intervals of two to three weeks, a number of stakes was installed normal to the ice face and the amount of ablation was measured daily for five or six consecutive days each time. Attempts were made to correlate the data on the rates of headwall retreat and rates of ablation with meteorological observations recorded at a small weather station established on the island. Further observations on the manner in which a mudslump headwall retreats were obtained through investigations of the seasonal evolution of a distinctive gully system which, while it exists, imparts a miniature 'badland' topography to the ice face. These process studies were combined with observations on mudflows to describe a model of the cyclic development of mudslumps and the factors which influence the longevity of this cycle.

Mudflows are the most effective agents by which thawed debris is removed from the foot of an actively retreating mudslump headwall. An active mudflow was surveyed in detail, and markers were installed on its surface to determine the rate of movement and the nature of the flow pattern. Samples of mud were collected to try to correlate variations in the velocity of the mudflow with changes in the viscosity of the mud. Detailed measurements and excavations of the mud levees bordering both old and active mudflows were made to determine variations in the height, slope, symmetry, composition and mode of origin of these features.

The studies of patterned ground were restricted to investigations of some of the more controversial aspects of the development of tundra polygons and earth hummocks. Particular attention was paid in the tundra polygon studies to the incipient frost crack stage, and the nature of the angular intersections of the cracks which can only be measured with any reliable degree of accuracy at this stage. Several areas of polygonal
ground were also surveyed in detail to examine some of the factors influencing the size and spacing of the polygonal units and the transition from low- to high-centred forms.

Most of the literature pertaining to earth hummocks consists of very generalized, descriptive statements concerning their shape and size, and a part of the field programme was aimed at replacing these qualitative statements with quantitative data. Preliminary observations of the hummocks on Garry Island suggested that their size and spacing were related to their position on the slope profile. Five slope profiles were surveyed and a series of six survey lines was established from each profile running parallel to the contours. Using a horizontal sight line, the height and spacing of each hummock and depression on each of the survey lines were recorded, and sufficiently large samples were obtained so that any differences in the calculated means could be tested statistically. At the same time observations were made relating to the alignment and profiles of the hummocks, and these were combined with a series of excavations to determine the structure and mode of origin of these micro-relief features.

The Role of Permafrost. The second contribution of the thesis is closely allied to the first and is related to the concept of climatic geomorphology and, in particular, the role of the permafrost conditions. The various geomorphic processes operating in arctic regions today may be peculiar to the northlands, or they may simply differ in degree from those shaping the landscape in more southerly latitudes. Any such differences, either in kind or degree, may possibly be related to the presence of permafrost, the role of which is imperfectly understood. The thickness and composition of the permafrost, and particularly the presence or
absence of large bodies of segregated ground ice, have a definite influence on the occurrence or non-occurrence and the rates of operation of certain geomorphic processes. Of particular significance to the genesis of some of the microrelief features in high latitudes are the conditions in the active layer. This is the layer, extending from the ground surface down to the permafrost table, which undergoes seasonal thawing during the summer months. A knowledge of the changes in the thermal regime of this active layer is relevant to all attempts to develop the economic potential of the northlands, as well as to a fuller understanding of arctic geomorphology. To date, however, relatively few measurements of ground temperature patterns in the active layer have been recorded in northern Canada.

Accordingly, the second aim of this thesis is to examine the influence of the composition of the permafrost on the rates of operation of the geomorphic processes, and some of the factors which contribute to variations in the overall thickness and thermal regime of the active layer.

Geomorphic History. The third contribution of the thesis is an attempt to decipher the complex geomorphological history of the outer Mackenzie Delta area in glacial and post-glacial times. This latest epoch of geological time witnessed immense expansions of glaciers in middle and high latitudes, the extent of which fluctuated in response to climatic changes. The waxing and waning of the ice sheets was accompanied by profound oscillations in the level of the sea. Large tracts of the earth's crust were depressed by the weight of these ice masses, and the subsequent melting of the ice contributed to rising sea levels and an extensive submergence of the coastal lowlands. At a later date these same lowlands emerged from beneath the sea as the earth's crust slowly responded to the
removal of the recently melted ice cover.

The number of glacial and interglacial episodes, and their orderly arrangement into a chronological sequence, is still imperfectly understood in the arctic regions of Canada. There is no doubt that the area in the vicinity of the Beaufort Sea was affected by glaciers advancing from the south, but there are differences of opinion as to the number of advances that affected the area and their relationship to the classical Pleistocene sequence established for more southerly latitudes. Similar controversies exist in the interpretation of evidence indicative of changing patterns of land-sea relationships and the extent of the post-glacial marine transgression. The identification and interpretation of this evidence, and an attempt to arrange the sequence of events into a chronological order, constitutes the third aim of this thesis.

The selection of Garry Island as a field study area was at the advice of Dr. J. Ross Mackay, my advisor, on the basis of his extensive knowledge of the Mackenzie Delta area. The field work was carried out during the periods June 25 - September 8, 1964, June 22 - September 13, 1965 and July 26 - August 29, 1966. I am deeply indebted to the former Geographical Branch, Department of Mines and Technical Surveys, Ottawa, for the generous provision of funds and equipment in support of each of the field seasons. I also gratefully acknowledge support for the field programme which was received by Dr. J. Ross Mackay from the Department of Northern Affairs and National Resources, by way of the Committee on Arctic and Alpine Research, the University of British Columbia, and from research funds of the University of British Columbia.
THE STUDY AREA

Garry Island is centred at latitude 69° 28' N and longitude 135° 42' W in the southern part of the Beaufort Sea (Figure 1). It lies at the distal end of the Mackenzie Delta; a low, flat area approximately 80 kilometres (50 miles) wide and 160 kilometres (100 miles) long. The modern delta is characterized by a myriad of interlacing channels and small lakes, and Garry Island forms part of an arcuate chain of islands which represent the seaward remnants of a formerly more extensive Pleistocene, or earlier, ancestor of the modern delta.

The island is approximately 11 kilometres (7 miles) long, oriented in a northwest-southeast direction, 0.8 to 3.2 kilometres (0.5 to 2 miles) wide, and reaches elevations exceeding 46 metres (150 feet) above sea level. These elevations, and those of adjacent islands, are considerably higher than the heights found in the modern delta of the Mackenzie River, and they owe their altitude to the development of ice-thrust features and the growth of substantial bodies of segregated ground ice. The major topographic features of Garry Island, which may be described as gently rolling, are shown in Figure 1. Extensive flat summit areas are lacking and the higher ground is characterized by smooth slopes seldom

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5 The metric standard of measurement is used in this thesis. However, on some of the maps, if the field surveys were done using British measures, the British units are used.

6 The topographic map of Garry Island shown in Figure 1 was compiled from aerial photographs by the former Geographical Branch, Department of Mines and Technical Surveys, Ottawa. Although this map accurately portrays the general features of the topography, and has therefore been reproduced with only minor modifications, the absence of any accurate ground height control implies that the positions of, and the numerical values assigned to, the form lines are only estimates.
Figure 1
GARRY ISLAND
TOPOGRAPHY
exceeding 5-10 degrees. The high ground is broken by a series of shallow valleys and depressions, the sides of which may have slopes of 25-35 degrees. On the north side of the island, three prominent aprons of coarse sand produce flat to gently-sloping surfaces ranging from 7.5-15.0 metres (25-50 feet) above sea level.

Drainage conditions over much of the island are poor and reflect the presence of permafrost at shallow depths beneath the ground surface. Despite the presence of a number of fairly well-defined stream courses, integrated drainage patterns are poorly developed. The present channels serve primarily as conduits for surface runoff derived from melting snow and the thawing of the active layer during the spring and early summer. Throughout the rest of the summer these channels are kept moist by seepage from the thawing ground, but surface runoff is generally lacking except for a short time following exceptionally prolonged periods of heavy rainfall. The floors of the depressions, particularly at lower elevations, and parts of the stream courses are further characterized by the development of polygonal ground with associated pond and marsh areas.

**Historical Significance.**

Despite its small size, Garry Island has played a controversial role in the history of the exploration and mapping of this northwestern section of the Canadian Arctic. In 1789, Alexander Mackenzie completed his epic voyage down the Grand River,^7 subsequently renamed in his honour, at a small island which he named 'Whale Island' after the numerous beluga, or white whales, which he observed in the surrounding

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waters. In 1825, Sir John Franklin journeyed down the same river and named the site of his most northerly camp in the delta Garry Island in honour of his friend the Deputy Governor of the Hudson's Bay Company. Franklin included a map of the delta in the account of his voyage and although he did not see 'Whale Island', he located it on his map using Mackenzie's latitudinal and longitudinal observations. Consequently, for more than a century, Garry Island and 'Whale Island' appeared adjacent to one another on Canadian topographic maps of the Mackenzie Delta area until the first accurate maps were produced from photographs taken during aerial reconnaissances of the delta flown during the Second World War. Since these maps failed to reveal any presence of land at the position described by Mackenzie, the name 'Whale Island' was rescinded by the Canadian Board on Geographical Names in 1960.

There are striking similarities in the respective explorers' descriptions of 'Whale Island' and Garry Island with respect to their size, elevation above sea level and panoramic vistas of adjacent islands.


9 Franklin, Sir John (1828) Narrative of a second expedition to the shores of the Polar Sea in the years 1825, 1826 and 1827, Carey, Lea and Carey, Philadelphia, p. 49.

10 Ibid., Map Frontispiece.


in the delta and the front of the Richardson Mountains. The major discrepancies are in the latitudinal positions of the two islands, and the compass directions of the topographic features in the panoramas. In attempting to reconstruct the original route of Mackenzie's voyage through the delta to the coast, Bredin discovered a number of errors in the distances and directions as reported by Mackenzie. The most significant of these errors are a consistent recording of the latitudes south of their actual positions, and recorded compass directions of travel always more westerly than his true directions, even allowing for magnetic variations. If due consideration is taken of these factors, the revised location of 'Whale Island' coincides, almost identically, with that of Garry Island. A similar conclusion, using somewhat differing criteria, was also reached by Mackay, by combining Mackenzie's descriptions of natural features with his own detailed knowledge of the conditions in the delta. Thus, the enigma of 'Whale Island' has been solved, for there is little doubt that the 'Whale Island' of Sir Alexander Mackenzie and the Garry Island of Sir John Franklin are one and the same island.

Climate.

There are five operating meteorological stations in the vicinity of the Mackenzie Delta, but few of these have records which extend back over a large number of years. Fairly continuous records are available for the town of Aklavik, from 1926 onwards, but, with the establishment of Inuvik, they were terminated in 1959. Data for the Inuvik

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airport are available from 1958. The most continuous records of the existing meteorological stations, dating from 1948, are those of Tuktoyaktuk. With the establishment of the Distant Early Warning (DEW line) system, additional weather-recording sites were provided at Shingle Point, in the Yukon Territory to the west; Tununuk, at the southern end of Richards Island; Atkinson Point and Nicholson Peninsula, approximately 80 and 160 kilometres (50 and 100 miles) northeast of Tuktoyaktuk respectively.\(^\text{15}\) The sites at Tununuk and Atkinson Point have subsequently been abandoned, and the records for Shingle Point and Nicholson Peninsula date back to the summer of 1957.

With the lone exception of Inuvik, the published observations at each of the meteorological stations are restricted to precipitation totals and temperature extremes. The lengths of the records are, in most cases, too short to provide truly reliable means and, consequently, the values presented in the following tables should be interpreted accordingly. Furthermore, there is the problem of the variable length of the records at each of the stations: 31 years at Aklavik, 21 years at Tuktoyaktuk, and 11 years at Inuvik, Shingle Point and Nicholson Peninsula. These two factors, lack of reliability and non-comparability of the means, are fundamental to any discussion of the regional climate.

The mean daily temperatures for each of the meteorological stations in the Mackenzie Delta area are shown in Table I. Mean daily temperatures are below freezing for eight months of the year. January is the coldest month for most of the stations, except for Tuktoyaktuk and

\(^{15}\)For locations of the place-names see the World Aeronautical Chart, I.C.A.O., 1:1,000,000. Sheet 2062, Firth River (1967) included at the back of the thesis.
TABLE I

MEAN DAILY TEMPERATURES FOR AKLAVIK, INUVIK, TUKTOYAKTUK, SHINGLE POINT AND NICHOLSON PENINSULA (Degrees Centigrade).

<table>
<thead>
<tr>
<th></th>
<th>Aklavik</th>
<th>Inuvik</th>
<th>Tuktoyaktuk</th>
<th>Shingle Point</th>
<th>Nicholson Peninsula</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feb.</td>
<td>-27.1</td>
<td>-27.5</td>
<td>-29.2</td>
<td>-24.3*(3)</td>
<td>-27.9*(2)</td>
</tr>
<tr>
<td>Mar.</td>
<td>-22.7</td>
<td>-23.9</td>
<td>-26.4</td>
<td>-26.1</td>
<td>-25.8*(4)</td>
</tr>
<tr>
<td>Apr.</td>
<td>-13.0</td>
<td>-13.3</td>
<td>-18.6</td>
<td>-17.5</td>
<td>-18.8</td>
</tr>
<tr>
<td>May</td>
<td>- 0.5</td>
<td>- 0.8</td>
<td>- 5.2</td>
<td>- 4.1</td>
<td>- 6.0</td>
</tr>
<tr>
<td>June</td>
<td>9.4</td>
<td>10.2</td>
<td>5.0</td>
<td>5.1</td>
<td>4.2</td>
</tr>
<tr>
<td>July</td>
<td>13.6</td>
<td>13.9</td>
<td>10.1</td>
<td>10.3</td>
<td>7.1</td>
</tr>
<tr>
<td>Aug.</td>
<td>10.1</td>
<td>10.4</td>
<td>9.2</td>
<td>8.8</td>
<td>7.4</td>
</tr>
<tr>
<td>Sept.</td>
<td>3.4</td>
<td>3.1</td>
<td>1.8</td>
<td>1.7</td>
<td>0.4</td>
</tr>
<tr>
<td>Oct.</td>
<td>- 6.8</td>
<td>- 7.6</td>
<td>- 7.2</td>
<td>- 7.7</td>
<td>- 7.8</td>
</tr>
<tr>
<td>Nov.</td>
<td>-19.4</td>
<td>-20.8</td>
<td>-21.3</td>
<td>-20.3</td>
<td>-21.1</td>
</tr>
<tr>
<td>Dec.</td>
<td>-26.9</td>
<td>-28.2</td>
<td>-25.6</td>
<td>-23.8</td>
<td>-25.9</td>
</tr>
</tbody>
</table>

* Unfortunately the mean daily temperatures are only intermittently reported for these months, and the means are of correspondingly less value. The figures in brackets indicate the number of years records on which these means are based.

Source: Canada, Department of Transport, Meteorological Branch, Monthly Record(s): Meteorological Observations in Canada, Queen's Printer, Ottawa.
possibly Nicholson Peninsula, where the average February temperatures are colder. The transition from winter to summer temperatures is quite rapid. As Table I shows, mean daily temperatures increase by 26-28°C between April and July, which is usually the warmest month. Using a climatic definition of the arctic, the mean July temperatures of approximately 10°C (50°F) for the warmest month at Tuktoyaktuk and Shingle Point indicate a location on the boundary between arctic and subarctic climates despite their locations well to the north of the tree-line. The transition from summer to winter temperatures is as rapid, with the onset of sub-freezing temperatures again in late-September or early-October.

The mean monthly precipitation totals for these same stations are shown in Table II. Annual total precipitation is low, averaging 14-19 cms. (5-7 inches) at the coastal locations and increasing to 25-28 cms. (10-11 inches) further inland. Each of the stations records a summer maximum, in the form of rain, during July and August, and this maximum is more pronounced at the coast with 40-50 per cent of the annual total occurring in these two months, compared to less than 30 per cent further inland. Approximately one-half of the precipitation is in the form of snow.

Garry Island, occupying an intermediate position between Tuktoyaktuk and Shingle Point, probably has an annual temperature and precipitation pattern similar to these stations, with the coldest month being January or February and below-freezing temperatures for eight months of the year. Light snowfalls were encountered during August and September in 1964 and 1965, but the snow did not persist for any length of time. Total snowfall is probably quite light, and the thickness of the cover is related to the action of the wind. Much of the snow is swept from the
<table>
<thead>
<tr>
<th></th>
<th>Aklavik</th>
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<th>Tuktoyaktuk</th>
<th>Shingle Point</th>
<th>Nicholson Peninsula</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jan.</td>
<td>1.68</td>
<td>2.39</td>
<td>3.45</td>
<td>0.64</td>
<td>0.18</td>
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<tr>
<td>Feb.</td>
<td>1.50</td>
<td>1.42</td>
<td>1.02</td>
<td>0.18</td>
<td>0.25</td>
</tr>
<tr>
<td>Mar.</td>
<td>1.12</td>
<td>1.35</td>
<td>0.23</td>
<td>0.15</td>
<td>0.25</td>
</tr>
<tr>
<td>Apr.</td>
<td>1.52</td>
<td>2.16</td>
<td>0.91</td>
<td>0.66</td>
<td>0.43</td>
</tr>
<tr>
<td>May</td>
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<td>1.30</td>
<td>0.84</td>
<td>0.51</td>
<td>0.48</td>
</tr>
<tr>
<td>June</td>
<td>2.13</td>
<td>2.18</td>
<td>1.30</td>
<td>2.49</td>
<td>1.88</td>
</tr>
<tr>
<td>July</td>
<td>3.53</td>
<td>4.60</td>
<td>3.33</td>
<td>4.65</td>
<td>2.64</td>
</tr>
<tr>
<td>Aug.</td>
<td>3.66</td>
<td>2.97</td>
<td>4.09</td>
<td>3.25</td>
<td>4.14</td>
</tr>
<tr>
<td>Sept.</td>
<td>2.39</td>
<td>1.78</td>
<td>1.30</td>
<td>1.37</td>
<td>1.45</td>
</tr>
<tr>
<td>Oct.</td>
<td>2.46</td>
<td>3.71</td>
<td>0.99</td>
<td>3.81</td>
<td>1.45</td>
</tr>
<tr>
<td>Nov.</td>
<td>2.21</td>
<td>1.96</td>
<td>0.61</td>
<td>0.71</td>
<td>0.41</td>
</tr>
<tr>
<td>Dec.</td>
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<td>1.80</td>
<td>0.56</td>
<td>0.18</td>
<td>0.25</td>
</tr>
<tr>
<td>Total</td>
<td>24.82</td>
<td>27.62</td>
<td>18.63</td>
<td>18.60</td>
<td>13.81</td>
</tr>
</tbody>
</table>

Source: Canada, Department of Transport, Meteorological Branch, Monthly Record(s): Meteorological Observations in Canada, Queen's Printer, Ottawa.
exposed slopes and summit areas and it is piled into thick drifts in the depressions and against the coastal bluffs.

A climate station was established on Garry Island, for the duration of each field season, in conjunction with observations on variations in the rate and depth of thaw of the active layer at selected sites on the island. Meteorological records from this station permit the only valid comparisons with the published records of the other stations in the delta area. The results of these comparisons are shown in Table III.

The temperature data contained in Table III demonstrate the modifying effect of proximity to the Beaufort Sea. Mean temperature values for each of the summer months on Garry Island were consistently 2-3°C cooler than those experienced at Inuvik. The fact that the Garry Island temperatures also averaged 1-2°C cooler than those at Tuktoyaktuk and Shingle Point probably reflects its insular character. A comparison of the temperature extremes recorded during the same time period exhibits the same features. Although there was little or no discernible pattern in the recorded minima, the maximum temperatures for each month at Inuvik were consistently 2-4°C warmer than those recorded on Garry Island. The values for the monthly precipitation totals do not reveal much of a pattern though, with the exception of Shingle Point, the amounts recorded at the coastal stations were less than further inland at Inuvik.

The number of hours of bright sunshine was also recorded on Garry Island during the 1964 and 1965 field seasons. An average of 321 hours of bright sunshine was recorded in the month of July and 197 hours in August. These totals were 7 and 22 hours less than Inuvik respectively. Although each station averaged four days without sunshine in the month of July, the corresponding figures for August for Garry Island and Inuvik
TABLE III


### Mean Daily Temperatures (Degrees Centigrade)

<table>
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<tr>
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<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
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</thead>
<tbody>
<tr>
<td>Garry Island</td>
<td>9.0</td>
<td>7.3</td>
<td>9.3</td>
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<td>9.7</td>
<td>5.9</td>
<td>9.3</td>
<td>6.8</td>
</tr>
<tr>
<td>Tuktoyaktuk</td>
<td>8.3</td>
<td>8.2</td>
<td>11.6</td>
<td>9.9</td>
<td>11.1</td>
<td>7.1</td>
<td>10.3</td>
<td>8.4</td>
</tr>
<tr>
<td>Nicholson Pen.</td>
<td>5.7</td>
<td>5.8</td>
<td>9.5</td>
<td>8.2</td>
<td>8.5</td>
<td>5.3</td>
<td>7.9</td>
<td>6.4</td>
</tr>
<tr>
<td>Shingle Point</td>
<td>8.8</td>
<td>8.2</td>
<td>9.8</td>
<td>9.2</td>
<td>11.7</td>
<td>7.1</td>
<td>10.1</td>
<td>8.2</td>
</tr>
<tr>
<td>Inuvik</td>
<td>11.6</td>
<td>10.2</td>
<td>13.9</td>
<td>10.7</td>
<td>14.3</td>
<td>9.6</td>
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<td>10.2</td>
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</table>

### Daily Temperature Extremes (Degrees Centigrade)

<table>
<thead>
<tr>
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<th></th>
<th></th>
<th></th>
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</thead>
<tbody>
<tr>
<td>Garry Island</td>
<td>26.7</td>
<td>22.5</td>
<td>26.7</td>
<td>-3.3</td>
<td>-1.1</td>
<td>-1.1</td>
</tr>
<tr>
<td>Tuktoyaktuk</td>
<td>26.7</td>
<td>22.8</td>
<td>25.0</td>
<td>1.9</td>
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<td>0.6</td>
</tr>
<tr>
<td>Nicholson Pen.</td>
<td>27.2</td>
<td>22.2</td>
<td>25.6</td>
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<td>-4.4</td>
<td>-1.1</td>
</tr>
<tr>
<td>Shingle Point</td>
<td>27.8</td>
<td>21.7</td>
<td>27.8</td>
<td>-3.9</td>
<td>0.0</td>
<td>1.1</td>
</tr>
<tr>
<td>Inuvik</td>
<td>28.9</td>
<td>23.9</td>
<td>29.4</td>
<td>-2.2</td>
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<td>-3.3</td>
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### Monthly Precipitation Totals (Cms.)

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<td>1.3</td>
<td>-</td>
<td>-</td>
<td>0.7</td>
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<td>3.1</td>
<td>4.4</td>
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<tr>
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<td>T</td>
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<tr>
<td>Inuvik</td>
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<td>1.9</td>
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<td>9.0</td>
<td>3.3</td>
<td>1.4</td>
<td>4.7</td>
<td>4.1</td>
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</tbody>
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Source: Data for Tuktoyaktuk, Nicholson Peninsula, Shingle Point and Inuvik taken from Monthly Record(s): Meteorological Observations in Canada, Queen's Printer, Ottawa.
were nine and three days respectively.

Comparisons of wind speeds and directions showed that the dominant winds during each of the summer months on Garry Island were from the northwest and east, the same as Inuvik. Periods of calm were relatively rare on the island however, and the mean wind velocities for each month, 8-10 m.p.h., were consistently 2-3 m.p.h. higher than those recorded at the inland station.
CHAPTER II

STRATIGRAPHY

The purpose of this chapter is to describe the major stratigraphic units occurring on Garry Island and the evidence for changes in the former relative positions of land and sea. This material will then be used, in the final chapter, in an attempt to decipher the geomorphological history of the island in late- and post-glacial times.

Garry Island is the westernmost member of an arcuate chain of islands, which includes adjacent Pelly, Kendall, Hooper and Pullen Islands, located in the outer part of the Mackenzie Delta. These islands, together with most of Richards Island, the Tuktoyaktuk Peninsula, a coastal fringe along the south side of the Eskimo Lakes, and an area stretching north and northeast of the Caribou Hills, represent the discontinuous remnants of one or more deltas constructed by a Pleistocene, or earlier, ancestor of the modern Mackenzie River. The stratigraphy consists entirely of a sequence of unconsolidated sands, gravels, silts, clays and stony-clays, cemented by ice, in which many of the beds have been deformed from their original position. Figure 2 is a map showing the major stratigraphic features of Garry Island. This map is based on a limited number of clean exposures, mainly in wave-cut bluffs, which have not been obscured by the combined effects of solifluction processes and slumping, or mantled beneath a thin veneer of glacial till.

Figure 2

GARRY ISLAND - STRATIGRAPHY

- **Sand Headlands**
- **Dip in Degrees**
- **Lineation Features**
- **Mudslumps**

**Scale**: 1:25,000

**Scale (Approximate)**: 0 - 2 Miles
Areas of Deformed Sediments.

The oldest sediments found on Garry Island are those represented in a series of discontinuous exposures in a number of mudslumps and coastal bluffs along the south and west coasts of the island. The following description outlines the major stratigraphic and structural features observed in a series of transects along the latter coastline where active slumping and coastal recession have resulted in the greatest number of clean exposures. The first transect A-B (see inset, Figure 2), includes approximately 900 metres (3,000 feet) of coastline in which a sequence of sands, silts and clays has been uncovered in a number of active mudslumps. The clays contain large quantities of segregated ground ice which has a distinctive banded appearance caused by an alternation of bands of frozen ground, with a high silt and clay content, and clear ice. These sediments, which dominate the stratigraphic sequence, are intercalated with beds of fine sand, 4.5-9.0 metres (15-30 feet) thick, containing an abundance of twigs, washed wood, bone fragments and shells. Most of the shells have been severely crushed during deformation of the strata, but two complete specimens, indicating a marine depositional environment, were identified as species of *Portlandia arctica* (Gray) by Dr. F.J.E. Wagner of the Geological Survey of Canada. All the sediments in this transect have been deformed (Plate I-A), and measurements taken from both the segregated ice bands and the sand beds show a remarkable degree of consistency in their attitude, being tilted to the southwest at angles ranging from 30-75 degrees.

The transect B-C traverses a series of high bluffs reaching maximum heights of approximately 29 metres (95 feet) above sea level. Samples were taken systematically from each of the major stratigraphic
A. Deformed body of segregated ground ice. Banded structures dip to the southwest at angles of 60-65 degrees.

B. Shear plane developed in silty-clay.

C. Granitic glacial erratic at an elevation of approximately 85 feet above sea level on the south side of Garry Island.

D. Structural (?) ridge at an elevation of 60-65 feet above sea level on the south side of Garry Island.
units exposed in these bluffs, with the exception of those occurring in
the mudslumps near C, and were analysed to determine their granulometric
composition. The results are illustrated graphically in Figure 3A. The
sediments are primarily silts and silty-clays, with occasional beds of
sandy-silt and, like the sediments in the previous transect, they exhibit
many signs of intensive deformation. Bedding planes, where preserved,
are tilted and occasionally contorted into a series of gentle folds. The
most salient feature of the deformation however is the occurrence of
large shear planes with well-preserved slickensided surfaces which cut
obliquely across, and locally offset, many of the original bedding
structures (Plate I-B). These shear planes, spaced at intervals ranging
from a few centimetres to several metres, are frequently concave up and
in places extend almost to the top of the bluffs. Their presence
produces a much more complex pattern of deformation than that described
in the previous transect, and the attitude of the individual beds often
changes rapidly over very short distances. Further evidence of the
complexity of the stratigraphic relationships in this section was found
in the sequential examinations of constantly changing exposures at the
same location as a result of continued marine erosion and slumping.
Seldom, if ever, did these new exposures repeat identically the pattern
which had been observed at an earlier date. Nevertheless, the general
pattern of deformation is similar to, albeit less consistent than, that
found in the previously described transect, with the strata maintaining
dips approximately to the southwest. Where the shear planes are concave,
the orientation of the concavity is also towards the southwest.

The deformed sediments are buried in the section C-D
(Figure 2) beneath a series of beach and lacustrine deposits, the
Figure 3

LOGARITHMIC GRAIN SIZE DISTRIBUTION DIAGRAMS

A. DEFORMED SEDIMENTS

B. SAND HEADLANDS
significance of which will be discussed below. The deformed sediments reappear again further along the coast but most of the exposures are obscured by surficial slump deposits. Two measurements were recorded in deformed ground ice bodies, exposed in a large mudslump, where it appears that the beds have a north or northwesterly dip of 20-30 degrees.

Exposures in the high bluffs along the south coast of the island are very limited due to the restricted active recession of the cluffs and their mantling by debris. Two observations made in deformed beds of silt and clay, and one in a small exposure of ground ice, indicate a generally northeasterly dip of 15-25 degrees. Only one exposure of deformed sediments was recorded along the whole of the north coast, where a band of vein ice in a mudslump appears to be gently folded and plunges almost due north at an angle of about 9 degrees. Direct evidence of deformation over the remainder of the island is lacking, but aerial photographs reveal the presence of a few marked lineation features which may be structurally controlled. Ground checks of these features however failed to confirm whether or not they were definitely related to any underlying structures.

Similar deformation of Pleistocene or earlier sediments has been recorded along adjacent sections of the mainland coast, from Herschel Island in the west to the Nicholson Peninsula in the east; a distance exceeding 485 kilometres (300 miles). Three possible mechanisms - slumping, tectonic disturbance and ice thrusting - were

\[2\] Mackay, J. Ross (1956) "Deformation by Glacier Ice at Nicholson Peninsula, N.W.T., Canada", Arctic, Vol. 9, pp. 219-228.

presented to explain the deformation patterns. Although the conditions on Garry Island are often very conducive to mudslump development, the scale of the deformation, the regularity of the pattern and the presence of deformation features, in areas where there is no sign of past or present slump activity, are considered to be sufficient criteria for eliminating this mechanism as a satisfactory explanation of the deformation pattern.

The most satisfactory interpretation of the deformation pattern is that it is the result of the overriding action of glacier-ice; the same mechanism which produced the disturbed features on the adjacent mainland. Direct evidence of the glaciation of Garry Island is difficult to assess, but the stony nature of the active layer suggests that many slopes are mantled by a thin veneer of glacial till. Glacial erratics found on the slopes, in solifluction deposits and along the beaches include granites, gneisses, quartzites, sandstones and slabs of fossiliferous (Devonian ?) limestone. Large erratics, up to 3 metres (10 feet) across, are found close to the highest summits of the island (Plate I-C), but since the whole island lies below the upper marine limit (see below), the possibility that they may have been ice-rafted cannot be excluded.

**Sand Headland Areas.**

Exposures on the north coast of the island (Figure 2) are dominated by thick deposits of sand which terminate in coastal bluffs 6-11 metres (20-35 feet) high. The precise areal extent and thickness of the sands are difficult to determine since very few contacts with the

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underlying sediments are exposed. The headland surfaces are gently sloping and devoid of any major relief features, and they contrast markedly with the more rugged topography of the area of deformed sediments to the south. This change in the character of the local relief occurs at elevations of approximately 12-15 metres (40-50 feet) above present sea level. The sands are brown in colour, horizontally stratified with occasional signs of current bedding, and consist mainly of sands in the medium- to fine-grain size category (Figure 3B) with inclusions of gravel lenses. The sands are not deformed, except for local upturning along the lines of the more prominent ice-wedges, and there is no evidence of any glacial deposition on any of the headland surfaces.

The sands contain iron-stained twig fragments and an abundant marine molluscan fauna. The following species were identified by Dr. Wagner:

\begin{verbatim}
Astarte borealis Schumacher
Astarte montagui (Dillwyn)
Astarte montagui (Dillwyn) forma typica
Astarte montagui var. striata (Leach)
Astarte montagui var. warhami
Macoma calcarea Gmelin
Mya truncata Linné
Trachoma balthica Linné
Tachyrhyncus sp. probably T. erosum
Trichatropis sp.
\end{verbatim}

A sample of these fossils submitted for radiocarbon dating yielded an age of >42,600 years (G.S.C.- 562). Many of these shells are in an excellent state of preservation and frequently have their outer valve cover (periostracum) intact. Consequently, although no hinged specimens of the shells were found, and despite the fact that the sands also contain many broken shell fragments, the fossils probably have not been reworked from earlier deposits, and the above date is therefore interpreted to be a
reliable indicator of the minimum time of sand deposition.

The textural similarity of all the sand exposures (Figure 3B) may indicate that they represent the discontinuous remnants of a formerly much more extensive sand plain formed when the relative level of the sea was 12-15 metres (40-50 feet) higher than at present. The discontinuity of the bodies of sand may be partially inherent, reflecting irregular deposition, or it may be entirely related to the effects of marine erosion subsequent to deposition. In either case, the main problem concerns the original source of the sand-size material and, in particular, whether it was derived locally or had an extraneous origin.

One possible mode of origin for the sands, implying a local source, is that they represent the residual accumulations of coarse material resulting from long-continued marine erosion of the island. The coastline of Garry Island is currently undergoing rapid recession in many places, and there is evidence that the shoreline has retreated a considerable distance during the past. A comparison of the two grain size distribution diagrams illustrated in Figure 3 is shown in the triangular graph of Figure 4, indicating relative percentages of material of sand-, silt- and clay-size particles of samples taken from both the sand headlands and the areas of deformed sediments. The latter have an average sand content of only 7 per cent, and only one per cent is in the medium and coarse sand fractions (<0.50 mm.). The major exception to these figures is the fossiliferous sand beds described in transect A-B which have an average sand content of 91 per cent, 10 per cent of which is in the medium sand or coarser range. These values contrast with the average of 91 per cent sand-size material in samples taken from the sand headlands and an average of 26 per cent of material with a grain size greater
Figure 4

GRAIN SIZE DISTRIBUTION FOR SOIL SAMPLES TAKEN FROM THE SAND HEADLANDS AND AREAS OF DEFORMED SEDIMENTS

- Samples from Sand Headlands
- Samples from Deformed Sediments
than 0.50 mm.

Whilst the number of samples upon which these figures are based is small, they do indicate that the volume of coarse material in the deformed sediments is quite minor and, if the sands are to be interpreted as a residual accumulation produced by long periods of marine erosion of the island, they must reflect the disappearance of very extensive tracts of older sediments. Some of the sand and gravel, of course, may have been derived in a similar manner through erosion of the surficial mantle of glacial till and the stony-clays, containing the segregated ice bodies, exposed in the mudslumps. Alternatively, the sand headland material may represent the residual deposits resulting from the erosion of stratigraphic units which are poorly represented in the existing succession. If the land, which has subsequently been eroded away by the sea, contained greater quantities of the fine sands described in the transect A-B, or was mantled by a greater thickness of glacial deposits, including till and/or outwash material laid down following the retreat of the glacier(s), the problem of a source material would be greatly alleviated.

As a corollary to this mode of origin, which interprets the sands as beach or spit deposits, it is interesting to note the distribution of lakes on the island. As Figure 2 shows, some of them occur along the contact zone of the sand bodies and the older, deformed sediments. The lakes may thus have originated as lagoon features on the landward sides of the sandspits, in much the same way as lagoons are currently being formed in association with the present day sandspits. The major difficulty encountered with this hypothesis is that the present lagoons are shallow, averaging 1.5-2.0 metres (5-6 feet) in depth, whereas the lake bottoms are
as much as 12-15 metres (40-50 feet) below the surfaces of the sand headlands. Part of this differential may possibly be explained by the thermo­karst or warming action of the lake water on the underlying sediments, since the thawing of any ice contained in these materials could have resulted in a settling of the lake floor.

An alternative mode of origin for the sands, inferring an extraneous rather than a local source, is that they represent coarse material brought down by streams following the retreat of the ice. These deposits may have been laid down under marine conditions when the relative level of the sea was 12-15 metres (40-50 feet) higher than at present, or it may be that the marine fossils represent a post-depositional phase during which the sands were reworked. Such an origin seems more probable than the above-mentioned local source on the basis of comparisons of the compositions of the sand headlands and the present day beach deposits. The latter contain abundant cobbles and boulders, derived from erosion of the glacial till, whereas similar material forms a very minor constituent in the rather uniform composition of the sand headlands.

Since much of the sand material may have been laid down under the influence of wave action and moulded into large spits, some of the lakes may still have originated as lagoon features. Alternatively, the lakes may represent deeper parts of the former river channels as in the case of the lake situated immediately south of the sand headland outlier on the northwest coast of the island. Yet another origin may be postulated for the deep, steep-sided lake incorporated within one of the headlands, which possibly may be interpreted as a kettle feature. Unfortunately, there are no good exposures of sand around the shores of this lake to check this hypothesis.
THE EXTENT OF THE MARINE SUBMERGENCE

The coastal lowlands of arctic Canada were influenced, to varying degrees, by the fluctuations in sea level produced by the waxing and waning of the ice sheets. Attempts have been made to determine the precise limits of the extent of the marine transgression using the four criteria of: (1) the highest altitude at which marine shells occur; (2) the highest altitude at which strand-lines are preserved; (3) the lowest altitude at which undisturbed ground moraines can be recognized; and (4) the lowest altitude at which perched boulders are found. As a result of research conducted along these lines, enough evidence has been accumulated to provide an overview of the pattern and extent of the post-glacial marine transgression in northern Canada.

Reference to the Glacial Map of Canada reveals that the area affected by the post-glacial marine transgression was much less extensive in the vicinity of the Beaufort Sea than in other sectors of the Canadian arctic. This undoubtedly reflects the fact that much of the eastern arctic was, in general, an area of thick ice cover, whereas the Mackenzie Delta area, being at or close to the northern limit of ice advance, was blanketed by a much thinner ice sheet. It may also reflect the fact that the eastern arctic has been more intensively investigated and thus there is a relative paucity of observations from the west. Also of significance

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may be the fact that the evidence of a marine transgression in this westernmost sector of the Canadian arctic is by no means as obvious as in its eastern and central counterparts. The distinctive flights of strand-lines, which form prominent features in the landscape of the central and eastern arctic, are generally lacking in the Beaufort Sea area. Most of the stratigraphy consists of unconsolidated silts and clays: materials which are easily eroded but are not conducive to the development of prominent and persistent wave-cut bluffs. The lack of persistence reflects the high susceptibility of these same sediments to frost action and mass movement, especially solifluction, and the operation of these processes, throughout at least post-glacial time, has tended to obscure much of the evidence of former submergence and emergence, if indeed it ever occurred. Intimately associated with this tendency is the evidence which suggests that the area in the vicinity of the Beaufort Sea was not glaciated during the late-Wisconsin, or most recent, stage of the Pleistocene period, thus presenting a longer time interval during which the traces of former sea levels could be obliterated. Even when the evidence for a marine transgression has been deciphered, there are further problems involved in establishing a chronological sequence in the Mackenzie Delta area. This sequence must take into consideration the complex interaction of an overall post-glacial rise in sea level which may possibly be coupled with two opposing forces in the earth's crust; an upward or positive movement representing a response to the removal of the weight of the ice, and a downward or negative movement representing crustal depression in response to the weight of the accumulating deltaic sediments brought down by the Mackenzie River in recent times.

Because the conditions that favour the development and
preservation of definite evidence of a marine transgression are so poor, and the interpretation of this evidence is so complex, it is difficult to determine, with any real degree of precision, how extensive it was. This is reflected in the existing literature which contains a number of widely-contrasting opinions. Richards claimed that there was no evidence of any post-glacial marine beaches in the vicinity of the Mackenzie Delta. Mackay, on the other hand, has described a number of extensive estuarine river terraces which suggest a relative submergence of approximately 15 metres (50 feet) when the coastal area first became free of ice.

The emergence of the land in the subsequent period may have been reversed more recently to be replaced by a period of submergence in the order of 3-6 metres (10-20 feet). The magnitude of these apparent changes in the land-sea relationships is quite small compared to the evidence, albeit more dubious, reported from the area lying to the west of the delta. O'Neill reported that the finding of marine fossils in high-level glacial deposits, and high terraces on the mountains facing the Arctic Ocean, indicated that glacial or post-glacial submergence of the Arctic coast extended at least to 152 metres (500 feet) above sea level.

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8 Ibid., p. 47.

More recent investigations, using fossil evidence and the mechanical properties of sediments found in excavations at the Engigstciak archeological site, near the mouth of the Firth River, suggest an alternative explanation for evidence of such high-level submergence. Although marine clays at this site are found at an altitude of 207 metres (680 feet), and fossils in these sediments indicate that they lived in water depths of more than 30 metres (100 feet), it is believed that the clays were transported to their present elevation by the thrusting action of glacier-ice.

East of the Mackenzie Delta there also appears to be evidence of a more extensive marine transgression than is found in the immediate vicinity of the delta. Mackay has described a series of elevated beaches and gravel terraces rising to 61 metres (200 feet), and O'Neill observed similar features at elevations reaching 67 metres (220 feet) above sea level. Further north, the evidence of a marine transgression on Banks Island has been found at a number of localities in the neighbourhood of 177-183 metres (580-600 feet).

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11 Ibid., p. 47.


13 O'Neill, J.J. (1924) op. cit., p. 33A.


The identification and interpretation of evidence indicating changes in the pattern of land-sea relationships was part of the field study programme on Garry Island. However, few of the afore-mentioned criteria for delimiting the extent of a marine transgression are readily applicable to the conditions on Garry Island. It is virtually impossible to employ the criterion of undisturbed ground moraine, since it appears that the whole island was affected by submergence, and therefore one cannot use a comparative investigation of disturbed and undisturbed till deposits to determine the upper limit of the marine transgression. No evidence was found in the form of perched boulders but, again, if the island were completely submerged in the past it is unlikely that any of these would have survived.

The use of marine fossils as evidence of a marine invasion of the land is also extremely limited. Even where this criterion has been adopted in other areas, there are problems in determining whether the fossils are 'in situ' or whether they were transported to their present elevations as 'shelly drift' by the thrusting action of glacier-ice. Insomuch as there is abundant evidence that the latter process has profoundly affected the strata on Garry Island, it would require careful consideration. However, due to the fact that the late-Wisconsin ice sheet did not cover the island, the long period of subaerial exposure has probably resulted in the destruction of much of the fossiliferous evidence by weathering processes. In any case, the only marine fossils found in association with the raised shorelines were restricted to elevations around 7.5-10.5 metres (25-35 feet) above sea level.

The presence of raised shoreline features affords the most direct evidence of a former submergence of the island. Unfortunately,
however, the conditions on Garry Island are similar to those found in other parts of the delta, and were generally unfavourable to the formation and preservation of these features. Most of the strand-lines were either only weakly developed, or evidence of their presence has been obscured, or even obliterated, by the operation of periglacial geomorphic processes in the interval since the withdrawal of the sea. As a general rule, the raised shorelines do not exhibit strong topographic expressions and seldom are they backed by prominent wave-cut bluffs (Plate II-A). In fact, the only surface expression of many of the strand-lines consists of a faint bevel, or break of slope, the presence of which might go completely undetected if it were not accentuated by contrasts in the vegetation pattern.

Since most of the stratigraphic units on Garry Island are composed of relatively fine-grained silts and clays, the raised shoreline features are rarely characterized by impressive shingle or boulder ridges. Where these are developed they constitute the exception rather than the rule. Mechanical probing of the active layer, however, frequently revealed concentrations of coarse sand, gravel and well-rounded, iron-stained, pebbles at depths ranging from 30-60 cms. (1-2 feet) below the ground surface. These deposits, found in association with the faint breaks of slope on the topographic profile, can often be traced quite extensively along the contours, but for distances of only a few metres in either an upslope or downslope direction. They are interpreted as residual beach deposits buried beneath a mantle of soliflucted material.

14The locations of the strand-lines are often marked by the development of a vegetation association which includes the tussock-like forms of the Sheathed Cotton-grass (Eriophorum vaginatum).
A. Wave-cut bluff at an elevation of approximately 75 feet above sea level.

B. Sandspit associated with the 25 foot raised strandline.

C. Peat accumulation damming the outlet of a lake at an elevation of 120-125 feet above sea level.

D. Interruption in the longitudinal profile of Stream 'B' at an elevation of 100 feet above sea level.
The distribution of these raised shoreline features is shown in Figure 5. Although many of them can be traced for considerable distances, the incompleteness of the pattern reflects: (1) the number of observations made; (2) the degree to which the strand-lines have been destroyed by the combined action of mudslump development and coastal recession associated with lower sea levels than those at which they were formed; (3) the depth to which the evidence has been buried by solifluction deposits; and (4) the type of sediment in which the shorelines were developed. The importance of the first factor is revealed in Figure 5 where only a limited number of observations was made in the central part of the island. A similar paucity of evidence along the south coast of the island can largely be attributed to its obliteration by slumping and coastal recession. The significance of the latter two factors is related to the thickness and composition of the active layer. If the residual accumulations of sand and pebbles lie at depths greater than the thickness of the active layer, their presence can only be determined by drilling into the permafrost beneath. Furthermore, if the composition of the substrate consists of coarse-grained sediments, it is difficult to differentiate between the parent material and possible residual beach deposits. It is for this reason that little evidence of raised strand-line features, if indeed they exist, is shown on the surfaces of the sand headlands.

As Figure 5 indicates, the evidence suggests the presence of a series of raised strand-lines, at approximately 7.5 metre (25 foot) intervals, reaching to heights of 46 metres (150 feet) above sea level. The approximate elevations of the strand-lines were determined using a telescopic alidade and an altimeter. Because of the weak topographic expression of the raised shorelines, the degree to which the majority of
Figure 5

GARRY ISLAND
RAISED SHORELINE FEATURES

Raised Shorelines
- 25' ft.
- 50' ft.
- 75' ft.
- 100' ft.
- 125' ft.
- 150' ft.

A-N Stream Profile Locations

Scale (Approximate) 0 1 2 Miles
them have been obscured by solifluction deposits and the virtual impossibility of locating the original breaks of slope beneath this material, and in the absence of a fixed datum for mean sea level resulting in an error of 0.3-0.6 metres (1-2 feet) produced by tidal fluctuations, it is almost impossible to determine the precise elevations of the strand-lines. The heights assigned to the raised shoreline features must consequently be regarded as approximations, and the 'regularity' of their spacing should be interpreted as apparent rather than real.

The highest strand-lines, at the '46' metre (150 foot) and '38' metre (125 foot) levels, are the least extensively developed since few of the summit areas reach these elevations. They also have the weakest topographic expression, and this is undoubtedly related to their greater antiquity and their exposure to the modifying influences of periglacial or other geomorphic processes for longer periods of time. One noticeable aspect of the distributional pattern of these highest shorelines, and to some extent that of the '30.5' metre (100 foot) shoreline, is their relationship to the major topographic features of the island. A reconstruction of the configuration of Garry Island when the relative level of the sea was 38 metres (125 feet) higher than at present, shows that it would actually consist of nine small islands separated by open stretches of water. The manner in which the elevated strand-lines can be traced on both the north and south sides of the island, and along the low cols in the summit areas, suggests that the main topographic features of Garry Island are of considerable antiquity, and that the effects of submergence and subsequent emergence have had little effect in the remoulding of the landscape.

Almost all the strand-lines developed at and below the
30.5 metre (100 foot) contour level have some topographic expression, and can be traced much more extensively along the length of the island. Each shoreline is readily detectable around the interfluve areas, but seldom is it possible to trace them across the lines of the valley reentrants. The possible reason for this will be discussed more fully below. Just to the east of Stream 'K' is a large, steep-sided depression across which there is a prominent ridge, the elevation of which is approximately 18.5-20 metres (60-65 feet) above sea level (Plate I-D). This ridge cannot be linked with any of the adjacent strand-line features and it is composed of relatively fine sands with few pebbles or boulders. Although no conclusive evidence could be found, the ridge is interpreted to be a structural feature in the deformed sediments behind which a small lake may have temporarily been ponded.

Between the '15' metre (50 foot) and '23' metre (75 foot) strand-lines are a number of isolated boulder accumulations developed at the 17-18 metre (55-60 foot) level. These are particularly noticeable on the north side of the island, to the east of Stream 'B', and on the west side of the open valley above the head of Stream 'I'. Their composition, consisting of large, well-rounded, iron-stained boulders, often exceeding 30 cms. in length, and their prominence contrasts markedly with the minor accumulations of beach deposits found in association with the series of strand-lines. They appear to be much older features and may be isolated remnants of an earlier position of the sea related to the time of deposition of the material in the sand headlands.

The evidence of strand-line development at the 7.5 metre (25 foot) level, where preserved, is the most pronounced of all the elevated shorelines, but its limited occurrence bears witness to the
extent of coastal recession in recent times. Virtually nowhere along the south coast of the island is there any indication of its presence, and it is best developed around the margins of bay-like depressions between the sand headlands on the north side of the island. Here the old shoreline feature can be traced quite readily around the lateral margins of the sand headlands and its development in the coarse-grained sediments probably accounts for its prominence and preservation, since the sands are less susceptible to slumping and solifluction than the silts and clays. Although, as mentioned previously, it is difficult to apply the criterion of residual beach deposits at depth to the sand headland areas, there appears to be no doubt that the '7.5' metre (25 foot) strand-line definitely post-dates their formation.

The '7.5' metre (25 foot) raised strand-line is also developed around the edge of another large depression on the northwest coast of the island (Figure 5). In this locality, the retreat of the present coastline is also responsible for its limited occurrence, but the stratigraphic sequences exposed in the coastal bluffs provide an excellent cross-section of the structure of the depression. The details of this cross-section constitute the profile C-D shown in Figure 6.

The depression is developed in the deformed clay sediments which occur in the large mudslump, where they also contain bodies of ground ice, at the northeastern end of the transect B-C (Figure 2). These clays are only exposed in the extreme southwestern part of the cross-section and elsewhere they are buried beneath 5.5-6.0 metres (18-20 feet) of pebbly-gravel. The altitude of the top of these gravels is approximately 7.5 metres (25 feet) above sea level at point C; the same elevation as that of the shoreline feature found around the edge of
Figure 6

STRATIGRAPHIC SECTION EXPOSED IN COASTAL BLUFFS ALONG NORTHWEST COAST OF GARRY ISLAND

For location of section see Inset Figure 2

Horizontal Scale 1 inch = 350 feet
Vertical Scale 1 inch = 35 feet
Vertical Exaggeration x 10

- Solifluction Material
- Peat
- Pebbly Gravel
- Lacustrine Sediments
- Beach Gravels
- Pebbly Clay
the depression. From this point the surface of the gravels slopes gently toward the centre of the basin, rising again to a height of 7.3 metres (24 feet) in a well-defined ridge. This ridge can also be traced across the floor of the depression, where the gravels appear at the surface, and it represents an old spit or bar associated with the '7.5' metre (25 foot) strand-line (Plate II-B). Beyond the spit the thickness of the gravels decreases until they disappear completely in the centre of the section. The gravels reappear again beyond the area of polygonal ground and increase to a thickness of 4 metres (13 feet) again at point D.

The gravels in turn are overlain by a sequence of organic-rich clays which locally exhibit a varve-like banding. These clays contain an abundant collection of gastropods, identified by Dr. F.J.E. Wagner as *Lymnaea* species, and these fossils indicate that the clays were deposited in freshwater conditions. The thickness of the lacustrine sediments, on both sides of the depression, increases towards the centre where they thin again and are replaced by thick accumulations of peat in the form of a number of high-centred tundra polygons. These polygons have been dissected by deep trenches created by melting along the lines of former positions of the intervening ice-wedges. A specimen of peat from one of these polygons, taken from the coastal bluff at a depth of 1.5 metres (5 feet) below the surface, was submitted for radiocarbon dating and yielded an age of 4120 ± 130 years (G.S.C. - 513).

A similar sequence of lacustrine sediments was deposited in the smaller marginal basin created by the formation of the gravel spit. A peat sample, collected by Dr. J.G. Fyles, taken from the basal layer of this sequence near point C indicated an age of 10,330 ± 150 years (G.S.C. - 517). At this same location, however, the lake sediments are
also buried beneath a further 1.5-1.8 metres (5-6 feet) of pebbly-gravel followed by an additional 0.6-1.2 metres (2-4 feet) of peat. This gravel, the upper surface of which is at a height of 10.5 metres (35 feet) above sea level, contains a number of iron-stained twigs and wood fragments and a sample of these, also collected by Dr. Fyles, provided a further radiocarbon date of 9730 ± 160 years (G.S.C. - 575). The interstratification of the gravels and organic material is the only evidence found which suggests that the changing pattern of land-sea relationships on Garry Island was not a simple, progressive emergence of the land or withdrawal of the sea.

The details of this stratigraphic cross-section provide an insight into the mode of formation of the elevated strand-line features on Garry Island. The configuration of the '7.5' metre (25 foot) strand-line is highly suggestive of the submergence of a pre-existing topography, and the submergence of the depressions in the topography created a series of embayments in the coastline. Residual deposits of sand and gravel, derived from the erosion of the adjacent sections of the coast, accumulated along the shoreline and on the floors of the depressions. Locally this material was concentrated into sandspits or bars developed across the mouths of the embayments creating a number of lagoons on their landward sides. As the bars extended completely across the mouths of the bays, the lagoons were transformed into freshwater lakes which were gradually infilled by the deposition of lacustrine sediments. The final stages of this infilling were accompanied by the development of tundra polygons. Although stratigraphic evidence of this sequential development can only be demonstrated conclusively at the one location on the northwest coast of the island, it is believed that the bay-like depressions on the north side
of the island represent a similar sequence of events, although the bays may not have been converted into freshwater lakes.

The large bay-like depressions are particularly well-developed in association with the '7.5' metre (25 foot) strand-line. Investigations of the longitudinal profiles of some of the main stream courses indicate that similar features were formed, albeit usually on a much smaller scale, in association with the other raised shorelines.

**Longitudinal Stream Profiles.**

Under favourable circumstances the longitudinal and cross-valley profiles of major river valleys may record the evidence of relative changes in base level. A negative or downward movement of the base level causes a rejuvenation of a stream at its mouth and a regrading of the stream towards its new base level. Such rejuvenation may result in the production of an interrupted or stepped profile, with the breaks of slope, or nickpoints, representing the headward extent of the regrading process. The longitudinal breaks in the profile can also often be correlated with 'valley in valley' forms in which river terraces, or simpler valley-side facets, mark the former levels of the valley floors. The existence of similar terraces in the estuarine sections of some of the main rivers on the adjacent mainland has already been discussed.

There are no large perennial streams on Garry Island. Indeed, the present watercourses carry only a very intermittent surface runoff during the spring and early summer when they receive water from the melting of the snow cover. Throughout the rest of the summer months,

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these channels receive moisture seepage, produced by thawing of the active layer on the adjoining valley sides, and this is seldom sufficient to maintain surface runoff except when combined with the effects of a prolonged period of heavy rainfall. The inefficiency of stream erosion is demonstrated by studies of the stream channels. Over most of their length the surfaces of these channels are aggrading by the growth and accumulation of organic material. As a result of this process most of the channels are ill-defined and their lines can best be traced by contrasts in the vegetation pattern. In the absence of a well-defined channel, surface runoff, when it occurs, is easily diverted to other routes. This was amply demonstrated in the case of Stream 'D' (see Figure 5) at the beginning of the 1965 field season, where snow meltwater no longer followed the stream course, but had been diverted along the line of a well-trodden path between the base camp and the beach. Attempts to lower artificially the levels of two lakes on the island, by means of ditches, provided yet another example of the weak erosive power of running water. The ditches were cut through peat and gravel barriers at the outlets of the lakes (Plate II-C). It was hoped that, once established, these channels would be excavated further by the flow of water draining from the lakes. At one of the lakes, however, it was soon demonstrated that the flow was insufficient to excavate the underlying peat, gravel and clay, and the channel could only be maintained by constant digging.

The longitudinal profiles of fourteen Garry Island stream courses were surveyed and the results are shown in Figures 7 and 8. Only at their mouths, where they cut through the coastal bluffs, do these streams possess a well-defined channel bordered by steep banks approximately one metre (3-4 feet) high. Over most of their lengths, as
Figure 7
LONGITUDINAL STREAM PROFILES (1)

Profile A

Profile B

Profile C

Profile D

Profile E

Profile F

Profile G

Horizontal Scale 1 inch 1000 feet
Vertical Scale 1 inch 200 feet
Vertical Exaggeration x 5
I–VI Cross-Valley Profile Locations
Figure 8
LONGITUDINAL STREAM PROFILES (2)

Profile H

Profile I

Profile J

Profile K

Profile L

Profile M

Profile N

Horizontal Scale 1 inch = 1000 feet
Vertical Scale 1 inch = 200 feet
Vertical Exaggeration x 5
mentioned in the previous paragraph, the channels have been filled by the accumulation of organic material, and their positions are marked by contrasts in the vegetation pattern where the higher moisture content of the substrate favours the growth of willows, sedges and moss.  

The lack of definition of the stream courses becomes increasingly apparent towards the higher elevations. Each of the streams has an ill-defined source area in either one of the steep-sided depressions or flat-floored cols in the summit areas. From these indefinite beginnings, as Figures 7 and 8 indicate, the descent to the coastline is not a smooth curve but exhibits a characteristic step-like form (Plate II-D). Where best developed, the interruptions on the longitudinal profile are marked by the occurrence of small lakes or, more commonly, areas of tundra polygons on the valley floor. Elsewhere, the breaks in slope are less prominent but are accompanied by a widening of the valley floor, as indicated by the vegetation pattern, to 2-3 times the normal width.

The distribution of the elevations of these interruptions in the longitudinal profiles of the fourteen streams is shown in Table IV. The heights have been grouped into selected height-range intervals to see if there is any correlation between the elevations of the breaks in slope and those of the elevated strand-lines. The altitudes in parentheses indicate those which fall outside the selected height-range intervals.

As Table IV shows, eight of the fourteen streams have an inflection point on their longitudinal profiles at an elevation of

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Further details on the vegetation patterns of the stream courses are included in the following chapter.
TABLE IV

ELEVATIONS OF THE BREAKS OF SLOPE ON THE LONGITUDINAL PROFILES
OF GARRY ISLAND STREAMS

<table>
<thead>
<tr>
<th>Stream</th>
<th>Elevation at Source (Metres)</th>
<th>Selected Height Ranges (Metres)</th>
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<tbody>
<tr>
<td></td>
<td>6-9</td>
<td>14-17</td>
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<tr>
<td>A</td>
<td>25.3</td>
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<td>B</td>
<td>49.4</td>
<td>(11.3)</td>
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<tr>
<td>C</td>
<td>33.2</td>
<td>7.6</td>
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<tr>
<td>D</td>
<td>22.9</td>
<td>(12.2)</td>
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<tr>
<td>E</td>
<td>29.9</td>
<td>7.9</td>
</tr>
<tr>
<td>F</td>
<td>28.3</td>
<td>7.6</td>
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<tr>
<td>G</td>
<td>39.9</td>
<td>7.6</td>
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<tr>
<td>H</td>
<td>24.7</td>
<td>(11.0)</td>
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<tr>
<td>I</td>
<td>28.0</td>
<td>7.9</td>
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<td>J</td>
<td>48.5</td>
<td>7.9</td>
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<tr>
<td>K</td>
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<tr>
<td>L</td>
<td>47.9</td>
<td>7.9</td>
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<tr>
<td>M</td>
<td>41.1</td>
<td>14.3</td>
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<tr>
<td>N</td>
<td>25.9</td>
<td>16.5</td>
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approximately 7.5 metres (25 feet) above sea level. Of the six streams which do not, three drain toward the south coast and one to the west coast where, in each case, they terminate in high coastal bluffs which have undergone considerable recession. As a result of this recession, the lower courses of these streams have become deeply entrenched and they reach the present shoreline through narrow 'V'-shaped valleys.

Interruptions in the longitudinal profiles at altitudes of both approximately 15 and 23 metres (50 and 75 feet), are represented in ten of the fourteen stream courses, but the evidence of similar breaks of slope at altitudes exceeding 30.5 metres (100 feet) above sea level is more restricted. Thus the numbers of inflection points in the profiles occurring at the 30.5, 38 and 46 metre (100, 125 and 150 foot) levels are only five, four and two respectively. The limited number of interruptions in the profiles at these levels can readily be explained by the fact that progressively fewer of the streams originate at these higher elevations (Table IV). For example, only eight of the fourteen streams shown in Figures 7 and 8 originate at elevations of more than 30.5 metres (100 feet) above sea level; similar figures for altitudes of 38 and 46 metres (125 and 150 feet) are six and three streams respectively.

In all, Table IV lists a total of 48 elevations, each of which represents a point of inflection on a longitudinal stream profile. Of this total, no fewer than 39, or more than eighty per cent, occur within the selected height-ranges. There may be some significance, however, to the fact that of the breaks in slope which do not occur within these height ranges, more than one-half are developed at an elevation of approximately 10.5 metres (35 feet) above sea level.

The evidence from the surveyed stream courses suggests that
there is a correlation between the altitudes of the inflection points on the longitudinal profiles of these streams and the elevations of the raised shoreline features. It is postulated that the two sets of features are closely interrelated and that both are associated with former positions of the sea.

When the relative level of the sea stood at each of the positions indicated by the strand-lines, it is postulated that the lines of the valleys formed small indentations or bays in the shoreline. Residual accumulations of coarse sand and gravel, produced by the erosion of the coastal bluffs, were deposited at the shoreline, and locally these were concentrated into small spits or bars extending across the mouths of the bays. The lagoons, created by the formation of these bars, may eventually have been sealed off from the open sea and transformed into shallow, freshwater lakes. Some of these lakes may have been drained immediately when the relative level of the sea was lowered but many were left occupying positions in the newly-exposed valley floors. The larger and deeper lakes have persisted through to the present time, but many of the smaller, shallower ones have subsequently been filled by the accumulation of organic material and become the loci for tundra polygon development. The repetition of this sequence of events is offered as an explanation of the stepped profile so characteristic of the stream courses on Garry Island.

The sequential stages of development, offered to account for the distribution and formation of the areas of polygonal ground, is similar, albeit on a much smaller scale, to that proposed for the origin of the exposures of lacustrine sediments found along the northwest coast of the island. The hypothesis gains a certain credibility from two
aspects of studies of the contemporary shoreline. Firstly, practically all of the present streams have their outlets blocked by accumulations of gravel, driftwood and peat. Even during periods of relatively strong runoff, the streams are only temporarily able to establish a channel through these materials to the sea. Such channels are very ephemeral features, however, and are soon choked by wave action. The second line of support comes from the fact that polygonal ground is currently developing around the margins of lagoons enclosed by the construction of the modern sandspits.

In an attempt to establish further the validity of this hypothesis a number of cross-valley profiles was surveyed at strategic points along Stream 'G'. These profiles are shown in Figure 9. At each of these points a series of drill holes was made across the stream course to determine the nature of the substrate and, if possible, locate the presence of the buried gravel ridges required to support the hypothesis. The depths at which gravels were encountered in these drill holes are also recorded in Figure 9. Cross-profile I was located at an elevation of approximately 4.5 metres (15 feet) above sea level where the stream course traverses the large bay-like reentrant in the '7.5' metre (25 foot) strand-line. The ill-defined nature of the channel is immediately apparent and the drilling operations revealed no sign of gravels, at least to depths of 2 metres (6 feet). Cross-profiles II, III and IV were located at elevations of approximately 7.5, 15 and 23 metres (25, 50 and 75 feet) above sea level. As Figure 9 shows each of these locations was characterized by the presence of a fairly prominent gravel ridge at depths of up to 1.5 metres (5 feet) below the surface. The details of one of these ridges were particularly well-developed at an altitude of 23 metres (75 feet) above
Figure 9
CROSS-VALLEY PROFILES - STREAM 'G'

Profile I

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Profile II

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Profile III

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Profile IV

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Profile V

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Profile VI

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</table>

Horizontal Scale 1 inch = 100 feet
Vertical Scale 1 inch = 20 feet
Vertical Exaggeration x5

- Buried gravel
- Willows
- Sedge/Moss
sea level where they could be traced laterally to prominent ridges on the side of the valley. Cross-profile V was located at an elevation of 27.5 metres (90 feet) above sea level. Although gravels were encountered beneath the stream course itself, they could not be detected at all on the sides of the valley. The final cross-profile was located just below an area of weakly-developed tundra polygons at an altitude of 38 metres (125 feet) above sea level. As the profile shows, gravels were encountered at shallow depths beneath the channel and for considerable distances on either side. Thus, although the subsurface profiles were only determined at strategic points along one of the streams, the limited evidence provided by these profiles is in accordance with the hypothetical sequence outlined above.

The studies of the longitudinal and cross-valley profiles of the stream courses corroborate the opinion that a series of elevated strand-lines, spaced at intervals of approximately 7.5 metres (25 feet) and reaching elevations of 46 metres (150 feet) above sea level, can be identified on Garry Island. In the absence of definitive fossil evidence, however, it is reasonable to question the validity of a further conclusion that these strand-lines mark the positions of former levels of the sea. The prime reason for stating that these shorelines are marine features is based entirely on the apparent uniformity of their elevations on all sides of the island. Irrespective of the aspect of the slope on which they are developed, the shorelines seem to exhibit a strong degree of consistency with respect to their elevation above sea level. Such consistency is not in keeping with a hypothesis that they were developed around the margins of proglacial lakes. Moreover, the conditions on Garry Island were rarely suitable for the development of these lakes. They could have only
developed, to any real extent, along the south side of the island where meltwater may temporarily have been ponded between the coastline and the ice-front as it retreated to the south. A further hypothesis, which was also considered, is that some of the shorelines were developed around lakes which were ponded by structural deformation features. The possible existence of one such lake was referred to previously. The absence of any marked anomalies in the heights of the shoreline features would appear to indicate that neither of these possible modes of origin was more than of local significance, if any at all.

SUMMARY

The stratigraphy of Garry Island consists of a sequence of sands, silts, clays, and stony-clays, cemented by ice, which have been intensively deformed by the thrusting action of glacier-ice moving from the south. The deformed sediments are locally overlain by sands and gravels, probably brought down by streams following the retreat of the ice. These materials are undisturbed and contain marine fossils dated at > 42,000 years. The absence of any signs of glacial till on top of the sands suggests that Garry Island lay beyond the northwest limits of the Laurentide ice sheet during the late-Wisconsin glaciation.

Attempts to determine the extent of changes in the former relative positions of land and sea are complicated by the weak topographic expression of raised shoreline features, and the degree to which they have been obscured, or even totally obliterated, by subsequent geomorphic activity. In addition to these difficulties, the absence of a fixed datum for mean sea level prevents a completely reliable determina-
tion of the precise altitudes of the shorelines. Despite these limitations, the evidence suggests the existence of a series of elevated strand-lines which occur at approximately 7.5 metre (25 feet) intervals to an altitude of 46 metres (150 feet). Some additional support for this view comes from surveys of the longitudinal profiles of 14 stream courses on the island. These profiles are characteristically step-like, and the altitudes of the inflection points on the thalwegs exhibit a strong degree of similarity to the elevations of the raised shoreline features.

Further comments on the overall significance of these stratigraphic observations and their incorporation into a possible chronological sequence will be discussed in the final chapter of the thesis.
CHAPTER III

VEGETATION

Garry Island is located wholly beyond the northern limit of trees which presently lies approximately 65-80 kilometres (40-50 miles) to the south in the modern delta of the Mackenzie River. The treeless character of the island places it in the arctic tundra region and the vegetation is composed primarily of dwarf shrubs, herbs, mosses and lichens. The objective of this chapter is to describe the major vegetation types which occur on Garry Island and to examine the interrelationships between the vegetation patterns and types of geomorphic activity.

Attempts to define tundra vegetation communities on the basis of their plant composition are complicated by the fact that there are not always distinctive or diagnostic species in each of the plant associations. Many species have a broad tolerance of environmental conditions, and therefore occur in a wide variety of habitats. This fundamental inadequacy of a classification of arctic vegetation on the basis of physiognomy or floral composition has been recognized by numerous botanists, as is exemplified by the following quotations:

"In the arctic, differences are merely quantitative. The habitat preferences of the individual species find expression merely in increased or decreased abundance in more or less favourable habitats rather than by presence here or absence there....

Arctic vegetation must be described by reference to the physical conditions of the habitat rather than by an attempt to discover and deal with
Accordingly, the major purpose of the vegetation study was to examine the various factors contributing to the physical character of the plant habitats and, in particular, the relationships of the vegetation pattern to geomorphic activity. Subsurface conditions were also checked, with specific reference to the relative amounts of the organic material and mineral soil fractions, and the depth of the active layer was recorded at various times throughout the summer for each of the habitats. A discussion of this data is contained in the following chapter.

The vegetation was mapped in the field on a scale of approximately 1:25,000 and the delineation of the types was checked through subsequent studies of aerial photographs and coloured transparencies. For each of the major habitats identified, an attempt was made to estimate the relative percentages of the area occupied by the dominant species. Since the emphasis was on the physical character of the habitat, however, this was done by visual estimation rather than by the employment of the more rigorous quadrat sampling technique. For completeness, and for readers having interests in botany, the various species identified have been listed under each of the vegetation types in which they occur. Although it is not claimed to be exhaustive, Appendix I contains a summary of this information and lists a total of 106 vascular species and 17 bryophytes.

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collected and identified on Garry Island.\textsuperscript{2}

VEGETATION TYPES

Figure 10 shows the areal extent and distribution of the principal vegetation types found on Garry Island. The classification is based primarily on the physical character of the habitat, but it also includes the names of the specific plant species wherever they tend to dominate the particular vegetation type.

I. \textbf{Dryas-Hummock Type.}

Most of the drier tundra sites are characterized by an irregular surface where the ground is covered by numerous, rounded earth hummocks, the size and spacing of which vary according to their position on the topographic profile. These microrelief forms are found on all summit areas and valley-side slopes with moderate to good drainage conditions (Plate III-A). Hummock profiles consist of a surface layer of turf and organic material, beneath which there is a domed core of mineral soil, but there is little or no soil beneath the intervening depressions which are the sites of organic accumulation.

The vegetation is composed primarily of low matted, woody shrubs together with lichens and mosses. This vegetation type is the most

\textsuperscript{2}An attempt was made in the field to identify the vascular plants using N. V. Polunin's book, \textit{Circumpolar Arctic Flora}, Clarendon Press, Oxford, 1959, and the format of Appendix I is based on this text. I am indebted however, to Dr. Eric Hultén of the Naturhistoriska Riksmusset, Stockholm, for his precise identification of the species listed. I am similarly indebted to Dr. Herman Persson, of the same institute, for the identifications of the bryophytes. Unfortunately it was not possible to identify the lichens.
Dryas Hummocks
Cassiope Snowpatches
Alnus crispa
Eriophorum Tussocks
Hummock - Tussock Transition
Stream Course Willow Thickets
Sedge - Moss Flats
Mudslump Communities
Strand Communities - Gravel Bars
- Marsh - Lagoon
Polygons - Low Centred
- High Centred

Figure 10
GARRY ISLAND
VEGETATION TYPES
Plate III

VEGETATION TYPES

A. DRYAS HUMMOCK.
Hummock in centre dominated by lichens, Arctic Avens, and Bigelow's Sedge. Darker colour of the inter-hummock depressions is due to the dominance of the Arctic White Bell-heather and mosses.

B. ALNUS CRISPA.
Almost pure stands of the Mountain Alder growing in a shallow, sheltered depression on the north side of Garry Island.

C. CASSIOPE SNOWPATCH.
Typical vegetation association found in areas of late-lying snowpatches. The dominant species are the Arctic White Bell-heather and willows.

D. ERIOPHORUM TUSSOCKS.
Characteristic tussock forms of the Sheathed Cotton-grass. The inter-tussock areas are dominated by mosses and the Arctic White Bell-heather.
extensive found on the island and it is also the most diversified in terms of its floristic composition. On the flat summit areas, the hummocks are quite subdued in form, but the microrelief factor is still sufficient to produce two distinct plant habitats. The drier, elevated hummock centres are dominated by the Arctic Avens (*Dryas integrifolia*), after which the vegetation type is named, together with mosses (chiefly *Dicranum*, *Cinclidium* and *Bryum* species) and lichens (the so-called 'reindeer moss'). Collectively these plants may account for 50-60 per cent of the vegetation cover on the hummock surface. Other major species found on the hummocks include Bigelow's Sedge (*Carex bigelowii*), Arctic Blueberry (*Vaccinium uliginosum var. alpinum*), Mountain Cranberry (*Vaccinium vitis-idaea*), Common Crowberry (*Empetrum nigrum*), and the Glandular Birch (*Betula glandulosa*). On the more sheltered flanks of the hummocks there is an increase in the percentage cover of these species, and a corresponding decrease in the cover of avens and lichens. Small willows (*Salix reticulata, S. glauca var. niphoclada*), rooted in the hummocks, and the Narrow-leafed Labrador-tea (*Ledum palustre ssp. decumbens*) are also found on the sides of the hummocks. Less common species encountered growing on the hummock centres include the Arctic Wintergreen (*Pyrola grandiflora*), Arctic Meadow Grass (*Poa arctica*), Capitate Lousewort (*Pedicularis capitata*), Alpine Bearberry (*Arctostaphylos rubra*), Veiny-leafed Willow (*Salex phlebophylla*), Northern Wood-rush (*Luzula confusa*), Woolly Lousewort (*Pedicularis lanata*), Long-stalked Stitchwort (*Stellaria longipes*), Mountain Meadow Bistort (*Polygonum bistorta*), Narrow-leafed Saussurea (*Saussurea angustifolia*), Alpine Bistort (*Polygonum viviparum*), Lapland Rose-bay (*Rhododendron lapponicum*) and the Lake Louise Arnica (*Arnica louiseana frigida*).
The inter-hummock depressions are sites of snow accumulation during the winter months and the organic substrate remains much moister than the more exposed hummock centres. These depressions support an entirely different and less diversified plant assemblage. Mosses (chiefly *Aulacomnium*, *Hylocomnium* and *Sphagnum* species) and the Arctic White Bell-heather (*Cassiope tetragona*) are the dominant constituents of the flora, and collectively account for 60-70 per cent of the vegetation cover. Other ubiquitous, though minor, species found in the depressions include the Lapland Butterbur (*Petasites frigidus*), Sudetan Lousewort (*Pedicularis sudetica*), Fragile Sedge (*Carex membranacea*), Sheathed Sedge (*C. vaginata*), Radiate Saxifrage (*Saxifraga radiata*), Lapland Reedgrass (*Calamagrostis lapponica*), Alpine Hedysarum (*Hedysarum alpinum americanum*), Alpine Foxtail (*Alopecurus alpinus*) and the Naked-stemmed Parrya (*Parrya nudicaulis*).

The above descriptions pertain to characteristic plant assemblages of hummocks and depressions on the upland surfaces. Changes in these plant compositions appear to be most markedly affected by the degree of exposure and the moisture supply. On exposed, windswept slopes the hummocks are even more subdued than on the flat summit areas, the vegetation cover is thinner, and there is patchy development of bare ground. The most noticeable effect of these conditions is an increase in the cover of the Arctic Avens, to a point where they are almost the only species found on the hummock surface. Contrasts in the moisture conditions of the hummock centres and the depressions are less pronounced and the avens are frequently found growing on dry moss pads in the latter areas. Other plants which appear to thrive in this exposed environment include the Veiny-leafed Willow, Woolly Lousewort, Northern Wood-rush and the Arctic
Lupin (*Lupinus arcticus*).

Between the upland summit areas and the lower elevations there is a gradual, but progressive, increase in the size of the hummocks. Coincident with this increase in the microrelief, the vegetation contrasts between the hummocks and depressions become more pronounced. This is particularly noticeable on the upper slopes, but towards the foot of the slope there are distinct changes in the vegetation cover on the hummocks. The lichens disappear almost completely and the Arctic Avens become only a minor constituent of the flora. Mosses, Sedges, the Common Crowberry, Arctic Blueberry and Labrador-tea achieve much greater prominence and the Arctic White Bell-heather is also found on the hummocks. The most notable change in the depressions is an increase in the amount of the moss cover.

It is not surprising that the vegetation type which has the greatest areal extent, and the most diversified floristic composition, lends itself to the possible recognition of abundant sub-types. Some of these have already been alluded to with reference to the effects of exposure, moisture conditions, etc. The problem of differentiating between a sub-type and a separate type is not an easy one, but in two cases the vegetation association that was produced was so distinctive - the *Alnus crispa* and the Cassiope Snowpatch types - that separate vegetation types were recognized.

II. *Alnus crispa* Type.

In a very few sheltered locations, with a moderate to good moisture supply, the vegetation is locally dominated by pure stands of the Mountain Alder (*Alnus crispa*). The largest stand of Alder was found on a north-facing slope and was composed of low bushes approximately one
71

metre (3 feet) high (Plate III-B). Each bush has a lateral spread of
almost 2 metres (6.5 feet), and this effectively shades out the under-
lying ground surface which is consequently devoid of any further plant
cover and mantled by a litter of dead leaves. The stand of Mountain Alder
shown in Plate III-B is the only substantial one on the island, although in
a number of isolated, favourable spots individual bushes were noted.

III. Cassiope Snowpatch Type.

In the section on the Dryas-Hummock vegetation type, downslope
changes in the floral composition were tentatively related to changes in
the moisture conditions of the soil. Locally, in addition to the increase
in moss cover, the hummocks and depressions alike are blanketed by a dense,
almost pure cover of the Arctic White Bell-heather (Cassiope tetragona) and
willows (Plate III-C). This vegetation pattern gives a distinctive dark
colouration to the ground surface which is readily detectable on aerial
photographs. The lower slopes receive water seepage, derived from the
thawing of the active layer, from the upper parts of the slopes, and are
also the sites of late-lying snow patches. These effects are most pro-
nounced in the larger sheltered depressions and on northeast-facing slopes
where the snow may remain on the ground well into the summer before it
disappears.

IV. Eriophorum Tussock Type.

Wet tundra habitats occur in areas where the slopes are only
of the order of 1-2 degrees and the resulting poorly developed drainage
conditions are reflected in a water table which is close to the ground
surface. This vegetation type is found primarily on the floors of the
major depressions and on the surfaces of the sand headlands, but it also
occurs locally along flats associated with the raised beach lines and around the margins of some areas of polygonal ground. In these sites the underlying soils are typically cold, grey silts or clays, and the surface is mantled with a litter of raw humus.

The vegetation of these areas is dominated by plants of the sedge (Cyperaceae) family and the Sheathed Cotton-grass or 'Niggerhead' (Eriophorum vaginatum) in particular. This plant exhibits a characteristic tussock form (Plate III-D), up to 35-40 centimetres (14.0-15.5 ins.) high and as much as 30-35 centimetres (12-14 ins.) across at the crown. Each tussock is a single plant and consists of a mass of dead and living organic material overlying a small plug of mineral soil. The roots form a tightly woven mat penetrating down into this mineral soil. The spacing of the tussocks is variable and they are separated by shallow troughs ranging in width from 10-75 centimetres (4.0-29.5 ins.). Where best developed, on slopes of 1-2 degrees, the tussocks occur in close juxtaposition and account for as much as 90 per cent of the vegetation cover. The floors of the intervening troughs may be occupied by small pools of standing water, raw organic debris or saturated pads of moss (chiefly Sphagnum and Hypnum species). Other plants of minor importance found within this same habitat, and particularly in the slightly drier sites such as elevated moss polders or the sides of the individual tussocks, include the Arctic White Bell-heather (Cassiope tetragona), Narrow-leafed Labrador-tea (Ledum palustre ssp. decumbens), Glandular Birch (Betula glandulosa), Common Crowberry (Empetrum nigrum), Arctic Wintergreen (Pyrola grandiflora), and the willows (Salix pulchra, S. reticulata).
V. Hummock-Tussock Transition Type.

Whereas the major extent of both the Dryas-Hummock and Eriophorum-Tussock vegetation types is easily identifiable, the margins are frequently blurred by extensive transition zones involving considerable interdigitation with each other. On slopes of 2-4 degrees the tussocks become smaller and further apart, accounting for only 20-40 percent of the plant cover. The inter-tussock areas become less moist, and there is an increase in the number and variety of other species and Cassiope tetragona in particular. Large earth hummocks, with floristic associations similar to those described in the Dryas-Hummock type, and bare mud boils are intermingled with the tussock forms. Finally, on slopes above 4 degrees the tussocks are gradually eliminated and the vegetation becomes of the Dryas-Hummock type.

VI. Stream Course Willow Thickets.

The majority of the stream courses are occupied by narrow strips of willow growing in a substratum of moist organic material and occasionally sandy-gravel (Plate IV-A). Such sites are nearly always amply supplied with water, receiving runoff from the melting snow in the spring and early summer, and are kept moist throughout the rest of the summer by seepage from the thawing ground. The typical vegetation association consists of a fairly dense thicket of willows, chiefly the Diamond-Leaf Willow (Salix pulchra) and the Northern Willow (S. glauca var. niphoclada), ranging from 0.5 to 1 metre (1.5 to 3.0 feet) high. The strip is commonly less than 5 metres (16 feet) wide, although it frequently expands to many times this figure at stream junctions and at the intakes and outlets of some of the lakes. In these locations, the
Plate IV

VEGETATION TYPES

A. STREAM COURSE WILLOW THICKETS.
Stream course marked by a narrow ribbon of willow species. Darker patches on the slopes in the centre of the photograph also show the Cassiope Snowpatch vegetation type.

B. SEDGE - MOSS FLATS.
Typical vegetation association found on the floors of the larger depressions, consisting of an almost featureless mat of mosses together with the Creeping Sedge, Arctic Marsh Willow and Alpine Bearberry.

C. MUDSLUMP COMMUNITIES.
Dark area on the upper right side of the photograph represents an active mudslump. The foreground is dominated by almost pure stands of the Marsh Fleawort. The scar of a former mudslump, dominated by grasses, can be seen in the centre background.

D. MUDSLUMP COMMUNITIES.
The vegetated floor of a former mudslump dominated by grasses. The old headwall in the background has been colonized by the Dryas Hummock vegetation.
willows may reach heights of as much as 2 metres (6.5 feet). Beneath the willows, the ground cover consists primarily of mosses (chiefly *Sphagnum* sp.) together with the Common Horsetail (*Equisetum arvense*) and the occasional 'niggerhead' tussock (*Eriophorum vaginatum*). Other species found in this same habitat, but of minor importance, include the Lapland Reedgrass (*Calamagrostis lapponica*), Lowly Fleabane (*Erigeron humilis*), Alpine Foxtail (*Alopecurus alpinus*) and the Northern Anemone (*Anemone parviflora*) and Richardson's Anemone (*A. richardsonii*).

VII. Sedge-Moss Flats.

Sedge-moss flats are developed in areas of impeded drainage as found on the floors of the larger depressions, around the margins of areas of polygonal ground, and bordering the willow thickets of the stream courses. In the upper portions of the stream profiles, this vegetation association frequently replaces the willow thicket type. The substratum is composed entirely of organic material which is usually saturated. Spongy mosses (*Sphagnum squarrosum*, *S. warnstorfiyanum*, *Tomenthypnum nitens* and *Hypnum callichroum*) are the dominant constituents of the flora and locally they may be the only plants present. Usually, however, they are found in association with the Creeping Sedge (*Carex chordorrhiza*) and the Arctic Marsh Willow (*Salix arctophila*) (Plate IV-B). Minor local relief in this habitat is provided by the growth of elevated moss polders, and these slightly drier sites support more extensive covers of the Alpine Bearberry (*Arctostaphylos rubra*), together with the Arctic Wintergreen (*Pyrola grandiflora*) and the Arctic Blueberry (*Vaccinium uliginosum*).

VIII. Mudslump Communities.

Mudslumps are large amphitheatre-like depressions formed by
the melting out of tabular bodies of segregated ground ice. Since coastal
recession is the major agency responsible for the exposure of these ice
bodies, the vegetation type associated with these features is largely con­
fined to coastal locations. Because of the high ice to mineral soil ratio
in these exposures, melting produces large quantities of excess water and
very little debris to accumulate on the floor of the slump. Prominent
headwalls formed in the slump persist for long periods after it becomes
inactive, so that a precise delineation of the habitat is often a simple
procedure. Vegetation associations in these mudslumps appear to be
related to colonization stages once the slump has become inactive, and
they can be subdivided into a number of sequential types.

Active mudslumps are characterized by large quantities of ice
exposed in the headwall, and the floor of the slump is covered to varying
degrees with a mobile layer of fluid mud. Most of the surface is bare
except for the presence of clumps of vegetation, hummocks and willows,
which have been detached intact from the rim of the slump. Away from the
ice face, the liquid mud is generally restricted to well-defined mudflows,
and the less active mud surfaces are rapidly colonized by almost pure
stands of yellow Marsh Fleawort (*Senecio congestus*) (Plate IV-C). This
species grows gregariously even in places where fresh mud and silt are
continually being deposited by streams of water coming from the active
slump face. Other plants found in this moist environment include the
Arctic Butterbur (*Petasites arcticus*), Langsdorf's Lousewort (*Pedicularis
langsdorffii*), Marsh Felwort (*Lomatogonicum rotatum*), Arctic Cotton-grass
(*Eriophorum scheuchzeri*), Scentless Mayweed (*Matricaria ambigua*) and the
Black-tipped Groundsel (*Senecio lugens*). In slightly drier areas, though
still moist, the above species are gradually replaced by the Alpine
Hedysarum (Hedysarum alpinum americanum), Arctic Dock (Rumex arcticus), Tilesius's Wormwood (Artemesia tilesii), Tawny Arctophila (Arctophila fulva), Kotzebue's Grass of Parnassus (Parnassus kotzebuei) and Anderson's Alkali Grass (Puccinellia andersonii).

The next stage of the colonization process develops when the floor of the mudslump is no longer subjected to mudflows or to deposition by running water. The surface of the mud becomes extremely hard and dry, and is often traversed by networks of desiccation cracks. Soil conditions are typical of the disturbed nature of the habitat, consisting primarily of mineral soil with patches of organic material irregularly distributed at depth. The percentage of bare ground ranges from 20-50 per cent, being least where the surface has been inactive for longer periods of time.

Where the mudslump as a whole is no longer active, the old headwall may be partially covered by Dryas-Hummock vegetation sliding down from the surface above. The typical vegetation of these areas is a dense cover of grasses (Plate IV-D), of which the following species were the most prominent: Violet Wheat Grass (Agropyron latiglume), Spiked Trisetum (Trisetum spicatum), American Hare's Ear (Bupleurum americanum), Smoothing Whitlow Grass (Draba glabella), Arctagrostis (Arctagrostis latifolia) and the Sheathed Alkali Grass (Puccinellia vaginata). Other species found in the same habitat include the Northern Asphodel (Tofieldia coccinea), Arctic Lychnis (Melandrium affine), Macoun's Poppy (Papaver keelei), Pale Paint Brush (Castilleja pallida ssp. elegans), Maydell's Oxytrope (Oxypotis maydeliana), Alpine Milk-vetch (Astragalus alpinus), Long-stalked Stitchwort (Stellaria longipes), Fingered Buttercress (Cardamine digitata), Low Northern Rockcress (Braya humilis ssp. arctica), Northern Tansy-mustard (Descuirainia sophioides), Mackenzie's Hedysarum (Hedysarum alpinum americanum).
mackenzii), Beringian Chickweed (Cerastium beeringianum), Dawson Hemlock Parsley (Conioselinum cnidiifolium), Acutish Jacob's Ladder (Polemonium acutiflorum), Reddish Sandwort (Arenaria rubella) and the Milfoil (Achillea borealis).

Following even greater periods of stability the ground supports a continuous cover of vegetation and the old headwall is similarly mantled with Dryas-Hummocks. Soil conditions still show the effects of the disturbed nature of the habitat, but they tend to be moister and there is a thin organic accumulation at the surface. The grass vegetation is eventually replaced by dense willow thickets composed mainly of the Northern Willow (Salix glauca var. niphoclada), Alaskan or Felt-leaf Willow (S. alaxensis) and the Net-veined Willow (S. reticulata). Beneath, and between, these willows is a scant ground cover comprised mainly of mosses together with the Common Horsetail (Equisetum arvense) and the Arctic Lupin (Lupinus arcticus). This type of vegetation association is also widely distributed along many of the stabilized bluffs, many of which formerly underwent active recession by a process similar to that operating in active mudslumps.

IX. Strand Communities.

Strand communities also constitute one of the most distinctive vegetation types and, like the mudslumps, are easily identifiable on aerial photographs. They are also relatively simple to delineate since they generally abut quite sharply against the other vegetation types with little or no transition zone in between. Four sub-types, two major and two minor, make up the strand communities.

The minor sub-types, too small to be shown effectively on
Figure 10, include the active beaches and coastal bluffs; two locations which, together with the active mudslumps, account for most of the un-vegetated areas on the island. Active beaches, composed of coarse sands, gravels and boulders are well-drained and subjected to ice scouring in the fall and winter months and wave abrasion during the summer. They also may be the sites of deep snow accumulation where it is piled in drifts against the bluffs. The net effect of these adverse environmental conditions is to keep the beaches almost completely devoid of any plant growth except for a few isolated clumps at the base of some of the cliffs. Actively retreating sections of the coastline are also vegetation free except for isolated clumps detached from the cliff edge during the retreat process. Stabilized cliffs, usually resulting from the formation of protective sandspits at the foot of the cliff, support a vegetation cover proportionate to their period of stability. The cliffs composed of fine-grained sediments, containing abundant ground ice, have already been discussed under the heading of mudslump communities. On the sand headlands, sections of the coastline that were actively retreating until relatively recent times, still have 40-50 per cent of the cliff face bare of any vegetation cover. The remaining surface supports a light cover of mosses (chiefly Psilopilum cavifolium) together with the Radiate Saxifrage (Saxifraga radiata), Arctic Avens (Dryas integrifolia) and the Sudeten Lousewort (Pedicularis sudetica). Bluffs which are also the sites of late-lying snowpatches, especially on northeast-facing exposures, are characterized by the appearance of such additional species as the Lowly Fleabane (Erigeron humilis) and the Small-flowered Prairie Rocket (Erysimum inconspicuum). Towards the upper portions of these same cliffs the vegetation is dominated by the Diamond-leaf Willow (Salix pulchra) which appears to colonize the cliffs from the
headland surface above. Cliffs which have been protected from erosion for much longer periods of time are covered by dense willow thickets similar in composition to those found in the final colonization of the mudslumps.

The greatest areal extent of the strand communities is developed in the vicinity of the large sandspits (Figure 10) where two major habitats can be distinguished: gravel bars and marsh-lagoons (Plates V-A, V-B). The seaward margins of the sandspits have the same unfavourable environment as the active beaches, and are subject to the same diurnal and seasonal fluctuations of ice-scouring and wave abrasion. On the higher, less-active portions of the gravel accumulations, as much as 90 per cent of the surface may still be devoid of any form of vegetation cover. Among the first plants to colonize these surfaces is the Lyme Grass (*Elymus arenarius ssp. mollis*), the fibrous roots of which penetrate deeply into the well-drained substratum. Other characteristic species in this environment, and commonly forming prostrate mats on patches of finer material or rafts of washed organic material eroded from the adjacent sections of the coastline, include the Sea-beach Sandwort (*Arenaria peploides*), Low Chickweed (*Stellaria humifusa*), Beringian Chickweed (*Cerastium beeringianum*), Common Scurvy Grass (*Cochlearia officinalis*) and the Alpine Milk-vetch (*Astragalus alpinus*). On the inner margins of the sandspit, bordering the marsh-lagoon, the percentage of bare ground decreases, and there is an increase in the number and variety of the plant species. The habitat is still subject to periodic flooding during storm surges, but the sands are finer, moister and frequently contain admixtures of organic material. Lyme Grass is less prominent in these areas in which the most common species are the Arctic Marsh Willow (*Salix arctophila*), Creeping Sedge (*Carex chordorrhiza*), Beach Pea
Plate V

VEGETATION TYPES

A. STRAND COMMUNITIES.

Sterile surface of the sandspit is locally colonized by tufts of Lyme Grass and rafts of the Sea-beach Sandwort. The marsh-lagoon habitat occurs between the sandspit and the stabilized coastal bluffs in the background.

B. STRAND COMMUNITIES.

The vegetation cover increases on the finer sands along the inner margins of the sandspit, and the species interdigitate with those of the lagoon-marsh habitat.

C. LOW-CENTRED POLYGON.

The margins of the central depression, often occupied by water, and the islands of vegetation in the centre are composed of Aquatic Sedge and Fisher's Dupontia. The raised edge of the polygon is characterized by lichens and mosses.

D. HIGH-CENTRED POLYGON.

Convex polygon centre is covered by marbeloid hummocks of lichen and moss together with the Glandular Birch and willow species. The wedge area in the foreground is almost completely overgrown with sedges, mosses and willows.
(Lathyrus maritimus), Alpine Hedysarum (Hedysarum alpinum americanum), Scentless Mayweed (Matricaria ambigua), Dawson Hemlock Parsley (Conioselinum cniidiifolium), Pale Paint Brush (Castilleja pallida ssp. elegans), Seaside Crowfoot (Ranunculus cymbalaria var. alpinus), Arctic Fireweed (Epilobium latifolium), Roseroot (Sedum rosea ssp. integrifolium), Gentian (Gentiana arctophila) and the Greenland Primrose (Primula egaliksensis). Locally, the junction between the sandspit and the coastal bluff is marked by the growth of tall stands of the Alaskan or Felt-leaf Willow (Salix alaxensis) as much as 3-4 metres (9-12 feet) tall.

The other major habitat within the strand communities includes the marsh-lagoons enclosed behind the gravel bars. These sites, which are also subject to periodic flooding, have numerous bodies of shallow, open water which may or may not be connected to the sea. The soil, which is almost always saturated, contains abundant organic material, partly due to the natural accretion of vegetation debris, and partly as a result of the accumulation of waterborne material eroded from the coastal bluffs. Many of the plants bordering the moist sand areas are also found along the periphery of the lagoons but they are gradually replaced by a flora in which the most characteristic species are the Lowly Fleabane (Erigeron humilis), Common Horsetail (Equisetum arvense), Hair-grass-like Reedgrass (Calamagrostis deschampsioides), Arctic Rush (Juncus alpinus), Alkali Grasses (Puccinellia andersonii, P. phryganodes, P. vaginata), Common Mare's tail (Hippuris vulgaris), Marsh Cinquefoil (Potentilla palustris), Sea-Pink (Armeria maritima ssp. arctica), Yellow Marsh Saxifrage (Saxifraga hirculis), Nodding Saxifrage (S. cernua), Pallas's Buttercup (Ranunculus pallasii) and Fisher's Dupontia (Dupontia fisheri).
X. **Polygonal Ground.**

The plant communities associated with polygonal ground are intimately related to the stage of development of these features and can be classified accordingly. The earliest stage with which a distinctive vegetation pattern can be linked is the low-centred type (Plate V-C), the characteristic form of which consists of a central depression surrounded by a raised rim of variable width and height. In many polygons of this type, the central depression may be occupied by a shallow body of open water which may be completely devoid of any vegetation. This water frequently has a distinctive golden-brown colour due to certain algae, the accumulated remains of which form a layer of soft, oozy material on the floor of the pool. Occasionally, isolated tufts of the Aquatic Sedge (*Carex aquatilis*) and Fisher's Dupontia (*Dupontia fisheri*) occur as small islands of vegetation in the water bodies. Around the shallower margins of the pool the vegetation is dominated by the Tawny Arctophila (*Arctophila fulva*) together with the Aquatic Sedge and Fisher's Dupontia. The surrounding ridges are composed of peat, and this drier habitat is reflected in a completely different floral assemblage dominated by mosses and lichens. The major vascular species growing on the ridges include the Veiny-leafed Willow (*Salix phlebophylla*), Alpine Bearberry (*Arctostaphylos rubra*), Cloudberry (*Rubus chamaemorus*), Arctic Blueberry (*Vaccinium uliginosum var. alpinum*), Mountain Cranberry (*Vaccinium vitis-idaea*), Narrow-leafed Labrador-tea (*Ledum palustre ssp. decumbens*), Glandular Birch (*Betula glandulosa*), Arctic Avens (*Dryas integrifolia*) and the Arctic White Bell-heather (*Cassiope tetragona*).

The troughs overlying the ice-wedges between the polygons also contain bodies of open water which may be partially filled with a shallow
blanket of Sphagnum and sedge. In this aquatic habitat, the flora is similar to that found in the central pools, together with the Gmelin's Buttercup (Ranunculus gmelinii), Marsh Marigold (Caltha palustris ssp. arctica), Richardson's Anemone (Anemone richardsonii), Meadow Bittercress (Cardamine pratensis), Nodding Saxifrage (Saxifraga cernua) and the Common Cotton-grass (Eriophorum angustifolium).

With increasing passage of time the central pools of the low-centred polygons become progressively shallower and they are gradually colonized by the plants growing around their margins. The accumulation of vegetable debris, chiefly the Aquatic Sedge and Fisher's Dupontia, raises the level of the central area until it is flat and equal in height to the surrounding ridges. At the same time, there is a lateral spreading of the species from the dry ridges onto the central area, and this association gradually replaces the sedges. Further accumulation of peat intensifies the dry nature of the habitat, and may eventually give the polygon the convex form of the high-centred type (Plate V-D).

SUMMARY

The arctic tundra vegetation of Garry Island can be classified into ten major types which can be related to variations in the physical character of the habitats. Drainage conditions and geomorphic activity, acting singly or, more often in combination, appear to afford the best criteria for the delineation of the habitats, with the possible exception of the 'Alnus crispa' type where shelter may be the most important factor.

Seven of the habitats, corresponding to the 'Dryas-Hummocks', 'Cassiope Snowpatch', 'Eriophorum Tussock', 'Hummock-Tussock Transition',...
'Stream Course Willow Thickets', and 'Sedge-Moss Flats' vegetation types, are recognized primarily on the basis of variations in the moisture conditions of the habitat. The influence of geomorphic activity is also evident in each of these types however. Hummocks and tussocks are generally regarded as products of frost action, and the microrelief produced by the development of these features is sufficient to produce wet and dry habitats within the same vegetation type. In the case of the hummocks, the influence of the microrelief factor becomes less pronounced towards the lower, moister sections of the slopes, and it virtually disappears, as in the 'Cassiope Snowpatch' type, in the sites of late-lying snow patches. The 'Stream Course Willow Thickets' and the 'Sedge-Moss Flats', vegetation types are found along the floors of the valleys and depressions into which intermittent runoff and moisture seepage are channelled throughout the summer months.

In the 'Strand Communities', 'Mudslump Communities' areas of 'Polygonal Ground', the physical character of the habitat is determined primarily by geomorphic activity. Within the 'Strand Communities' two contrasting habitats can be identified: these are the gravel bars, which are subject to diurnal and seasonal fluctuations of wave-abrasion and ice-scouring, and the marsh-lagoon areas, enclosed and protected by the bars, where the conditions are relatively quiescent. Differences in the vegetation patterns of these two environments may also be related to variations in the moisture conditions of the substrate. In the 'Mudslump Communities' there appears to be a distinctive sequence of plant colonization related to the length of time that the mudslump has been inactive. Thus the vegetated sections of active mudslumps are dominated by almost pure stands of the Marsh Fleawort (*Senecio lugens*).
Once the floor of the mudslump is no longer subjected to mudflows or
deposition by running water, the surface becomes colonized by a cover of
grasses and, following even greater periods of stability, this grass vege-
tation is eventually replaced by willow thickets. In the areas of poly-
gonal ground, the growth of ice-wedges also results in the production of
wet and dry habitats, and another distinctive plant colonization sequence
can be identified through which the polygons are transformed from low-
centred to high-centred types.

The statistical validity of the percentages for the dominant
plant species in each vegetation type is limited due to the subjective
method of visual estimation employed. Despite the crude nature of these
percentages however, it was possible to recognize four species, *Dryas
integrifolia*, *Alnus crispa*, *Cassiope tetragona* and *Eriphorum vaginatum*,
as being diagnostic of specific vegetation types on the basis of their
dominance of the plant composition. Though not dominated by a single
species, the 'Strand Communities' were also characterized by a distinctive
floral assemblage probably due to the stricter tolerance conditions
produced by the presence of saline or brackish water. Furthermore, little
difficulty was encountered in determining the areal extent of the
communities in the field. Even where the classification was based on
changes in the drainage conditions of the habitat, it was found that the
contacts between adjacent vegetation types were quite distinct. Only
where the lower slopes were gentle, and drainage conditions changed
gradually, were there extensive transition zones necessitating the
recognition of the 'Hummock-Tussock Transition' type. Where the habitat
was determined primarily by geomorphic activity, the vegetation type
usually formed a distinct unit and there was no problem in determining the
precise areal extent of the plant community.
CHAPTER IV

PERMAFROST CONDITIONS

The term permafrost, or permanently frozen ground, is used to describe a thickness of soil or other superficial deposit, or even of bedrock, at a variable depth beneath the surface of the earth in which a temperature below freezing has existed continually for a long time (from two to tens of thousands of years). This thermal condition may be wholly contemporaneous with the existing climate, or it may be a relic feature which was initially developed during an earlier, colder climate and has been preserved under the negative mean annual temperatures of the present climate.

Approximately one-fifth of the land area of the world, and as much as one-half of the area of Canada, is underlain by permafrost in either a continuous or discontinuous distribution. Whilst the areal extent of the perennially frozen ground is reasonably well established in Canada, only a limited amount of data is available relating to its vertical thickness. Largely as a result of townsite investigations and oil exploration drilling programmes, more is known about the thickness of


the frozen ground in the Mackenzie Delta area than in other parts of the Canadian Arctic. Brown has reported permafrost to depths of 76-91 metres (250-300 feet) in the vicinity of Inuvik, and Mackay thicknesses of 107-122 metres (350-400 feet) near Arctic Red River and Fort McPherson.  

Temperature data from a drill hole near Tununuk on Richards Island reveal that permafrost occurs to a depth of 366 metres (1200 feet). Thus, although no information is available concerning the thickness of permafrost on Garry Island, it may well be that the frozen ground extends to a depth of 305 metres (1000 feet) or more beneath the centre of the island.

The precise thickness of the frozen ground is of relatively minor importance to the geomorphic processes operating in permafrost areas. Of greater significance is the active layer which thaws during the summer months and is subject to alternate freezing and thawing during successive seasons. The thickness of this active layer is quite variable and is related to differences in slope, natural drainage, aspect, type of vegetation cover and the nature of the material beneath the surface vegetation.

The purpose of this chapter is to describe a number of investigations made on Garry Island designed to: (1) determine the rate and depth of thaw in the active layer under varying slope, exposure, 


4Mackay, J. Ross. Personal communication, October, 1968.
vegetation, moisture and microrelief conditions; and (2) measure the ground temperatures at selected sites in this active layer in order to better understand the processes involved in the development of earth hummocks.

These studies were accomplished primarily by making comparative investigations of the depths of thaw, at various times throughout the summer, beneath each of the major vegetation types identified in Chapter III. The depth to the frost table was determined by using a metal rod as a probe. Similar measurements, though using a network of wooden stakes and on a daily basis, were also made to examine changes in the configuration of the frost table beneath the surface of a small vegetation plot 5.6 square metres (60 square feet) in area. To complement these observations, excavations were made to determine the nature of the substrate. Five strings of thermistor cables were also installed to different depths beneath the centres of an earth hummock, two inter-hummock depressions, and a mud boil and adjacent depression, in an attempt to detect variations in the thermal regime of the seasonally thawed layer.

DEPTH OF THAW MEASUREMENTS

A number of authors have investigated and documented the effects of a vegetation cover on the thermal regime of the underlying
These investigations have shown that the influences of the vegetation cover on permafrost are exceedingly complex, and that quantitative evaluations of these influences are extremely difficult to obtain.

One of the most readily measurable characteristics of these relationships is the variation in the thickness of the active layer beneath contrasting surface covers. The data presented in Table V show some of the variations in the thickness of the active layer beneath the major vegetation types on Garry Island as they were recorded at the end of the 1964 field season. As the table shows, the greatest depths of thaw were encountered in areas having little or no vegetation cover, as exemplified by the bare ground of some of the mudslumps and active sandspits. In both these type localities, the position of the frost table was in excess of one metre (3 feet) below the ground surface and, in the case of the sandspit areas, could not be detected by probing. The influence of the type of mineral soil in the substrate may also be reflected in the greater depth of thaw in the coarse sands and gravels of the strand areas compared with the silt- and clay-sized material found on the floors of the mudslumps.

Comparisons of the thickness of the active layer beneath the


TABLE V

DEPTH OF THAW BENEATH THE MAJOR VEGETATION TYPES, GARRY ISLAND, SEPTEMBER 1, 1964.

<table>
<thead>
<tr>
<th>Vegetation Type</th>
<th>Depth of Thaw (Cms.)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Dryas-Hummock</strong></td>
<td></td>
</tr>
<tr>
<td>Hummocks</td>
<td>45 - 65</td>
</tr>
<tr>
<td>Depressions</td>
<td>22 - 30</td>
</tr>
<tr>
<td>Mud Boil</td>
<td>70 - 75</td>
</tr>
<tr>
<td><strong>Eriophorum Tussocks</strong></td>
<td></td>
</tr>
<tr>
<td>Tussocks</td>
<td>45 - 60</td>
</tr>
<tr>
<td>Depressions</td>
<td>18 - 25</td>
</tr>
<tr>
<td><strong>Sedge-Moss Flats</strong></td>
<td></td>
</tr>
<tr>
<td></td>
<td>18 - 22</td>
</tr>
<tr>
<td><strong>Stream Course</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Willow Thickets</strong></td>
<td>25 - 30</td>
</tr>
<tr>
<td><strong>Mudslump Communities</strong></td>
<td></td>
</tr>
<tr>
<td>Bare Ground</td>
<td>&gt; 100</td>
</tr>
<tr>
<td>Grass Cover</td>
<td>45 - 50</td>
</tr>
<tr>
<td><strong>Strand Communities</strong></td>
<td></td>
</tr>
<tr>
<td>Sandspits</td>
<td>&gt; 100</td>
</tr>
<tr>
<td>Lagoon Flats</td>
<td>40 - 50</td>
</tr>
</tbody>
</table>
vegetated surfaces show that the amount of thawing was greatest beneath the domed centres of the Dryas-Hummocks and tussock-like forms of the Sheathed Cotton-grass (*Eriophorum vaginatum*). In actual fact, it is extremely difficult to provide a meaningful average for these localities, and this is illustrated by the wide ranges indicated in Table V. The depth of thaw is influenced considerably by the microrelief factor and, in general, the larger the hummocks and the more prominent the tussocks, the greater the depth of thaw. Because of the variations introduced by this microrelief factor, it is, however, virtually impossible, using simple probing techniques, to evaluate precisely the relative effects of the various vegetation types on the thermal regime of the underlying ground.

One noticeable aspect of Table V is the uniformly lower depths of thaw recorded beneath vegetation associations with a considerable percentage of moss in their floral composition. As described in the previous chapter, the shallow depressions between the earth hummocks are frequently dominated by mosses and accumulations of organic debris. Such localities were characterized by depths of thaw which were frequently less than one-half of those recorded in the raised centres of the hummocks. This relationship was also observable on the summit areas and on south-facing slopes where the hummocks were often more subdued in form and, consequently, the microrelief factor was of relatively less importance. A similar pattern was also observed in the *Eriophorum*-Tussock communities where the inter-tussock depressions were again characterized by depths of thaw which were usually less than one-half of those measured in the adjacent tussocks. Further evidence of the insulating property of a moss cover on the underlying ground was demonstrated
by the fact that the average depth of thaw beneath the major vegetation types was lowest, 18-22 cms. (7.0-8.5 ins.), beneath the featureless surfaces of the sedge-moss flats.

The figures presented in Table V, despite their limitations, corroborate the findings of other investigators and demonstrate that the thickness of the active layer is greatest beneath bare ground surfaces, and that a cover of mosses allows less heat to penetrate to greater depths in the underlying ground than does a vegetation cover dominated by vascular plants.

The above descriptions are related to measurements of the thickness of the active layer at a number of selected, isolated points. To complement these observations, a vegetation plot was established during the 1964 field season, to examine the influences of some of these same factors on the configuration of the frost table over a small contiguous area.6 The dimensions of this plot were approximately 0.9 metres by 6.1 metres (3 feet by 20 feet), and it was located on the lower part of the west-facing slope of a valley, close to the junction with the valley floor. A series of wooden stakes, graduated in centimetres and spaced at 30 cm. (1 foot) intervals, were installed in the plot and were driven into the ground until they were halted by the frost table, at which point the depth of penetration was recorded. This procedure was repeated on a daily basis over the period July 9 - August 28, 1964.

Figure 11 illustrates the surface contours and the vegetation

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6The vegetation plot constituted part of the field study programme of Dr. J. Ross Mackay and Dr. J.K. Stager, of the University of British Columbia, and I am most grateful to them for permission to refer to their studies in this thesis.
Figure 11

VEGETATION PLOT

SURFACE CONTOURS
above datum

VEGETATION TYPES

- Lichens
- Heather
- Cranberry
- Crowberry
- Ground Birch
- Labrador Tea
- Tussock
- Willows
- Heather
- Moss

1-21 Location of Profiles
Contour Interval 5 cms.

Scale
0 50 20 40 60 80 Cms.

Bare Ground
cover of this plot. Most of the surface was dominated by the dwarf shrubs of the **Ericaceae** or Heath Family including the Alpine Bearberry (*Arctostaphylos rubra*), Arctic White Bell-heather (*Cassiope tetragona*), Narrow-leafed Labrador-tea (*Ledum palustre ssp. decumbens*), Arctic Blueberry (*Vaccinium uliginosum var. alpinum*), and Mountain Cranberry (*Vaccinium vitis-idaea*), together with minor quantities of lichens and Arctic Avens (*Dryas integrifolia*). This flora covered a number of subdued earth hummock forms, similar to those described in the previous chapter, the central portions of which were elevated by 20-30 cms. (8-12 ins.) above the surrounding depressions. The plant associations occurring in these depressions were composed principally of mosses and the Arctic White Bell-heather. The other principal constituent of the flora of the vegetation plot was the distinctive tussock-like forms of Sheathed Cotton-grass (*Eriophorum vaginatum*). The central part of the plot was dominated by the unvegetated surface of a prominent mud boil.

The depth of thaw measurements are shown in Figure 12, showing the configuration of the frost table at the beginning of August and September, 22 and 53 days after the installation of the stakes respectively. The isolines on these maps represent the depth of the frost table beneath the ground surface, and the higher values thus correspond to depressions in the frost table. The greater detail shown in the map for August 1, reflects the number of observations made at intermediate points between the stakes, whereas the map for September 1 was based solely on the data obtained in the excavations of the profiles shown in Figure 13.

Reference to Figure 12 reveals that the depth of thaw was quite variable and imparted an irregular topography to the top of the
Figure 12

VEGETATION PLOT

POSITION OF FROST TABLE (DEPTH BELOW GROUND SURFACE IN CMS.)

Aug. 1, 1964

Sept. 1, 1964

Contour Interval 5 cms.

Scale

0 20 40 60 80 Cms.
Figure 13

VEGETATION PLOT
DEPTH OF THAW PROFILES

For locations of profiles see Figure 11
frozen ground. Comparison with Figure 11 shows that the contours of the frost table do not parallel the configuration of the ground surface. In general, the upper surface of the frozen ground occurs at greater depths where the ground surface is highest, and it lies at shallower depths where the ground surface is lowest. Thus the frost table is frequently deeper beneath the earth hummocks and tussocks than beneath the intervening depressions.

The inverse relationship between the configurations of the ground surface and the permafrost surface undoubtedly reflect, at least in part, the significance of the microrelief factor. The elevated nature of the earth hummocks and tussocks allows heat to penetrate the ground laterally from their sides, as well as vertically from the top, thus contributing to a greater rate of thawing. The undulations in the frost table cannot, however, be attributed solely to the influence of variations in the microrelief. The rate and total depth of thaw are also influenced by the type of material occurring in the substrate. Figure 13 shows a total of 21 cross-sectional profiles in the vegetation plot which were excavated at the beginning of September, 1964, when the position of the frost table was approximately coincident with the upper surface of the perennially frozen ground. As these profiles illustrate, there is apparently also an inverse relationship between the total depth of thaw and the thickness of organic material in the profile. Thus the greatest depth of thaw, in excess of 75 cms. (29.5 ins.) was recorded beneath the surface of the mud boil where the substrate was composed entirely of mineral soil, and the next greatest depths of thaw were recorded beneath the earth hummocks which were also composed predominantly of mineral soil. As the ratio of organic material to mineral
soil in the profiles increased, the depth of thaw decreased accordingly, and the elevated parts of the permafrost surface, corresponding to the lowest depths of thaw in Figure 12, occurred beneath the accumulations of organic material occupying the depressions in the ground surface.

**Earth Hummock Experiments.**

In the preceding paragraphs the discussion was centred on variations in the total depth of thaw beneath each of the major vegetation associations found on Garry Island. These variations, whilst providing an indicator of the effects of contrasts in the floristic composition, must equally reflect the numerous other climatic and terrain features, which also combine to influence the depth of thaw from the ground surface to the permafrost table.

A number of experiments was undertaken during the 1965 field season to investigate some of the factors influencing the rate and depth of thaw beneath the centre of a typical earth hummock. Specifically these experiments were designed to examine the influence of the vegetation cover, living and dead, and the addition of controlled quantities of water on the thickness of the thawed layer.

The first set of experiments was designed to examine the role of the vegetation cover alone. An attempt was also made to differentiate between the effects of the surface mat of living vegetation and the underlying accumulation of dead organic material which frequently overlies the domed core of mineral soil in a typical earth hummock. The success in making this distinction was restricted by the fact that, as others have noted, it is extremely difficult to delineate the boundary between these
living and dead components of the organic layer.\(^7\)

Six hummocks were selected for these studies, each of which occupied a similar position with respect to aspect and general location on the topographic slope profile. In addition, to eliminate the possible influence of variations produced by the microrelief factor, each of the hummocks was of very similar dimensions, being about 70 cms. (27.5 ins.) in length, 55 cms. (21.5 ins.) in width and having a raised centre which projected about 35 cms. (14 ins.) above the level of the adjacent inter-hummock depressions. From two of these hummocks, the surface vegetation layer, averaging 7 cms. (3 ins.) in thickness, was removed leaving the raised centre still covered by a layer of 4-5 cms. (1.5-2.0 ins.) of peat material. From two of the other hummocks the complete organic cover of living vegetation and peat was removed, exposing the mineral soil core. The remaining two hummocks were left intact to act as controls.

The depth from the ground surface to the frost table was recorded at weekly intervals over a six-week period and the results are shown in Table VI. In this table, the values given for the hummocks from which the organic layer was either partially or completely removed do not include the thicknesses of the removed layers.

As the figures in Table VI indicate the response to the partial or complete removal of the organic material was quite rapid. During the first week of the experiment, although characterized by only

TABLE VI

DEPTHS OF THAW BENEATH EARTH HUMMOCKS ON GARRY ISLAND,


<table>
<thead>
<tr>
<th>Type of Cover</th>
<th>Depth of Thaw (Cms.)</th>
<th>July</th>
<th>August</th>
<th>Total Change</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(a) Natural</td>
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<td></td>
<td>19</td>
<td>26</td>
<td>2 9 16 23 30</td>
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<td></td>
<td></td>
<td>51</td>
<td>54</td>
<td>55 58 59 60 61</td>
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<td>52</td>
<td>54</td>
<td>54 57 58 60 62</td>
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<td></td>
<td>+10</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>+10</td>
</tr>
<tr>
<td>(b) Living Vegetation Removed</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>40</td>
<td>49</td>
<td>51 55 56 59 60</td>
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<td></td>
<td></td>
<td>39</td>
<td>48</td>
<td>50 53 55 57 58</td>
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<td></td>
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<td></td>
<td>+20</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>+19</td>
</tr>
<tr>
<td>(c) Complete Organic Layer Removed</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>37</td>
<td>47</td>
<td>51 55 57 59 61</td>
</tr>
<tr>
<td></td>
<td></td>
<td>36</td>
<td>47</td>
<td>50 54 55 58 59</td>
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<td></td>
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<td></td>
<td></td>
<td>+24</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>+23</td>
</tr>
</tbody>
</table>
85 thawing degree-days, the level of the frost table in the control hummocks was lowered by 2-3 cms. (1 inch), whereas in the hummocks from which the organic layer was either partially or completely removed the corresponding values were 9 cms. (3.5 ins.) and 10-11 cms. (4.0-4.5 ins.) respectively. Over the remainder of the observation period the differential rates were not always as marked, though they remained quite significant. The depth of thaw beneath the centres of the control hummocks increased by an average of 10 cms. (4 ins.) during the six-week period in response to a total of 560 degree-days of thawing. The removal of the surface mat of living vegetation resulted, however, in a lowering of the frost table by an average of 19.5 cms. (7.5 ins.), whilst the complete removal of the entire organic layer produced an average increase in the depth of thaw of 23.5 cms. (9.5 ins.) over the same time span.

Assuming that the subsurface conditions in each of the hummocks were the same, with respect to the type of mineral soil and frozen moisture content, these figures demonstrate, quite conclusively, the important influence which a surficial layer of organic material exerts on the thermal regime of the underlying ground. The complete removal of this insulating layer of vegetation increased the depth of thaw by 135 per cent over that recorded in the control hummocks. Even where this layer was only partially removed, the corresponding increase in the depth of thaw was 95 per cent. Due to the afore-mentioned problem

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8 Thompson, H.A. (1963) "Freezing and Thawing Indices in Northern Canada", Proc. of the First Canadian Conference on Permafrost, Ottawa, April 17-18, 1962, p. 21. The number of degree-days for any one day is the difference between the average daily air temperature and 32°F and thawing degree-days occur when the former exceeds 32°F.
of distinguishing accurately the boundary between the living and dead components of the organic material, it cannot be stated affirmatively that the differential between the two percentage increases can be attributed solely to the relative influences of these two constituents. It does indicate, however, that a thin layer of peat, 4-5 cms. (1.5-2.0 ins.) in thickness, had sufficient insulating effect to result in a depth of thaw which was almost 17 per cent less than that recorded in the hummock from which the organic layer was removed entirely.

The second part of the experiment was designed to examine the influences of aspect and moisture, singly and in combination, on the depth of thaw. A total of twenty earth hummocks was used for these investigations and again, in an attempt to achieve as much uniformity in the other variables as possible, each hummock was of approximately the same dimensions and occupied a similar position on the topographic slope profile. Nine of these hummocks were located on the southwest-facing slope of a valley, and another nine were located on the opposing northeast-facing slope. Three of the hummocks in each of these groupings were sprinkled with one litre of water daily, another three received two litres of water each day whilst the remaining three, left unwatered, were used as controls. In addition, two hummocks, also located on the southwest-facing slope, were partially or completely stripped of their vegetation cover, as described in the previous experiment, and were sprinkled with one litre of water daily. The temperature of the water was recorded before it was applied to the hummock surfaces. These observations were continued over a five-week period, and the depths of thaw were measured at weekly intervals. One additional problem was introduced by these measurements, insomuch as the insertion of the metal probe to the frost table might
leave an open conduit presenting easy penetration of the water. An attempt was made to prevent this by plugging the hole at the surface with a length of wooden dowelling, but it cannot be claimed that these precautions were completely successful.

The results of this project are presented in Table VII, and as the figures show the experiments yielded inconclusive results. Comparisons of the measurements in the control hummocks on the two opposing slopes reveal no influence of aspect as the average lowering of the frost table, 8.67 cms. (3.5 ins.) was identical on both sides of the valley. Similarly, the addition of water to the hummock surfaces appeared to have few contrasting effects on the two sides of the valley. On the southwest-facing slope the application of one litre of water daily resulted in a slight increase in the amount of lowering of the frost table, whereas a doubling of the quantity of water applied produced a slight decrease. In each case the differences represented a deviation of less than one centimetre from the value recorded in the control hummock. The application of water to the hummocks on the northeast-facing slope resulted in slight decreases in the depth of thaw irrespective of the quantity of water added, though, once again the differences from the control value involved a maximum of one centimetre. Although the magnitude of the changes is small, it appears that the application of one litre of water to the hummocks on the northeast-facing slope produced a larger reduction in the depth of thaw than the application of two litres.

Comparisons of Tables VI and VII give some indication of the effects of adding water to the surfaces of earth hummocks from which the vegetation cover had been either partially or completely removed. In the hummock from which only the surface layer of living vegetation was
<table>
<thead>
<tr>
<th>Type of Treatment</th>
<th>Depth of Thaw (Cms.)</th>
<th>July</th>
<th>August</th>
<th>Net Change</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>26</td>
<td>9</td>
<td>16</td>
</tr>
<tr>
<td><strong>A. Southwest-facing Slope</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(a) Control</td>
<td></td>
<td>50</td>
<td>51</td>
<td>53</td>
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<tr>
<td></td>
<td></td>
<td>53</td>
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<td>58</td>
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<td>52</td>
<td>53</td>
<td>57</td>
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<tr>
<td>(b) 1 Litre of water added daily</td>
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<td>48</td>
<td>49</td>
<td>52</td>
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<tr>
<td>(c) 2 Litres of water added daily</td>
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<td>48</td>
<td>50</td>
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<td>56</td>
<td>59</td>
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<tr>
<td>(d) Surface vegetation removed. 1 litre added daily</td>
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<td>43</td>
<td>45</td>
<td>49</td>
</tr>
<tr>
<td>(e) Complete organic layer removed. 1 litre added daily.</td>
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<td>44</td>
<td>45</td>
<td>48</td>
</tr>
<tr>
<td><strong>B. Northeast-facing Slope</strong></td>
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<tr>
<td>(f) Control</td>
<td></td>
<td>52</td>
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<td>55</td>
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<tr>
<td></td>
<td></td>
<td>49</td>
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<td>52</td>
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<tr>
<td>(g) 1 Litre of water added daily</td>
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<td>50</td>
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<td>59</td>
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<tr>
<td>(h) 2 LITRES of water added daily</td>
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<td>55</td>
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<td>58</td>
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stripped, the observed lowering of the frost table amounted to 9 cms. (3.5 ins.), whereas the removal of the entire organic material resulted in a corresponding figure of 10 cms. (4 ins.). In each case these were 1.5 and 3.0 cms. (0.5 and 1.0 ins.) less than those recorded over the same time period in the identically prepared hummocks to which no water was added.

The application of 35 or 70 litres of water respectively, with an average temperature of 8.25°C, to the two groups of hummocks over the five-week period represented a considerable potential source of heat to the underlying ground. Unfortunately, it is impossible to infer whether this water was able to penetrate into the mineral soil core of the hummock, or whether it was absorbed by the superficial mantle of organic material. In the case of the hummock from which the vegetation cover was removed completely, it was readily observed that, despite the light sprinkling nature of the application, some of the water was lost by surface runoff. The effect of any water which was able to penetrate the organic layer would also depend on the existing moisture content of the soil. The replacement of the air in the pores of the soil by water would have the effect of increasing the heat capacity of the soil, thereby reducing the amount of heat available to warm the soil at greater depths.

It seems reasonable to infer, however, that most of the water was probably absorbed by the layers of organic material and was subsequently lost by evaporation, including evapotranspiration. Since the evaporation process requires heat, which may be drawn from the surrounding atmosphere, vegetation or soil, Tyrtikov has postulated that this may result in a lowering of the air temperature near the ground surface and
consequently a reduction in the warming of the soil. Whether or not this postulate can be applied to such a small area as the surface of a hummock is debatable, but, if valid, it may account for the slight cooling effect of the water applied to the hummocks.

GROUND TEMPERATURE MEASUREMENTS

The preceding discussion has been based on observations made in the rate and total depth of thaw beneath each of the vegetation types. A series of observations was also made to determine more precisely the variations in the thermal regime of the thawed layer above the permafrost and the uppermost parts of the permafrost.

Five sites were selected for these measurements to evaluate the specific effects of certain types of surface cover. Three of the sites were in one of the typical hummock-depression associations found in the Dryas-Hummock vegetation type. The raised centre of the earth hummock, almost circular in plan and 60-70 cms. (23.5-27.5 ins.) in diameter, reached elevations of 30-35 cms. (12-14 ins.) above the level of the surrounding depressions, and supported a surface cover dominated by Arctic Avens, Narrow-leafed Labrador-tea, Arctic White Bell-heather, together with a few lichens and dry moss pads. This vegetation was rooted in a surficial layer of 10-15 cms. (4-6 ins.) of organic material overlying a prominent domed core of mineral soil extending down to the frost table. The adjacent depressions, 50-60 cms. (19.5-23.5 ins.) in length and 20-40 cms. (8.0-15.5 ins.) across, were dominated by the growth of sphagnum mosses

resting on a substratum of organic material which extended down almost to
the base of the active layer. The remaining two sites were located in a
large mud boil and adjacent depression. The mud boil surface, 1.4-1.5
metres (4.5-5.0 feet) in diameter, was largely devoid of vegetation and,
at the centre, rose approximately 20-25 cms. (8-10 ins.) above the
surrounding moss-filled depressions.

At each of the sites, ground temperatures were recorded daily
by cables of bead thermistors. The cables, each of which consisted of
five thermistors, were encased in lengths of rubber tubing which were
sealed to prevent the entry of soil moisture. One of the cables was
installed in the earth hummock and two in the adjacent inter-hummock
depressions. The uppermost thermistor on each of these cables was placed
at a depth of 10 cms. (4 ins.) below the ground surface. Beneath the
raised centre of the earth hummock the other four thermistors were spaced
at intervals of 25 cms. (10 ins.) to a depth of 110 cms. (43.5 ins.)
whilst beneath each of the depressions the remaining thermistors were
spaced at intervals of 15 cms. (6 ins.) to a depth of 75 cms. (29.5 ins.).
In the mud boil, the uppermost thermistor was installed at a depth of
23 cms. (9 ins.) below the ground surface and additional beads were spaced
at intervals of 30 cms. (12 ins.) to a depth of 113 cms. (44.5 ins.).
Only two thermistors were installed in the depression adjacent to the mud
boil at depths of 14 cms. (5.5 ins.) and 24 cms. (9.5 ins.) beneath the

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All the thermistors used were manufactured by the Yellowstone Springs Instrument Company, Series 401 beads, with a tolerance at
0°C of ± 0.2°C. The thermistors were calibrated by the B.C. Research
Council and by Dr. J. Ross Mackay of the Department of Geography, U.B.C.
Field readings were taken with a small bridge, also constructed by
Dr. Mackay, and calibrated to read with an operational range of ± 0.1°C.
Figure 14 shows the mean ground temperature profile and the amplitude of the ground temperature fluctuations for four of these sites for the period July 1 to September 12, 1965. Table VIII also shows the mean, maximum and minimum ground temperatures, together with the date of occurrence of the maximum and minimum temperatures recorded by each of the thermistors.

Each of the sites exhibits a similar pattern in which the highest mean and maximum ground temperatures, and the greatest amplitude of ground temperature fluctuations, were recorded by the thermistors located at the shallowest depth beneath the ground surface. Strict comparisons of the thermal regimes at each of the sites are limited by the absence of ground surface temperature data. With this consideration in mind, Figure 14 shows that the highest mean temperature and greatest fluctuations were recorded at a depth of 10 cms. (4 ins.) beneath the surface of the earth hummock. Such a simple comparison of the profiles is misleading, however, since the uppermost thermistor in the cable installed in the mud boil was located at a depth more than twice that of the uppermost thermistor installed in the earth hummock. It is probable, therefore, that the mean summer ground temperature, and the amplitude of the temperature fluctuations, at a depth of 10 cms. (4 ins.) beneath the surface of the mud boil, were of even greater magnitude than those

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The means and amplitudes shown for the mud boil are actually for the slightly longer period June 26 to September 12, 1965. In the depression adjacent to the mud boil, continuous readings were only recorded at a single depth, due to a faulty thermistor at a depth of 14 cms. (5.5 ins.). As a result, the profile at the fifth site could not be plotted.
Figure 14
MEAN GROUND TEMPERATURES AND GROUND TEMPERATURE FLUCTUATIONS

- MUD BOIL
- EARTH HUMMOCK
- DEPRESSION

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Levels of Thermistors.
Mean Ground Temperature Profile
Amplitude of Ground Temperature Fluctuations
<table>
<thead>
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<th>Depth below surface (cms.)</th>
<th>Mean</th>
<th>Max.</th>
<th>Date of Max.</th>
<th>Min.</th>
<th>Date of Min.</th>
<th>Amplitude</th>
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<tr>
<td>23</td>
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<td>June 26</td>
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<td>-1.4</td>
<td>June 26</td>
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<td>June 26</td>
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<td>-0.5</td>
<td>Sep. 1*</td>
<td>-3.7</td>
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<td>15.9</td>
<td>July 8</td>
<td>-0.4</td>
<td>Sep. 3</td>
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<td>Sep. 1</td>
<td>-2.9</td>
<td>July 1</td>
<td>2.1</td>
</tr>
</tbody>
</table>

* Earliest date at which temperature was attained.
actually recorded at the hummock site. The most valid comparison of near surface temperatures, which can be made reliably, is between the hummock and adjoining inter-hummock depressions. The mean ground temperature recorded at a depth of 10 cms. (4 ins.) beneath the hummock was 2.7°C and 3.5°C higher than that recorded at an equivalent depth beneath the surfaces of the two depressions. The maximum ground temperature and the amplitude of the temperature fluctuations also exceeded those in the depressions by more than 5°C.

Each of the sites also exhibits a similar pattern in which the mean ground temperature and the amplitude of the temperature fluctuations decreases with increasing depth beneath the ground surface. As Figure 14 shows, however, the rate of decrease is not the same at each of the sites. The most gradual decrease occurred beneath the centre of the mud boil where the mean ground temperature did not reach 0°C until depths of 75-80 cms. (29.5-31.5 ins.) below the surface, and the amplitude of the fluctuations was still in excess of 3°C at a depth of 113 cms. (44.5 ins.). These figures contrast with those beneath the surface of the earth hummock where the mean ground temperature reached 0°C at a depth of 60-65 cms. (23.5-25.5 ins.), and amplitudes in excess of 3°C were not experienced below these depths. The most rapid decrease of ground temperatures, and diminishing of temperature fluctuations, occurred beneath the surfaces of the inter-hummock depressions. The mean ground temperature dropped to 0°C at the shallow depths of 30-35 cms. (12-14 ins.) and amplitudes in excess of 3°C were not recorded below 25-30 cms. (10-12 ins.) from the ground surface.

The graphs in Figure 14 and the values in Table VIII summarize the absolute magnitude of the ground temperature fluctuations at each of
the sites over the whole of the observation period. The general picture conceals the number and depth of penetration of minor temperature fluctuations which bear a distinct temporal relationship to the changes in the mean daily air temperature. Figures 15 and 16 present a more detailed picture of these minor fluctuations in the ground temperatures, by showing the pattern of isotherms over the same time period.

The near surface layers at each of the sites underwent a number of definite cycles of warming and cooling over time periods ranging from three to nine days. The largest fluctuations were recorded beneath the surface of the earth hummock (Figure 15A), where temperature changes of as much as 7-8°C in one day were observed at a depth of 10 cms. (4 ins.). Maximum temperatures achieved during these cycles reflected an almost immediate response to a warming of the ambient air temperatures with lag factors involved being less than one day. The pattern of these minor fluctuations also shows a decrease in amplitude with increasing depth beneath the ground surface. At a depth of 35 cms. (14 ins.), the largest fluctuations, over similar time periods, were only of the order of 2-3°C or approximately 25 per cent of those recorded at a depth of 10 cms. (4 ins.). Below depths of 50 cms. (19.5 ins.) most of these minor fluctuations are damped out completely, and the thermal regime shows a generally progressive warming trend, with the extremes of the temperature record occurring at the beginning (coldest) and end (warmest) of the observation period.

The pattern of isotherms in the ground beneath the surface of the mud boil (Figure 16A) is difficult to compare with those of the earth hummock, due to the previously-mentioned difference in the depth spacing of the temperature sensors. Broad comparisons with the thermal regime in
Figure 15
GROUND TEMPERATURE PATTERNS IN AN EARTH HUMMOCK AND ADJACENT DEPRESSION (°C)
Figure 16

GROUND TEMPERATURE PATTERNS IN A MUD BOIL (°C)

Depth in Cms.
the earth hummock, however, show that the pattern of daily fluctuations is similar and extends to greater depths. Figure 16A also shows the deeper penetration of the 0°C isotherm beneath the surface of the mud boil, almost to a depth of one metre, compared with a maximum depth of 70-75 cms. (27.5-29.5 ins.) beneath the centre of the earth hummock.

The decrease of the minor temperature fluctuations beneath one of the inter-hummock depressions is shown in Figure 15B. Although the near surface layer experienced as many cycles of alternate warming and cooling as the earth hummock, comparisons of the temperature maxima, during corresponding time periods, show that the near surface ground temperatures beneath the depressions were 5-7°C cooler than at similar depths beneath the centre of the earth hummock. As was noted in the case of the overall seasonal amplitudes, the minor temperature fluctuations penetrated to much shallower depths beneath the depressions than at any of the other sites. Very few of the warm cycles, for example, were felt below a depth of 25 cms. (10 ins.), and the maximum penetration of the 0°C isotherm was to a depth of 40 cms. (15.5 ins.) during the last week of August. Below 25 cms., the ground temperatures indicated a gradual, progressive warming with the extreme temperatures, shown in Table VIII, being recorded at the beginning and end of the observation period.

The data obtained in the ground temperature studies are in accordance with the results of the depth of thaw measurements. Just as vegetation, including the microrelief factor, exerts a marked influence on the total depth of thaw to the frost table, so it also influences the ground temperature patterns in the active layer and uppermost parts of the underlying permafrost. Thus the total depth of thaw was greatest, and ground temperatures were highest, beneath unvegetated surfaces and
earth hummocks where the substrate was composed predominantly of mineral soil. Conversely, the depth of thaw was lowest and the ground temperatures were several degrees cooler beneath areas covered by mosses, and in which the substrate was composed almost entirely of organic material. In such localities, these lower values are probably related to the greater insulating qualities of organic material compared to mineral soil, the shade produced by microrelief factors, and the afore-mentioned effects of the evaporation process.

**Freeze-Back in the Active Layer, 1964.**

The graphs of the temperature penetrations and isotherms at each of the sites show a temporary re-freezing of the surface layers in response to below-freezing air temperatures at the end of August and during early September, 1965. Ground temperatures beneath the hummock centre were at or just below $0^\circ C$ to depths of 20-25 cms. (8-10 ins.) for three days. The cooling was not as pronounced in the inter-hummock depressions where the ground was frozen for one to two days to depths of 10-15 cms. (4-6 ins.) below the ground surface. This cooling of the ground from the surface downwards was replaced by a period of above-zero temperatures as the mean air temperature rose above the freezing point again.

Unfortunately, it was not possible to remain in the field and record the pattern of the freeze-back at each of the sites. A partial record of the freeze-back was obtained, however, for the mud boil site for the three-month period September to December 1, 1964, using temperature values recorded by an arctic thermograph. The full significance of the following discussion of the pattern of isotherms shown in Figure 16B
is limited by the absence of any data pertaining to ambient air temperatures on the island. To partially offset this problem, the temperature data for Tuktoyaktuk have been used as a guide.

The mean daily air temperature at Tuktoyaktuk fell below freezing during the second week in September. The start of the freeze-back on Garry Island probably began at this time and, as Figure 16B shows, the 0°C isotherm had penetrated to a depth of 23 cms. (9 ins.) by September 17. Figure 16B also indicates that a further lowering of the ground temperature did not take place until the beginning of the second week of October. This slowdown in the rate of downward penetration of the cold may be attributed to a slight warming in the air temperatures, which fluctuated around 0°C for most of the second half of September, but it may also be related to the moisture conditions of the soil. Once the soil temperatures reach the freezing point, a further loss of heat may temporarily be compensated by the release of the latent heat of fusion as any moisture in the soil is converted to ice. This condition has been termed the 'zero curtain'.

The duration of the zero curtain condition is dependent primarily upon the quantity of moisture in the soil. Cook has also suggested that it may be aided by the development of hydrostatic pressure in the unfrozen material, between the downward penetrating frost line and the underlying permafrost table, resulting in a lowering of the freezing point of the soil. Recent investigations by Mackay, using soil pressure cells, indicate, however, that the role of the hydrostatic

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12 Muller, S.W. (1947) op. cit., p. 17.
pressure factor is limited by the low soil strength, and hence any depression of the freezing point is quite small.14

Any depression of the freezing point, either by hydrostatic pressure or by the presence of minerals in the soil water, complicates the identification of the zero curtain condition in the temperature record. Since the tolerance of the thermistors was also $+0.2^\circ\text{C}$ at $0^\circ\text{C}$, and the ground temperature records showed a number of days which fell in the range $-0.2^\circ\text{C}$ to $+0.2^\circ\text{C}$, the identification of the zero curtain condition in Figure 16B is only an approximation.

With these considerations in mind, the duration of the zero curtain at a depth of 23 cms. (9 ins.) beneath the surface of the mud boil was interpreted as being in the order of 18 days (September 18 - October 6). Meteorological records for Tuktoyaktuk indicate that the mean daily air temperature dropped permanently below freezing on October 9, and in response to the lower air temperatures the downward penetration of the cold was resumed. The $0^\circ\text{C}$ isotherm reached a depth of 53 cms. (21 ins.) beneath the surface of the mud boil on October 26, and the position of the permafrost table, at a depth of approximately 85 cms. (33.5 ins.), was reached on November 6. These dates correspond to indices of -245 and -536 degree-days of freezing respectively following the drop in air temperatures permanently below $0^\circ\text{C}$. Approximate calculations of the duration of the zero curtain effect show that it lasted for about 36 days (September 20 - October 26) at a depth of 53 cms. (21 ins.), and achieved its maximum duration, of as much as 48 days, at the permafrost table. This general pattern of an increasing length of the zero curtain time period with depth

14 Mackay, J. Ross. Personal communication, October, 1968.
can be related to a slowdown in the rate of freezing, which is proportional to the square root of time, and also probably to the presence of greater quantities of soil moisture in the lower parts of the active layer. The slow penetration of the frost line provides abundant time for the formation of segregated ice lenses encountered in excavations made during the summer months.

The ground was frozen solidly by the end of the first week in November and, as Figure 16B shows, the penetration of the cold continued with only minor fluctuations through to December 1. Once temperatures of -2 to -3°C were attained, the lag factor at depth was gradually diminished to the order of seven days throughout the complete profile. The temperature record was terminated on December 1st, and no further data were available concerning the continuation of the cooling process.

The record of ground temperatures from the moss-filled depression surrounding the mud boil was far less complete due to a malfunctioning of the recorder. From the extremely limited ground temperature data available, it appears that the frost line in this depression had penetrated to a depth of 24 cms. (9.5 ins.) by about the beginning of October. A comparison with the ground temperatures recorded at a similar depth beneath the unvegetated surface of the mud boil, indicates that the frost line had penetrated to this level almost two weeks prior to this date. The evidence suggests, therefore, that a surface layer of vegetation, whilst reducing the amount of thawing which takes place during the summer months, also retards the initial penetration of the cold temperatures during the winter.
SUMMARY

The thickness of the active layer on Garry Island is greatest, in excess of one metre (3 feet), in areas having little or no vegetation cover and where the substrate is composed primarily of mineral soil. In the vegetated areas of the island, the maximum depths of thaw, 60-70 cms. (24-28 ins.), occurred beneath the raised centres of the 'Dryas-Hummocks' and the tussock-like forms of the Sheathed Cotton-grass (Eriophorum vaginatum). In such localities, the thickness of the active layer is influenced considerably by the microrelief factor and, in general, the larger the hummocks or tussocks the greater was the depth to the permafrost table. Uniformly lower depths of thaw were recorded beneath vegetation associations with a substantial component of moss in their floral composition, as in the 'Sedge-Moss Flats' and the inter-hummock or inter-tussock depressions, where the permafrost table was encountered at depths ranging from 18-30 cms. (7-12 ins.) below the ground surface. The lower depths of thaw are believed to be due to a combination of an organic substrate beneath the moss, a higher moisture content and greater shade produced by the microrelief.

These observations were supported by evidence from studies of the changing position of the frost table beneath a small vegetation plot approximately 0.9 by 6.1 metres (3 by 20 feet) in dimension. Comparisons of contour maps of this plot reveal an inverse relationship between the configurations of the ground surface and the permafrost table reflecting, at least in part, the significance of the microrelief factor. Elevated parts of the ground surface allow heat to penetrate laterally from the sides as well as vertically from the top. Excavations of the plot also
reveal an inverse relationship between the depth of thaw and the relative abundance of organic material in the substrate. The greatest depths of thaw, in excess of 75 cms. (29.5 ins.), occurred beneath the raised, unvegetated surface of a mud boil where the substrate was composed entirely of mineral soil. As the ratio of organic material to mineral soil in the substrate increased, the depth of thaw decreased accordingly, and the elevated parts of the permafrost table were located beneath accumulations of organic material flooring depressions in the ground surface.

The complete removal of the vegetation cover from two earth hummocks resulted in an increase in the depth of thaw of 135 per cent over that recorded in control hummocks during a six-week period. Where the vegetation cover was only partially removed, in an attempt to distinguish between the living and dead components of the organic layer, the corresponding increase in the depth of thaw was 95 per cent. Difficulties in determining accurately the boundary between the living and dead organic material limit the conclusiveness of the data, but the figures indicate that a layer of peat, 4-5 cms. (1.5-2.0 ins.) thick, was sufficient to produce a depth of thaw which was 17 per cent less than that recorded in the hummocks from which the organic layer was removed completely.

The type of vegetation cover, microrelief and composition of the substrate exert a similar influence on the thermal regime of the active layer and uppermost parts of the underlying permafrost. Ground temperature data obtained for four sites on the island - a mud boil, an earth hummock and two inter-hummock depressions - exhibit a similar pattern in which the mean summer ground temperatures, and the amplitudes of the temperature fluctuations, decreased with increasing depth beneath the ground surface. The rate at which these decreases take place, however, is
far from uniform. The most gradual rate occurred in mineral soil beneath the unvegetated surface of the mud boil, where the mean ground temperature for the summer did not reach 0°C until a depth of 75-80 cms. (29.5-31.5 ins.), and the amplitude of the temperature fluctuations was still in excess of 3°C at a depth of 113 cms. (44.5 ins.). In comparison, a similar mean temperature and magnitude of amplitude occurred at a depth of 60-65 cms. (23.5-25.5 ins.) beneath the vegetated surface of the earth hummock. The most rapid decrease of ground temperatures and diminishing of the temperature fluctuations took place in the organic substrate beneath the moss-covered surfaces of the inter-hummock depressions, where a mean summer ground temperature of 0°C occurred at the shallow depth of 30-35 cms. (12-14 ins.), and amplitudes in excess of 3°C were not recorded below 25-30 cms. (10-12 ins.) from the ground surface.

Ground temperature data for the freeze-back in the mud boil for the winter of 1964 indicate that the zero curtain condition lasted approximately 18 days at a depth of 23 cms. (9 ins.) below the ground surface, 36 days at a depth of 53 cms. (21 ins.), and achieved a maximum duration of as much as 48 days at the permafrost table. This general pattern of an increasing length of the zero curtain time period with depth can be related to a retardation of the rate of freezing and also probably to the presence of greater quantities of soil moisture in the lower parts of the active layer. The slow penetration of the frost line also provides abundant time for the formation of the segregated ice lenses encountered in excavations made during the summer months.
CHAPTER V

GEOMORPHOLOGICAL PROCESSES

The purpose of this chapter, and one of the major aims of this thesis, is to assess some of the contemporary geomorphic processes operating on Garry Island. The specific processes considered involve problems associated with coastal recession, mudslumps, mudflows, and the genesis of certain types of patterned ground. In each case, wherever applicable, an emphasis is placed on quantitative measurements of the rates of operation of these processes, and an evaluation of the various factors, especially the role of permafrost, influencing these rates.

COASTAL RECESSION

Rapid recession of many sections of the coastline between Point Barrow, Alaska and Langton Bay, N.W.T., in post-glacial and historic times, has been described by several authors citing both geomorphological and historic evidence. Leffingwell, using maps of the region drawn by Franklin in 1826, reported erosion rates of as high as 30.5 metres (100 feet) a year at Cape Simpson, northern Alaska, but concluded that the average retreat was less than 1.2 metres (4 feet) per annum.¹ MacCarthy measured rates of retreat at Point Barrow ranging from 0.0-4.5 metres

Mackay has described both geomorphological and historical evidence indicating similarly rapid rates of recession along sections of the coastline in the Yukon and Northwest Territories. Despite the abundant evidence of coastal retreat, many of the rates quoted are at best approximations only. In the historic evidence there are problems relating to the accuracy of the early maps. Unfortunately, many of the distances from the coastline to identifiable control points were estimated, thus precluding the calculation of accurate rates of coastal recession. Similarly, the lack of a detailed chronological scale for the area limits the validity of rates using geomorphic evidence based on the total recession which has taken place in a post-glacial period of, as yet, unknown duration.

Accordingly, a programme of field studies was conducted on Garry Island for the dual purposes of: (1) providing exact data on the annual rates of recession along coastlines of varying lithology; and (2) investigating the nature and relative importance of the specific processes which contribute to the observed retreat values.

Evidence of Coastal Recession.

Active recession of the Garry Island coastline, apart from a few local mudslump features, currently is restricted primarily to the exposed west and northwest coasts, and to segments of the prominent sand

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Mackay, J. Ross (1963) "Notes on the shoreline recession along the coast of the Yukon Territory", Arctic, Vol. 16, pp. 195-197.
headlands on the north side of the island. In these localities, the bluffs are characterized by numerous fresh exposures with debris piles on, and at the base of, the cliff face, and by an absence of vegetation on the faces.

Historical evidence of coastal recession on Garry Island is available but does not yield satisfactory quantitative data. In a recent survey, Captain Ages, of the C.S.S. 'Richardson', refers to a number of hydrographic control points, located in 1930, in the outer Mackenzie Delta. Of twelve control points shown on Pelly, Kendall and Whale (Grassy ?) Islands in the original survey, Captain Ages concluded that four, all located on Pelly Island, had disappeared possibly due to erosion; in six cases, only remnants of the markers remained with the collapse frequently attributable to caving in of the ground; and only two of the markers were still intact. The possibility exists that one of the markers on Kendall Island had been moved by natives. The 1930 survey also shows the locations of three hydrographic control points on Garry Island. Ground checks made in 1965 revealed no trace of one of these markers; a second (possibly dismantled) was found on the floor of an inactive mudslump, but the third marker, located on the southeast tip of the island, was found collapsed on the cliff face (Plate VI-A). Unfortunately, no figures are available indicating the distance of these control points from the original cliff edge, thereby preventing any reliable estimate of the rate of coastal recession in recent historic time.

Additional evidence of coastal recession in historic times can

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4Ages, Captain A.B. Personal communication to Dr. J. Ross Mackay, July 4, 1965. The exact date of the hydrographic survey in 1930 is not mentioned.
Plate VI

COASTAL RECESSION

A. Collapsed hydrographic marker on the cliff face along the south coast of Garry Island.

B. Coastal recession along the northwest coast of Garry Island showing a truncated lagoon.

C. Measurement of coastal recession rates. Stakes along the northwest coast of Garry Island.
possibly be inferred from the 'disappearance' of islands in the outer delta area. Sir Alexander Mackenzie's account of the panoramic vista from Whale (Garry) Island includes a reference to two small islands in the ice lying to the northwest by compass direction. Even allowing for discrepancies in Mackenzie's directional observations, there are no islands in that position today and it is possible that they have been removed subsequently by wave action. Alternatively, as Mackay has suggested, Mackenzie may have observed two patches of dirty ice covered with debris derived from the Mackenzie River break-up. Albert Oliver, a native of the area and our guide during the field seasons, also tells of the former existence of a small island, to the south of Hooper Island, which has been destroyed by wave action during his lifetime.

Topographic and stratigraphic evidence of coastal recession over even longer periods of time yields similarly inconclusive results with respect to actual rates of cliff retreat. Features developed along the northwest coast of the island include an example of a truncated lagoon, with a straight coastal shore barrier and actively receding cliffs on either side (Figure 17 and Plate VI-B). Raised shoreline features can also be traced to the coast in many places, but no evidence of them can be found

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Figure 17

COASTAL RECESSION FEATURES
NORTHWEST COAST OF GARRY ISLAND

- Truncated lagoon
- Tundra polygons on cliff top
- Stake #95
- High centred polygons
- Stake #31
- Tundra polygons on cliff top
- Stake #1

Mudslumps
Polygonal Ground

Scale 1:17,000 (Approximate)
in stratigraphic sections exposed in the cliffs. The longitudinal profiles of stream courses draining towards the south coast of the island exhibit a characteristic steepening of the gradient in the lower parts, which may also reflect the effects of downcutting in response to coastal recession combined with mudslump development. Exposures along the northwest coast of the island reveal a sequence of lacustrine and peat deposits (see Figure 6), and the tops of the high bluffs in places along this same coastline are capped by a truncated series of tundra polygons (Figure 17). The lacustrine and peat deposits, exposed in these sections, are indicative of freshwater conditions which could only have been produced as a result of ponding behind a barrier, since removed, on the seaward margins of the topographic depressions in which they occur.

Thus there is abundant evidence that the coastline of Garry Island has undergone considerable recession in recent geological and historical time. Just how much recession has taken place, and at what rate, is impossible to determine, but there may be some significance in the fact that the depth of water for 16-24 kilometres (10-15 miles) off the shore of Garry Island averages only 4-5 fathoms. Such uniformly shallow depths may represent an extensive platform of marine planation, though the possibility that it is partially a product of deltaic sedimentation cannot be excluded.

**Coastal Stake Measurements.**

Approximately 2.5 kilometres (1.5 miles) of coastline were staked during the summer of 1964 to provide quantitative data on the current rates of coastal recession (Plate VI-C). A total of 95 stakes was installed along the exposed northwest coast where the bluffs locally
exceed 30.5 metres (100 feet) in height (Figure 17). The positions of these stakes were checked periodically throughout each of the summers, and the amount of recession was recorded in metres at the beginning and end of each summer. Since the exposures in these bluffs covered a wide range of materials, ranging from fine-grained silts and clays, which in places contained large bodies of segregated ground ice, to coarse sands and boulders, the data permitted a ready evaluation of the effect of lithology on the rate of recession. Comparisons of the amount of retreat recorded at the beginning of the summer with that recorded at the end of the previous summer also gave indices of variations in the rate of recession through the year.

Average retreat figures tabulated in August, 1966 showed that the average rate of recession for the 95 stakes was 6.4 metres (20.8 feet), or 2.1 metres (6.9 feet) per annum. As expected, however, this average covered a wide range of individual values which ranged from a maximum of 30.6 metres (100.4 feet) to a minimum of 0.1 metres (0.3 feet).

Thirty-one of the stakes were located along a series of high bluffs ranging from 9.0-30.5 metres (30-100 feet) in elevation. Sediments exposed in this section of the coastline were fine sands, silts or clays, and bodies of segregated ground ice were visible where the cliffs cut across the distinctive scars of old mudslumps. In addition, the tops of the cliffs also cut across a series of well-developed, high-centred tundra polygons and associated network of ice-wedges. The highest retreat values were recorded where the cliffs intersected and reactivated a number of old mudslumps, and in these localities the average recession amounted to 20.9 metres (68.6 feet), or 7 metres (23 feet) a year. (Plate VII-A). The effects of segregated ground ice were shown by the variable rates of recession
Plate VII

COASTAL RECESSION

A. Coastal recession is most rapid where wave action has exposed bodies of segregated ground ice in the cliffs.

B. The detachment of a high-centred tundra polygon from the cliff top as a result of melting along the lines of the ice-wedges.

C. Mineral soil pinnacle left by the collapse of a tundra polygon.
recorded by five stakes (#21-25), located across one of these slumps. During the summer of 1964, no ground ice was exposed at these points and the average retreat during the summer was only 3.5 metres (11.5 feet). Towards the end of that summer, however, a large block was detached from the cliff face, and ground ice was visible throughout the summers of 1965 and 1966, when the average rate of retreat increased to 10.5 metres (34.4 feet) per summer. High rates of recession were also observed in the areas of tundra polygons, where melting along the lines of the ice-wedges resulted in an average recession of the cliff face of 15.3 metres (50 feet), or slightly more than 5 metres (16.4 feet) a year. The intervening polygonal peat units showed a much more variable rate of recession, averaging only 2.5 metres (8.2 feet) a year. Since the peat in these polygons forms a coherent unit, which is undermined by thawing of the ice-rich basal layers, the rates of recession show a wide range from summer to summer. In any one summer, large overhangs, in the order of several metres, may be produced with little or no material actually being detached from the cliff edge. By way of contrast, the following summer may be characterized by continued undermining and eventual collapse of the complete polygon, and a sudden retreat of the cliff edge by 7-10 metres (23-33 feet) (Plates VII-B and VII-C).

Sediment types exposed in the remaining section of the coastline were much more uniform, and consisted of coarse sands and gravels with minor variations caused by the development of polygonal ground. The average total rate of retreat along this part of the coast amounted to only 2.6 metres (8.6 feet) or less than one metre (3 feet) per annum. The figure is even less, 0.6 metres (2 feet) a year, if a small slump (average 2.7 metres or 8.9 feet), ice-wedges (average 1.2 metres or 4 feet), and
peat sections (average 0.7 metres or 2.3 feet) are excluded from the calculations.

In addition to quantitative values of actual rates of recession, the data also indicate that most of the retreat occurs during the short summer period. For most of the year, sea ice is packed close to the shore, and the bluffs are buried by large snow drifts which persist through late June and early July. The measurements show that fully 60-70 per cent of the observed retreat occurred during the summer months. Unfortunately, it was not possible to remain in the field until freeze-up occurred, when this percentage would be even higher. Much of the retreat recorded between the last observation of one summer and the first observation of the following summer probably represents further detachment of material from the cliff edge during the month of September.

Sand Headland Profile Studies.

Two prominent sand headlands on the north side of the island were selected as suitable sites for detailed studies of cliff profile changes throughout the summer months. These headlands terminate in abrupt cliff faces, 7-12 metres (23-39 feet) high, many sections of which are currently undergoing active recession as is indicated by the numerous fresh exposures and lack of vegetation on the cliff face. Stable sections of the coastline, mantled to some degree with a vegetation cover, can be attributed largely to the development of a protective sandspit formation at the base of the cliffs (Plate VII-A).

The cliffs have a fairly straight, uniform appearance, and are generally devoid of gullying except for the presence of deep 'V'-shaped notches created by the melting out of ice-wedges. The material in these
A. Stabilized cliffs of the sand headland areas protected by sandspits.

B. Profile IV, July 1965, showing the locations of the stakes.

C. Crevices on the sand headland surface prior to the detachment of hummock blocks from the edge of the cliff.

D. Profile I, August 1965, after slumping of the thawed sand had taken place.
headlands is composed predominantly of medium to coarse sands, with intercalated bands of pebbles, gravel, wood and shell fragments. Boulders are generally lacking, but locally they may occur in sufficient quantities to dominate the whole exposure.

Four locations, currently undergoing active recession, were chosen for the profile studies. Each of these profiles was surveyed at the beginning and end of the 1965 field season, and Profile IV was surveyed again during the summer of 1966. The results of these surveys are shown in Figures 18 and 19. To obtain data on cliff profile changes over 1-2 weeks, a procedure was adopted similar to that used by Twidale in his study of river bank erosion in South Australia. At each site, wooden dowelling, approximately 45 cms. (18 ins.) in length and 2.5 cms. (one inch) in diameter, was driven into the cliff face, normal to the surface, and the stakes were spaced at approximately equal intervals with only a small portion of each left exposed (Plate VIII-B). The positions of these stakes on the four profiles are also shown in Figures 18 and 19. In each profile, stake 1 was installed on the headland surface to act as a control point, and the distance to the edge of the cliff was recorded. The remaining stakes on each profile were numbered consecutively from top to bottom of the cliff. Reference to individual stakes in the text also follows the system used by Twidale: e.g. stake (I,4) refers to Profile I, stake 4.

The visible length of the stake was measured and recorded, and at subsequent observations the procedure was repeated so that an increase, or decrease, in the length of the stake exposed indicated whether erosion,

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8 Twidale, C.R. (1964) "Erosion of an alluvial bank at Birdwood, South Australia", Zeitschrift für Geomorphologie, Band 8, pp. 189-211.
Figure 18

SAND HEADLAND PROFILES (I)

PROFILE I

PROFILE II

Profiles on July 5, 1965
Profiles on August 31, 1965
Positions of stakes
Sea Level

SCALE
0 5 METRES
Figure 19

SAND HEADLAND PROFILES (2)

Profiles on July 5, 1965
Profiles on August 31, 1965

Positions of stakes

S.L. = Sea Level

SCALE
0 5 METRES
or deposition, was taking place. These changes, measured over two-weekly periods, were too small to illustrate diagrammatically, and are summarized in Table IX. At the same time as these readings were being made, a metal probe was used to determine the approximate thickness of the thawed layer on the cliff face.

When the profiles were first surveyed in early July, 1965, late-lying snow drifts still remained at the foot of the cliffs and, in Profile I, extended as high as stake (I,8). The absence of any marked concentrations of debris on the snow surface indicated that little or no material had been dislodged from the cliff face prior to the installation of the stakes. Probing revealed that the thawed zone on the cliff face extended to depths of 15-20 cms. (6-8 ins.), producing an unstable layer of loosely-packed sand at the surface.

The general forms of the profiles are shown in Figures 18 and 19. The uppermost morphological facet in each profile consists of a small vertical element, usually 0.5-1.0 metres (1.5-3.5 feet) high, and accompanied by a short overhang reflecting the binding effect of the vegetation on the headland surface. Small earth hummocks dominate this vegetation association, and in many places lunate tension cracks parallel the cliff edge on the landward sides of these hummocks (Plate VIII-C). Below this facet, the profile consists essentially of a fairly uniformly sloping element, of 40-50° inclination, which in many cases extends to the base of the profile where it terminates at the beach level. In other places, however, the junction with the beach may be more or less obscured by fallen

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9 The other, lower stakes on this profile were installed progressively as the snowbank melted.
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<th>Profile II</th>
<th>Profile III</th>
<th>Profile IV</th>
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The figures are in centimetres and refer to the period July 5 - August 22, 1965, when the last measurements were recorded. The figures in brackets for Profile IV indicate the length of stake exposed on August 22, 1966. Negative values refer to erosion of the cliff face, while positive figures represent the accumulation of debris derived from upper sections of the profiles.
debris composed of sand, detached hummocks which show distinct signs of washing by wave action, and driftwood. Occasionally, some of the hummocks come to rest on the cliff face before reaching the beach level, and these are responsible for most of the minor irregularities shown on the profiles.

Comparisons of Figures 18 and 19 and Table IX show that the changes recorded by the stake measurements account for only a minor portion of the total profile changes through the entire summer. For the period July 5 - August 22, 1965, of the 56 stakes installed on the four profiles, a total of 23 experienced an increase in the length of stake exposed, indicating erosion of the upper sections of the profiles. The average rate of erosion recorded by these stakes amounted to 5.4 cms. (2.2 ins.), with maxima of 11.0 cms. (4.3 ins.). A further 24 stakes indicated that deposition had taken place on the lower sections of the profiles, averaging 4.2 cms. (1.7 ins.) and reaching maxima of 6-7 cms. (2.4-2.8 ins.). By way of contrast, measurements taken from the surveyed diagrams of Profiles I - III show that the upper portions of the cliff faces experienced a retreat of 75-100 cms. (29.5-39.5 ins.) over the slightly longer period ending August 31, 1965. The losses, or erosion, recorded by the stake measurements therefore account for only 5-6 per cent of the total profile changes, despite the fact that they cover approximately 85 per cent of the observation period. Similar percentages are also applicable to the rates of deposition recorded on the lower parts of the profiles.

Coincident with these changes indicated by the stake measurements, the depth of the thawed zone on the cliff face increased to 50-65 cms. (19.5-25.5 ins.) by August 1, and to 90-100 cms. (35.5-39.5 ins.) by
August 22. Beginning in late July and early August, prominent cracks, extending for several metres across the face of the cliff and to depths of 10-20 cms. (4-8 ins.), appeared in many places in the upper sections of the profiles. Locally, as in Profile I, the appearance of these cracks was followed by minor slumping action. New cracks also opened up along the boundaries of the hummocks on the headland surface, and pre-existing cracks were widened and deepened as the hummocks tilted bodily towards the cliff edge.

In direct contrast to this long period of relative stability, during which the profiles underwent slow changes, the events observed in Profiles I - III within the last week of August can only be described as catastrophic. By August 31, only the three stakes located on the headland surface as control points remained intact, and the remainder had been completely obliterated by mass slumping of the thawed sand from the upper parts of the cliff faces (Plate VIII-D). In Profiles I and III, the earth hummock at the top of the profile was also detached from the cliff edge. As Figure 19 and Table IX show however, slumping did not take place on Profile IV during that summer, nor the following summer of 1966, and most of the changes observed in this profile are indicated by the additional figures in Table IX. Towards the end of August, 1966, however, the hummock was also detached from the top of this profile, and a number of stakes was either broken or tilted during its fall. No attempt was made to record further changes in Profiles I - III following the slumping, but two stakes were relocated in the upper part of Profile I to see whether slumping occurred again during the summer. These stakes were still in place at the end of August, 1966.
Relevance of the Profile Studies to other Coastal Areas. The sand headlands were chosen for the profile studies because the slow rate of change permitted ample time to study the processes involved. It was evident, however, that similar changes and processes to those observed on the sand headlands also apply to the tracts of staked coastline on the northwest shore of the island. As noted previously, many of the cliffs along this section of the coast are also composed of sands and gravels which locally are capped by varve-like lacustrine sediments and intersected by a network of ground ice-wedges. The retreat figures recorded in these localities correspond well with those made on the sand headlands, and the general appearance of the cliff profiles indicates that the method of cliff retreat is the same.

In the finer-grained sediments the processes are probably the same but differ in degree. This difference can readily be attributed to the higher ice content of these sediments. The larger quantities of water released on thawing of this material, together with the fact that the cliff faces are usually much steeper, and frequently vertical, preclude the accumulation of any appreciable thickness of thawed material at the surface. Frequent probing of the cliffs showed that the thickness of this thawed layer seldom exceeded 10-15 cms. (4-6 ins.). The ice in these sediments is also predominantly pore ice, locally augmented by vein ice along bedding and shear planes, but moisture contents are commonly in the order of 100 per cent by weight, and thawing produces a relatively mobile mud which soon slides to the base of the cliff and provides a fresh exposure. Whereas slumping in the sands may have a maximum frequency of only once during an entire summer, it may occur daily, or more often, in these finer-grained sediments. The rate is even higher in the cliffs with
exposures of segregated ground ice which have moisture contents in the order of several thousand per cent by weight. Thawing of the cliffs in these localities produces large quantities of excess water, and the interval between thawing and slumping of the material to the foot of the cliff reaches a minimum.

Coastal recession in areas where the cliffs intersect well-developed networks of tundra polygons produces a distinctive topography. In such localities, as was the case in the sand headlands, recession takes place most rapidly along the lines of the ice-wedges. Where the polygons are of the high-centred type and are located on the tops of the bluffs, rapid melting also occurs in the basal sections of the polygonal units which also contain large quantities of segregated ice. Melting out of the ice-wedges, with an orientation normal to the cliff edge, exposes additional wedges which lie parallel to the cliff, and the subsequent melting of these leads to an isolation of the polygonal unit from the main face of the bluff. In this way a peat block is formed which rests precariously on a pedestal of mineral soil. Further melting of the high ice-content basal sections of the polygon results in further undermining of the peat block which finally tumbles, usually intact, to the foot of the cliff, leaving behind distinctive pinnacles of mineral soil (Plate VII-C). Under favourable conditions, a complete tundra polygon, up to 10 metres (33 feet) in diameter, may be removed in this manner during the course of a single summer.

**Processes at work in Coastal Recession.**

From the preceding paragraphs, it is quite evident that the coastline of Garry Island is retreating primarily as a result of 'thermal
erosion', or thawing of the frozen ground, accompanied by slumping of the thawed material. Coastal sections composed of sediments with a high moisture content, particularly in the form of ice segregations, are naturally the most susceptible to the sun's rays, and this is readily substantiated by the observed retreat figures.

The material in the sand headlands has a frozen moisture content of only 15-20 per cent by weight, and it was in bluffs composed of these and coarser sediments that the lowest retreat values were recorded. In their frozen state, the water is present in the form of pore ice which acts as a strong cementing agent, but melting of this ice results in a considerable loss of strength and transforms the sand into a loosely-packed mass. As the summer progresses, the frost table retreats further into the cliff face and, as the thickness of the thawed zone increases, the surface layer becomes increasingly unstable due to the fact that the inclination of the cliff face, 40-50 degrees, is considerably steeper than the angle of repose of the sand grains. Frictional resistance between the sand grains may keep most of the thawed layer intact, but the opening of surface cracks and the changing attitude of the stakes installed on the surface reflect localized movements within this layer and temporary stress relief. This process continues until the weight of the unfrozen sand reaches a critical level capable of overcoming the internal frictional cohesion, and failure occurs. Generally this failure takes place towards the end of each summer, when the thawed zone is approximately one metre (3 feet) thick, although it may occur locally before this thickness is reached. The slumping usually takes place along fairly well-defined planes at, or close to, the position of the frost table. Minor slumps are primarily of the rotational type, but the chaotic mixture of debris at
the foot of the larger slumps indicates considerable overturning and disintegration of the sand masses during their descent.

The above comments are mainly applicable to coarse-grained sediments with low ice contents, the thawing of which releases negligible quantities of water. As the ice content increases however, the volume of water released upon melting becomes much more significant. This is particularly noticeable in supersaturated sediments where thawing produces large quantities of excess water. In such sediments, the water released imparts an added mobility to the thawed layer and greatly facilitates its removal from the cliff face. Consequently, the frequency of removal of the unfrozen material increases from a maximum of once or twice during the whole summer, as in the case of the sand headlands, to an almost daily or even hourly occurrence. At the same time, as the volume of water increases, the mass movement removal process gradually acquires the characteristics of a mudflow rather than a simple slump.

On a short term basis, the major role of wave action appears to be in the removal of slumped material from the base of the cliffs. Such removal is necessary to prevent the accumulation of debris and burial of the lower sections of the profile, and thus permit the maintenance of fresh exposures for the 'thermal erosion' process. In places where the beach and foreshore are narrow, as along the bluffs on the northwest coast of the island, or where mudflows carry material from coastal exposures of ground ice directly to the sea, removal by wave action may occur almost instantaneously despite the limited tidal range. Where the cliffs are more distant from the shoreline, the major part of the removal process is accomplished during storm surges, especially in the late summer and early fall.
Although the chief role of wave action on a short term basis is in the removal of slumped debris from the base of the cliffs, direct undercutting by waves may locally be of major importance during these same storm surges. The two lowermost stakes of Profile II were removed by waves during a storm in early August of 1965. Wave-cut notches are a common feature along the high bluffs along the northwest coast, and the most spectacular example of undercutting was observed in this area in the summer of 1964. In late July of that year, a deep cleft, 50 metres (165 feet) long and up to 7 metres (23 feet) deep, opened up in the site of an old mudslump at a distance of 5-7 metres (16-23 feet) from the edge of the cliff. The bluffs at this point were 15-20 metres (50-65 feet) high, and had been undercut at beach level for distances of 4-5 metres (13-16 feet). As the summer progressed, the cleft gradually became wider and deeper as the whole block tilted bodily seaward until it finally collapsed into the sea. Although the formation of this cleft exposed a large body of ground ice, which undoubtedly facilitated the collapse, it was apparent that direct undercutting by the waves was primarily responsible for the removal or erosion of approximately 5,250 cubic metres (185,000 cubic feet) of coastline in one single block. On a long term basis therefore, in some areas, undercutting by wave action may be the most important process involved in cliff retreat, particularly during big storms when as much recession may take place as in several years of 'normal' erosion.

Erosion due to wind action, through deflation of the finer material and mechanical dislodgement of individual particles, is of minor importance, but probably accounts for most of the changes recorded by the stakes on the sand headlands before slumping occurred. Indirectly, wind action may contribute to coastal recession in another way. Large tracts of
vegetation along the northwest coast have been killed off by salt spray, and the reduced binding effect would assist in the detachment of earth hummocks from the cliff edge in these areas.

Erosion by running water is of little or no consequence in the coastal retreat process. The only minor exception was in the vicinity of the notches in the sand headlands, where further melting of the ice-wedges and snow accumulations temporarily provides sufficient quantities of water for the transportation of material, and the construction of miniature alluvial fans on the beach.

MUDSLUMPS

Many sections of the Garry Island coastline exhibit a distinctive, scalloped appearance on aerial photographs, reflecting the occurrence of numerous, large, crescent-shaped depressions. Their presence is a reliable indicator of the existence of massive bodies of segregated ground ice, and they are in fact large thermokarst features resulting from the exposure and melting of this ice. Similar features have been described in other parts of the Canadian Arctic, where emphasis has been placed on the role of mudflows found in the floors of the depressions and, in some cases, the term mudflow (coulée de boue) was the only name applied to these
landforms. Mudflows are also found in association with the amphitheatres on Garry Island, and their significance in the cyclic development of the landforms will be discussed below. Mackay, in his studies in the Mackenzie Delta area, has classified these features as slumps or ground ice slumps. Since the overwhelming characteristic of active features of this type is the ubiquitous presence of a surficial layer of mud debris derived from the melting ice, the term mudslump is adopted here.

A map showing the distribution of mudslumps on Garry Island (Figure 20) suggests the most probable mode of origin of these features. The mudslumps are almost exclusively confined to coastal locations where the bodies of ground ice have been exposed in the bluffs. The ice may be uncovered directly by wave action or indirectly as the result of over-steepening of the cliff profile, and subsequent mass movement of the vegetation layer from the cliff top. At one location on the south coast of the island, such oversteepening had led to the downslope motion of a mass of vegetation extending as much as 25-30 metres (80-100 feet) along, and back from, the edge of the cliff (Plate IX-A). The layer remained fairly

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Figure 20
GARRY ISLAND
DISTRIBUTION OF MUDSLUMPS

SLUMP A
SLUMP B
SLUMP C

Active Mudslumps
Inactive Mudslumps
Foreshore Flats

SCALE (Approximate)
0  1  2 Miles

N
A. Sliding of the vegetation layer produced by oversteepening of the coastal bluffs.

B. General view of Slump A with a prominent mudflow extending into the sea.

C. Overburden of a first-generation mudslump showing the high ice content.

D. Overburden, composed predominantly of mineral soil, of a second- or later-generation mudslump.
intact during its descent, and bold striations marked its path down the cliff face. The resultant depression was approximately 1.0-1.5 metres (3-5 feet) deep, so that failure probably occurred along a plane more or less parallel to the ground surface and at, or close to, the base of the active layer. The bare floor of the depression is being accentuated by deeper thawing and surface flowage relative to the adjacent vegetated surface, and fallen hummocks around the margin of the hollow indicate that it is expanding areally. A further continuation of these processes could feasibly lead to the eventual exposure of ground ice at depth, and the initiation of slump development. A few smaller slumps are located around the edges of some of the larger lakes, where similar undercutting of the banks by wave action has exposed the ice.

Figure 20 also shows a classification of the mudslumps into active and inactive forms. Since the ground ice exposures frequently have ice contents of several hundred per cent by weight, melting of the permafrost leaves deep depressions which persist for long periods of time after either complete thawing, if this ever takes place, or partial thawing and reburial of the ice body. Apart from their persistence as negative relief features, the identification of these scars on aerial photographs is a comparatively easy task. Due to the disturbed nature of the substratum following periods of slump activity, the inactive mudslumps support a highly diagnostic vegetation association, dominated by grasses, as described in Chapter III. The stabilized headwall scarp of an old mudslump, averaging 2-3 metres (6-10 feet) in height, is generally smaller than that of an active slump, and it progressively loses some of its identity as it is colonized by vegetation. In longitudinal profile, the floors of many of both active and inactive depressions exhibit a distinctive ribbed
appearance. The ribs may be annual features, representing the deposits of mud derived from the melting of the ice face in a summer, or they may mark the terminal positions of previous cycles of mudslump activity following renewed undercutting at the toe of an immediately preceding cycle.

Many of the currently active slumps are second- or later-generation features located wholly, or partially, within the confines of the older mudslumps. Others are first-generation forms cutting back into terrain which has not been affected previously by slumping processes. The headwalls of active slumps, ranging in height up to 10 metres (33 feet), contain variable quantities of segregated ground ice, and retreat rapidly during the summer months. The floors of the depressions are covered, to varying degrees, with a liquid mud debris derived from the melting of the ice face and the overlying active layer or overburden. Depending upon the ratio of ice to mineral soil in the headwall exposure, this mud may accumulate as a relatively static or slowly advancing mud lobe at the base of the ice face, or, in less viscous cases, it may be concentrated into strong, well-defined mudflows extending across the floor of the depression (Plate IX-B).

Rates of Retreat.

Lamothe and St-Onge considered this slumping process to be one of the most rapid erosional agents operating in certain parts of the arctic. Their observations during the summer of 1960 showed that the thermo-scarp retreated an average of 7 metres (23 feet), with a maximum recorded recession of 10 metres (33 feet). Erosion rates on the lateral walls of the depression, with less southerly aspect, were considerably lower, averaging 0.5 metres (1.5 feet) on a northeast-facing slope and
2 metres (6.5 feet) on a west-facing slope. Mackay, using field observations in the Mackenzie Delta area, concluded that the average retreat of active scarp faces is variable but probably lies in the range of 1.5-4.5 metres (5-15 feet) per annum.

Three very active mudslumps, the locations of which are also shown in Figure 20, were investigated on Garry Island, and data on the annual rates of retreat were obtained by installing a series of numbered stakes around the headwalls of each slump. These stakes were visited periodically throughout the 1964 and 1965 field seasons, and one of them, Slump B, was revisited during the summer of 1966. The amount of recession was recorded in metres and a summary of these observations is presented in Table X. Figure 21 also shows the surface configuration of Slump B in detail, with the locations of the various stakes and the lines of retreat at selected intervals (the beginning and end of the individual field seasons) during the observation period.

The figures in Table X confirm Mackay's conclusions that the rates of retreat are highly variable and the average values, in each of the mudslumps, approach or even exceed the upper limit of his estimate. The highest average annual retreat, 6.4 metres (20.8 feet), was recorded in Slump A on the south coast of the island, and this value contrasts with annual averages of 4.6 metres (15.2 feet) and 3.9 metres (12.8 feet) for Slump B, located on the north coast, and Slump C, located on the west coast, respectively. In each of the mudslumps, more than 80 per cent of the observed recession occurred during the months of July and August.

---

TABLE X

MUDSLUMPS - RATES OF RETREAT (Metres)

<table>
<thead>
<tr>
<th>SLUMP A.</th>
<th>Average</th>
<th>Maximum</th>
<th>Minimum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Summer 1964</td>
<td>5.51</td>
<td>10.40</td>
<td>0.0</td>
</tr>
<tr>
<td>Fall 1964/65</td>
<td>0.84</td>
<td>3.70</td>
<td>0.0</td>
</tr>
<tr>
<td>Summer 1965</td>
<td>5.15</td>
<td>9.55</td>
<td>0.0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>SLUMP B.</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Summer 1964</td>
<td>3.75</td>
<td>6.50</td>
<td>0.0</td>
</tr>
<tr>
<td>Fall 1964/65</td>
<td>0.88</td>
<td>1.70</td>
<td>0.0</td>
</tr>
<tr>
<td>Summer 1965</td>
<td>3.68</td>
<td>6.20</td>
<td>0.0</td>
</tr>
<tr>
<td>(July 4/64 - Aug. 22/66)</td>
<td>11.66</td>
<td>21.10</td>
<td>0.0</td>
</tr>
<tr>
<td>*(Aug. 22/66 - Aug. 21/67)</td>
<td>4.26(5.96)</td>
<td>6.87</td>
<td>0.0</td>
</tr>
<tr>
<td>*(Aug. 21/67 - July 10/68)</td>
<td>1.54</td>
<td>2.90</td>
<td>0.0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>SLUMP C.</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Summer 1964</td>
<td>3.14</td>
<td>5.20</td>
<td>0.0</td>
</tr>
<tr>
<td>Fall 1964/65</td>
<td>0.75</td>
<td>1.90</td>
<td>0.0</td>
</tr>
<tr>
<td>Summer 1965</td>
<td>4.81</td>
<td>6.90</td>
<td>0.0</td>
</tr>
</tbody>
</table>

Representative annual retreat values can be obtained for each mudslump by adding together the average figures for Summer 1964 and Fall 1964/65.

* Information supplied by Dr. J. Ross Mackay. Personal communications August 1967 and October 1968. The rates cited actually represent minimum values since they include measurements based on the last recorded positions of stakes which had been obliterated by headwall retreat. The figure in brackets represents the average rate of retreat based solely on 21 stakes which were still in position on August 21, 1967. By July 10, 1968, only 14 of the original 27 markers were still intact, and of these only 4 were located along actively retreating sections of the headwall.
Figure 21

MUDSLUMP
SLUMP B
(Surveyed July 7, 1964)

---

Base of Headwall (July 7, 1964)
Top of Headwall (July 7, 1964)
Lines of Headwall Retreat
+170 Positions of Stakes
+190 Old Mud Leveses

Scale in Metres

0 10 20 30

Sea Level

Contour interval 2 metres. Broken lines represent 1 metre interval.
Aerial reconnaissance of the island in mid-June of 1965 revealed that the mudslumps were still largely filled with snow, and the paucity of fresh debris at the base of the ice face, or on the surface of the snow, at the beginning of July, indicates that most of the retreat recorded during the fall represents continued recession during the preceding September before the onset of continuously freezing air temperatures.

Since the maximum recession recorded by any of the individual stakes also occurred in Slump A, it may seem easy to conclude that slope aspect is a dominant factor influencing scarp retreat. Comparisons made between stakes located around the same mudslump, however, revealed that the maximum retreat did not always occur on the slopes with the most southerly aspect.

The field studies indicated that the rate of recession of a mudslump headwall reflects the complex interplay of a number of factors including climate, the height and composition of the scarp face, and the rate of removal of the thawed debris. Of these, the climatic factor appeared logically to be the most significant, and an attempt was made to establish the relationship between the rate of retreat, as measured between successive observation periods, and the number of thawing degree-days occurring during the same periods. Only actively-retreating sections of the scarp face in each of the three mudslumps were used for this study, and the recession values thus represent the average readings taken from approximately 18-20 stakes at each of the slumps. These values were plotted against the thawing indices and are shown graphically in Figure 22. The regression line fitted to these points yielded the following equation:
Figure 22

RELATIONSHIP BETWEEN RATE OF RETREAT AND NUMBER OF THAWING DEGREE-DAYS FOR THREE GARRY ISLAND MUDSLUMPS

\[
\begin{align*}
\text{Slump A: } & \quad Y_c = 0.91 + 0.0022X, \quad r = +0.95 \\
\text{Slump B: } & \quad Y_c = 0.53 + 0.0034X, \quad r = +0.87 \\
\text{Slump C: } & \quad Y_c = 0.39 + 0.0046X, \quad r = +0.87
\end{align*}
\]
\[ Y_c = 0.50 + 0.004X \]

where \( Y_c \) is the estimate of average retreat of the headwall in metres for a given value of \( X \), and \( X \) is the number of thawing degree-days. Computation of the coefficient of correlation yielded a value of +0.92 indicating a strong positive correlation between the two variables. The equations of the regression lines and the coefficients of correlation for measurements taken from the individual mudslumps are also given in Figure 22.

By computing the coefficient of determination \( (r^2) \) it can be seen that approximately 85 per cent of the variability in the observed rates of retreat can be 'explained' by variations in the air temperature patterns.

Each of the mudslumps investigated was similar insomuch as they were all partially located, albeit to varying degrees, within the limits of an older slump. For example, Slump A, when first visited, was wholly located within an older slump. At the end of the observation period, recession of the ice face had completely eliminated the evidence of the previous cycle along all but a small portion of the rim. In Slump B, evidence of an earlier cycle was found between stakes 170-175 (see Figure 21), and in Slump C approximately one-third of the rim was similarly located. The significance of this type of location is primarily in its influence on the structural composition of the headwall. In terrain which has not previously been affected by mudslumps, the overburden is virtually restricted to the active layer, and rarely exceeds 1.0-1.5 metres (3-5 feet) in thickness although locally this figure may be augmented by solifluction. Moreover, this type of surface mantle may have a moderately high ice content (Plate IX-C). In contrast to this, the composition of the headwall in a second- or later-generation slump is intimately related to
the sequence of events during the previous cycle. The amount of ice exposed is partially controlled by the level at which it was planed off during the previous cycle, and it may be mantled by an overburden of slumped material only a portion of which corresponds to the current active layer. This type of overburden, which has the appearance of a chaotic mixture of mud, stones, turf and willows, also frequently has a very low ice content (Plate IX-D).

The amount and type of ground ice exposed in the headwall, and the ratio of this ice to the overburden above, is a critical factor influencing the rates of recession. It is the ice face segment which undergoes the most rapid recession, and the maintenance of fresh exposures of the ice is imperative for continuous retreat. In Table X, it was shown that the maximum and minimum rates recorded in each of the mudslumps covered wide ranges. Minima, in actual fact points at which no recession was observed, in all cases coincide with headwall sections in which no ground ice was exposed. At all other points ice was exposed for some time during the observation period and, in general, the greatest recession occurred where the ratio of ground ice to overburden was highest, and the former was thus continually exposed throughout most of the summer months. Another indirect influence of this ratio on the rates of recession is related to its effect on the viscosity of the thawed debris. High proportions of segregated ice in the headwall represent a greater potential moisture supply affecting the mobility of the debris, and thereby facilitating its removal from the base of the ice face. In this respect, it is also significant to point out that there was a considerable variation in the ice content of the ground ice exposures themselves in each of the mudslumps, and therefore important differences in
the volumes of debris derived from the melting of these sections of the scarp face. Active removal of this debris, allowing the maintenance of fresh exposures, is another important contributor to continued retreat. In addition, where the headwall is high, the momentum gained by the debris during its descent aids in its displacement from the immediate vicinity of the foot of the slope.

It is now possible to re-evaluate the statistics given in Table X in terms of the preceding statements. The highest average retreat values recorded in Slump A reflect the combination of the influence of a southerly aspect; the widespread occurrence of segregated ground ice with ice contents of several hundred per cent, including many bands of almost clear ice; an overburden which, although thick, in many places also contained large quantities of segregated ice; a high headwall ranging up to 10.0 metres (33 feet) in height; and an extremely active rate of removal of the thawed debris in the form of strong mudflows. The latter factor was extremely significant in sections of the mudslump where the headwall was dominated by thick deposits of slump debris from an earlier cycle. A brief visit to the same slump at the end of the 1966 field season showed that a weakening of the mudflow activity had led to an almost complete burial of the ground ice exposures in these sections. Higher retreat values recorded in both the other mudslumps generally reflected a similar combination of these conditions. The lower average figure for Slump B is probably most related to its northerly aspect and the prevalence of a weak rate of removal of debris. Several factors account for the lowest recession rates recorded in Slump C including a low headwall averaging only 2.0-3.0 metres (6-10 feet) in height; ground ice exposures in this headwall which were more akin to a frozen mud, with ice contents averaging less than one
hundred per cent; and the presence of numerous gullies on the floor of the depression. Whilst these gullies assist the concentration of the debris into well-defined mudflows, some of which would break through with considerable force to the sea, they provided numerous constriction points, at which many of the flows became blocked, resulting in a highly intermittent, and sometimes complete lack of, removal of the debris.

Ablation Studies. The retreat values cited in the preceding paragraphs were related to the rate at which material, composed predominantly of mineral soil, was detached from the rim of the headwall. It was also established that one of the key factors influencing this detachment process was the melting back of the segregated ice exposures in the scarp face. To obtain additional data on this latter aspect of the retreat process a series of ablation studies was made during the 1965 field season.

The technique employed for these ablation studies was similar to that used to record changes in the cliff profiles of the sand headlands. A number of stakes was installed in the ice face, normal to the surface, and the amount of ablation was determined by measuring changes in the exposed lengths of the stakes (Plate X-A). Several problems were encountered in using this technique. Firstly, the drilling of the holes to accommodate the wooden dowelling was an arduous task due to the presence of numerous small pebbles in the segregated ice body. These pebbles were of sufficient size to halt the penetration of the drill before the required depth of 45 cms. (18 ins.) was achieved. Thus, on one occasion, a total of 27 holes was started before seven could be completed to install the stakes on one of the ablation profiles. Secondly, even though the dowelling used for the stakes was 2.5 cms. (one inch) in
Plate X

MUDSLUMPS

A. Ablation studies in Slump B showing the locations of the stakes in Profile I.

B. Gullies produced by the differential melting of bands of ground ice with contrasting mineral soil contents.

C. Meltwater gully system on the headwall in Slump B.

D. Rejuvenation of Slump A caused by undercutting at the toe of the slump leading to renewed exposure of the ground ice.
diameter, there were a number of instances where it was either broken off or dislodged by hummocks and debris detached from the overhanging rim above. Thirdly, problems were also introduced in the actual measurements of the amount of ablation due to the formation of small pits produced by accelerated melting at the base of the exposed portion of each stake. To alleviate this problem and obtain representative ablation measurements therefore, a ruler was placed across these pits, flush with the adjacent ice surface, and the ablation level was interpreted as being the point of intersection of the ruler and the stake.

For these ablation studies, two profiles were established in Slump B. Observations, covering periods of 3-4 days, were made at intervals ranging from 2-3 weeks. Profile I was located midway between stakes 180 and 181 (see Figure 21), at a point where the headwall just exceeded 8.0 metres (26 feet) in height and the ice face was relatively smooth with only incipient gullies at the base. Profile II was situated midway between stakes 187 and 188 where the headwall was just under 6.0 metres (19.5 feet), high and the lower parts of the ice face were ribbed by a number of distinct gullies. The forms of these profiles, the locations of the ablation stakes on each, and the changes in the positions of the ice face are illustrated in Figures 23 and 24.

Each profile was surveyed by stretching a tape between two rods, one anchored in the ground surface above the rim and the other in the ground ice floor of the slump, and taking plumb readings to the ice surface at approximately 0.5 metre (1.6 foot) intervals. This procedure

14 On the majority of these days two sets of observations were made, but the changes were too slight to be recorded on Figures 23 and 24.
Figure 23

ABLATION STUDIES IN SLUMP B
PROFILE I

<table>
<thead>
<tr>
<th>Location of Ablation Stakes</th>
<th>Date</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>July 8</td>
<td>5.30 p.m.</td>
</tr>
<tr>
<td>B</td>
<td>July 9</td>
<td>4.30 p.m.</td>
</tr>
<tr>
<td>C</td>
<td>July 11</td>
<td>1.30 p.m.</td>
</tr>
<tr>
<td>D</td>
<td>July 12</td>
<td>1.30 p.m.</td>
</tr>
<tr>
<td>E</td>
<td>July 27</td>
<td>4.40 p.m.</td>
</tr>
<tr>
<td>F</td>
<td>July 28</td>
<td>4.30 p.m.</td>
</tr>
<tr>
<td>G</td>
<td>July 30</td>
<td>4.00 p.m.</td>
</tr>
<tr>
<td>H</td>
<td>July 31</td>
<td>4.00 p.m.</td>
</tr>
<tr>
<td>I</td>
<td>Aug. 15</td>
<td>10.45 p.m.</td>
</tr>
<tr>
<td>J</td>
<td>Aug. 17</td>
<td>10.30 p.m.</td>
</tr>
<tr>
<td>K</td>
<td>Aug. 19</td>
<td>10.30 p.m.</td>
</tr>
<tr>
<td>L</td>
<td>Sep. 5</td>
<td>12.30 p.m.</td>
</tr>
</tbody>
</table>
Figure 24

ABLATION STUDIES IN SLUMP B

PROFILE II

<table>
<thead>
<tr>
<th>Location</th>
<th>Date</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>July 28</td>
<td>4:40 p.m.</td>
</tr>
<tr>
<td>B</td>
<td>July 30</td>
<td>4:00 p.m.</td>
</tr>
<tr>
<td>C</td>
<td>July 31</td>
<td>2:30 p.m.</td>
</tr>
<tr>
<td>D</td>
<td>Aug. 14</td>
<td>11:00 a.m.</td>
</tr>
<tr>
<td>E</td>
<td>Aug. 15</td>
<td>10:55 a.m.</td>
</tr>
<tr>
<td>F</td>
<td>Aug. 17</td>
<td>10:40 a.m.</td>
</tr>
<tr>
<td>G</td>
<td>Sep. 5</td>
<td>12:45 p.m.</td>
</tr>
</tbody>
</table>
was repeated several times, usually at the beginning and end of each
observation period, and the surveyed profiles are indicated by the solid
lines in Figures 23 and 24. The intermediate positions of the ice face,
as determined by the ablation stake measurements, are represented by
broken lines in the same diagrams.

A comparison of the individual ablation stake measurements
for each observation period showed that in Profile I there was very little
variation over the length of the profile, and that the ice face underwent
essentially parallel retreat (Figure 23). By way of contrast, a similar
comparison of the values obtained in Profile II showed a progressive
increase in the amount of ablation from the top to the bottom of the
profile. This differential was most pronounced at the beginning of the
observation period in late July, when it was in the order of 200 per cent,
but its magnitude gradually diminished until, by late August, it was less
than 100 per cent. This miniature ablation-altitude gradient can probably
be attributed to the presence of the gully system, extending over the
lower part of the scarp face, which effectively concentrated meltwater,
derived from the upper part of the ice face, into well defined-channels.
The two lower stakes in Profile II were deliberately positioned in the
floor of one of these channels. The greater rate of melting of the ice
at these locations may therefore represent the effects of additional
mechanical erosion by the meltwater.\textsuperscript{15} Furthermore, the observed decrease
in the differential rates of ablation may possibly be attributed to the

\textsuperscript{15}Part of this differential may also be attributed to the
fact that the lower stakes in Profile II were installed vertically rather
than at right angles to the ice surface.
gradual contraction of the gully system towards the end of the summer. This sequence of events is apparent in Figure 24 by the progressive 'straightening' of the ice profile and a diminution in the vertical extent of the lower concave facet.

An analysis of the rates of retreat for the rim of the headwall showed a strong positive correlation with air temperatures. Due to the short time periods (ranging from 7-48 hours) used in the ablation studies it was impractical to employ the number of thawing degree-days as an index of air temperatures and, instead, the number of thawing degree-hours was used. These were calculated by taking the hourly readings from the continuous temperature record at the climate station, subtracting 32°F from each, and cumulating the totals for the respective observation periods.

Figure 25 illustrates graphically the relationship between the ablation rates and air temperatures. The regression line fitted to the plotted points was determined by the method of least squares, and the resultant equation was:

\[ Y_c = 0.14 + 0.019 X \]

where \( Y_c \) is the estimate of the amount of ablation in centimetres for a given value of \( X \), and \( X \) is the number of thawing degree-hours. The regression equations for the individual profile data are also shown in Figure 25.

Computations of the coefficients of correlation (\( r \)) and the coefficients of determination (\( r^2 \)) yielded uniformly high values of +0.99 and 0.98 respectively. Thus, approximately 98 per cent of the variability in the ablation data can be 'explained' by variations in the air temperature patterns.
Figure 25
RELATIONSHIP BETWEEN ABLATION RATES AND THE NUMBER OF THAWING DEGREE-HOURS IN SLUMP B

\[ Y_c = 0.14 + 0.019X \]
\[ r = 0.99 \]

- Profile I: \[ Y_c = 1.34 + 0.016X \]
- Profile II: \[ Y_c = 0.030 + 0.019X \]
The Recession Process and Evolution of the Gully System.

Headwall recession in a typical mudslump involves the thermal and mechanical erosion of the scarp face, accompanied by the slumping of the thawed debris and free fall or sliding of the overlying active layer. The relative importance of each of these processes depends primarily on the nature and composition of the scarp face, and in particular, the type and quantity of ground ice exposed.

The recession values, cited in the preceding paragraphs, describe the rates at which blocks of material were detached from the crown of the mudslump. Many actively-retreating headwalls include small sections in which the original ground ice exposures have been eliminated either by complete melting or by burial beneath deep mantles of thawed debris. Although active recession may still take place in these sections, the rate is extremely slow. Small tension cracks are developed along the crown of the slump, parallel to the rim, and blocks of turf or mud, bounded by these cracks, gradually tilt forward and are ultimately detached from the headwall. Since the thawing of these sections releases little or no moisture, the debris merely accumulates on the scarp face and the recession is eventually terminated. This process, the detachment and free falling of the active layer, is greatly facilitated where underlying bodies of ground ice are exposed in the main scarp face. A more rapid recession of the ice face segment leads to undermining at the base of the active layer, the development of large overhangs, and a sudden, rapid collapse of large blocks of debris to the foot of the scarp face.

The thermal and mechanical erosion of the main scarp face is

---

16 Mackay, J. Ross (1966) op. cit., p. 74.
thus the dominant process influencing the rate of headwall recession, and
one of the most apparent manifestations of this process is the presence of
a well-defined gully system covering sections of the ice face. Two types
of gully can be distinguished in the mudslumps on Garry Island. The first
type, observed in Slump A, is structural and occurs in heterogeneous bodies
of ground ice composed of alternating, more or less vertical bands of
frozen mud and clear ice (Plate X-B). The frozen muds, with ice contents
averaging only slightly more than 100 hundred per cent by weight, melt
quickly and form negative features in the ice face, while the clear ice
bands, which melt more slowly, stand out as positive rib features.
Differential melting of the bands therefore produces an embryonic gully
system which is accentuated by the channelling of meltwater streaming down
the ice face. The width of the channel is controlled by the width of the
dirt bands, but mechanical and thermal erosion by the running water results
in a maximum amplitude of the gullies, in the order of 15-20 cms.
(4-6 ins.), at the base of the ice face. The amplitude is partially con-
trolled by the fact that excavation along the lines of the frozen mud
results in greater exposure and thus more rapid melting of the ribs of
clear ice. Since the gully system is structurally controlled, there is no
evidence of cyclic development, and the pattern remains relatively stable
throughout the summer months. Where the ground ice has been strongly
deformed, as in Slump A, the orientation of the gullies is not necessarily
in the direction of steepest slope down the scarp face.

In contrast to the diminutive, structurally-controlled
features described above, the second type of gully system includes the
pattern of large ridges and gullies which produces the distinctive badland
topography described recently by Mackay. It is best developed in massive bodies of relatively homogeneous ground ice, devoid of any marked structural controls, and with ice contents ranging from 100-300 per cent by weight. These conditions occurred in Slump B (Plate X-C), and the following description of the development of the badland topography is related to a number of investigations made in this mudslump.

Unfortunately, the earliest date at which it was possible to visit this mudslump was at the beginning of July, when evidence of the ridge and gully system was found between stakes 178 and 190. Between stakes 178 and 181, an incipient ridge and gully system was developed on the lower metre (3 feet) of the ice face while the upper portions of the headwall were smooth. The ridges, spaced at intervals of 30-35 cms. (12-14 ins.) exhibited a typical buttress form, being approximately 20 cms. (8 ins.) across in their upper portions and increasing to about twice this width at the base. The intervening gullies averaged 6.0 cms. (2.5 ins.) in depth near their heads, and 6-8 cms. (2.5-3.0 ins.) in depth at the base of the ice face, with maximum depths below the ridge crests of 10-12 cms. (4-5 ins.). Small trickles of water were being channelled down the gullies, which were floored by clean ice exposures, but the adjacent ridges were mantled by a surficial dirt accumulation up to 3.0 cms. (one inch) thick. Between stakes 182 and 190, the ridges and gullies became progressively larger and covered an increasing proportion of the ice face until, by stake 190, they extended to within one metre (3 feet) of the base of the active layer and exemplified the typical badland topography par excellence. At

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17 Mackay, J. Ross (1966) op. cit., pp. 68-69.

18 The stake numbers refer to the positions shown in Figure 21.
this point, the ridges were approximately 3.0-3.5 metres (10-12 feet) apart, as measured between crests, and reached widths of 2-3 metres (6-10 feet) across near the base of the ice face. The depth of the gullies increased from an average of 25-35 cms. (10-14 ins.) near the head to a maximum of 1.0-1.5 metres (3-5 feet) at the foot of the slope. Between stakes 190 and 196, any ground ice exposures were still mantled by snow patches and debris, and the headwall was not affected by any form of gullying.

In early August, one month later, several notable changes had occurred in the appearance of the headwall. Ground ice was then exposed in the scarp face between stakes 172 and 191, and the badland topography was only evident between stakes 182 and 191. All previous evidence of a gullying pattern between stakes 178 and 182 had now been eliminated, and the headwall was now essentially a smooth ice face except for a few minor ripples at the base. Measurements of the size, amplitude and areal extent of the ridge and gully system between stakes 182 and 191 showed that they covered an increasing proportion of the ice face as the latter marker was approached, and this was accompanied by a corresponding increase in their dimensions similar to the pattern described above. No further extension of the badland topography occurred during the month of August, since no additional exposures of ground ice occurred beyond stake 191, and the badland topography was eliminated as far as stake 184.

Whereas no evidence of a cyclic pattern was found in the gully system in Slump A, the recession of the headwall of Slump B exhibits a definite cycle during which the badland topography is developed and ultimately disappears. During the winter months, the mudslumps are sites of deep snow accumulation driven in by the prevailing winds. With the
arrival of warmer temperatures in spring and early summer, the snow begins to melt and the uppermost portions of the scarp face are the first to be exposed. Rapid melting of the ice and the base of the active layer results in the detachment of hummocks and debris from the rim of the slump which accumulate on the surface of the snow. Water, derived from the melting of the snow and thawing of the ice face, soon erodes a series of deep gullies in the ice surface. Once the gully pattern has been established on the ice face, it becomes progressively larger and deeper as it continues to channel the excess water released upon melting of the ice face. The system reaches its maximum development when almost the entire face is covered by the badland topography with strong channels, 1.0-2.0 metres (3.0-6.5 feet) deep, separated by prominent ridges, of the buttress type, which may be as much as 2-3 metres (7-10 feet) across at the base. As noted previously however, the pattern of ridges and gullies rarely reaches within more than one metre (3 feet) of the top of the ice face, and this probably reflects the minimum surface area required to produce a sufficiently large quantity of water that can be collected together and channelled into a surface flow (cf. Schumm, 1956). Once the ridges reach the dimensions cited above, they occupy a large proportion of the ice face, and their large surface area, coupled with their additional exposure as positive relief features, reaches a size whereby melting releases sufficient water to form another set of gullies on the buttresses themselves. Entrenchment and headward extension of these new gullies gradually reduces, and finally eliminates, the large ridges and produces the more closely spaced ripple

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remnants at the base of the scarp face. This entire sequence, the develop­
ment of new channels at points formerly occupied by ridges during an earlier
period of gullying, is very similar to the process of gully-gravure described
by Kirk-Bryan in the arid south-western parts of the United States.

The length of time in which this cycle is completed of course is
much less than that cited by Kirk Bryan, and appears to vary according to
the location within the mudslump. The smooth nature of the ice face between
stakes 173 and 178, except for the minor ripples at the foot of the slope,
indicated that the cycle had already been completed on these sections of
headwall with a northwest or northern aspect, whereas, on a northeast
facing slope the cycle was not completed until late September. On slopes
with a more easterly aspect, the cycle may not be completed before freezing
temperatures set in, and remnants of the ridges and gullies may be buried
beneath the drifting snow.

During the stage of maximum development of the badland top­
ography, mechanical and thermal erosion of the ice face by running water
is a decisive factor influencing the rate of recession of the mudslump
headwall. Besides contributing to active erosion, the water is also an
important agent in quickly removing thawed debris from the ice surface, and
thereby maintaining a clean exposure for more rapid thermal erosion. Since
both thermal and mechanical erosion occur simultaneously, it is impossible
to evaluate precisely the relative contributions of each, but comparisons
of headwall recession values, over smaller intervals of time, at the
individual stake positions demonstrate the efficiency of the mechanical

erosion. These comparisons are shown in Table XI.

**TABLE XI**

RATES OF RECESSION AT SELECTED STAKE POSITIONS IN SLUMP B (Metres).

<table>
<thead>
<tr>
<th>Stake #</th>
<th>July 7 - 26</th>
<th>July 26 - Aug. 13</th>
<th>Aug. 13 - Sept. 9</th>
</tr>
</thead>
<tbody>
<tr>
<td>179</td>
<td>2.05</td>
<td>1.70</td>
<td>1.20</td>
</tr>
<tr>
<td>182</td>
<td>3.30</td>
<td>1.80</td>
<td>1.10</td>
</tr>
<tr>
<td>190</td>
<td>1.35</td>
<td>1.85</td>
<td>2.30</td>
</tr>
</tbody>
</table>

The pattern for stakes 179 and 182 is one in which the greatest retreat was recorded during the first observation period in July, when the ridge and gully system was strongly developed, and a decreasing rate of recession, through August and into September, as the ridges and gullies disappeared and mechanical erosion was reduced. In comparison to this, the pattern of retreat shown by stake 190 is one of increasing rates through to late August and early September, at which time the badland topography had reached its maximum development.

With the eventual disappearance of the badland topography the ice face undergoes more or less parallel retreat. On the smooth ice face losses are due mainly to melting in response to incoming short and reflected long wave radiation, and the water, released by melting, follows a sinuous passage between particles of ablation debris protruding from the ice surface. The recession process becomes even slower as the layer of surface dirt accumulates to maximum thicknesses of 2-3 cms. (one inch). Once this thickness is attained, the surface dirt becomes unstable and moves as a mud slide to the base of the ice face. Locally, instability may be reached before these thicknesses are attained, being triggered by the impact of stones and debris detached from the overhanging active layer. An indication of the slow nature of this process was obtained by spreading a green
fluorescein dye on a clean section of the upper part of the cliff face. Despite the fact that the scarp face had an inclination of 66 degrees, the coloured water took a minimum of 15 minutes to seep down to the base, whereas a similar dye introduced into one of the sliding mud slimes reached the base in a matter of only a few seconds.

**The Mudslump Cycle.**

The maintenance of fresh exposures of ice, permitting the continued recession of the scarp face, is a critical factor influencing the longevity of the mudslump cycle. The length of time that an exposure of ground ice is maintained in turn is largely determined by the delicate balance between the rates at which debris is supplied to, and removed from, the base of the scarp face.

Figure 26 is a composite profile across a section of Slump B for the period July 4, 1964 to August 13, 1966, showing the individual mud lobes, representing the accumulated debris derived annually from melting of the scarp face, and the approximate position of the buried surface of the ground ice as determined by a series of drill holes. Figure 27 is a generalized diagram of the same profile, showing the position of the ice face at selected intervals during the same time period.²¹

Total recession of the headwall (r) in this time amounted to a horizontal distance of 16.5 metres (54 feet), during which the height of the scarp face (h) decreased from an initial value \( h_1 \) of 9.1 metres (30 feet) to only 5.7 metres (19 feet) - \( h_2 \) - at the end of the observation period. This decrease, involving a reduction of 37.5 per cent, was due

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²¹The profile shown in Figures 26 and 27 was located near stake 181 (see Figure 21).
Figure 26

GARRY ISLAND MUDSLUMP PROFILE 1964-1966

SLUMP B

<table>
<thead>
<tr>
<th>1964</th>
<th>1965</th>
<th>1966</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- Fresh mud and silt being deposited by running water.
- Surface colonized by almost pure stands of Marsh Fleabane.
- Bare mud surface with occasional live hummocks.
- Fresh mud surface with pools of standing water and fallen hummocks.

Mud Accumulation

Buried Ground Ice

Scale in Metres

0 5 10

Vertical Exaggeration x2
Figure 27

RECESSION DIAGRAM OF A GARRY ISLAND MUDSLUMP 1964 - 1966

Scale in Metres
0 5 10

Vertical Exaggeration x2

Debris derived from melting of the ice face during the period July 4, 1964 - August 13, 1966
Depression created by thawing at base of scarp

1-6 Approximate former positions of the ice face

1 July 4, 1964 (Surveyed) 4 August 10, 1965 (Surveyed)
2 September 4, 1964 5 September 6, 1965
3 July 7, 1965 6 August 13, 1966 (Surveyed)
primarily to a slow rate of removal of debris, as indicated by the gently overlapping nature of the individual annual lobes, with the resultant burial of the basal sections of the ice face. The reduction would have been even greater, 44.0 per cent, but for the fact that the height of the scarp was augmented by a rising slope of two degrees on the surface above the rim of the mudslump.

In a recent publication, Mackay has derived an equation for computing the approximate thawed volume of a unit section of a mudslump, provided that the excess water is free to escape. Assuming that the volume changes incurred during thawing of the active layer are negligible, the thawed volume is approximately equal to: \[ ra + rV^{-1} (h - a + d) \]

where \( r \) = the horizontal distance of scarp retreat
\( a \) = the average thickness of the active layer
\( V \) = the ratio of the initial volume of frozen ground to the total volume of segregated ice
\( h \) = the height of the scarp face
and \( d \) = the mean depth of thaw at the scarp foot.

The above equation was derived from a theoretical situation in which there was parallel retreat of the ice face, with no alteration in height, across a perfectly horizontal surface.

The major contrast between this situation and the one illustrated in Figure 27 is that the height of the scarp face (h) did not remain constant in the latter. Since it was found that the base points of the surveyed profiles in Figure 27 were located approximately along a straight line, it was possible to overcome this problem by averaging a series of measurements taken directly from this diagram. The mean height of the

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scarp face, derived in this manner, amounted to 7.5 metres (24.6 feet) and this value incorporates the changes brought about by the sloping of the surface to the crown of the slump and basal mantling of the ice face by thawed debris. The value of \( V \) was estimated using the nomograph included in Mackay's article. A total of 40 samples (Table XII), collected at different times from the ice face, gave an average ice content of 300 percent (weight of ice to dry soil), and combining this with an estimated porosity of the original unfrozen ground of about 0.3 yields a value for \( V \) of 0.15. Representative values of the average thickness of the active layer (a) and the mean depth of thaw (d), also taken from Figure 27, were 0.46 and 0.34 metres (1.5 and 1.1 feet) respectively. Substitution of these values into the equation gives an approximate thawed volume along a unit section of 0.3 metres (1 foot) width of 7.82 cubic metres (276 cubic feet).

Planimetric measurement of the volume of debris shown in Figure 27 gives a corresponding volume of 7.13 cubic metres (252 cubic feet). The close similarity of these two figures indicates the prevalence of a very weak export of material, and the degree to which most of the thawed debris derived from the melting of the scarp face merely accumulated at the foot of the slope. Assuming that the present status quo remains essentially unchanged, the longevity of the present cycle in Slump B can be reliably estimated. A continuation of the current rate of reduction in the height of the ice exposure, one metre (3 feet) per annum, would result in the termination of the cycle by approximately 1972.

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### TABLE XII

ICE CONTENTS (WEIGHT OF ICE TO DRY SOIL) OF SAMPLES TAKEN FROM EXPOSURE OF GROUND ICE IN SLUMP B.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Total Weight (grams)</th>
<th>Weight of Ice (grams)</th>
<th>Weight of Dry Soil (grams)</th>
<th>Ice Content (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>179.06</td>
<td>112.09</td>
<td>66.97</td>
<td>167.37</td>
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<tr>
<td>2</td>
<td>154.95</td>
<td>114.47</td>
<td>40.48</td>
<td>282.78</td>
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<td>3</td>
<td>161.98</td>
<td>94.52</td>
<td>67.46</td>
<td>140.11</td>
</tr>
<tr>
<td>4</td>
<td>169.10</td>
<td>123.99</td>
<td>45.11</td>
<td>274.86</td>
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<tr>
<td>5</td>
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<td>133.59</td>
<td>83.78</td>
<td>159.45</td>
</tr>
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<td>111.47</td>
<td>71.90</td>
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<td>54.72</td>
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<td>95.91</td>
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<tr>
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<td>123.53</td>
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</tr>
<tr>
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<tr>
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<td>120.29</td>
<td>36.75</td>
<td>327.32</td>
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<tr>
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<td>142.38</td>
<td>39.37</td>
<td>361.65</td>
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<tr>
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<td>121.36</td>
<td>41.87</td>
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<tr>
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<td>159.13</td>
<td>127.98</td>
<td>31.15</td>
<td>410.85</td>
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<tr>
<td>32</td>
<td>168.78</td>
<td>123.69</td>
<td>45.09</td>
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<td>34</td>
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<td>100.89</td>
<td>72.91</td>
<td>138.38</td>
</tr>
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<td>35</td>
<td>179.20</td>
<td>130.97</td>
<td>48.23</td>
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<td>36</td>
<td>166.80</td>
<td>140.67</td>
<td>26.13</td>
<td>538.35</td>
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<td>37</td>
<td>186.88</td>
<td>142.24</td>
<td>44.64</td>
<td>318.64</td>
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<td>38</td>
<td>167.05</td>
<td>134.46</td>
<td>32.59</td>
<td>412.58</td>
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<td>39</td>
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<td>119.14</td>
<td>38.03</td>
<td>313.28</td>
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<tr>
<td>40</td>
<td>194.69</td>
<td>148.31</td>
<td>46.38</td>
<td>319.77</td>
</tr>
</tbody>
</table>

Average 167.69  299.85
The sequence of events in Slump A indicates the manner in which the period of mudslump activity may be prolonged. In August 1964, a second cycle of slumping was initiated even before the existing cycle had been terminated. Undercutting at the toe of the latter resulted in the exposure of ground ice previously buried beneath the mud debris (Plate X-D). By the summer of 1966, the new exposure had retreated headward to join up, and locally eliminate, all evidence of the first cycle. Unless a similar sequence of events exposes the ground ice buried beneath the floor of Slump B, a continuation of mudslump activity beyond the estimated six-year period appears unlikely, and the mud surfaces will gradually be colonized by a vegetation succession similar to that described in Chapter III.

MUDFLOWS

The significance of mass-wasting as a major geomorphic process in the moulding of landforms was slowly recognized as a result of numerous, independent studies in a wide variety of climatic environments. The important role of weathering and mass-wasting in the sculpturing of Arctic landscapes is generally acknowledged, and some authors regard the cumulative effect of all forms of mass-wasting as being the most important levelling process operating in these high latitudes. While this may be undeniably true, these studies have been dominated by investigations of slow-moving forms of mass-movement under the general heading of solifluction features, whereas scant attention has been paid to more rapidly-moving forms. Most

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24 By the summer of 1968, Slump A was virtually inactive. Information supplied by Dr. J. Ross Mackay, personal communication, October, 1968.

of the geomorphological literature pertaining to mudflows for example consists of descriptions of these features from temperate latitudes, and arid or semi-arid environments in particular. Few authors have described mudflows in Arctic lands, and one has even expressed surprise that they should be important components of mass-wasting in these latitudes. This certainly is not the case in permafrost areas underlain by unconsolidated sediments containing variable quantities of segregated ground ice. During the warm summer months, such sediments are readily transformed from their frozen state to mobile mud slurries, and the mudflow is a ubiquitous feature in these localities.

In his classic monograph dealing with all forms of mass-movement, Sharpe, following earlier work done by Blackwelder, listed four major conditions which appear to be most favourable for the occurrence of mudflows:

1. an abundant but intermittent water supply
2. the absence of a substantial vegetation cover
3. unconsolidated or deeply weathered material containing enough clay or silt to aid in lubrication of the mass, and
4. moderately steep slopes.

In the case of mudflows on Garry Island, the moisture supply comes primarily from the thawing of the frozen ground, and of bodies of ground ice in

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28 Sharpe, C.F.S. op. cit., p. 56.
particular. As long as fresh exposures of ice are maintained, there is a fairly steady water supply throughout the summer months. The vegetation associations range from a continuous mat of herbs, shrubs and sedges on the upland surfaces, to a variable cover of grasses in the case of second- or later-generation slumps. The restricting influence of the vegetation cover is limited however by the fact that most of the plants are only shallow-rooted in the active layer, and the recession of the ice face frequently results in an undermining of the plant cover. The floors of the depressions, over which the mudflows travel, are often devoid of any vegetation at all. Since large bodies of segregated ground ice are best developed in silts or fine sands, the predominant mineral sizes accord with those specified by Sharpe. The slope factor does not appear to be too critical in Garry Island flows, since the ice faces frequently have ice contents of several hundred per cent (expressed as the weight of ice to dry soil), and thawing produces large quantities of excess water which greatly facilitate mudflow movement over very gentle slopes.

Sharpe's classification of mudflows recognized three well-defined types - semi-arid, alpine and volcanic - which he claimed were created differently and bore dissimilar relations to other processes. The significant relationship of mudflows to other processes in the mudslump cycle has already been alluded to in the preceding section. The perpetuation of this cycle depends in part upon the delicate balance between rates of supply of debris to, and removal of this debris from, the base of the ice scarp. Unless the debris is transported away, the base of the ice face is buried and the height of the ice face, and consequently the potential

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volume of moisture supply which is capable of contributing to the mobility of the flows, is thus progressively attenuated. Mudflows are the primary agents responsible for the transportation and removal of this debris. In this respect, it should be noted that in all the mudflows studied in the Mackenzie Delta area, the only functional role observed was that of transportation of debris, and there was nothing to indicate that mudflows are responsible for the actual excavation of the depressions as suggested by Lamothe and St-Onge. On this basis, using the classification criteria established by Sharpe, it seems valid to distinguish yet another type of mudflow - the arctic - the genesis of which, and relationship to other processes, is uniquely or intimately related to specific permafrost conditions.

All the mudflows observed in the Mackenzie Delta area are produced by seasonal thawing of the permafrost. They occur in a wide range of sizes depending primarily on the nature of, and volume of ice contained in, the sediments. Small flows, often less than one metre (3 feet) wide, and considerably shallower in depth, descend well-defined gullies in the coastal bluffs and are generated by the melting out of ice-wedges. Since the ratio of ice to mineral soil in these exposures may be quite small, and since almost all the debris comes from the sediments themselves, rather than from within the ground ice, the importance of sediment type and slope is probably much more critical than in the case of the larger flows. Channel gradients in these gullies frequently reach 30-40 degrees. The influence of sediment type is also demonstrated in these small flows.

The ice-wedges found in the silt-clay bluffs are larger than those found in the sand headlands, but the thawed material found in the latter localities is not a fluid, mobile mud.

The largest mudflows are found in association with the mud-slumps, where ice cliffs in the headwalls may extend for several tens of metres horizontally and from 5-10 metres (16-33 feet) vertically. Figure 28 represents a contour map of one of these flows on the south side of Garry Island. The mudflow is located within the confines of a second- or later-generation slump, and flows over deposits, having a minimum thickness of 2.75-3.0 metres (9-10 feet), laid down by former mudflows. Whilst the main body of the mudflow occupies a well-defined channel, this is generally a secondary characteristic rather than the result of flowing along a pre-existing channel. The positions of two former mudflows are shown on the same map, and their temporal sequence was determined by the overlapping nature of the mud deposits. The positions of these successive flows are determined by the general slope trend of the slump floor, and also by points of weakness in the margins of the earlier flows.

The mudflow in Figure 28 originates at the headwall of a mud-slump in which segregated ground ice, 2.75-3.0 metres (9-10 feet) thick, is overlain by an average of 1.5-1.8 metres (5-6 feet) of overburden. The mudflow extends for a distance of approximately 80 metres (260 feet) from the base of the ice face to the shoreline, and three distinct sections can be identified in this distance. The uppermost section consists of a mud reservoir with a surface area of 135 square metres (1450 square feet) and an average surface gradient of 1 in 12 (Plate XI-A). The main channel of the mudflow, which constitutes the second section, extends for a distance of approximately 43 metres (143 feet) from the outlet of the mud reservoir.
Figure 28
A GARRY ISLAND MUDFLOW

- Rim of Mudslump Headwall
- Margins of Individual Mudflows
I-III Sequence of Mudflows
- Active Mud Levees
- Old Mud Levees

Contour interval 0.5 metres
A. General view of the upper section of the mudflow showing the mud reservoir and ground ice exposed in a slump headwall.

B. Main channel of the mudflow immediately below the outlet of the mud reservoir showing the locations of the upper and middle rows of markers.

C. Terminal section of the mudflow showing its descent over a wave-cut bluff, two positions of the lower row of markers, and the surface of the mud lobe.
to the apex of the mud lobe (Plate XI-B). The width of the channel, measured from the inner margins of the mud levees, ranges from 0.75-3.0 metres (2.5-10.0 feet), and has an average surface gradient of 1 in 10. There are two noticeable sections of the channel however, where the surface gradient is as steep as 1 in 2. One of these sections is just at the outlet of the mud reservoir, and the other is at the lower end of the channel where the mudflow descends a wave-truncated bluff cut in earlier mudflow deposits (Plate XI-C). The third, and final, element of the mudflow comprises an almost semicircular mud lobe which covers an area of just over 170 square metres (1830 square feet) on the foreshore (Plate XI-C). The irregular nature of the eastern side of this mud lobe (Figure 28) reflects the restricting influence of two large driftwood logs on the beach. The mud lobe, which is approximately 2 metres (6.5 feet) thick near the apex, has an average surface gradient of about 5 degrees increasing to 75 degrees along the terminal edge of the lobe. The central portions of the mud lobe have a fresh mud surface in which a series of crudely concentric ridge patterns is visible. The drier, peripheral regions of the lobe however are characterized by a well-developed system of transverse and radial crack patterns similar to those found at the snouts of many glaciers.

Rates of Movement.

Preliminary observations of the mudflows on Garry Island showed that they exhibited highly irregular rates of movement, and attempts were made to record these rates and determine the nature of the processes influencing them. Three lines of styrofoam balls, 6.5 cms. (2.5 ins.) in diameter, and two lines of sticks, approximately 50 cms. (19.5 ins.) in length, were installed across the main channel of the mudflow. The
points at which the lines of balls were installed are shown in Figure 28. Attempts to use table tennis balls as markers were unsuccessful, as they were too buoyant and were easily moved by wind and surface streams of water. The positions of the various markers were recorded at intervals over a 78-hour period, and the results are shown diagrammatically in Figure 29.

In the descriptive comments pertaining to the mud lobe, an analogy was made between the pattern of cracks found on the surface of the mud lobe and those observed in the snout regions of many glaciers. The flow patterns in the mudflow, as indicated by the lines of markers, are also analogous to those found in some glaciers. The greatest velocities occurred in the centre of the channel, and there was a decrease towards the margins reflecting frictional drag against the bordering mud levees (Figure 29). In curved sections of the channel, the maximum average velocities occurred towards the outer side of the curve. The changing attitudes of the lines of sticks also indicated that the surface layers of the mudflow moved more rapidly than the mud at depth. As the lines of sticks moved down the mudflow, the markers were gradually rotated, becoming increasingly inclined at angles and pointing in a downstream direction, until eventually the sticks were lying horizontally on the surface of the mud.

Observations over a 78-hour period showed that the upper and middle lines of balls moved at average rates of 8.5 and 6.0 cms. (3.3 and 2.4 ins.) per hour respectively, while the lower line of balls moved at
Figure 29
MUDFLOW - RATES OF MOVEMENT

Figures against flow lines represent the number of hours elapsed since the markers were installed.
an average rate of 28 cms. (11 ins.) per hour. These overall averages are not truly representative however, since values calculated for shorter lengths of time show that two distinct patterns of movement were discernible during this period. During the first 24 hours of observation, the average velocities for the upper, middle and lower lines of balls were 2.5, 7.5 and 28.0 cms. (1.0, 3.0 and 11.0 ins.) respectively, while for the last 10 hours in which these rates were recorded the average velocities for the upper and middle lines were 37.0 and 15.0 cms. (14.6 and 5.9 ins.) respectively, and the lower line of balls experienced practically no movement. These figures indicate that, during the 78-hour period, there was a change from an initial state in which the average velocity of the mudflow increased fairly regularly towards the terminal mud lobe, to a later state in which the greatest average velocities were recorded in the section of the channel immediately below the outlet of the mud reservoir.

The observation period to which the above values apply ended at 6.30 p.m. on August 20, 1966. The mudflow was not visited again until 6.00 p.m. the following day when it was found that several major changes had taken place. All the balls, with the exception of two which had been left stranded on the mud levees, had been transported down onto the surface of the mud lobe, indicating that much greater velocities had occurred during this time period. (Plate XII-A). Markers located in the upper line of balls for example, which had previously moved a total of 6.6 metres (21.7 feet) over a period of 78 hours or an average rate of 8.5 cms.

31 These averages represent the mean values of each of the balls in each line excluding those which were left stranded on the mud levees. Since the lower line of balls was located near to the terminal section of the channel, the markers were frequently relocated and the rate cited is actually an average of three independent sets of measurements.
Plate XII

MUDFLOW - SURGE PHENOMENA

A. Appearance of the mud lobe following a period of surge flow, showing the fresh mud surface and the transported markers.

B. Fresh striations and scour marks on the inner margins of a mud levee, indicating the level to which mud rose in the channel during the surge.

C. Deformation of organic material on the beach produced by the advancing mud lobe.
(3.4 ins.) per hour, had since been transported an additional 48.8 metres (160 feet) in only 24 hours; an average rate of slightly more than 2 metres (6.6 feet) per hour. Studies made on other mudflows on the island show that the velocities achieved during these surges are considerably higher than those indicated by this average. During the summer of 1964, a mudflow of similar dimensions, located in the floor of another mudslump, reached velocities ranging from 1.5-3.0 metres (5-10 feet) per second during one of these surges.

As a result of this surge, small blocks, previously bounded by desiccation cracks, were plucked from the inner margins of the mud levees. Fresh striations and scour marks on these same levees indicate that the level of the mud rose 45-60 cms. (17.5-23.5 ins.) within the confines of the channel (Plate XII-B). The edge of the mud lobe advanced by distances ranging from 1.75-3.5 metres (5.5-11.5 feet), pushing ahead of it rafts of washed organic material on the beach (Plate XII-C). A large driftwood log, approximately 20.5 metres (67 feet) long and up to 0.6 metres (2 feet) in diameter, which was anchored on the beach by a 0.9-1.2 metre (3-4 foot) root spread, was also pushed bodily forward by the advancing edge of the lobe. During this particular surge, the mud lobe did not reach the sea, but on numerous other occasions it was observed that mudflows had built prominent lobes out into the sea. Although these lobes are extremely soft underfoot, the mud is highly tenacious, and many lobes may resist wave erosion for several weeks before they are finally obliterated - usually during storm surges.

The characteristic wave-like motion of mudflows has been
described by numerous authors. 32 Sharp and Nobles, in their description of the Wrightwood mudflow in Southern California, gave the following account of the flow:

"The debris came down the channel above Wrightwood in a succession of waves or, more appropriately, surges which usually started about 9:00 or 9:30 in the morning, reached a peak of frequency in the early afternoon, and tapered off to an end by late afternoon. Fluidity was greatest at midday when the surges succeeded each other at intervals of a few seconds to tens of minutes. At other times, particularly in late phases of the activity, hours intervened between surges". 33

In another study of the same mudflow, four possible explanations of the surges were offered: (1) periodic sloughing of debris in the source area; (2) temporary choking of the channel; (3) caving of undercut banks; and (4) friction between the moving debris and the channel. 34 The first two factors, considered to be the most significant in the case of the Wrightwood mudflow, appear to be the most satisfactory explanations for the surge phenomena exhibited by the mudflows on Garry Island. The immediate cause of the Wrightwood flow was the melting of winter snow in the head regions, and the periodicity of the surges, with maximum frequency occurring during the daytime and a lack of flowage at night, was thought to be related to diurnal variations in the amount of melting. 35 It was hoped that it would be possible to check this relationship on Garry

32 For example, Blackwelder, E. (1928) op. cit., pp. 465-480.
Island, since the occurrence of the mudflows is intimately related to the thawing of ice bodies in the permafrost. Accordingly, hourly observations of the amount of movement and rates of ablation of the ice face, measured by recording the exposed length of nails driven into the ice, were made continuously over a 32-hour period to determine whether or not there was any correlation.

The values obtained during this period showed that there was little or no statistical correlation between the rate of movement of the mudflow and the rate of ablation of the ice face. The ablation measurements, crude as they were, did show evidence of a diurnal cycle, but there was no evidence of a similar cycle in the mudflow velocities. Indeed, the upper line of balls experienced practically no movement at all. Figures for the maximum movements encountered in both the middle and lower lines of balls showed that there was a progressive decrease in the rate of movement throughout the period.

Attempts were also made to determine the influence of the viscosity of the mud on the flow using the formula given by Sharp and Nobles:  

\[ n = \frac{dg \sin \theta Z_o^2}{2V_s} \]

where  
\( n \) = the coefficient of viscosity  
\( d \) = the density of the fluid debris  
\( g \) = the gravitational force  
\( \theta \) = the angle of slope of the ground  
\( Z_o \) = the thickness of the flow (cms.)

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and \( V_s = \) the velocity at the surface (cms./sec.)

The use of this formula involves simplifying assumptions, among which are Newtonian viscosity, no marginal or terminal influences, no slip on the base and no shear stress on the upper surface, and laminar flow parallel to the base. Of these assumptions, only the second one is perhaps completely valid, since the surface velocity value is a maximum taken from the centre of the mudflow.

Since the density of the fluid was not measured directly, an approximation was made using the data for the weight of mineral soil and weight of water in each of the samples taken, and a value of 2.65 gm cm\(^{-3}\) as the average unit weight of the soil debris. Using the latter figure, an equivalent volume was obtained for the soil, and the overall density of the sample was then calculated. The calculations of the coefficients of viscosity of the mud at the three lines of balls are shown in Table XIII.

<p>| TABLE XIII |
| COEFFICIENT OF VISCOSITY OF A GARRY ISLAND MUDFLOW |</p>
<table>
<thead>
<tr>
<th>d</th>
<th>sin ( \theta )</th>
<th>( Z_o )</th>
<th>( V_s )</th>
<th>n</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper Balls</td>
<td>1.7</td>
<td>.0698</td>
<td>88.4</td>
<td>.00088</td>
</tr>
<tr>
<td>Middle Balls</td>
<td>1.7</td>
<td>.1045</td>
<td>82.3</td>
<td>.00124</td>
</tr>
<tr>
<td>Lower Balls</td>
<td>1.7</td>
<td>.1736</td>
<td>39.6</td>
<td>.00353</td>
</tr>
</tbody>
</table>

As these figures indicate, there is an expected inverse relationship between viscosity and rate of flow; i.e. the higher the viscosity, the slower the movement. Since each of the samples taken had the same fluid density, the most significant factors influencing the rate
of movement appear to be the angle of slope and the thickness of the flow.

In summary, it is apparent that the mudflows on Garry Island exhibit two types of flow which occur in an alternating sequence, albeit with variable periodicity. The controlling factor determining the type of flow is the temporary blocking of the channel, in this case just below the outlet of the mud reservoir. Once blockage of the channel occurs, either by stagnation of the mud deposit or by clumps of organic material, the downstream sections of the mudflow are deprived of additional supplies of debris, although continued lubrication of the flow may be aided by streams of meltwater which percolate through and around the blockage. During this period the mudflow exhibits a form of extending flow, as witnessed by a pattern of increasing velocities in a downstream direction; an overall general decrease in all velocities as the level of the mud in the channel is lowered; and the accompanying development of lunate tension cracks across the surface of the mud. Under these flow conditions, the influence of the gradient of the channel floor appears to be more significant than the thickness of the mudflow, since the lower line of balls moved faster than either of the other two lines despite the fact that the thickness of the flow was only one-half as great as at the other localities. The decrease in the velocities towards the end of this phase of extending flow, besides reflecting the thinning of the flow, probably reflects the fact that, as the mud levees were exposed, increasing quantities of water were channelled off through desiccation cracks.

The phase of extending flow is terminated first in the upper reaches of the mudflow, as shown by the increased velocities recorded in this section towards the end of the observation period. This transition takes place when the accumulation of mud in the reservoir builds up
sufficient pressure to force the blockage of debris downstream. The increased velocities recorded at the upper line of balls corresponded with the removal of debris from the constriction just below this line. Once the material choking the channel has been cleared, the contents of the mud reservoir are discharged rapidly, and the mudflow attains its greatest velocities during these pressure surges. The frequency with which these surges occur depends on the size and nature of the blockage, the most favourable locations for which are points of constriction or slackening gradient in the channel, and the rate of debris accumulation, and consequently pressure build-up, in the reservoir area or upstream sections of the channel. In addition to the pressure factor, the augmented velocities during these surges may also be related to viscosity changes as the thickness of the mudflow increases.

**Mud Levees.**

The edges of many mudflows, irrespective of their size, are marked by sharp, linear ridges termed mud levees. Figure 28 shows both active and inactive mud levees bordering a series of mudflows.

Mud levees are generally symmetrically arranged on either side of the median channel, but there may be a marked asymmetry, with broader, higher levees on the outer curves, where the course of the mudflow is sinuous. The ridges, the crests of which may be either sharp or rounded, vary in height from only a few centimetres to almost one metre (3 feet). These heights normally increase towards the terminal portions of the flow, but the pattern is by no means uniform since high ridges often occur at

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points of constriction in the channel irrespective of their location along its length. The individual levees are highly asymmetrical with the inner margins being shorter and steeper than the outer sides. This difference reflects the fact that the inner margin of a mud levee is initially produced by shearing, along more or less vertical planes, developed between mud which has stagnated along the outer edges of the flow and less viscous mud still moving in the axial part of the flow. The inner faces of levees bordering active mudflows are often characterized by distinctive scour marks or striations indicating that, once established, their slopes may be modified by either the erosive or plastering action of subsequent mudflows moving down the same channel. The outer slopes of the mud levees on the other hand are shaped entirely by deposition, and they frequently exhibit a multi-lobate character where small flows have topped the crests of the ridges and cascaded down the outer sides.

Excavations of mud levees bordering inactive flows showed that they are composed of silt and clay with very few stone accumulations. The upper parts of the levees often exhibit a weak stratification. Since the ridges are composed essentially of solidified mud, their surfaces are frequently covered with networks of desiccation cracks. Excavations were also made across the channels of inactive mudflows, and these often contained a larger number of stones than the adjacent levees.

In the only definitive paper relating to mud levees, Sharp, describing features in the St. Elias Range, Yukon Territory, attributed them to be residual features of bouldery alluvium pushed aside by advancing streams of mud.\(^{38}\) The mudflows on Garry Island do not traverse

\(^{38}\)Ibid.
steep, boulder-strewn slopes similar to those described by Sharp in the mountainous terrain of the St. Elias Range. The structure and composition of the mud levees on Garry Island suggest that they originate in an entirely different manner, and studies of active mudflows indicate that the levees are produced by a progressive bleeding of moisture from the mudflows. The mud loses water by direct surface runoff and by percolation into the underlying ground, a process which is often aided by frost and desiccation cracks covering the surface, until the viscosity is such that motion ceases. This stagnation process occurs first along the outer margins of the flow, while the central parts are still relatively mobile and continue to move. Shear surfaces are developed along the inner margins of the stagnant mud, and this produces the central channel between the bordering ridges or levees. The height of the ridges may be increased by temporary choking of the channel and lateral spilling of the mud, which explains the weak stratification observed in the excavations. In extreme cases, and especially during the pressure surges, the mud may completely override the levees at low, or weak, points and establish an entirely new course.

PATTERNED GROUND

Patterned ground, which may be classified on the basis of geometric shape and presence or absence of sorting, is a widely-adopted term for the more or less symmetrical forms, such as circles, polygons, nets, steps and stripes, that are characteristic of, though not necessarily
confined to, a mantle subject to intensive frost action. Patterned ground in the Mackenzie Delta area is restricted primarily to non-sorted types. Although other factors may be involved, the absence of the sorted forms can largely be attributed to the fact that the mantle frequently lacks a sufficient concentration of stones to exhibit marked frost sorting. This discussion of patterned ground features on Garry Island is restricted to a consideration of some aspects of the development of two of the non-sorted forms: tundra, or ice-wedge, polygons and earth hummocks.

**Tundra Polygons.**

Of the non-sorted forms, tundra or ice-wedge polygons constitute one of the most widespread types of patterned ground in the Mackenzie Delta area. Readily discernible on aerial photographs, the ground exhibits a polygonal microrelief pattern formed by the intersection of shallow furrows underlain by ground ice-wedges. Leffingwell, working on the coastal plain of North Alaska, was among the first to postulate that the networks of tundra polygons were generated by contraction cracks in the frozen ground, produced by intense stresses created as a result of

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41A few crudely-sorted stone circles were discovered on the floors of a number of shallow, artificially drained lakes on the island. See Mackay, J. Ross (1967) "Underwater patterned ground in artificially drained lakes, Garry Island, N.W.T.", Geographical Bulletin, Vol. 9, pp. 33-44.
pronounced seasonal changes in the ground temperature. His 'thermal contraction' theory was outlined as follows:

"The permanently frozen ground contracts in the cold Arctic winter and cracks are formed which divide the surface into polygonal blocks. In the spring these frost cracks become filled with surface water which immediately freezes. In the expansion of the frozen ground as the temperature rises in summer, the vein of ice becomes more rigid than the country formation, and the readjustment takes place in the latter. The result is to bulge up the inclosed block either bodily or else locally along the sides of the ice. During the next winter's cold wave a new crack forms at the same locus so that a continually growing wedge of ground ice is formed. Thus the tundra becomes underlain by a network of ice-wedges, which inclose bodies of the original formation".

The general principles of Leffingwell's contraction theory have been accepted by most of the subsequent research workers investigating tundra polygons. Despite the voluminous literature on this subject, however, the precise details of their origin are still imperfectly understood. Black and Lachenbruch attribute some of this ignorance to an absence of quantitative, rather than qualitative, data but it may also reflect the paucity of observations describing the initial development of the frost crack patterns.

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43 Leffingwell, E. de K. (1915) op. cit., p. 654.


Incipient Frost Crack Patterns. An examination of the literature pertaining to tundra polygons reveals abundant references to, and descriptions of, the polygonal ground in relatively advanced stages of development, but surprisingly little relating to the formation of the initial frost crack patterns. Leffingwell shows illustrations of incipient cracks on the coastal plain of north Alaska, and Black also makes brief reference to similar features. Lachenbruch has made a theoretical study of frost crack patterns in his examination of Leffingwell's thermal contraction hypothesis from the point of view of mechanics, but he does not cite any field evidence to corroborate his conclusions. Washburn et al., to the writer's knowledge, have produced the only recent paper describing the occurrence of frost cracks, albeit in a non-arctic environment.

Observations in the Mackenzie Delta area during the summers of 1964 and 1965 revealed three locations where incipient frost cracks had developed on the ground surface. The locations, each characterized by an absence of any major relief features and elevations of less than one metre (3 feet) above mean sea level, included lake-strewn, alluvial flats on Kendall and Grassy Islands and the flats bordering the lagoons enclosed behind sandspits on Garry Island. All of these sites are frequently inundated during periods of high water, especially during storm surges. The frost cracks were found to be equally well developed on bare ground.

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45 Leffingwell, E. de K. (1919) op. cit.
46 Black, R.F. (1953) op. cit., p. 130.
47 Lachenbruch, A.H. (1962) op. cit.
surfaces (Plate XIII-A), and on flats supporting a dense cover of grasses and sedges 20-40 cms. (8.0-15.5 ins.) tall (Plate XIII-B). In these latter areas, the vegetation was flattened, presumably by a combination of prevailing winds, snowfall and flood surges in the preceding fall. The vegetation was cut by sharp, knife-like fractures and was probably frozen to the ground surface at the time of the frost cracking to produce the clean break. In many places, the cracks were observed to extend beneath the surfaces of shallow lakes, though none were traced entirely across the lake floor. This indicates that the water, at least in the shallower parts of the lakes, was frozen to the bottom although water in the central sections of the lakes may have remained unfrozen at depth. The fact that the fissures on Kendall Island cut through the vegetation into the underlying mineral soil, would appear to substantiate the view that the cracks were produced by intensive frost action. The cracks on the bare ground surfaces are interpreted as having originated in a similar manner, although the possibility that they were produced by desiccation of the soil cannot definitely be excluded.

Excavations in one of the sandspit-lagoon areas on Garry Island revealed that the frost cracks were best developed in organic-rich silts and silty loams. Mechanical analyses of the soils showed that they were composed of 59.2 per cent silt, 21.3 per cent sand, and 19.5 per cent clay (Wentworth classification categories). The soils were mantled by a thin layer of organic material, and the organic content of the soil samples averaged 5.5 per cent by weight of the dried sample. The surficial organic layer and the organic matter at depth, often in the form of thin intercalations, probably represent washed peat derived through erosion of the adjacent coastal bluffs. The soils also possessed a high
Plate XIII

INCIPIENT FROST CRACK PATTERNS

A. Orthogonal intersections of frost cracks on bare alluvial surface of Grassy Island, Mackenzie Delta area, N.W.T.

B. Frost cracks developed through a layer of vegetation, Kendall Island, N.W.T.

C. Frost crack intersection pattern forming three obtuse angles of about 120 degrees, Kendall Island, N.W.T.
moisture content, with frozen samples having an average ice content of 91.7 per cent (expressed as weight of ice to dry soil). Mackay has already documented the granulometric composition of the soils underlying the sedge-covered flats on Kendall Island, where the proportions of clay and sand were slightly lower (silt 79 per cent, sand 13 per cent and clay 8 per cent).

Most of the frost cracks exhibited little or no topographic expression at the ground surface, but some of the larger fissures traversing the unvegetated areas were marked by the presence of shallow troughs 30-70 cms. (12.0-27.5 ins.) across and 10-20 cms. (4-8 ins.) deep. When examined in early August, 1964, the frost cracks on Garry Island exhibited a wedge-like form extending down through the active layer and into the frozen ground at depths of 50 cms. (19.5 ins.) below the ground surface. At the surface, the open fissures were up to 4 cms. (1.5 ins.) across, and they remained open to depths of 15-25 cms. (6-10 ins.) but narrowed to only a few millimetres in width at the level of the frost table. In many localities, the cracks were infilled at depth by sand-size material that had probably been blown or washed in from the ground surface. These miniature sand-wedges are similar in form to the larger scale features described by Péwé in the McMurdo Sound area of Antarctica.

Below the level of the frost table, the cracks were occupied by small veins of ice, approximately one millimetre across, which could be traced


to a depth of 76 cms. (30 ins.) below the ground surface.

Rarely did the frost cracks in the sandspit-lagoon areas of Garry Island reveal any arrangement into a definite polygonal network. The majority of the fissures appeared to be randomly distributed over the ground surface, and showed no preferred directional orientation except for a weak tendency to occur along lines developed at right angles and parallel to the margins of the lagoons. The only other salient feature of the distribution was the contrast in the density of the pattern between the silty loam and coarser sand areas of the sandspit. Although the frost cracks were present in both of these areas, the density was much higher in the silty loam sections.

The distribution of the frost cracks on Kendall and Grassy Islands showed a much greater tendency to be organized into crude polygonal patterns. Figure 30 is a map showing the spatial arrangement of the frost cracks on a part of the sedge-covered flat on Kendall Island. As this diagram shows, the ground surface was subdivided into a number of highly irregular polygons of variable size but averaging 2-3 metres (6.5-10.0 feet) across. The majority of these irregularly-shaped polygons were four- or five-sided, and hexagonal forms were notably conspicuous by their absence. Most of the fissures on Kendall Island also exhibited little preferred directional orientation except in the vicinity of the larger water bodies.

The spatial distribution of the frost cracks on Grassy Island demonstrated the existence of a much more regular polygonal network, although on a considerably larger scale. On these bare alluvial flats the individual polygons averaged 20-30 metres (65-100 feet) across, and tetragonal forms were predominant. The pattern of these frost cracks
Figure 30
INCIPIENT FROST CRACK PATTERN
KENDALL ISLAND, N.W.T.

- Orthogonal intersections
- $60^\circ$ intersections

Scale in metres

0 1 2
moreover revealed much stronger trends in their preferred directional orientation. The larger fissures, up to 5 cms. (2 ins.) wide and located in the floors of shallow troughs in the ground surface, were oriented at right angles to the bank of a distributary of the Mackenzie River. The smaller cracks, less open and having almost no topographic expression on the ground surface, on the other hand were aligned more or less parallel to the same river bank. These preferred orientations were especially noticeable within distances of approximately 50-60 metres (165-200 feet) from the edge of the channel, but became less distinct with increasing distance from the bank.

It is generally agreed that frost cracks originate as a result of large thermal stresses created by a sudden cooling of the ground.

"When the tensile strength (of the ground) is exceeded near the surface, a tension crack forms and propagates downward. ... The formation of a crack causes a local relief of tension in the surficial materials. ... Each crack is, therefore, surrounded by a band in which cracking has caused appreciable reduction of horizontal tension - the "zone of stress relief". ... The component of thermal tension at the ground surface in the direction parallel to the crack is relieved only slightly by the cracking and, thus, large horizontal stress differences occur within the zone of stress relief. A second crack entering this zone tends to align itself perpendicular to the direction of greatest tension, and, hence, tends to intersect the first crack at right angles. Conversely, the occurrence of an orthogonal intersection generally implies that one of the cracks predated the other".51

Lachenbruch's conclusion that the angular intersections of a polygonal network of frost cracks will exhibit a preferred tendency toward an orthogonal pattern, contrasts with many descriptions of polygonal

ground in which authors have expressed a tendency for hexagonal forms and angular intersections of 120° to predominate. The implications of the hexagonal pattern, and angular intersections of 120°, are that the frost cracks originated at a series of points and each crack developed more or less simultaneously. In an attempt to determine the validity of Lachenbruch's conclusion, particular attention was paid to the nature of the angular intersections of the frost crack patterns on Garry and adjacent islands. A total of 101 angular measurements was recorded including those shown in Figure 30. An additional fifty intersection patterns are illustrated diagrammatically in Figure 31, where an attempt has also been made to indicate the relative order of occurrence and propagational direction of each of the fissures. Primary frost cracks, usually the larger, are defined as those which originated first at any location, and their propagational directions were inferred, wherever possible, from their orientation with respect to the water bodies (i.e. cracks which were oriented at right angles to, and propagated outward from, the body of water). Secondary frost cracks are defined as those which developed later at each location, and these cracks terminate at, and propagate towards, pre-existing primary fissures.

Of the 101 angular measurements recorded, no fewer than 79, or eighty per cent, were of the orthogonal type. As Figures 30 and 31 indicate, most of these orthogonal intersections were formed by the

52 For example:
Leffingwell, E. de K. (1915) op. cit., p. 638.
Black, R.F. (1953) op. cit., p. 129.
Figure 31
DIAGRAMMATIC SKETCHES OF
FROST CRACK INTERSECTION PATTERNS

Primary Frost Cracks
Secondary Frost Cracks
Orthogonal Intersections
60 Angle of Intersection in Degrees
Inferred Propagational Directions of Cracks
junction of a primary and secondary frost crack, and only rarely were two primary frost cracks observed to intersect one another. The influence of a zone of stress relief is also manifest in the manner in which many of the secondary fissures curve to intersect the primary cracks at right angles. Where the primary cracks were sinuous, the most favoured loci for the intersection points of secondary frost cracks were located on the convex sides of the curves. This is in accordance with the distributional pattern of stress relief on a curved section of a frost crack as described by Lachenbruch.\(^53\)

Angular intersection values of 60° were by far the most common of the non-orthogonal intersection patterns. This angle was most frequently developed as a result of the bifurcation of a primary frost crack, and at points of intersection where two frost cracks of the same order approached one another obliquely. Very few of the angles measured were neither 90° nor 60°; and only two examples were found of tri-radial intersections, forming three obtuse angles of about 120°, suggesting that the frost cracks originated at a point (Plate XIII-C).

The field evidence collected in the outer Mackenzie Delta area thus appears to substantiate the conclusions of Lachenbruch's theoretical study. Primary frost cracks were developed, essentially in a random pattern, across the ground surface, and the junctions of secondary frost cracks with these primary fissures showed a definite preferred tendency toward an orthogonal intersection pattern. According to Lachenbruch's classification scheme, the resultant crude polygonal network would

\(^{53}\) Lachenbruch, A.H. (1962) \textit{op. cit.}, p. 50.
therefore be classified as a 'random orthogonal system'. Only in the vicinity of large bodies of water did preferred directional orientations become sufficiently pronounced to be classified as 'oriented orthogonal systems'.

The apparent dichotomy between this evidence and the fact that most tundra polygons appear to be of a non-orthogonal type has been explained by Lachenbruch to be the result of an obscuring of the intersection angles by the growth of large ice-wedges. The incipient frost crack pattern is practically the only stage in the development of a network of polygonal ground therefore in which the angular intersection patterns can be determined with any real degree of accuracy. Moreover, these determinations can only be made in the field through ground inspection, since the frost cracks are generally too small to be identified from aerial photographs.

The transformation of an initial pattern of frost cracks into a network of tundra or ice-wedge polygons requires that recurrent fracturing takes place at the same loci. The evidence collected on Garry Island suggests that once a fracture is formed, it tends to persist as a permanent line of weakness in the mantle. Most of the larger cracks remained as open fissures throughout the summer months, possibly indicating that the ground was sufficiently elastic to absorb the strain produced by its expansion under the summer's heat and consequently no deformation took place. Where the ground surface was covered by a thin layer of washed

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55 *Ibid.*, Figure 13, p. 49.
peat, it is also possible that the maintenance of the open fissure may have been aided locally by a slight desiccation and shrinkage of this layer. Even where the cracks were closed, this probably did not take place before some material had infiltrated from the ground surface, and the miniature sand-wedges, produced in this manner, also assist in the preservation of the lines of weakness.

**Low-Centred Polygons.** The frost cracks extend down below the base of the active layer where they are occupied by a thin vein of ice. Recurrent fracturing at the same loci results in the addition of successive increments of ice, and the eventual formation of a large, foliated ice-wedge. Accompanying the growth of these ice-wedges, and bounding them on either side, distinctive ridges are formed which may partially represent the upturning of strata adjacent to the growing wedge. Thus the first polygons to form consist of a central, saucer-shaped depression enclosed between bordering ridges, and they are accordingly referred to as low-centred or raised-edge polygons.

These polygons are best developed in fine-grained sediments underlying poorly-drained flats, but if the drainage is too poor they do not necessarily exhibit the characteristic saucer-shaped form. A number of polygons has developed around the edges of a lagoon enclosed by the sandspit on the north-central coast of Garry Island. This lagoon is open to the sea, and the areas of polygonal ground are frequently inundated during periods of high water. Such polygons have very little topographic

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expression and bordering ridges are non-existent.

Figure 32 shows the surface contours and cross-sectional profiles of a classical low-centred polygon form, located at an elevation of 4.5-6.0 metres (15-20 feet) above sea level. The polygon is surrounded by shallow troughs, marking the positions of the ice-wedges, ranging in width from 3.0 to 4.5 metres (10-15 feet). In places, the troughs are occupied by water 0.5-1.0 metres (1.5-3.0 feet) deep (Plate XIV-A), but elsewhere they have been partially infilled by the accumulation of organic material which supports a vegetation cover composed predominantly of sedges. The polygon ranges in width from 10.5 to 14.5 metres (35-48 feet) as measured between the crests of the bounding ridges which reach maximum elevations of 65 cms. (25.5 ins.) above the level of the water in the adjacent troughs. These same ridges enclose a shallow depression in the central part of the polygon which, at the time of surveying, was floored by a marsh-sedge vegetation, but at other times during the summer was occupied by a shallow pool of standing water 5-10 cms. (2-4 ins.) deep. Central areas of other low-centred polygons in the same general location were occupied by pools of water throughout the summer. The retention of this water is aided by the configuration of the frost table which closely follows the surface microrelief as illustrated in the profile in Figure 32.

The polygon shown in Figure 32 was actually part of an extensive area of low-centred polygons located between the large lake and the truncated lagoon on the northwest coast of the island (see Figure 1). A larger grouping of these polygons is shown in Figure 33. As this map illustrates, the most characteristic form of the unit polygons was a four- or five-sided figure. The sizes of the individual polygons ranged from
Figure 32
SURFACE CONTOURS AND CROSS-SECTIONAL PROFILE
OF A TYPICAL LOW-CENTRED POLYGON

SURFACE CONTOURS
ABOVE DATUM
(Cms.)

CROSS-SECTIONAL PROFILE

Standing water
Ice floor

Ridge
Dry and peaty

Sedge/marsh

Sedge in standing water

Scale in metres
0
10
20

Contour interval 15 cms.

Standing water
Muck floor

Unfrozen

Frozen Aug. 16, 1965

Distance in metres
A. Low-centred or raised-edge tundra polygon with central depression occupied by pool of standing water.

B. Infilling of central depression to produce a flat-topped polygon which has been subdivided by the growth of additional ice-wedges.

C. Oriented, orthogonal system of low-centred polygons developed around a small lake. (Photograph courtesy of Dr. J. Ross Mackay).
Figure 33

LOW-CENTRED POLYGON NETWORK

Surveyed Polygon shown in Figure 32

Legend:
- Water
- Willows
- Sedge mounds
- Sedge/marsh
- Sedge in standing water

Scale in metres:
0 5 10 15 20
9 to almost 24 metres (30-80 feet) across, but much of this variation can be attributed to the subdivision of the original, larger polygonal units by the subsequent growth of additional ice-wedges (Plate XIV-B).

It is virtually impossible from Figure 32 to determine the angular intersections of the polygonal network. Lines drawn along the central axes of the ice-wedge troughs could be interpreted to intersect orthogonally, as in the case of the incipient frost crack patterns, but definitive conclusions cannot be made. In a few locations deep, open fissures in the ice-wedges, presumably marking the positions of frost cracks produced during the preceding winter, could be observed beneath the water, but, unfortunately, none of these were located at the ice-wedge intersection points. Similarly, the presence of any preferred orientation in the alignment of the ice-wedges shown in Figure 33 is difficult to detect. A group of polygons around a small lake in the same area of patterned ground showed a definite orientation with respect to the lake, with the major fissures radiating outward from the lake like the spokes of a wheel (Plate XIV-C). It is surprising that the polygonal network shows no pronounced orientation with the shore of the lake shown in Figure 33. If any pattern is discernible, it is perhaps suggestive of a crude radial and concentric arrangement around the focal points A and B. If this interpretation is correct, these focal points may represent the former positions of two small lakes on the flat ground around each of which an oriented orthogonal(?) system was developed.

Ice-wedge or tundra polygons are not restricted in their development to areas of moist, fine-grained sediments. Large networks of subdued polygons were also developed on Garry Island on the surfaces of the sand headlands (Figure 34). Although these polygons were also of the
Figure 34
LOW-CENTRED POLYGON NETWORK
ON SAND HEADLANDS

Scale in metres
0  5  10  15  20

Lines of Ice Wedges
Cliff Edge
low-centred type, there was a major contrast in the surface microrelief. Thus the bounding ridges of the polygons barely rose more than 15-25 cms. (6-10 ins.) above the levels of the troughs or the central sections of each polygonal unit. The troughs, marking the positions of the ice-wedges, contained no surface water and the ice was mantled by a layer of moss and sedge growing in a peat substrate. Only near the edges of the cliffs did the troughs become more pronounced, where thawing of the ice-wedges had produced prominent 'V'-shaped notches, 1-3 metres (3.5-10.0 feet) deep, in the cliff top. The polygons on the sand headland surface also exhibited a wide variation in size, reflecting a similar subdivision process to that described in an earlier paragraph. The configuration of the more prominent surface expressions of the ice-wedges suggests that the headland surface was initially divided into a series of irregular blocks, 25-35 metres (80-115 feet) across, and that these have subsequently been subdivided by the growth of additional ice-wedges into a number of predominantly tetragonal forms, 6-10 metres (19.5-33.0 feet) across. The greater regularity and uniform widths of the troughs outlined in Figure 34 make it easier to infer the nature of their angles of intersection, which appear to exhibit a definite tendency toward a preferred orthogonal pattern.

Thus the main effects of a coarse sand substrate on the network of patterned ground appear to be in a slightly coarser spacing of the primary crack patterns, and a less pronounced topographic expression. The wider spacing of the primary frost cracks may reflect the lower coefficient of expansion of frozen sand compared to fine-grained sediments, and the subdued microrelief may be related to a more restricted moisture supply.
High-Centred Polygons. The major sequential stages in the infilling of a low-centred polygon, and its transformation into a high-centred form, were outlined in Chapter III. Standing pools of water in the central depressions of low-centred polygons are often floored by a thick layer of soft ooze, believed to be the accumulated remains of algae. The ooze deposit corresponds to the grey silty material observed in the basal sections of high-centred polygons exposed by wave action in the coastal bluffs. The continuity of this deposit in the same exposures also indicates that the accumulation of algal remains is a major factor in the infilling of initial lakes prior to the development of a system of ice-wedges. The deposition of the ooze within the central areas of low-centred polygons leads to a shallowing of the water depths, and allows the areas to be colonized by vascular species in the sequence also described in Chapter III. The accumulation of peat results in a further elevation of the central areas of the polygons relative to the levels of the bordering ridges and, since the grey silt layers often have ice contents of several hundred per cent (by weight), the formation of syngenetic (penecontemporaneous), segregated ice lenses in the ooze may also contribute significantly to an elevation of the surfaces of the central depressions.

The sequential stages in this shallowing process were readily observable in the group of low-centred polygons shown in Figure 33, where, in general, the surfaces of the polygons located around the edge of the flats were level with the bounding ridges. Nowhere, however, had this infilling process led to the production of the characteristic, dome-shaped, convex profile of a typical high-centred polygon (Plate XV-A). Figure 35 shows the surface contours and cross-sectional profile of one of these high-centred forms, located at an elevation of approximately 21-23 metres
A. Characteristic, dome-shaped, convex profile of a typical high-centred polygon.

B. Thermokarst features in an area of high-centred polygons exposed by coastal recession.

C. Thermokarst features showing slumping of the side of a low-centred polygon. Stadia rod, extended to 8 feet, rests on the floor of the trough created by melting of the ice-wedge.
SURFACE CONTOURS AND CROSS-SECTIONAL PROFILE
OF A TYPICAL HIGH-CENTRED POLYGON

SURFACE CONTOURS
ABOVE DATUM
(Cms.)

Contour interval 15 cms.

Scale in metres
0 1 2 3

CROSS-SECTIONAL PROFILE

Water filled wedge

Flat, dry and peaty hummocks with narrow litter filled depressions

Unfrozen

Dry wedge = willow and sedge

Water

Willow and sedge

Sedge

Distance in metres

Frozen Aug. 16, 1963
(70-75 feet) above sea level. Compared to their low-centred counterparts, these polygons were generally much more regular in shape and averaged 6-8 metres (19.5-26.0 feet) in diameter. At their highest points, usually in the centres of the polygons, the surfaces were about 1.5-2.0 metres (5.0-6.5 feet) above the level of the surrounding troughs. The latter, marking the positions of the ice-wedges, were predominantly filled with moss and sedge although locally they contained pools of water 15-50 cms. (6.0-19.5 ins.) deep.

Most of the areas of tundra polygons on Garry Island at elevations exceeding approximately 15 metres (50 feet) above sea level are of the high-centred type. The height-distribution pattern of these areas appears to be intimately related to the elevations of raised shoreline features. It is postulated that most of the polygonal pattern was initially formed on lagoon-flats developed behind small sandspits, or bars, associated with former positions of the level of the sea. Many of these areas of tundra polygons are extremely limited in their extent, and they typically take the form of small pockets occupying the narrow floors of some of the valleys. In these restricted localities, however, the configurations of the networks of ice-wedges exhibit a very definite tendency toward the development of an oriented orthogonal system. Thus the most prominent wedge lines were invariably aligned along the axis of the valley floor, where undoubtedly much of the reason for their prominence was their accentuation by intermittent surface runoff, and the other ice-wedges were frequently aligned at right angles to these main axes.

**Thermokarst Features.** The term thermokarst is used to describe surface hollows and depressions that originate through the melting of ground ice. Because of the high ice content of many of the sediments, the
conditions on Garry Island are extremely favourable for the development of thermokarst topography, especially when these sediments are exposed by the recession of the coastline. Thus the most dramatic manifestations of this process occur when the retreat of the cliffs exposes massive sheets of segregated ice resulting in the development of the large mudslumps described earlier in this chapter. The shallow water depths, usually 1-2 metres (3.0-6.5 feet), around the margins of the larger lakes on the island, and the concentrations of coarse gravel and boulders on their floors, may possibly be interpreted as evidence of thermokarst enlargement of the lakes in a manner similar to that described by Wallace in eastern Alaska.  

A distinctive type of thermokarst topography was developed on Garry Island where networks of tundra polygons, of both the low- and high-centred types, had been exposed in the bluffs as a result of coastal recession (Plates XV-B and XV-C). Melting along the lines of the ice-wedges had transformed the shallow troughs into prominent trenches several metres deep. In the sand headland areas, the melting of the ice-wedges imparted a characteristic notched appearance to the cliffs. In the area of high-centred polygons, located on the northwest coast of the island (see Figure 6), the trenches were as much as 3-4 metres (10-13 feet) deep, and the individual polygonal units had been left standing as isolated mounds of peat. Melting of the ice-wedges had also left the sides of the polygons unsupported, and a considerable amount of slumping had taken place thereby accentuating the convexity of their surface profiles. Since the majority of the areas of high-centred polygons on the island also

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appear to have been affected by thermokarst action, though usually to a lesser degree, it seems reasonable to infer that the development of the typical convex profile of these polygons may represent the operation of this same slumping process.

It should be noted that the examples of thermokarst topography cited above were, or could have been, developed entirely by the operation of existing natural processes without any recourse to an amelioration of climate. Three further examples, observed during the field seasons, demonstrated the rapidity with which thermokarst features can be developed by an interference with the natural conditions. The first example was associated with attempts to lower artificially the level of a lake by digging a ditch across the peat barrier damming its outlet. The water was led out through this artificial channel, at an elevation of approximately 36.5 metres (120 feet) above sea level, and then allowed to seek its own course to lower elevations. Immediately prior to the opening of the channel, the depth of thaw just beyond its outlet was recorded as 30-35 cms. (12-14 ins.), yet after only three weeks of intermittent flow this had increased fivefold, to over 1.5 metres (5 feet), and the surface mat of living vegetation was literally floating on the thawed substrate. Without flooding, the position of the frost table might have retreated by approximately 10 cms. (4 ins.) at the most during the same three-week period.

The second example was much more impressive in terms of its effect on the surface topography. As discussed earlier in Chapter II, the majority of the stream courses on Garry Island have ill-defined channels, and, consequently, the flow of water is easily diverted from its normal path. An example of this occurred when water was diverted from its
original course to follow well-defined, sub-parallel paths between the base camp and the coast. At the coastline, this path terminated at a series of tundra polygons, the existence of which was only feebly expressed at the ground surface. Surface runoff, derived principally from melting snow, was observed to be flowing along these paths at the beginning of the 1965 field season. In the summers of 1967 and 1968 there was slight seepage down the paths, but no flow. The effects of this re-routing of the water were apparent by the summer of 1967, where rapid thermokarst erosion of the ice-wedges had occurred over distances extending back to about 30-35 metres (100-115 feet) from the coastal bluff. This erosion had produced a number of prominent troughs, approximately 2 metres (6.5 feet) wide and, at the intersection points of the ice-wedges, 2 metres (6.5 feet) deep.\(^{59}\) By 1968, the inter-ice-wedge areas of several polygons had been undermined by thaw to produce subsurface overhangs as much as 5 metres (16.5 feet) square and 0.6-1.0 metres (2-3 feet) high.\(^{60}\)

The third example of the development of thermokarst features occurred in an area where a dog had been tethered during the 1965 field season. The vegetation cover of a circular area, approximately 3 metres (10 feet) in diameter, was killed as a result, and the accelerated thawing had led to a settling of the ground surface and the creation of a bowl-shaped depression, 20 cms. (8 ins.) deep, by the summer of 1968.\(^{61}\)

\(^{59}\) Information supplied by Dr. J. Ross Mackay, personal communication, August 27, 1968.

\(^{60}\) Information supplied by Dr. J. Ross Mackay, personal communication, October, 1968.

\(^{61}\) Ibid.
Earth Hummocks.

The term earth hummock was first introduced by Sharp to describe low, rounded knobs of fine material consisting of an earthen core covered by a tight mat of moss, grass and scrubby plants. According to Washburn's classification scheme, they fall into the category of non-sorted nets. On Garry Island, these microrelief features are generally confined to well-drained sites where they form a continuous, three-dimensional mesh on the gently-inclined upland surfaces and the steeper valley-side slopes. Although, as will be discussed below, it is possible that similar microrelief forms may be produced in differing environments by the operation of dissimilar processes, this situation contrasts markedly with that described by Raup in the Mesters Vig District of northeast Greenland. Raup found that (turf) hummocks, which from his descriptions and illustrations appear to be identical to the earth hummocks on Garry Island, occurred only on sites abundantly supplied with gently-flowing surface water, derived from the melting of perennial snowdrifts or the thawing of frozen ground, throughout most of the summer season. Perennial snowdrifts are lacking on Garry Island, and no incidence of surface runoff was observed on the hummock sites during three summers' observations. Moreover, earth hummocks were almost conspicuous by their absence on the lower, poorly-drained flats.

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64 Raup, H.M. (1965) "The structure and development of turf hummocks in the Mesters Vig District, Northeast Greenland", Meddelseer om Grønland, Bd. 166, Nr. 3, p. 5. Raup further states that turf hummocks may be common on drier sites, but here they are always in some stage of disintegration.
where they are usually replaced by the tussock forms of the Sheathed Cotton-grass (*Eriophorum vaginatum*) or featureless mats of moss and sedge.

The apparent dichotomy between these environmental conditions illustrates one of the most salient aspects of patterned ground studies. Hummocky ground, for example, has been extensively described in both geomorphological and botanical literature, where numerous names have been applied to superficially similar forms. Anatomically, however, it is evident that the broad term 'hummocky ground' has been used loosely to incorporate individual forms with widely differing structures. Whilst it is possible that these dissimilar structures may be nothing more than different expressions of the same, or similar, genetic processes, it is equally probable that they each represent important modifications of these processes in response to significant variations in such specific environmental conditions as soils, vegetation, slope and available moisture supply.

Several authors have recognized that types of hummocky ground can be classified either on the basis of the plant species of which they are composed, or on their internal composition. A classification according to plant species affords distinguishing criteria for those microrelief features which have a tussock form. Individual tussocks are developed by the upward growth of a single plant on a columnar base of its own dead leaves and roots, and the height of these tussocks is further accentuated by differential frost action and the doming-up of mineral soil beneath the plant. On Garry Island, the Sheathed Cotton-grass (*Eriophorum vaginatum*) is the major tussock-forming species, and it thrives on flat to gently-sloping, poorly-drained surfaces. Since the structure and development of tussocks have been described in detail by Hopkins and Sigafoos, they will

A classification of hummocks on the basis of their internal composition is much more complex, but it would seem logical to make a fundamental subdivision relating to the degree of homogeneity of the substrate. In this way the hummocks which are composed entirely of peat could be differentiated from those which have a prominent mineral core. It is into this latter category that the hummocks on Garry Island fall and, since the domed mineral core is the most diagnostic feature of these microrelief forms, Sharp's nomenclature of earth hummocks has been adopted.

The Structure of Earth Hummocks. Information pertaining to the structure of earth hummocks was collected using the following methods. Three locations were selected subjectively to illustrate diagnostic hummock features at specific locations on a typical slope profile, and a fourth location where the hummocks had coalesced into stripe forms. At each of these locations the surface configuration was obtained by superimposing a 1.8 metre (6 foot) square grid horizontally above the ground surface, and taking plumb readings to the surface at horizontal intervals of 10 cms. (4 ins.). This data was used to prepare contour maps with a 2.5 cm. (one inch) contour interval, rough copies of which were made at the time to permit field checks. On the slope profile, the grid size was usually sufficient to show a group of hummocks, but where the stripe features were developed the process was repeated four times to cover a 3.6 metre (12 foot)
square plot. Before the grid was removed, the dominant aspects of the vegetation cover were also mapped. Profile lines were selected to give representative longitudinal- and cross-sections of a typical hummock in each of the locations, and excavations to the frost table in late August provided the structural data.

Figure 35 and Plate XVI-A show earth hummocks on the gently-inclined upper portions of a slope profile. Individual hummocks rose about 12-14 cms. (4.5-5.5 ins.) above the mean level of the surrounding depressions, and they were approximately circular in outline, averaging about 50-60 cms. (19.5-23.5 ins.) in basal diameter. In profile the hummocks were broadly convex, and generally they did not exhibit any marked asymmetry. The intervening depressions commonly took on the form of shallow, open troughs.

There were quite pronounced differences between the vegetation associations of the hummocks and the depressions as shown in Figure 37. The higher, drier sites of the hummock centres were dominated by the Arctic Avens (*Dryas integrifolia*), Arctic Blueberry (*Vaccinium uliginosum var. alpinum*), small sedges (*Carex* sp.), lichens and dry moss pads (chiefly *Dicranum* sp.). The Arctic Blueberry was particularly abundant on the sides of the hummocks and sometimes extended down into the floors of the depressions, but these were dominated by the Arctic White Bell-heather (*Cassiope tetragona*) growing in a damp substratum of mosses (chiefly *Aulacomnium* and *Sphagnum* sp.). Small willows (*Salix arctica*) were occasionally found on the surface of the hummocks, but they were most abundant on the lower parts of the sides. There were also appreciable differences, between hummocks and depressions, in the relationship of this vegetation cover to the underlying surface. The plants on the hummocks formed a tight, inter-
Figure 36

EARTH HUMMOCK

LOCATED ON UPPER PART OF SLOPE PROFILE

SURFACE CONTOURS ABOVE DATUM

STRUCTURAL PROFILES

- Living vegetation
- Peat
- Mineral soil

Contour interval 2.5 cms.
Figure 37

EARTH HUMMOCK
LOCATED ON UPPER PART OF SLOPE PROFILE

VEGETATION TYPES

- Edge of Hummock
- Lichen/avens/sedge association
- Avens
- Sedge species
- Moss and/or Heather
- Willow
- Blueberry patch

Scale in cms.

0 20 40 60
Plate XVI

EARTH HUMMOCKS

A. Earth hummock located on the upper part of a slope profile showing the almost circular outline.

B. Earth hummock located on the middle part of a slope profile showing the elongation in a downslope direction.

C. Earth hummock located on the lower part of a slope profile exhibiting an almost perfect circular form.

D. Structure of a typical earth hummock showing the mineral core, the wedges of organic material beneath the troughs, and an intermittent buried organic layer near the top of the permafrost.
woven mat which was intimately bound to the ground below by root systems which extended down into the peat and, in some cases, into the mineral core. Plants occupying the depressions on the other hand tended to be very shallow rooted, and were only loosely anchored in the moss which in turn rested loosely on the underlying peat.

Figure 36 also shows the structural features of these hummocks along the indicated profile lines. The living turf mat, including a zone of brownish, loosely-packed organic material, averaged 4-8 cms. (1.5-3.0 ins.) in thickness, but increased locally to almost 15 cms. (6 ins.) in some of the larger depressions. Beneath this surface mat was a layer of tight, black peat averaging 5-8 cms. (2-3 ins.) in thickness in the central mound areas, but thickening to form organic wedges penetrating down to the frost table beneath the depressions. It is perhaps significant that the positions of these organic wedges did not always coincide exactly with those of the surface depressions. Moreover, these organic wedges frequently did not extend down either vertically, or with uniform width, to the frost table, but were often decidedly convex in a downslope direction, tapering to thin strips towards the base of the active layer. Local thickenings of the same peat layer were also evident beneath some of the central mounds, often in close association with minor depressions on the hummock surface. The central core of the hummocks consisted of a prominent dome of mineral soil. This core reached its maximum thickness, approximately 35 cms. (14 ins.) under the centres of the hummocks, but laterally it was greatly attenuated and occasionally was absent completely beneath the depression areas. The basal, structural feature of these hummocks was a buried organic layer which occupied a position close to the frost table. This layer always attained its greatest prominence towards
the lateral margins of the hummocks where it was nearly always observed to unite with the organic wedges. In longitudinal, or downslope, sections it was best developed on the upslope sides of these same wedges. The basal organic layer reached its maximum thickness, 2-3 cms. (0.75-1.25 ins.), in these lateral positions, but it thinned appreciably towards the centres of the hummocks where only thin traces were sometimes present. In some instances the organic layer could be traced entirely beneath the complete hummock structure, but in others it appeared to be absent in the central areas. The material beneath the organic layer consisted of mineral soil similar in composition to that forming the hummock cores.

Figure 38 and Plate XVI-B show a typical earth hummock located on the middle slope region of the topographic profile. The hummock rose 15-20 cms. (6-8 ins.) above the surfaces of the depressions, but rather than being circular in outline, it exhibited a definite elongation in a downslope direction. Whilst the hummock was still broadly convex in profile, longitudinally there was a definite asymmetry with the downhill face steeper than that on the uphill side. The intervening depressions were stronger features than those described on the upper slope, and were more continuous, narrower and had steeper sides. The structural diagrams in Figure 38 show that this hummock was similar in composition to the one described on the upper slope, and the vegetation associations of the hummock and depression areas were also similar, as is indicated by the map.

Since the frost table continues to recede into September, the position of the buried organic layer is perhaps more aptly described as at, or just above, the base of the active layer. Additional excavations of these and other hummocks to depths below the frost table in late August demonstrated a greater extent of this layer, but confirmed that in some instances it is completely lacking beneath the centres of some hummocks.
Figure 38

EARTH HUMMOCK
LOCATED ON MIDDLE PART OF SLOPE PROFILE

SURFACE CONTOURS ABOVE DATUM

STRUCTURAL PROFILES

- Living vegetation
- Peat
- Mineral soil

Contour interval 2.5 cms.
Figure 39

Earth Hummock
Located on Middle Part of Slope Profile

Vegetation Types

- Edge of Hummock
- Lichen/avens/sedge association
- Avens
- Sedge species
- Moss and/or Heather
- Willow
- Blueberry patch

Scale in cms.
0 20 40 60
of vegetation types shown in Figure 39.

Figure 40 and Plate XVI-C show a large earth hummock located on the lower slope near the base of the topographic profile. This hummock rose as much as 30-35 cms. (12-14 ins.) above the adjacent depressions, and it was approximately circular in outline, averaging 70-75 cms. (27.5-29.5 ins.) in basal diameter. The structural and vegetation patterns (Figure 40, Plate XVI-D and Figure 41) of this hummock and the neighbouring depressions also followed the same pattern as that described higher up the slope, but a few notable exceptions are worthy of mention. The proportion of the hummock occupied by the mineral core was greater, and the buried organic layer reached thicknesses of 5-8 cms. (2-3 ins.) beneath the hummock areas. In the depressions, the proportion of moss was much higher and they were also much damper than the depressions higher up the slope. Other small changes in the vegetation types included the presence of the Narrow-leafed Labrador-tea (*Ledum palustre ssp. decumbens*) and Mountain Cranberry (*Vaccinium vitis-idaea*) with the lichens/avens/sedge association; the inclusion of the Common Crowberry (*Empetrum nigrum*) and Mountain Cranberry with the sedge species; and the appearance of tussocks and the Glandular Birch (*Betula glandulosa*) which are largely absent on the higher slopes.

Figure 42 shows another hummock profile excavated on the lower slope close to the junction with the floor of the depression. This hummock was also almost circular in outline, but averaged almost 1.2 metres (4 feet) in diameter. The height of the hummock, 20-25 cms. (8-10 ins.) was considerably less than the one shown in Figure 40, although two large tussocks of the Sheathed Cotton-grass (*Eriophorum vaginatum*) rose several centimetres above its general surface. The continuity of the vegetation mat was broken by the growth of these tussocks, but even in between it was extremely thin.
EARTH HUMMOCK
LOCATED ON LOWER PART OF SLOPE PROFILE

SURFACE CONTOURS ABOVE DATUM

STRUCTURAL PROFILES

- Living vegetation
- Peat
- Mineral soil

Contour interval 2.5 cms.
Figure 41

EARTH HUMMOCK
LOCATED ON LOWER PART OF SLOPE PROFILE

VEGETATION TYPES

- Edge of Hummock or Tussock
- Lichen/avens/sedge association with Labrador tea and Cranberry
- Avens
- Sedge species with Cranberry and Crowberry
- Sedge tussock
- Moss and/or Heather
- Willow
- Ground birch
- Blueberry patch

Scale in cms.
0 20 40 60
Figure 42
STRUCTURAL PROFILE OF AN EARTH HUMMOCK
LOCATED AT THE FOOT OF A SLOPE

Tussocks

![Diagram of structural profile]

- Moss
- Peat
- Living vegetation
- Mineral soil

Scale
0 20 40 60 cms.

Figure 43
MUD-BOIL

SURFACE CONTOURS ABOVE DATUM

![Contour map of mud-boil]

Contour interval 2.5 cms.
The underlying peat layer was only a few centimetres thick over the centre of the hummock, but it thickened laterally and extended down in typical peat wedges beneath the adjacent depressions. The size of the mineral core is also much greater than that shown in Figure 40, and the mineral soil was by far the dominant constituent of the hummock. The buried organic layer exhibited the same thickening towards the margins of the troughs, but it was even thinner and less continuous beneath the centre of the hummock. The appearance of the tussocks reflects an obvious change in the plant composition of the vegetation cover, and in the depressions the build-up of a substantial layer of moss was more pronounced than at locations higher up the slope.

Figure 43 shows a large mud boil located on the floor of the depression close to the junction with the slope above. The mud boil, typical of many developed in similar locations, was almost circular in outline, averaging 1.2-1.4 metres (4-5 feet) in diameter, and its central area rose 25-35 cms. (10-14 ins.) above the adjacent depressions. A large part of the surface of the mud boil was completely devoid of, or only scantily covered with, vegetation (Figure 44). The bare mud areas were often covered with a network of miniature cracks which gave a blocky appearance to the surface. In places these cracks had developed into strong radial furrows 10-15 cms. (4-6 ins.) deep. Small sedges (Carex sp.) were the dominant species of the sparsely vegetated areas of the mud boil surface. The Common Crowberry (Empetrum nigrum) and Mountain Cranberry (Vaccinium vitis-idaea) were prominent in the larger surface furrows and along the margins of the mud boil where they were found in association with the Narrow-leafed Labrador-tea (Ledum palustre ssp. decumbens). Also flanking the outer slopes of the mud boil was a flora characterized by
MUD-BOIL
VEGETATION TYPES

- Edge of Mud-Boil or Tussock
- Sedge species with Cranberry and Crowberry
- Sedge tussock
- Moss with Sedge species
- Heather
- Willow
- Ground birch
- Blueberry patch
- Bare ground

Scale in cms.
0 20 40 60
willows (*Salix arctica*), Arctic Blueberry (*Vaccinium uliginosum*), Glandular Birch (*Betula glandulosa*) and small tussocks of the Sheathed Cotton-grass (*Eriophorum vaginatum*). Sedges, Arctic White Bell-heather, and the Sheathed Cotton-grass, along with several moss species, were the dominant plants of the surrounding depression areas.

Structurally, the mud boils were made up entirely of mineral soil. The surface mantle of vegetation and peat was very thin and discontinuous, but it thickened towards the margins where similar peat wedges occurred beneath the depressions. The buried organic layer was also extremely patchy, and in many places was non-existent. One other notable feature of the mud boil was the occasional presence of small quantities of dark, organic material embedded in the mineral soil at various levels.

Individual hummocks were generally to be found from top to bottom of most slope profiles, and on all but the gentlest slopes the hummocks were aligned in a downslope direction. Locally, however, the hummocks had coalesced to produce distinctive, continuous vegetated stripe features which were also aligned in the same manner. These stripe features were often readily discernible through the contrasting vegetation patterns of the raised centres and the intervening depressions. On gently-sloping terrain, the difference in elevation between the ridges and the furrows was seldom more than a few centimetres. On steeper slopes, averaging 10-15 degrees, especially those which were south-facing or the sites of late-lying snow patches, the stripe forms achieved much greater prominence.

Figure 45 and Plate XVII illustrate some of the aspects of these earth hummock stripes. The ridges, which were sometimes continuous over distances of about 10-20 metres (30-65 feet), were approximately 70-80 cms. (27.5-31.5 ins.) in width and as much as 50-60 cms. (19.5-23.5 ins.)
Figure 45

EARTH HUMMOCK STRIPES

SURFACE CONTOURS ABOVE DATUM
Contour interval 5 cms.

SCALE 1 Metre

STRUCTURAL PROFILES

- Living vegetation
- Peat
- Mineral soil
Figure 46
EARTH HUMMOCK STRIPES
VEGETATION TYPES

- Edge of Hummock Stripes
- Lichen/avens/sedge association
- Avens
- Sedge species and Bearberry
- Moss
- Heather with Sedge species
- Willow
- Blueberry patch
Plate XVII

EARTH HUMMOCK STRIPES

A. Stripe features produced by the coalescence of earth hummocks.

B. Excavation along the longitudinal axis of an earth hummock stripe, showing the progressive burial of the organic material. (Tape extended to 1 foot for scale).

C. Transverse or cross-slope excavation of an earth hummock stripe, showing the mineral core and wedges of organic material beneath the troughs. (Pocket tape case, 2 inches, shows scale).
high. Seldom, however, were these ridges simple straight features, and they frequently exhibited a beaded form involving a distinct lateral displacement across the slope. The intervening troughs were very strongly developed, and often took on the form of narrow, steep-sided clefts.

The vegetation cover of the stripes (Figure 46) was similar to that described for the hummocks, except for higher percentages of Cassiope tetragona and moss occurring in small depressions on the surfaces of the ridges, and the absence of Eriophorum vaginatum and Betula glandulosa from the vegetation types. The underlying peat layer was continuous but highly irregular in thickness, ranging from a few centimetres to 45 cms. (17.5 ins.). Local thickenings of peat material occurred in close association with the hollows on the stripe surface and with the narrower widths in the beaded forms. The mineral core of the ridges (see Figure 45), varied in thickness from 20-45 cms. (8.0-17.5 ins.), and was thicker near the frontal downslope end. This mineral core frequently contained thin, tapering wedges of organic material, which extended down below the thicker portions of the peat layer above. These wedges dipped steeply downward in an upslope direction, and detached, elongated strips of organic material, wholly incorporated within the mineral soil, showed the same general orientation. The frontal lobe of the stripe showed a wedge of organic material in the process of being buried by the mineral core (Plate XVII-B), and this could be traced upslope into the buried organic layer. In cross-section, the profiles revealed wedges of organic material extending down in places to unite with organic material at the frost table (Plate XVII-C). Apart from the presence of the buried organic layer, these features show a distinct similarity to those described by Sharp, and this would seem to justify the adoption of his nomenclature for the microrelief features.
The Size and Form of Earth Hummocks. The literature contains few references to the specific size, spacing or form of hummocks, and, when these dimensions are given, they are frequently extremely generalized and descriptive. For example, Sharp, describing earth hummocks in the St. Elias Range, wrote:

"The Wolf Creek hummocks are 1 to 2 feet high with ground dimensions of 1 to 5 feet. On flats or slopes of 5 degrees the hummocks are crudely hemispherical, but on steeper slopes they develop an elongation across the slope. The downhill side is higher and steeper than the uphill side, and in a few places the upper surface grades back into the hill slope without an intervening depression, thus forming a small terrace".67

The diagrammatic illustration of an earth hummock in Sharp's paper suggests that they are similar to the microrelief features found on Garry Island, and the two structures may indeed have a similar origin. The change from a roughly hemispherical to an elongated form was also observed on Garry Island, but the direction of elongation appeared to be downslope rather than across it.

Preliminary observations in the field suggested that there might be a correlation between the form of the hummock and the angle of the slope. Attempts to establish such a simple correlation proved fruitless, however, since the prevalence of smooth, convex-concave slope profiles provided very few slope segments of constant inclination where sufficiently large samples could be obtained to examine this relationship. However, these observations suggested a change in the size and form of the hummocks between the tops and bottoms of these same slope profiles.

The field method adopted to investigate these changes was based on that used by Strahler and Koons to measure terrain roughness. Five slope profiles were selected to cover the possible variations in aspect. The cross-profiles of the slopes were then surveyed and, on each of them, stations were established for sight lines across the slope. The slope profiles and the locations of the sampling stations are shown in Figure 47. The locations of the stations were determined subjectively, rather than objectively as in Strahler's study, at points where the hummock form appeared to be visually different from that at the adjacent upslope station. At each of these points an alidade was set up, and a horizontal sight line was made along the contour to a stadia rod. Since the hummocks were not aligned perfectly along the contours, it was necessary to interpret the sight line as an angular sector. The stadia was moved within this sector to the highest or lowest points of hummocks or depressions respectively, parts of which actually crossed the sight line. A tape was also stretched along the contour to provide data on the spacing of these microrelief features. In order to provide sufficiently large samples for statistical comparisons, the procedure was repeated at each station with another sight line along the contour in the opposite direction.

Data on hummock heights were obtained by subtraction of successive stadia height readings as representing the vertical distance through which the ground profile is displaced between adjacent hummocks and depressions along the angular sight line sector. The data were then

Figure 47

SLOPE PROFILES SHOWING LOCATIONS OF EARTH HUMMOCK SAMPLING STATIONS

Profile I

Profile II

Profile III

Profile IV

Profile V

Distance in Metres

Distance in Metres

Distance in Metres

Distance in Metres

Distance in Metres

Distance in Metres

Distance in Metres

Distance in Metres

Distance in Metres

Distance in Metres

Distance in Metres
processed by frequency distribution analysis to provide indices of mean height, variance and standard deviation. Since most of the frequency distributions were not markedly skewed (Figures 48-52), it was not considered necessary to transform the data before further statistical tests could be performed.

The mean values for the hummock heights are presented in Table XIV. The means were further analysed by running paired 't'-tests on each profile to determine whether or not the differences between the means for adjacent sampling stations were significant at the .01 or .05 significance levels. The procedure for the 't'-test followed that outlined by Croxton and Crowden, where it is assumed that the samples are independent, and that the sample means follow a normal distribution.69

Reference to the range values in Table XIV shows that at each of the stations there was a considerable variation in the heights of the hummocks. This range value, calculated as the difference in centimetres between the height of the largest and smallest hummocks observed along the individual sight lines, increased in a downslope direction. The greater uniformity of hummock heights in the upper portions of the slope profiles was due to the absence of any extremely large hummocks in these locations. Despite these variations, each of the five profiles shows that there was a gradual increase in the mean height of the hummocks from the top to the bottom of the slope. The majority of these changes were found to be significant at the .01 level (Table XIV). It is also quite noticeable that most of the non-significant values encountered were in tests involving

Figure 48

HISTOGRAMS OF HUMMOCK HEIGHTS - PROFILE 1

STATION 1

\[ \bar{X} = 7.92 \quad n = 51 \]

STATION 2

\[ \bar{X} = 10.06 \quad n = 53 \]

STATION 3

\[ \bar{X} = 13.11 \quad n = 60 \]

STATION 4

\[ \bar{X} = 17.68 \quad n = 50 \]

STATION 5

\[ \bar{X} = 21.03 \quad n = 54 \]

STATION 6

\[ \bar{X} = 16.15 \quad n = 65 \]
Figure 49
HISTOGRAMS OF HUMMOCK HEIGHTS - PROFILE II

STATION 1

\[ \bar{X} = 7.32 \quad n = 55 \]

STATION 2

\[ \bar{X} = 9.75 \quad n = 68 \]

STATION 3

\[ \bar{X} = 12.50 \quad n = 55 \]

STATION 4

\[ \bar{X} = 15.24 \quad n = 56 \]

STATION 5

\[ \bar{X} = 19.81 \quad n = 51 \]

STATION 6

\[ \bar{X} = 15.54 \quad n = 67 \]
Figure 50

HISTOGRAMS OF HUMMOCK HEIGHTS - PROFILE III

**Sta tion 1**

- \( \bar{X} = 7.01 \), \( n = 59 \)

**Sta tion 2**

- \( \bar{X} = 10.97 \), \( n = 67 \)

**Sta tion 3**

- \( \bar{X} = 12.80 \), \( n = 68 \)

**Sta tion 4**

- \( \bar{X} = 17.37 \), \( n = 73 \)

**Sta tion 5**

- \( \bar{X} = 23.47 \), \( n = 61 \)

**Sta tion 6**

- \( \bar{X} = 22.25 \), \( n = 69 \)
Figure 51

HISTOGRAMS OF HUMMOCK HeIGHTS - PROFILE IV

**STATION 1**
- $\bar{x} = 6.71$
- $n = 80$

**STATION 2**
- $\bar{x} = 9.45$
- $n = 63$

**STATION 3**
- $\bar{x} = 12.80$
- $n = 56$

**STATION 4**
- $\bar{x} = 15.54$
- $n = 50$

**STATION 5**
- $\bar{x} = 21.03$
- $n = 52$

**STATION 6**
- $\bar{x} = 21.64$
- $n = 50$
Figure 52

HISTOGRAMS OF HUMMOCK HEIGTHS - PROFILE V

STATION 1

\[ \bar{x} = 7.32 \]
\[ n = 70 \]

STATION 2

\[ \bar{x} = 7.62 \]
\[ n = 66 \]

STATION 3

\[ \bar{x} = 11.28 \]
\[ n = 63 \]

STATION 4

\[ \bar{x} = 13.72 \]
\[ n = 58 \]

STATION 5

\[ \bar{x} = 17.37 \]
\[ n = 72 \]

STATION 6

\[ \bar{x} = 21.03 \]
\[ n = 63 \]
TABLE XIV
ANALYSIS OF GARRY ISLAND EARTH HUMMOCK DATA - HEIGHTS (Cms.).

PROFILE I  (Azimuth - 360 )

<table>
<thead>
<tr>
<th>Station</th>
<th>Sample Size</th>
<th>Range</th>
<th>$\bar{X}$</th>
<th>s</th>
<th>t</th>
<th>Significance Level</th>
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<td>3.66</td>
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<td>S.</td>
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<td>13.11</td>
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<td>5.08</td>
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</tr>
<tr>
<td>4</td>
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<tr>
<td>6 (Bottom)</td>
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<td>16.15</td>
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PROFILE II  (Azimuth - 285 )

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<th>$\bar{X}$</th>
<th>s</th>
<th>t</th>
<th>Significance Level</th>
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<td>S.</td>
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PROFILE III  (Azimuth - 180 )

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<th>s</th>
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<tr>
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</tr>
<tr>
<td>6 (Bottom)</td>
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TABLE XIV (Continued)

PROFILE IV (Azimuth -55°)

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PROFILE V (Azimuth -230°)

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<td>6 (Bottom)</td>
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<td>27.43</td>
<td>21.03</td>
<td>7.03</td>
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paired means at the terminal parts of the profiles. This probably reflects the fact that an attempt was made to establish six stations, approximately equally spaced, on each of the profiles. Where the topographic profile consisted of a short, steep mid-section and relatively longer upper convexities and lower concavities, as in Profile III, the stations in these terminal positions were probably too close together. Three of the profiles show that towards the base there was a tendency for the mean height of the hummocks to decrease again, and two of these cases were significant at the .01 level. On the other two profiles, IV and V, the mean height of the hummocks increased right to the base of the profile. Variations in aspect may be partially responsible for this, but it appears to be more related to the drainage conditions at the foot of the slope. Where it was observed that there was a decrease in hummock height at the base of the slope, the profiles terminated in semi-closed depressions with poor drainage. There was considerable evidence of a moss-peat accumulation on the floor of the depression, and the trough areas between the individual hummocks showed moss accumulations as described in the preceding section. It is this infilling of the depressions that is mainly responsible for the apparent decrease in height of the hummocks. In the case of profiles IV and V 'active' stream channels drained the foot of the slope, and there was little evidence of the build up of organic material.

Data on the sizes of the hummocks were obtained by combining the horizontal distance measurements between each depression, and these data were subjected to the same form of analysis. The results of the analyses are presented in Table XV. As in the case of the height data, there was a considerable range in the sizes at each station, but the
### TABLE XV

**ANALYSIS OF GARRY ISLAND EARTH HUMMOCK DATA - SIZES (Cms.).**

**PROFILE I**

<table>
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<tr>
<th>Station</th>
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<th>X</th>
<th>s</th>
<th>t</th>
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<td>147</td>
<td>99.92</td>
<td>31.72</td>
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**PROFILE II**

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<th>s</th>
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increase in range values in a downslope direction was not as marked. As Table XV shows, there was an increase in the size of the hummocks towards the base of the slope, but tests of paired means yielded very few significant values. Tests on the mean hummock size of samples 1 and 6 of each of these profiles, however, yielded 't' values of 5.00, 6.42, 6.10, 6.30 and 6.73 for profiles I to VI respectively, all of which were significant at the .01 level, and indicate that there is a significant increase in the size of hummocks in a downslope direction.

Although moderate success, demonstrating changes in the size of hummocks, was achieved using this method, it was hoped that more success could be obtained using the idea of an 'index of circularity'. The size measurements were made by taking readings directly from the metal tape. Insomuch as the tape was fixed along the sight line, while the points establishing hummock and depression positions were considered within an angular sector, the linear distances obtained were not a true indicator of the size of the hummocks. Moreover, these readings measured only the variations in the cross-slope dimensions of the hummocks, and gave no insight into corresponding changes in the downslope dimensions. The idea of an index of circularity was introduced therefore to investigate changes in the ratio of downslope to cross-slope dimensions of hummocks at different positions on the topographic profile. Equidimensional hummocks would have an index of 1.0, whilst hummocks which were elongated down or across the slope would have indices greater or less that 1.0 respectively.

Profile V was selected to investigate this index as well as certain angular properties of the hummock faces. Three sample plots were established near the top, middle, and base of this profile. Each plot
extended for a distance of approximately 8 metres (26 feet) in a downslope direction, and for variable distances along the contours on either side of the profile line. The sampling procedure consisted of taking the first 25 hummocks in this plot on either side of the profile line, and measuring their downslope and cross-slope dimensions. These values were then used to calculate the index of circularity.

The mean index of circularity for 50 hummocks at the upper part of the slope profile was 1.05 with a maximum and minimum of 1.47 and 0.82 respectively. Eighty per cent of the hummocks in this plot had an index greater than 1.0, and only eight per cent had an index of less than 1.0. The mean index for 50 hummocks in the middle section of the profile however was 1.95. The maximum and minimum values of 2.58 and 1.42 show that all the hummocks, without exception, exhibited an elongation in the downslope direction. In the third plot, located at the base of the profile, the mean index of circularity was 1.09, with a maximum and minimum of 1.31 and 0.82 respectively. Once again only eight per cent of the hummocks had an index value of less than 1.0. Paired tests of the mean index values were run using the value for the middle plot against the values for the plots in the terminal positions of the profile, and yielded 't' values of 21.57 and 24.40. Both these values are significant at the .01 level. These figures indicate that, in addition to changes in the height and size of the hummocks in a downslope direction, there is also a significant change in the form of the hummocks from an almost circular outline at the upper slope position, to an elongated form on the steeper portions of the slopes, and a return to an almost circular shape at the foot of the slope. Since only eight of the one hundred and fifty hummocks investigated showed an elongation across the slope, these findings contrast
with those observed by Sharp. 70

At the same time as the index of circularity measurements were being made, the inclinations of the downslope and upslope faces of the individual hummocks were also recorded. An arbitrary decision was made that if the two inclinations differed by less than five degrees the hummock would be classed as symmetrical. For the 50 hummocks in the upper plot, it was found that 72 per cent were steeper on the downslope face, 18 per cent were symmetrical and only 10 per cent had steeper faces on the upslope side. The mean angle of the downslope face was 48 degrees compared to 31 degrees for the upslope face. In the middle plot the classification gave corresponding values of 72, 18 and 10 per cent and 55 and 42 degrees. Most of the hummocks thus exhibited a marked asymmetry similar to that observed by Sharp, but decidedly different from the observations of Raup who found that turf hummocks have steeper upslope faces. 71 It was also noticeable that many of the hummocks were not aligned perfectly in a simple upslope-downslope direction, but were sometimes obliquely oriented to the general direction of the slope. Furthermore the direction of the oblique tendency was found to be highly variable over even small areas. The studies of the angles of the hummock faces also revealed the influence of lemming activity, which was especially evident in sites frequently occupied by late-lying snow patches. At these sites the downhill faces of the hummocks were frequently vertical, or even overhanging, and were punctured by the burrows of these small

70 Sharp, R.P. (1942) op. cit., p. 283.
71 Sharp, R.P. (1942) op. cit., p. 283.
Raup, H.M. (1965) op. cit., p. 105.
rodents.

It was mentioned earlier that the locations of the five profiles were carefully selected to try to evaluate the varying form of the hummocks on slopes with different aspects. As Table XV shows, the results were not particularly illuminating, although it may be significant that the largest hummocks encountered were on the south-facing slope or conversely on northeast-facing slopes, the most favourable sites for late-lying snow patches. It was in these same two environments that the hummocks were visually the most distinct, and where the tendency to coalesce into a stripe form was best developed. On a smaller scale, it was found that the influence of aspect gave a further quality of asymmetry to the individual hummocks. One hundred hummocks were studied on a west-facing slope and it was found that, using similar criteria to the preceding inclination studies, 14 per cent of the hummocks could be classed as symmetrical, 10 per cent had steeper faces on the south-facing side, while 76 per cent of the hummocks had a steeper slope on the north-facing side. At the same time it was noticed that the north-facing sides tended to be shorter and higher when compared to the gentler, longer profiles facing in a southerly direction.

In summary, these studies show that there is a considerable change in the forms of individual earth hummocks in a downslope direction. Hummocks show significant increases in height and size from the top to the base of a slope, and appear to go through a cyclical form change from circular through elongated and back to a circular form. Individual hummocks exhibit a preferred orientation in a downslope direction, and where they coalesce to form stripes they demonstrate the same preferential alignment. Downslope faces of the hummocks are steeper than corresponding
upslope faces by an average of 15 degrees. On west-facing slopes the
influence of varying aspect imparts an additional factor of asymmetry with
north-facing sides of the hummocks being shorter, higher and an average of
15 degrees steeper than the opposing south-facing sides. Each of these
facts deserves full consideration in any discussion concerning the origin
and development of these microrelief features.

The origin and development of Earth Hummocks. In the
voluminous literature that has been published describing various forms of
patterned ground, numerous theories have been proposed concerning their
origin. Although it is now almost universally agreed that they are the
result of frost action, there is still a great deal of controversy con­
cerning the precise mode of origin of many of these forms. Washburn, in
his classical review of these features, listed no fewer than nineteen
different hypotheses, summarized according to the dominant processes, that
various authors have proposed to explain their genesis, and concluded that
the origin of most forms is uncertain and, in the majority of cases, is
polygenetic. 72

The most commonly accepted origin for the doming-up of the
mineral soil to form the earth cores of hummocks follows the theories pro-
posed by Thoroddsen and Beskow. 73 In his discussion of the formation of
'thufur', Thoroddsen concluded that the mineral soil particles were

72 Washburn, A.L. (1956) op. cit.

73 Thoroddsen, Th. (1914) "An account of the physical geography
of Iceland with special reference to the plant life", pp. 187-343, in
Kolderup Rosenvinge, L. and Warming, E. The Botany of Iceland, Vol. 1,
675 p.

Beskow, G. (1930) "Erdfliessen und Strukturboden der Hoch-
gebirge im Licht der Frosthebung, Geol. Foren. Stockholm, Forh., Bd. 52,
gradually moved upward under the hummocks through the combined action of 
deep freezing in the troughs and the upward movement of capillary water in 
the hummock centres.\textsuperscript{74} Beskow claimed that deeper, more-rapid freezing of 
the damp trough areas took place while the centres of the hummocks remained 
unfrozen at depth, and the resulting pressures forced material into the 
unfrozen cores.\textsuperscript{75} The distribution of snowfall was considered to be an 
important factor by Griggs, who suggested that its effect would be to 
create differences in the growing season period between hummocks and 
troughs, in favour of more luxuriant growth on the hummock centres.\textsuperscript{76} He 
further claimed that the snow would exert lateral pressures against the 
sides of the hummocks thereby squeezing them higher.

In the chapter on permafrost conditions, it was shown that the 
raised hummock centres are sites of deeper thaw during the summer than the 
adjacent troughs. Excavations of different hummocks through the summer 
months showed that, in each case, there was a gradual increase in the water 
content down to the position of the frost table, and this was accompanied 
by an increase in the percentage of fine material with depth. Where these 
excavations were continued below the position of the frost table, it was 
evident that the mineral soil contained many small ice lenses of the sirloin type. The size of these lenses increased with depth and with the 
size of the hummock, and in the mud boils there was a distinct layer of 
clear ice near the base of the active layer. Unfortunately it was not

\textsuperscript{74} Thoroddsen, Th. (1914) \textit{op. cit.}

\textsuperscript{75} Beskow, G. (1930) \textit{op. cit.}

possible to obtain a complete picture of the penetration of the frost line during the fall and winter months, but, from the limited data available, it appears that freezing of the ground surface occurs most rapidly in the trough areas where the moist organic material acts as a good conductor of heat. The penetration of the frost line is slower under the hummocks and once the troughs are completely frozen, any confined pressures could result in further continued slow penetration below the hummocks. The combinations of slow freezing and fine material is extremely favourable for the formation of ice lenses and, provided that there is a source of water, the growth of these lenses may cause a general doming of the hummock surface.

Assuming that the doming of the hummocks is primarily a consequence of differential frost action between the hummock centres and the adjacent troughs, several authors have expressed concern over the type of topography upon which this process could work during the initial stages of hummock development. Beskow thought that this relief could develop from chance variations in the soil surface and vegetation cover, but the ubiquitous occurrence of these features would seem to require much more than simple chance variations in the surface form. Raup suggested that these micro-elevations could be achieved in a number of ways such as cobbles, boulders, local sand and silt deposits in stream beds, moss polsters in snow beds, upfrozen stones, pre-existing gelifluction features or primarily through the development of a normal irregular surface in mats of aquatic mosses. The general paucity of stones and the occurrence of hummocks in locations which are not, and never were, occupied by stream

77 Cited in Raup, H.M. (1965) op. cit., pp. 15-16.
channels would appear to eliminate the possibility that the earth hummocks on Garry Island had a similar mode of origin.

Attempts to lower the level of a lake on the island during the summer of 1965 provided a valuable opportunity to study this problem. A lowering of the water level exposed a gently-sloping, vegetation-free lake bottom which, towards the shoreline, was locally mantled by a litter of peat debris 4-5 cms. (1.5-2.0 ins.) thick. By the end of the summer, this surface was covered by a network of desiccation cracks. Observations during the summer of 1966 showed that some of these cracks had been accentuated into a trough-like form, probably in part by frost action during the preceding fall, but also by running water derived from spring melting of snow. The largest troughs, as much as 20-30 cms. (8-12 ins.) wide and 15-20 cms. (6-8 ins.) deep, ran directly down the slope and extended as far as the new shoreline on the peat-free surface. In other places, consisting of bare mineral soil, a similar, though less prominent, network of troughs was also evident. Although the surface was still largely devoid of any vegetation cover, a few small sedges had taken root on the peat mat.

Only time will tell whether or not this pattern of cracks will develop into a system of earth hummocks, but these observations suggest that the formation of earth hummocks may be polygenetic from even the most incipient stages. The initial topography may be produced by a combination of desiccation and frost action locally accentuated by rillwork. In this respect the former two processes result in a subdivision of the ground into a block form, and subsequent development of the major cracks provides the framework for subsequent hummock development. Some of the initial relief and alignment pattern of the hummocks however may be the result of running
water during this initial stage. It is also quite probable that an analogy may be drawn at this stage between earth hummock formation and the incipient frost crack stage of the tundra polygon development. The accentuation of the major cracks at the expense of the weaker ones to give the basic hummock form, may possibly be the result of the formation of a miniature ice-wedge pattern, and the subsequent growth of these wedge areas may serve to increase the height of the hummocks during their early period of growth.

Once the production of an initial topography has provided a surface upon which differential frost action can take place, the role of solifluction becomes of major importance in the further development of earth hummocks. As noted previously, the presence of a buried organic layer was detected in all the hummock excavations that were made. A number of theories has also been proposed concerning the origin of this organic material, including climatic change, convectional movements within the soil and progressive burial by the downslope movement of material. With the possible exception of the small quantities of organic material incorporated within the mineral soil of the mud boil, there is little or no evidence to suggest that any type of convectional movement is involved in the earth hummocks on Garry Island, similar to that described by Hopkins and Sigafoos.\textsuperscript{79} The fact that, in a number of the excavations made, the wedge of organic material beneath the depressions was strongly convex in a downslope direction, and in many places was found to taper upslope again beneath the hummock centres, is the most convincing evidence that, as Mackay has suggested, the organic layer at depth is the result of prog-

pressive burial. This in turn suggests that solifluction plays an important role in further earth hummock development. The relevance of these statements will now be applied to a complete interpretation of the field data.

Summary. The earth hummocks on Garry Island probably originated through the formation of miniature desiccation/frost crack patterns on newly-exposed surfaces. In the past, such surfaces would have been common following the marine submergence of the island and the subsequent withdrawal of the sea. Locally, the action of running water may have contributed to an accentuation of the major cracks, and produced the dominant alignment in a downslope direction. Contrasting vegetation associations, established over the hummock areas and intervening troughs, would lead to differential frost action due to their varying insulating properties on the underlying ground. By deeper, more rapid freezing of the trough areas, pressures may have been established beneath the hummocks, and additional quantities of fine clay may have been carried up beneath the hummocks thereby accentuating the domed form.

The formation of ice lenses in the mineral core results in an expansion of the substrate and a heaving of the ground surface. During the thaw period of the following summer, melting occurs most rapidly beneath the hummock centres, and melting of the ice results in settling of the material under the influence of gravity. Brown has also pointed out that during the spring, the mineral soil is close to saturation, the frost

80 Mackay, J. Ross (1958) "A subsurface organic layer associated with permafrost in the Western Arctic", Geographical Branch, Ottawa, Geographical Paper, No. 18, 21 p.
table is close to the surface, and the soil flows more readily, and Everett has produced quantitative data indicating that the greatest movements in similar features in Alaska occur during the freeze-up and thaw. On the gently-sloping surfaces, the differences between the elevations of the hummocks and adjacent troughs are quite small, and the available moisture supply is most limited. Consequently the amounts of ice lensing in these locations will be minimal, and the low angle of slope will further result in very slow downslope migration of these features in the solifluction process. Once these hummocks reach steeper slopes, however, the process becomes relatively more rapid.

On the steeper slopes the influence of gravity becomes more pronounced, and the downslope movement of the material is reflected in an elongation of the hummock form in this direction. Downslope faces of the hummock advance over the vegetation of the depressions, and this organic material is buried at depth. Since the amount of organic accumulation in the troughs, located on the upper parts of the slope, is small compared to similar situations on the wetter, lower slopes, this organic layer is quite thin and may be highly discontinuous. Furthermore as the height of the hummock increases, the augmented exposure of the hummock centres results in deeper penetration of the summer thaw and the formation of larger depressions in the frost table, relative to the surrounding troughs. These


depressions are favourable sites for the accumulation of water which may seep down through the soil from up-slope. This in turn creates a situation whereby more moisture is available for ice lens formation during the next fall. Differences in the homogeneity of the soil, and in the available moisture supply, may be primarily responsible for the wide range of hummock heights encountered along the sample transects. As a result of these differences, there could be variations in the amounts of heaving and rates of downhill movement of the individual hummocks. Consequently, some of the larger hummocks may tend to override smaller hummocks immediately below them, and coalesce into stripe forms. The impeding nature of some of the hummocks may modify the downslope movement of others, so that an oblique component may be introduced. This factor may partially explain the oblique nature of many hummocks and the alignment of their downslope faces observed in the plot studies. An additional factor influencing the direction of movement could be variations in aspect. As noted in the plot studies, there was a marked asymmetry between north- and south-facing sides of hummocks. These differences may be due indirectly to contrasts in the vegetation patterns, but the steeper, higher and shorter faces on the north sides of the hummocks may also reflect a more limited amount of insolation received which, combined with the effects of the vegetation, may result in slow rates of thaw. On the south-facing sides of the hummock, the amount and rate of thaw may be greater, resulting in flowage of the material on that side of the hummock. The influences of varying aspect may be felt on all hummocks, and produce deflections of the downhill movement from the direction of the steepest slope.

At the foot of the slope, the available moisture supply reaches a maximum and, consequently, the potential amount of heaving is also
greatest. With the gradual removal of the slope factor, these heaving forces are directed vertically, and may exceed the binding influence of the surface vegetation. This cover is thus stretched and thinned, until locally it may be ruptured exposing the bare mineral soil of the mud boil areas. With the thinning and eventual breaking of the surface vegetation cover, the summer thaw proceeds to even greater depths in the exposed mineral soil, and it may extend below the level of the buried organic layer. As additional mineral soil is drawn up into the mud boil, the organic material may become incorporated into it.

In the above scheme, the mud boil is regarded as a possible disintegration stage of earth hummock development. The distribution of mud boils however shows another significant feature. Mud boils are also found on the flat upland surfaces, where they are much smaller than those described above. On such flat surfaces, the forces of heaving exerted beneath a hummock surface will be directed almost vertically, and the hummock will not undergo a pronounced downslope movement. Thinning of the vegetation on the surfaces of these hummocks may also be due partially to the high degree of exposure to strong winds in these locations, and to the action of ptarmigan. Under this proposed system of earth hummock development, there will be a gradual movement of a hummock from the upper slope to the lower slope. The formation of new hummocks on the upland surface will not be identical to that described in the initial stages, but will more likely result from variations in the surface cover created by the downhill movement of these features.

No attempt was made to determine the age of these earth hummocks, but it is quite evident that they are the result of very slow processes operating over many thousands of years. Similar features have
been dated in other areas by radiocarbon dates of the buried organic layer, or by the analysis of the ages of willows growing in the hummocks. Recent measurements from the lower part of a slope on Garry Island indicate a downslope movement of the hummocks at a rate of approximately 0.25-1.25 cms. (0.1-0.5 ins.) per annum. 83

83 Information supplied by Dr. J. Ross Mackay, personal communication, October, 1968.
CHAPTER VI

SOME OBSERVATIONS ON THE GEOMORPHOLOGICAL EVOLUTION
OF GARRY ISLAND

In this final chapter an attempt will be made to synthesize some of the material contained in the preceding chapters by outlining the major episodes, including their relative arrangement into a chronological sequence, in the geomorphological evolution of Garry Island.

PLEISTOCENE DEPOSITS AND GLACIATION

This evolution began with the deposition of the fine sands, silts and silty clays which, apart from the sand headland areas, constitute the bulk of the stratigraphic succession found on the island. The beds of fine sand included in this succession provide the only identifiable clues as to the type of depositional environment in which the sediments were formed. Fossiliferous evidence, and the abundant fragments of washed wood and peat, are indicative of a marine deltaic environment, and the sediments were probably deposited by an ancestral version of the present Mackenzie River. Unfortunately, no age determinations were made for any material in these strata and the geological age of the sediments therefore cannot be stated with any degree of accuracy, but presumably they are Pleistocene.

Subsequently these sediments have been deformed by the overriding action of glacier ice, and the evidence suggests that the sediments were frozen at the time of deformation. This evidence comes from crude petrographic examinations of deformed bodies of segregated ground ice
contained in some of the fine-grained sediments in the stratigraphic succession. In places this ground ice has a distinctive banded appearance caused by an alternation of bands of dirty and clear ice. Examinations of Tyndall figures and the orientations of elongated bubbles in specimens of the clear ice showed that the 'c'-axes of the ice crystals were oriented at right angles to the layering structures. The orientation of these axes in ice crystals forming at the level of a slowly-penetrating freezing plane is usually parallel to the direction of heat flow, i.e., normal to the freezing plane. Since this freezing plane in turn penetrates downward from, and approximately parallel to, the ground surface, this suggests that the banded ice structures were originally parallel to the overlying ground surface.

Another notable aspect of the segregated ground ice is that it contains a surprisingly large number of pebbles and boulders, the only source regions for which are the mainland areas to the south. Three possible origins may be inferred for these pebbles and boulders: (1) they may have been brought down by the same river which deposited the fine-grained sediments; (2) the boulders may have been ice-rafted into the area; and (3) the segregated ice may have developed, at least partially, in a layer of glacial till.

Whichever of these hypotheses is correct it is now possible to infer something about the interval between the deposition of the sediments and their subsequent deformation. At some time prior to the deform-

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ation there was a relative emergence of the land which may have occurred as a result of shoaling in the ancestral delta or it may have been produced by glacio-eustatic fluctuations in the level of the sea. When the sediments were exposed, the climate must have been similar, or possibly even colder, than the present climate, and the exposure was accompanied by the formation of permafrost, including the development of segregated ground ice. If the hypothesis that this ice is in fact developed in glacial till is correct, the exposure of the sediments may have been the result of a lowering of sea level during a glacial advance, and some freezing of the ground may have taken place beneath a cold glacier. There is no evidence however to indicate when freezing of the sediments first occurred, nor to what depths. Although the deformed ground ice is exposed over 610-915 metres (2,000-3,000 feet) of coastline along the southwest part of the island, this figure gives no reliable indication of the thickness of the permafrost at the time of deformation since it undoubtedly includes a considerable amount of imbrication produced during the deformation process.

There is little doubt that this deformation was produced by the overriding and thrusting action of glacier ice. Glacial lineation features show that an arm of the Laurentide ice sheet moved from the vicinity of Great Bear Lake, along the Mackenzie River valley and into the delta area. The northernmost extent of this ice sheet is imperfectly known, but it seems definite that at some time the ice extended as a lobe,  

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or a series of lobes, across the floor of the Beaufort Sea.

Although the pattern of ice flow in the vicinity of the Mackenzie Delta is clear, there are conflicting opinions as to the number and relative extent of ice advances responsible for this pattern. Muller, in his description of the stratigraphic cover of the Ibyuk Pingo near Tuktoyaktuk, has identified a till, possibly deposited subaqueously, underlain by sand and gravel, containing a driftwood log $28,000 \pm 200$ years old (Be - 49), and overlain by clayey and sandy silts which also contained driftwood dated at $12,000 \pm 300$ years (S - 69). From this section he claimed that the Mackenzie Delta area was occupied by an ice sheet which lasted from 25,000 B.P. to 15,000 B.P. and therefore belonged to the late-Wisconsin period. Mackay has subsequently suggested that the 'Ibyuk Till' may be a 'pseudo-till' resulting from the melting of a ground ice sheet. Johnston and Brown have recently reported the occurrence of a pebble-rich silty clay, tentatively identified as a till, at a depth of 67.4-70.1 metres (221-230 feet) below the surface in a drill hole near Inuvik.

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6 Ibid. p. 285.

7 Mackay, J. Ross (1963) op. cit., pp. 21-22.

The till was underlain by bedrock and overlain by another 12.5 metres (41 feet) of silty-clay, interpreted to have been deposited under glacio-marine or estuarine conditions, followed by 55 metres (180 feet) of deltaic sediments deposited by the present Mackenzie River and its post-glacial ancestors. The deltaic sediments at a depth of 38 metres (125 feet) were dated at 6900 + 110 years (G.S.C. - 54), but no age was suggested for the till. It would seem unlikely, however, that the interval between the evacuation of the area by the ice sheet and its subsequent occupation by the river was of any great length, and a late-Wisconsin age for the till could probably be inferred. Craig and Fyles on the other hand have suggested that a coastal strip of the mainland on both sides of the Mackenzie River lay within the maximum limits of the area affected by the Laurentide ice sheet, but beyond the northwestern limit of the ice throughout the Wisconsin glaciation.

Opinions as to the date of the last ice advance to affect the Mackenzie Delta area thus range from pre- to late-Wisconsin. The only evidence as to the date of the ice advance which produced the deformation of the sediments on Garry Island comes from the marine fossils collected from the sand headland areas. These shells are in an excellent state of preservation, many with their periostracum intact, and, although no hinged specimens were found, it is believed that the fossils have not been re-worked from an earlier deposit. The age determination of > 42,600 years (G.S.C. - 562) is consequently interpreted to be a reliable indicator of the minimum time of sand deposition.

8 Ibid.
The relevance of this age determination to the time of deformation of the fine-grained sediments lies in the complete absence of any signs of similar deformation in these sands. It may be possible that the frozen sands responded quite differently to the thrusting action of the glacier ice, and thus exhibit little or no deformation, but this is considered to be most improbable. Moreover, the surfaces of the sand headlands show no evidence of a till deposit unless it is very fine-grained and almost completely stone-free. Such a deposit may formerly have existed and subsequently have been removed during the later submergence of the island, but this again is considered to be unlikely. The inference is therefore, that these sand deposits post-date the deformation of the other sediments on the island and, furthermore, they probably post-date the last ice advance to reach Garry Island.

In the absence of additional age determinations, attempts to correlate this ice advance with the Pleistocene chronology established along the southern margins of the Laurentide ice sheet can only be inferred on a tentative basis. The duration of the Wisconsin state of the Pleistocene sequence in central North America has been progressively extended, and events believed to have occurred between 70,000 and 10,000 years ago are now assigned to the Wisconsin glaciation. The ice advance responsible for the deformation of the sediments on Garry Island may therefore tentatively be identified as early-Wisconsin or possibly pre-Wisconsin in age. A possible correlation with the Pleistocene sequence established

for the central Brooks Range and the Arctic Slope of Alaska would be with
the Sagavanirktok glaciation, considered to be pre-Wisconsin (Illinoian)
in age.

The next identifiable episode in the evolution of Garry Island,
following the withdrawal of this ice sheet, was the deposition of the
sands and gravels exposed in the sand headlands on the north side of the
island. Granulometric analyses of these deposits, and the similarity in
radiocarbon dates, indicate that they are broadly contemporaneous with
the terraces described by Fyles along the west side of Richards Island
and along the east bank of the East Channel of the Mackenzie River which
were dated at > 40,000 years (G.S.C. - 709). Fyles has also dated marine
shells, found in a lake shore bluff located 10 miles south of Kendall
Island, which yielded an age of > 42,600 years (G.S.C. - 690), and Mackay
obtained a radiocarbon date of > 38,000 years (I - 482) from material
contained in a terrace at the mouth of the Kugaluk River. The sand
and gravel deposits on Garry Island also appear to be similar in age and
texture to part of the Gubik formation of northern Alaska.

The striking dissimilarity between the texture of these sands
and gravels and any other sediments on Garry Island, suggests that they
are not simply residual accumulations derived through long-continued erosion

\begin{footnotes}
\footnote{Detterman, R.L., Bowsher, A.L., and Dutro, J.T., Jr., (1958)
"Glaciation on the Arctic Slope of the Brooks Range, Northern Alaska",
Arctic, Vol. 11, pp. 43-61.}

\footnote{Porter, S. (1964) "Geologic history of the Anaktuvuk Pass

\footnote{Mackay, J. Ross (1963) \textit{op. cit.} pp. 38-39.}

\footnote{Coulter, H.W., Hussey, K.M., and O'Sullivan, J.B. (1960)
Radiocarbon dates relating to the Gubik Formation, Northern Alaska",
\end{footnotes}
of the island. Rather, an extraneous source appears to be indicated. The most probable origin of the sands is that they represent deposits brought down by streams, following the withdrawal of the ice, and deposited under marine conditions when the relative level of the sea was at least 9-15 metres (30-50 feet) higher than at present. These deposits may have accumulated in the form of large sandspits, but the discontinuous nature of the sand headlands probably also represents the effects of subsequent erosion. The age of the sands, > 42,600 years (G.S.C. - 562), may represent an interstadial period in the early-Wisconsin or an even earlier interglacial (Sangammon ?) period.

Garry Island probably lay beyond the northwest limits of the Laurentide ice sheet during the late-Wisconsin period, although the adjacent mainland and the area of the modern Mackenzie Delta to the south may have been occupied by ice at this time. The fresh, unaltered appearance of a number of large erratics on the island, however, may indicate deposition by ice of late-Wisconsin age, but since they all occur well below the marine limit, they may have been rafted in by drifting icebergs.

THE EXTENT OF THE MARINE TRANSGRESSION

The existence of a series of weakly developed raised strandline features, up to heights of 46 metres (150 feet) above sea level, indicates that the island was completely submerged by the post-glacial rise in sea level. Moreover, the manner in which these elevated shorelines are developed around the major elements of the topography, with pronounced re-entrants along the valleys and depressions, suggests that the pattern was produced by the drowning of a pre-existing topography.
This in turn could have been developed during pre-late-Wisconsin times.

This submergence was then followed by a progressive emergence of the land relative to the level of the sea; a process which was halted intermittently at elevations of approximately 38, 30.5, 23, 15 and 7.5 metres (125, 100, 75, 50 and 25 feet) above present sea level. None of these periods of standstill were of any great duration as witnessed by the weak expression of the strand-lines, even allowing for the obscuring effects of later solifluction processes. During these halts, however, small sandspits or bars, composed of residual accumulations of material derived through erosion of the adjacent bluffs, were constructed across the mouths of some of the valleys. The formation of small lagoons or flats, behind these spits or bars, provided numerous sites for the development of tundra polygons which have produced the distinctive stepped profiles of the present stream courses. The larger embayments in the elevated shorelines were occupied by large freshwater lakes in which a series of lacustrine sediments were deposited.

It is impossible, from evidence presently available, to establish an absolute chronological scale for these fluctuations in the relative positions of the land and sea. If the hypothesis that the tundra polygons are intimately related to the shorelines is correct however, radiocarbon dates from peat exposed in some of the high-centres polygons provide certain clues. Samples of peat taken from a depth of about 3.7 metres (10.0 feet) below the surface of a high-centred polygon on the northwest coast of the island yielded an age of $11,700 \pm 250$ years (S - 276). These polygons are developed in a small depression floored by gravels which occur at an elevation of about 23 metres (75 feet) above sea level. As the peat in these polygons shows no signs of having been buried, it
would seem logical to assume that the relative level of the sea could not have exceeded the 38 metre (75 foot) elevation since the peat began to accumulate. This implies a minimum date of \( >11,500 \) years for the 38 metre (75 foot) raised strand-line. No age determinations were made for any organic material occurring at higher elevations, and therefore no dates can be suggested for the higher strand-lines. Similar reasoning can be applied however to age determinations made in peat deposits occurring at lower elevations. A sample of peat occurring in the basal part of a series of lacustrine sediments, which rest on beach gravels at an elevation of approximately 7.5 metres (25 feet) above sea level, yielded an age of \( 10,330 \pm 150 \) years (G.S.C. - 516). These lake sediments are overlain by a layer of sand and pebbly gravel containing iron-stained wood fragments dated at \( 9730 \pm 160 \) years (G.S.C. - 575). These figures suggest that the emergence of the island continued until the relative level of the sea stood only 7.5 metres (25 feet) higher than at present at least 10,000 - 10,500 years ago. This emergence was then temporarily halted by a period of renewed submergence which affected areas up to elevations of approximately 10.5 metres (35 feet) above present sea level, (the altitude of the upper surface of the sand and pebble gravel). The radiocarbon date of 9730 years may indicate the date of this submergence but it is possible that the wood has been reworked from earlier sediments. Since that time there has been a renewed emergence of the island which has probably continued through to the present day. Another age determination made on a peat sample occurring in a high-centred polygon at an elevation of approximately 3.5-4.0 metres (12-13 feet) above sea level yielded an age of \( 4,120 \pm 130 \) years (G.S.C. - 517). The absence of any signs of burial on these polygons provides a minimum date for the
afore-mentioned period of submergence, and further suggests that the relative level of the sea has not exceeded this elevation since that time.

Mackay has indicated that the last episode in the changing relationship of the land and sea in the delta area may have been a slight submergence of 3, 6 or more metres (10, 20 or more feet). There is no conclusive evidence that a similar submergence has affected Garry Island. The existence of a channel outlet from the large lake in one of the sand headlands on the north side of the island may be relevant however. The outlet, several tens of metres long and maintaining a depth of 6 metres (20 feet) almost to the present coastline, may indicate the submergence of a channel graded to a former, lower sea level. Alternatively, the depth may be attributed to thermokarst melting of the underlying sediments. Throughout this period of submergence, the mean temperature of the sea water must have been close to 0°C, for it appears that very little thawing of the underlying permafrost took place.

The present outline of Garry Island has been produced by coastal recession associated with the present sea level. Stratigraphic, geomorphic and historic evidence shows that a considerable amount of coastal recession has occurred in recent times. If the latest episode in the fluctuations of sea level has been a period of submergence, this would have contributed to the continued recession of the shoreline by increasing the offshore depths of water.

As the land surface emerged from beneath the sea it was subjected to intense thermal stresses produced by the seasonal temperature variations of the arctic climate. Contraction of the ground upon freezing

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14 Mackay, J. Ross (1963) *op. cit.*, p. 41.
During the winter produced networks of frost cracks, and recurrent fracturing at the same loci led to the formation of ice-wedges. On the lower, flatter ground, the networks of ice-wedges led to the development of systems of orthogonal, slightly-oriented, tundra polygons and, with increasing passage of time, these polygons were transformed from low- to high-centred forms. On steeper, drier sites the newly-exposed ground surface was probably covered by a miniature network of similar frost or desiccation cracks. These networks have been accentuated to produce the microrelief of the typical earth hummocks. Once established, the subsequent development of these earth hummocks was largely the result of differential frost action and solifluction as evidenced by the buried organic layer at depth.

CURRENT GEOMORPHOLOGICAL PROCESSES

Throughout the period of post-glacial time, the geomorphic processes, with the possible exception of fluvial action, shaping and remoulding the surface topography of Garry Island have probably remained the same, though they may have varied in their relative intensity from time to time. Observations of the geomorphic processes currently operating on the island reveal the dominant influence of the underlying permafrost on the rates at which they operate.

Continued recession of the coastline is constantly re-shaping the outline of the island. Actively retreating parts of the coast are presently restricted to sections of the northwest coast of the island, and parts of the sand headlands which have not been protected by the formation of sandspits. Observations on the processes involved in the retreat of the cliffs demonstrate the importance of permafrost and especially its
composition. The dominant process by which material is detached from the cliff face is a thermal erosion of the frozen ground, which is extremely susceptible to the sun's rays when exposed. Melting of the ice, which acts as a strong cementing agent, leaves the sediments unsupported and often at angles higher than the angle of repose, so that they slump to the base of the cliffs. The rate of retreat is profoundly affected by the composition of the frozen sediments. Where the sediments are coarse-grained, and have a low ice content, the rate of retreat is usually less than one metre (3 feet) a year, but where the frozen ground contains large masses of segregated ground ice the rate may be as high as 30 metres (98 feet) per annum. The major role of wave action, on a short term basis, appears to be in the removal of the slumped material from the base of the cliffs, and this is particularly effective during storm surges. Locally, however, and on a long term basis, direct undercutting by wave action may assume the most important role in the cliff retreat process.

The exposure and subsequent melting of the permafrost is also responsible for the production of one of the most distinctive landforms found on Garry Island - the mudslump. These are amphitheatre-like depressions produced by the melting out of tabular bodies of segregated ground ice. Once again, the rate of retreat of the mudslump headwall is profoundly influenced by the composition of the frozen ground. The highest rates of recession, in excess of 10 metres (33 feet) per annum, occur in frozen sediments with a high ice content, and as the proportion of mineral soil in the headwall decreases the rate of recession decreases to a point where, if no ice is exposed, little or no retreat takes place. The ratio of ice to mineral soil in the frozen ground also determines, in part, the longevity of the mudslump activity, and the degree to which the scars
persist as recognizable features in the landscape. In general, the higher the ice content the deeper is the depression produced by melting, and the longer this depression persists before it is obscured by vegetation.

The longevity of the period of mudslump activity is also affected by the degree to which thawed material is removed from the base of the headwall, thus permitting, as in the coastal recession processes, the maintenance of fresh exposures of ground ice and continued thermal erosion. Where the ice contents are high, releasing large quantities of excess water upon melting, the thawed debris is efficiently removed by strong mudflows, but if the amount of water released is small the thawed debris may accumulate at the foot of the headwall.

The action of running water as an active geomorphic agent on Garry Island is limited, reflecting a combination of low precipitation, small catchment areas and the presence of an almost continuous cover of vegetation. The existing stream courses are poorly defined, and serve primarily as conduits for surface runoff derived from melting snow and the thawing of the active layer during the spring and early summer. Throughout the remainder of the summer, these channels are kept moist by seepage from the thawing ground, but surface runoff is generally lacking except for a short time following prolonged periods of heavy rainfall. The rapidity of surface runoff after such rainfall reflects the presence of permafrost at shallow depths beneath the ground surface. The fact that the ill-defined channels are located in a number of well-defined 'V'-shaped valleys may bear witness to the greater significance of the action of running water in the past. Additional evidence of the present insignificance of running water comes from the fact that the floors of many of the stream courses are being raised by the accumulation of organic material. The most
important, single criterion restricting the effectiveness of running water today, however, appears to be the continuous vegetation cover. Once this cover is breached, exposing the underlying frozen ground, and especially where this has a high ice content, a considerable amount of thermokarst erosion may be accomplished by only small quantities of water in a very short time.

The Concept of a Periglacial Morphogenetic Region.

Finally, from these observations an attempt can be made to examine the concept of a periglacial morphogenetic region. According to Peltier, the characteristics of the various geomorphic processes operating in periglacial regions are strong mass movement, moderate to strong wind action and a weak effect of running water.\(^\text{15}\) Although it was not studied in detail, solifluction is undoubtedly one of the most widespread processes moulding the landscape of Garry Island. Reference has been made to its importance in the partial obliteration of raised strand-line features and the growth and gradual downslope movement of earth hummocks. The local presence of solifluction lobes, and the ubiquitous occurrence of a buried organic layer, testify to its significance on all slopes of the island. The inclusion of mudslumps and mudflows supports the contention that the phenomena of mass movement are the most important geomorphic processes operating in periglacial regions. Certain qualifications are necessary however. Observations of some of these processes on Garry Island demonstrate the influence of the composition of the underlying frozen ground.

on the rate at which they operate. If additional credence is to be given to the concept of morphogenetic regions on the basis of quantitative measurements, there will be a definite need to distinguish between bedrock and areas of unconsolidated sediments and between areas of wet and dry permafrost. Otherwise, there will be as much variation between the rates of operation of mass movement processes within periglacial regions as between contrasting climatic environments. In this respect, Peltier's paper is deficient since it infers the presence of bedrock, and makes no reference to the effects of changes in the composition of the frozen ground. Furthermore, even in areas which are underlain by a relatively homogeneous substrate, and especially where this consists of unconsolidated sediments, there is still a need to consider the areal scale problem. This problem is very well illustrated where thermal erosion is an important process since variations in aspect may also contribute to significantly wide ranges in the rates at which this process operates. All of these factors must be given due consideration in any attempt to establish the concept of morphogenetic regions on a quantitative basis.

Wind action on Garry Island plays a very minor role despite its coastal location and exposure to strong winds. This possibly reflects the presence of a continuous vegetation cover, and there is a further need in Peltier's paper to differentiate between vegetated and unvegetated areas. The vegetation cover is probably also the most significant factor contributing to the restricted efficiency of fluvial action on the island, together with the absence of perennial streams. The rapid thermokarst erosion of the frozen ground by only small amounts of water, however, probably indicates an underestimation of the role of running water in the hierarchy of relative importance of geomorphic processes. Since the
existence of a number of well-defined 'V'-shaped valleys on the island may bear witness to the greater significance of the action of running water in the past, there is also a need to recognize an additional scale problem involving the time period over which these present geomorphic processes have operated at the same absolute or relative intensity as at present.

The action of waves was excluded from Peltier's paper because of its applicability only to coastal locations. On Garry Island, the recession of the coastline, especially where it exposes masses of ground ice, represents one of the more spectacular aspects of the operation of geomorphological processes. Furthermore, the stratigraphic, geomorphic and historic evidence indicates that coastal recession has substantially altered the outline of the island throughout recent geological time.

\[16\text{Ibid., p. 218.}\]
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APPENDIX I

A. LIST OF VASCULAR SPECIES FOUND ON GARRY ISLAND

1. PTERIDOPHYTA

Equisetaceae  Equisetum arvense

2. SPERMATOPHYTA

Monocotyledoneae

Grainae

Agropyron latiglume
Alopecurus alpinus
Arctagrostis latifolia
Arctophila fulva
Calamagrostis deschampsioides
Calamagrostis lapponica
Calamagrostis purpurascens
Dupontia fisheri
Elymus arenarius ssp. mollis
Poa arctica
Puccinellia andersonii
Puccinellia phryganodes
Puccinellia vaginata
Trisetum spicatum

Cyperaceae

Carex aquatilis
Carex bigelowii
Carex chordorrhiza
Carex membranacea
Carex vaginata
Eriophorum angustifolium
Eriophorum scheuchzeri

Dicotyledoneae

Juncaceae  Juncus alpinus
Luzula confusa

Salicaceae  Salix alaxensis
Salix arctophila
Salix glauca var. niphoclada
Salix phlebophylla
Salix pulchra
Salix reticulata
Betulaceae
- Alnus crispa
- Betula glandulosa

Polygonaceae
- Oxyria digyna
- Polygonum bistortum
- Polygonum viviparum
- Rumex arcticus

Caryophyllaceae
- Arenaria peploides
- Arenaria rubella
- Cerastium bearingianum
- Melandrium affine
- Stellaria humifusa
- Stellaria longipes

Ranunculaceae
- Anemone parviflora
- Anemone richardsonii
- Caltha palustris ssp. arctica
- Ranunculus cymbalaria var. alpinus
- Ranunculus gmelinii
- Ranunculus pallasii

Papaveraceae
- Papaver keelei

Cruciferae
- Braya humilis ssp. arctica
- Cardamine digitata
- Cardamine pratensis
- Descurainia sophoides
- Draba glabella
- Erysimum inconspicuum
- Parrya nudicaulis

Crassulaceae
- Sedum rosea ssp. integrifolium

Saxifragaceae
- Parnassia kotzebuei
- Saxifraga cernua
- Saxifraga hirculus
- Saxifraga radiata

Rosaceae
- Dryas integrifolia
- Potentilla palustris
- Rubus chamaemorus

Leguminosae
- Astragalus alpinus
- Hedysarum alpinum americanum
- Hedysarum mackenzii
- Lathyrus maritimus
- Lupinus arcticus
- Oxytropis maydelliana

Empetraceae
- Empetrum nigrum
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<td>Senecio lugens</td>
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B. LIST OF BRYOPHYTES FOUND ON GARRY ISLAND

Abietinella abietina (Schwaegr.) C.M. (Thuidium abietinum)
Aulacomnium palustre (Hedw.) Schwaegr.
Aulacomnium turgidum (Wg.) Schreb.
Bryum ovatum Jur.
Calliergon Richardsonii (Mitt.) Kindb.
Cinclidium stygium Sw.
Dicranum elongatum Schleich. c. fr.
Dicranum fuscescens Turn.
Drepanoclados revolvens (Sw.) Kindb. koll.
Hylocomium alaskanum (Lesq. & James) Kindb.
Hypnum callichroum (Brid.) Br. & Sch.
Pogonatum alpinum Hedw.
Psilopilum cavifolium (Wils.). Hag.
Sphagnum squarosum Pers.
Sphagnum Warnstorffianum DR. (S. Warnstorfi Russ. non Roll)
Tomenthypnum nitens (Schreb.) Loeske
Tritomaria quinuedentata (Huds.) Buch