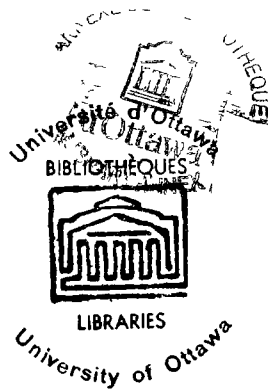


THERMOKARST AND RELATED GEOMORPHIC PROCESSES

EASTERN BANKS ISLAND, N.W.T.

Paul Egginton

Thesis presented to the School of Graduate Studies in
partial fulfilment of the requirements for a masters
degree in Geography



Ottawa, Canada, 1976

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ABSTRACT

A ground-ice slump and an area of badland thermokarst terrain on eastern Banks Island were examined and rates of development determined.

Significant microclimatic variations exist in the badland thermokarst terrain, with sites of rapid development associated with high temperatures. Total headwall retreat during 1973 was estimated at 23.7 cm/yr: deflation accounted for 8.17 cm/yr, nivation 1.36 cm/yr and thermokarst 14.7 cm/yr.

Ground-ice slumping is rapid e.g. 10.2 m/yr, 1973) and headwall retreat in the short term is associated with climatic input. In the long term the rate of debris removal from the base of the headwall controls the rate of development of the feature, as inadequate debris removal leads to burial and stabilization.

RESUME

Dans le secteur oriental de l'île de Banks, un glissement associé à la fusion de la glace de sol et une région de "badland" résultant de l'activité thermokarstique ont été étudiés. Le rythme d'évolution de ces formes, lié à des processus géomorphologiques et à des facteurs climatiques, a été évalué.

Le micro-climat dans la région de "badland" variait de façon significative et les sites d'évolution rapide étaient étroitement associés aux zones plus chaudes. En 1973, le recul des parois des niches thermokarstiques a été évalué à 23.7 cm/année: la déflation étant responsable d'un recul de 8.17 cm/année, la nivation d'un recul de 1.36 cm/année et le thermokarst d'un recul de 14.7 cm/année.

L'évolution du glissement associé à la fusion de la glace de sol est rapide, soit de 10.2 m/année en 1973. A court terme, l'évolution de la paroi rapide est liée à des facteurs climatiques. A long terme, c'est la vitesse d'évacuation des débris, à la base de la paroi rapide, qui contrôle la vitesse d'évolution de la forme. La stabilisation de ce type de glissement se produit lorsque les sédiments s'accumulent au pied de la paroi.

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I wish to thank the members of my advisory committee and the members of the Department of Geography and Regional Planning, University of Ottawa for their encouragement and advice.

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Last but not least I would like to thank G. Gruson and J. Lai who acted as capable field assistants, the former in 1972 and the latter in 1973.

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CHAPTER I
THE STUDY AREA

1.1 Introduction

This thesis was undertaken to provide information on naturally occurring thermokarst phenomena on the hummocky morainic terrain of eastern Banks Island, in the western Canadian Arctic. It was part of a longer term study of thermokarst and terrain sensitivity undertaken by H.M. French and supported by the National Research Council of Canada, and the Terrain Sciences Division of the Geological Survey of Canada.

Relatively little work has been undertaken on thermokarst in the High Arctic islands, although it is well documented in other parts of North America and Siberia (e.g. Kachurin 1962; Kerfoot 1972; Mackay 1966; Péwé 1954). In the Canadian High Arctic, the only studies dealing directly with thermokarst are those of Lamothe and St-Onge (1961); French and Egginton (1973); and French (1974a; 1975b). The field work for this thesis was concentrated around two thermokarst forms; a ground-ice slump and an area of badland thermokarst terrain. This study attempts to assess the rate of growth of these features and relate such growth to geomorphic and climatic variables.

The thesis is organized into five chapters and a concluding summary. Chapter I provides a basic description of the study area and Chapter II provides a brief review of the literature on thermokarst.

In Chapter III, actual active layer depths at selected sites in the study area are related to climatic and soil conditions. Chapters IV and V deal with thermokarst forms, per se, emphasizing morphology and dynamic evolution. In Chapter IV, the nature, distribution, and rate of evolution of ground-ice slumps in Eastern Banks Island are examined. In Chapter V, other geomorphic processes operative in areas of badland thermokarst terrain are discussed. An attempt is made to assess the rate of thermokarst activity and the contribution of these other geomorphic processes to the development and maintenance of these features. The conclusions of the study are presented in Chapter VI.

1.2 The Location of Study Area

The field work for this thesis was carried out on Banks Island in the western Canadian Arctic during the summers of 1972 and 1973 (Figure 1). The island is the fourth largest in the Canadian Arctic Archipelago and, lying between 71° - 74° N, is underlain by continuous and thick permafrost (Brown, 1972). A base camp was maintained for the periods June 20 to August 15, 1972 and June 18 to August 15, 1973 at latitude $72^{\circ}51'$ N and longitude $119^{\circ}31'$ W, approximately 35 km west of Johnson Point (Figure 1). The study area lies on the western margin of a complex morainic system which extends the length of the east coast of Banks Island (Fyles, 1962). This topography forms a distinct physiographic unit on Banks Island, Victoria Island (see Fyles, 1963) and the Beaufort Sea coastal lowlands (see Geological Survey of Canada,

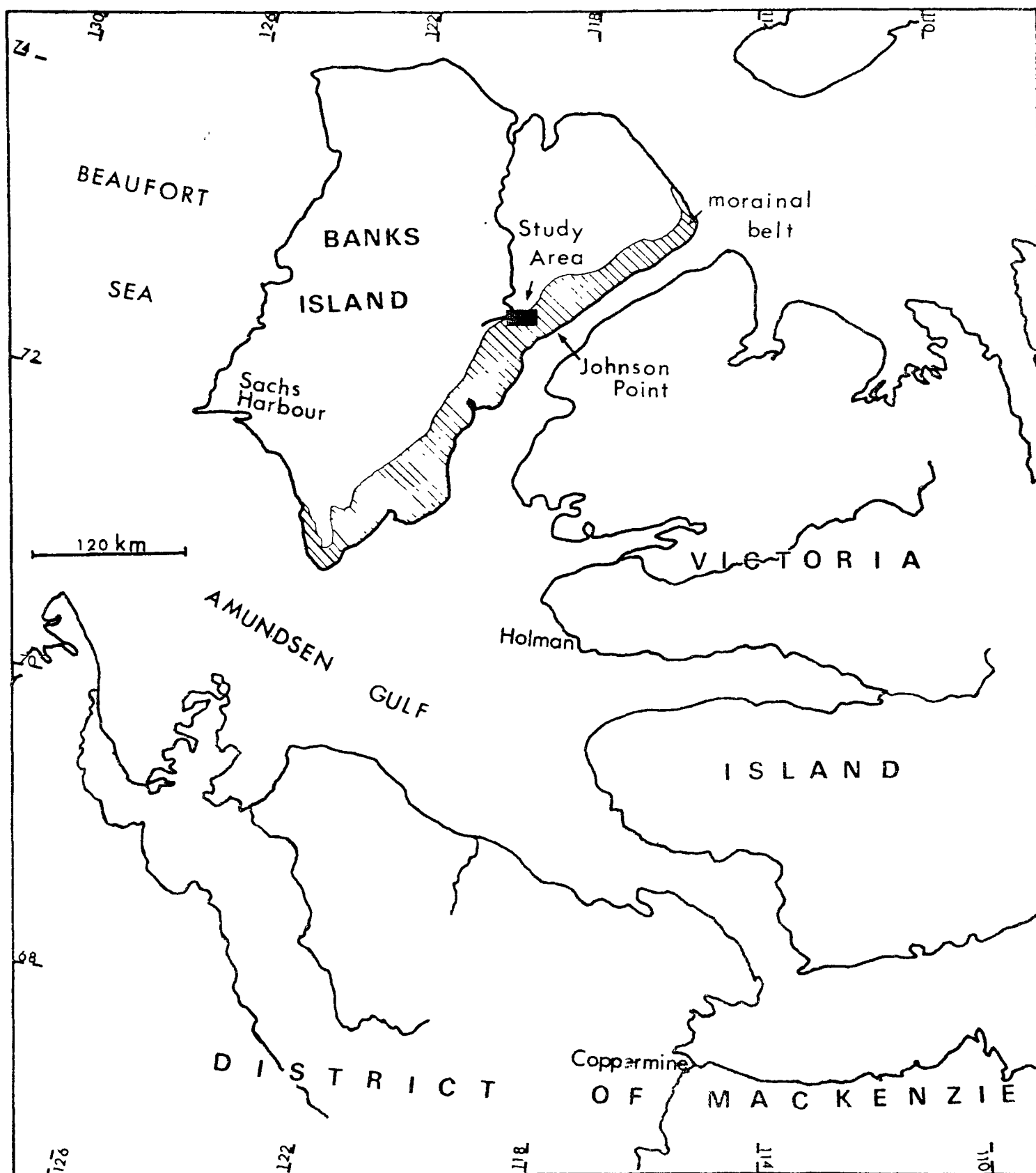


Figure 1 - Map showing the location of the study area. The numbers at the edges of the map refer to latitude and longitude respectively. The immediate study area as delimited by the box above is shown in Figure 2.

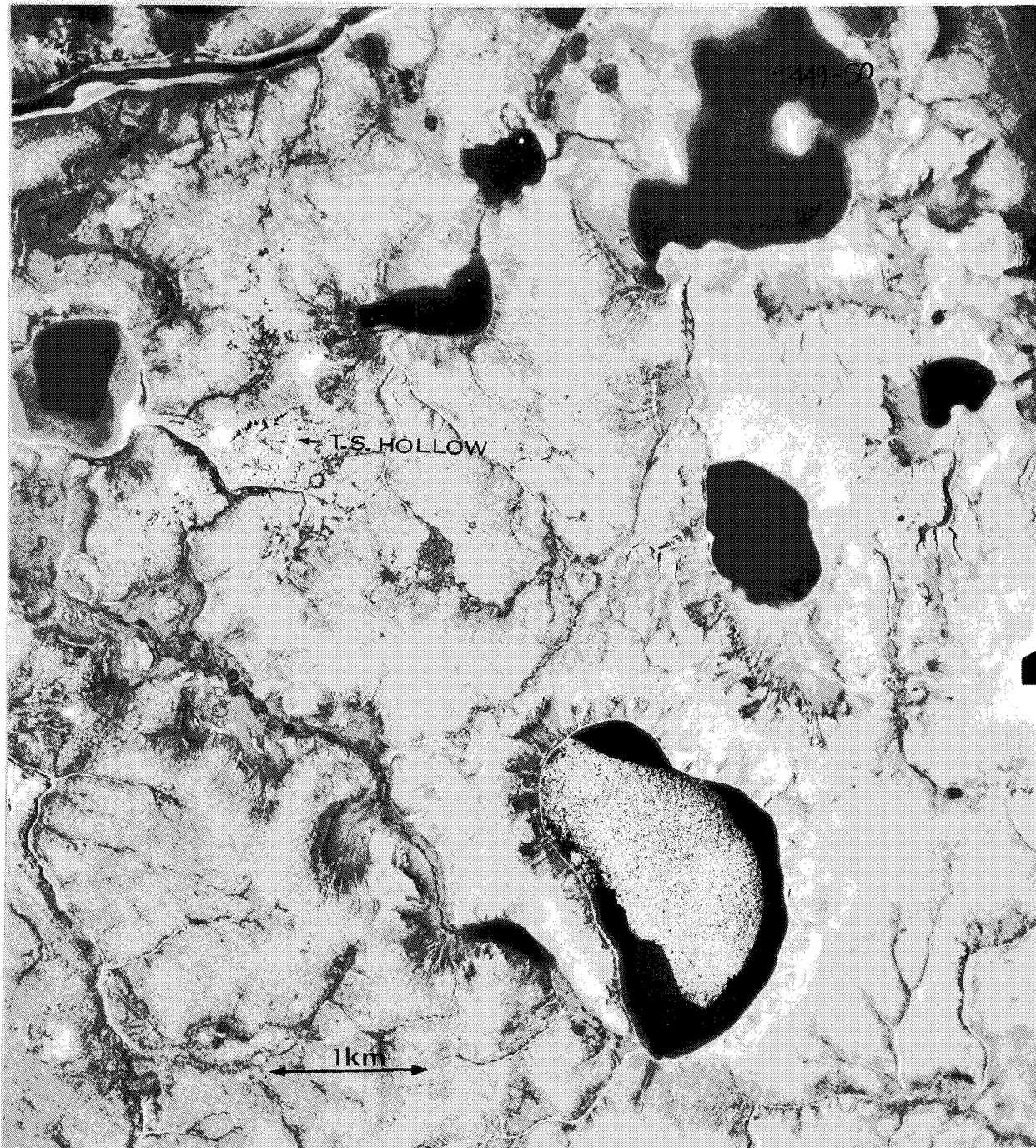


Figure 2 - Aerial photographs of the study area

- (a) Trimetrogon photo T449-50, taken in 1950
- (b) A-17379-44, taken in 1961

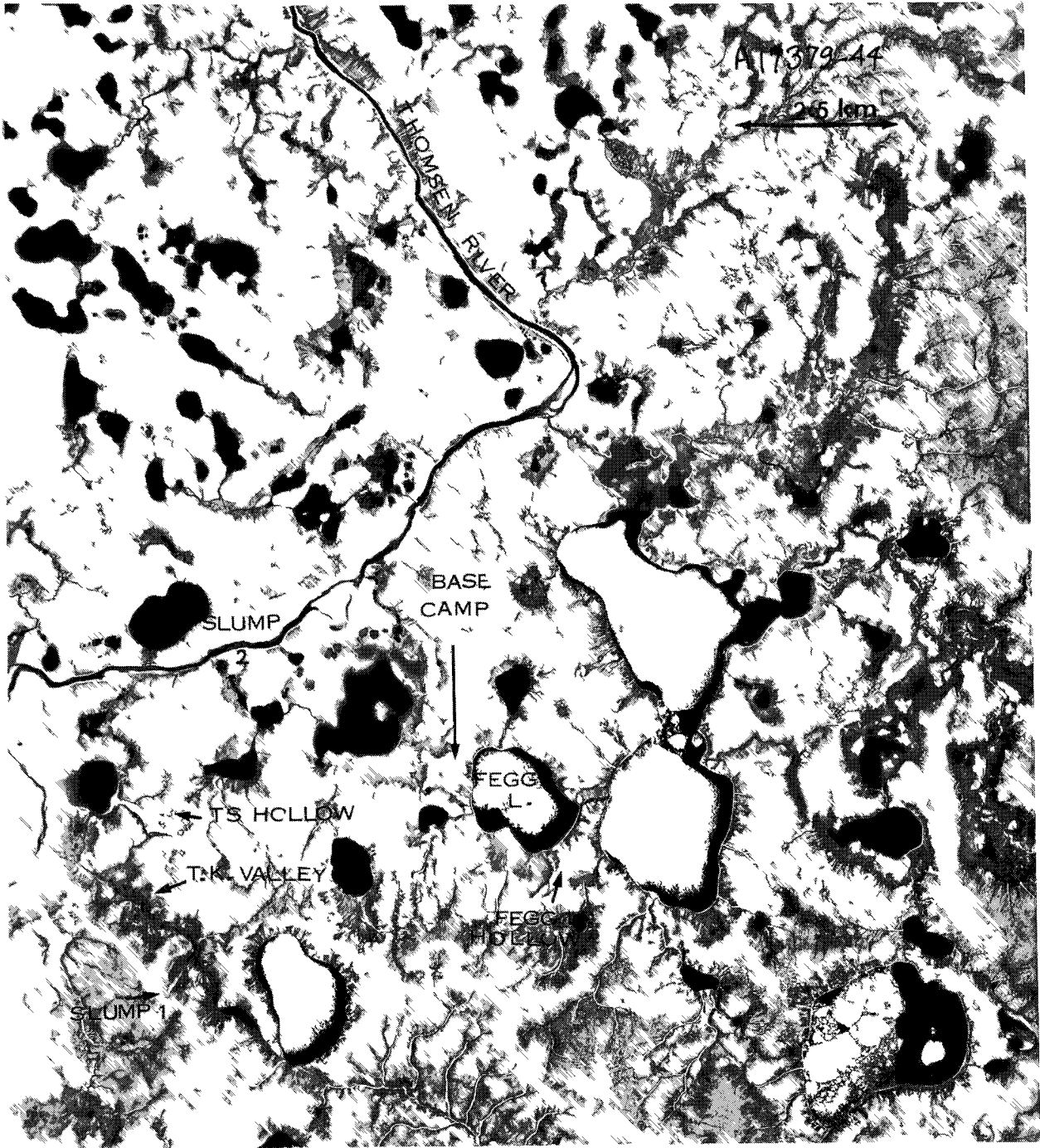


Figure 2b

Map 1253A). On Banks Island, this unit is distinctive in that it possesses 1) well developed fissure polygons, which are readily discernable from aerial photographs, 2) a poorly integrated drainage net, and 3) numerous ground-ice exposures and kettle lakes. Various landscape features of the immediate study area are identified on aerial photographs in Figure 2.

The study area was chosen on the basis of the high concentration of thermokarst forms found in this portion of the morainic belt and the proximity of Johnson Point. The latter is the major staging point for oil exploration on the island. In most summers a barge is able to reach Johnson Point in late August. A gravel airstrip is maintained throughout the year and provides year round accessibility.

1.3 Relief

The relief varies locally from 50 m to 300 m. The morainic belt is characterized by low angled slopes which form rounded and subdued hills that are subject to mass movement and solifluction. For example, of 117 slope segments measured in a small stream valley in the study area, 79% were less than 6° in angle (see Figure 3). French (1974c) has measured solifluction and mass movement of between 2-4 cm/yr on similar terrain at Sachs Harbour on the southwest corner of the island and comparable rates probably occur within the study area. Break-in-slope areas retain snow for considerable periods of time and appear to be dominated by nivation processes.

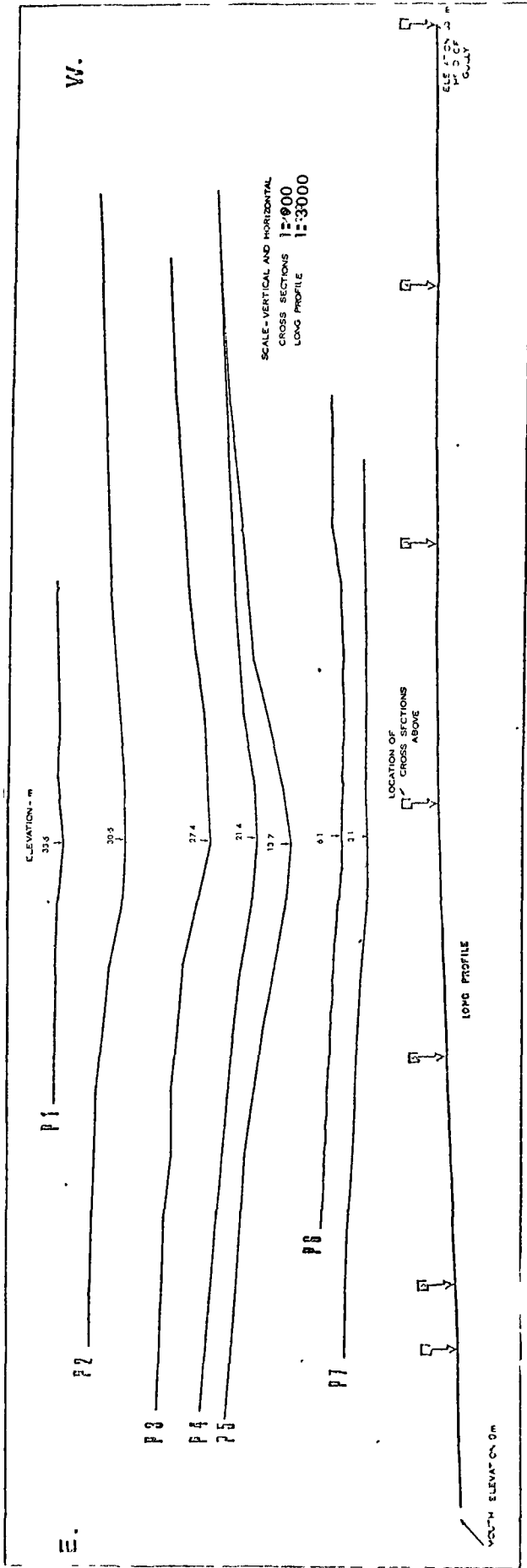


Figure 3 - Slope profile and longitudinal profile of a small stream valley in the study area.

Ten to fifteen percent of the study area is presently covered by lakes; however, lake levels appear to have dropped since glaciation by as much as 20.0 m as suggested by the presence of beach strandlines, lake platforms, and deltas. High centred fissure polygons ranging in size from 30 m in diameter on relatively flat terrain to over 50 m or better on slopes of 5-6° are common throughout the study area. The linear depressions associated with the fissures increase in size and depth with increasing polygon size and slope. In some instances the junction of two or more fissures produces a slight depression which leads to the formation of small ponds between 4 and 170 m² in area.

1.4 Geomorphic History

The geomorphic history of the study area is not yet clear. However, there is evidence to suggest that the area was ice covered during the maximum of the classical Wisconsinan glaciation (Fyles, 1962; French, 1974a). Flutings and indistinct traces of end and/or lateral moraines can be identified from aerial photographs (see Figures 2a and 2b). The morainic belt is underlain in part by thick drift or glacial deposits, but also includes areas of stratified gravel, silt and sand (Fyles, 1962). The presence of stratified deposits and the presence of ground ice in significant quantity ($\geq 30\%$ excess ice content*) is substantiated by core samples obtained by the Geological Survey of Canada from a portable drilling rig under the direction of J. Veillette (see French, 1974b).

* Excess ice content is defined as the volume of supernatant water to the volume of saturated sediment. (Pihlainen and Johnston, 1963).

A distinctive feature of the drift deposits is the presence of fissure polygons on the upland terrain. In many ways this "polygon-drift" terrain is similar in topography and surficial materials to the hummocky morainic terrain found in other parts of the western Arctic. In the Mackenzie-Beaufort region Rampton (1974) and Rampton and Walcott (1974) have shown that much of this topography is ice-cored and it is possible that a similar situation exists on eastern Banks Island.

Rampton envisages several stages in the development of the ice-cored terrain of the Mackenzie-Beaufort region (Figure 4). In the early Wisconsinan, at the maximum extent of the ice sheet, permafrost degraded as temperatures reached the pressure-melting point. When the ice retreated, meltwater percolated through the glacial sediments towards the advancing freezing plane. In this way a substantial body of segregated ice formed beneath the newly deposited sediments. Then, in the late Wisconsinan, as the climate progressively ameliorated (between 8000 and 4500 B.P.), the active layer thickened and thermokarst developed through the partial melting of the buried ice bodies. In the last 3,000 to 4,000 years, temperatures have cooled and regional thermokarst has ceased probably.

Such a sequence may be applicable to the development of the morainic belt on eastern Banks Island. The similarity of that terrain to the morainic topography described by Rampton, the presence of icy bodies in both regions, the lowering of lake levels, numerous kettle-like lakes, and the presence of pingo-like remnants in the study area

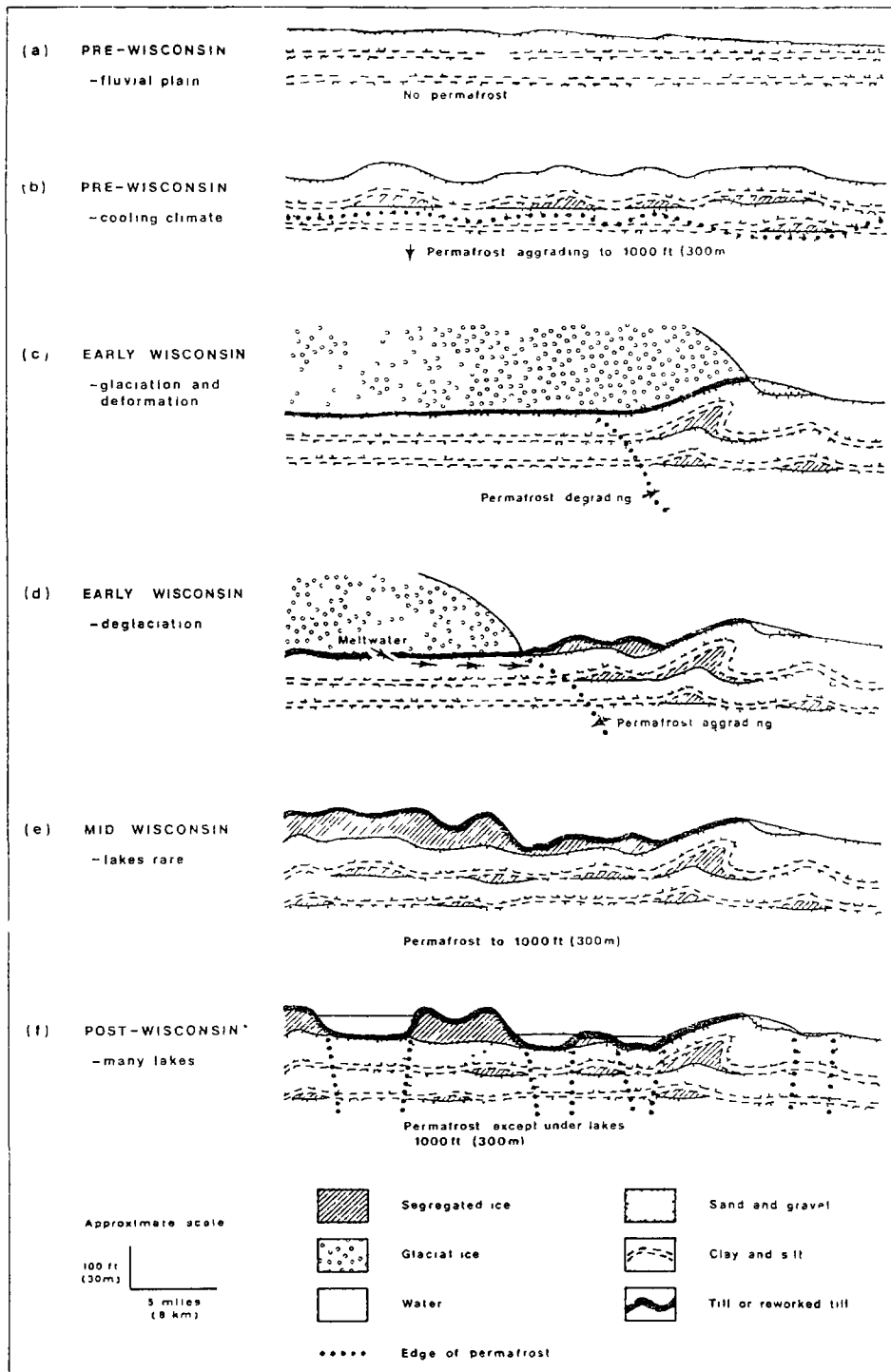


Figure 4 - Schematic development of ice-cored topography in the Mackenzie-Beaufort region (Rampton, 1974).

(Figure 5) are circumstantial evidence, but not proof, of such an evolution.

1.5 Climate

There is no permanent meteorological station within the study area. The nearest is at Johnson Point, located some 35 km away on the Prince of Wales Strait. Unfortunately, records are only available from 1972. However, a permanent station has been maintained at Sachs Harbour on the southwest corner of Banks Island for a number of years and records are available since 1955. Representative data from these two locations are given in Table I.

In all probability, conditions in the study area are more similar to those occurring at Johnson Point than at Sachs Harbour. Mean monthly temperatures can be expected to range from 6.6°C in the summer to -31.5°C in the winter. As in other parts of the island, summer soil temperatures may be considerably higher than air temperatures. In interior regions of Banks Island for example, soils may have temperatures in excess of 15°C at the 1 cm depth in July (French, 1970). Wind direction is predominantly from the northeast at Johnson Point, from the east and south at Sachs Harbour. In the study area the distribution of snow on lee slopes suggests that dominant winds are from the northeast during winter. Field observations during the summers of 1972 and 1973 also suggest a dominance of northeasterly winds. The region, in common with other areas of the High Arctic,



Figure 5 - Pingo-like remnant in the study area. The feature is similar to some of those reported by French (1975b).

TABLE 1 - GENERAL CLIMATIC DATA, JOHNSON POINT AND SACHS HARBOUR

1972

Months	J	F	M	A	M	J	J	A	S	O	N	D	
1972													
JOHNSON POINT													
TEMP. (°C)	---	---	---	-24.40	-11.80	-.88	5.17	2.50	-4.39	-16.33	-25.50	-27.50	-15.76
PPTN. (cm)	---	---	---	.58	3.81	.89	.10	1.06	2.38	2.16	.79	.74	EX 12.55
WIND	NW	NW	ENE	ENE	ENE	ENE	ENE	ENE	NW	ENE	NW	NW	
SACHS HARBOUR													
TEMP. (°C)	-34.00	-35.06	-28.44	-21.17	-9.17	1.94	5.83	3.61	-3.94	-11.83	-24.00	-26.63	-15.26
PPTN. (cm)	.38	.38	1.04	.28	1.96	.81	.28	3.40	2.39	.89	.76	1.17	EX 13.74
WIND	NW	N	SE	SE	N	SSE	N	ESE	ESE	SSE	ENE	NE	
1973													
JOHNSON POINT													
TEMP. (°C)	-31.50	-33.44	-35.06	-22.28	-8.33	3.44	5.11	2.33	-0.67	-9.11	-18.50	-24.28	-14.36
PPTN. (cm)	2.05	.91	.05	.56	.74	2.70	2.18	4.01	2.29	2.16	.58	1.30	EX 19.5
WIND	SW	NW	ENE	ENE	ENE	ENE	NE	ENE	NE	ENE	ENE	ENE	
SACHS HARBOUR													
TEMP. (°C)	-31.39	-30.17	-32.05	-17.72	-6.30	5.67	6.56	5.17	1.17	-8.22	-17.11	-21.78	-12.18
PPTN. (cm)	.69	.86	.28	1.01	1.98	.91	2.40	4.30	2.18	4.50	.64	.23	EX 20.02
WIND	SE	ESE	SE	SE	SE	SE	SE	N	SE	SE	SE	SE	E

is arid and precipitation can be expected to be of the order of 100 mm per annum, with 50% of this total falling in the summer months (May through September).

With respect to thermokarst, the length of the thaw period and the number of thawing degree days is of interest. On this portion of Banks Island the thaw period may be in excess of 80 days and the total number of thawing degree days in excess of 350. This is considerably less than for other more southerly sites (Table 2). From this it may be expected that thermokarst activity in the study area will be less intensive than at warmer mainland sites.

TABLE 2 THAW DATA

A - A comparison of Banks Island thaw data with that from two mainland sites

		No. of Thaw Days	Thawing $^{\circ}\text{C}$ Days
Johnson Point	1972	80	350
	1973	104	404
Sachs Harbour	1972	91	364
	1973	120	588
Inuvik	1972	121	1162
	1973	138	1537
Norman Wells	1972	148	1651
	1973	159	1967

B - Data showing the variability of the length of the thaw season and mean temperature on Banks Island

Year	Length of Thaw Season Days	Mean Temperature of thaw period ($^{\circ}\text{C}$)	Thawing Degree ($^{\circ}\text{C}$) Days
1974	79	3.8	300
1973	120	4.9	588
1972	91	4.0	364
1971	91	5.0	455
1970	89	6.6	587
1969	89	3.5	311
1968	109	4.1	447
1967	69	1.4	97
1966	105	3.5	368
1965	69	6.0	414
1964	74	3.2	237
1963	88	5.2	456
1962	109	5.3	578
1961	86	4.6	396
1960	---	---	---
1959	82	3.7	303
1958	107	4.8	514
1957	88	4.6	405
1956	68	4.7	320
(Mean)	\bar{x} 89.6	\bar{x} 3.9	\bar{x} 396.7
(Standard Deviation)	s_x 15.28	s_x 1.16	s_x 127.8

(Source: station records, Sachs Harbour)

CHAPTER II

THERMOKARST: A LITERATURE REVIEW

2.1 Introduction

'In permafrost areas of North America and Siberia, there is often a peculiar topography of pits, dry gullies and valleys, small hummocks and closed depressions, frequently with lakes. This karst-like topography is due to the melting of ground ice and for it the Russian geologist Ermolaev coined the term "thermokarst"' (Dylik, 1968).

Subsequently thermokarst has become known as a collective term for a variety of processes associated with the degradation of permafrost and the melting of ground ice. Czudek and Demek (1970), for example, define thermokarst as "...the process of melting of ground ice accompanied by local collapse of the ground surface and the formation of depressions". As such, thermokarst is a process distinguishable from "karst" since the latter is a chemical solutional process whereas "thermokarst" is a physical thermal process.

Dylik (1968) has suggested that the melting of buried glacial ice be excluded from the term "thermokarst". This is unnecessarily limiting as glacial ice may become an integral part of permafrost in high latitudes. Furthermore, the process remains the same and the resultant topographic forms are similar (French and Egginton, 1973).

2.2 Ground Ice and Thermokarst

Ground ice may be an initiator of both aggradational and degradational landforms in permafrost areas (Shumskii, 1959; Brown, 1973). Several workers have discussed the importance of ground ice in the formation of pingos, palsas and involuted hills (e.g. Mackay, 1963, 1971a; Rampton and Walcott, 1974).

Ground-ice types have been classified over the past few decades. Some classifications are not as comprehensive as they might be, due to the lack of variety of ground-ice types in the study area of the particular researcher. Some of the earlier authors have suggested that there is only one ground-ice type; for example, Smugin (in Shumskii, 1959) suggested that ground ice was formed by the burial of either snow or glacial ice.

Later classifications, such as that by Shumskii (1959, 1964), incorporate other ground ice forms. Shumskii's classification is based upon the role of ice in the soil structure. The ice may be either (a) a soil forming mineral and an integral part of the soil or (b) a non soil forming mineral, forming in soil voids or (c) an entirely separate entity.

J.R. Mackay has simplified Shumskii's classification and produced (Mackay, 1971a; 1972) a more useful and comprehensive classification. The basis is the origin of the water prior to freezing and the principal transfer process. It is highly likely that this classification will be widely adopted by North American researchers (Figure 6).

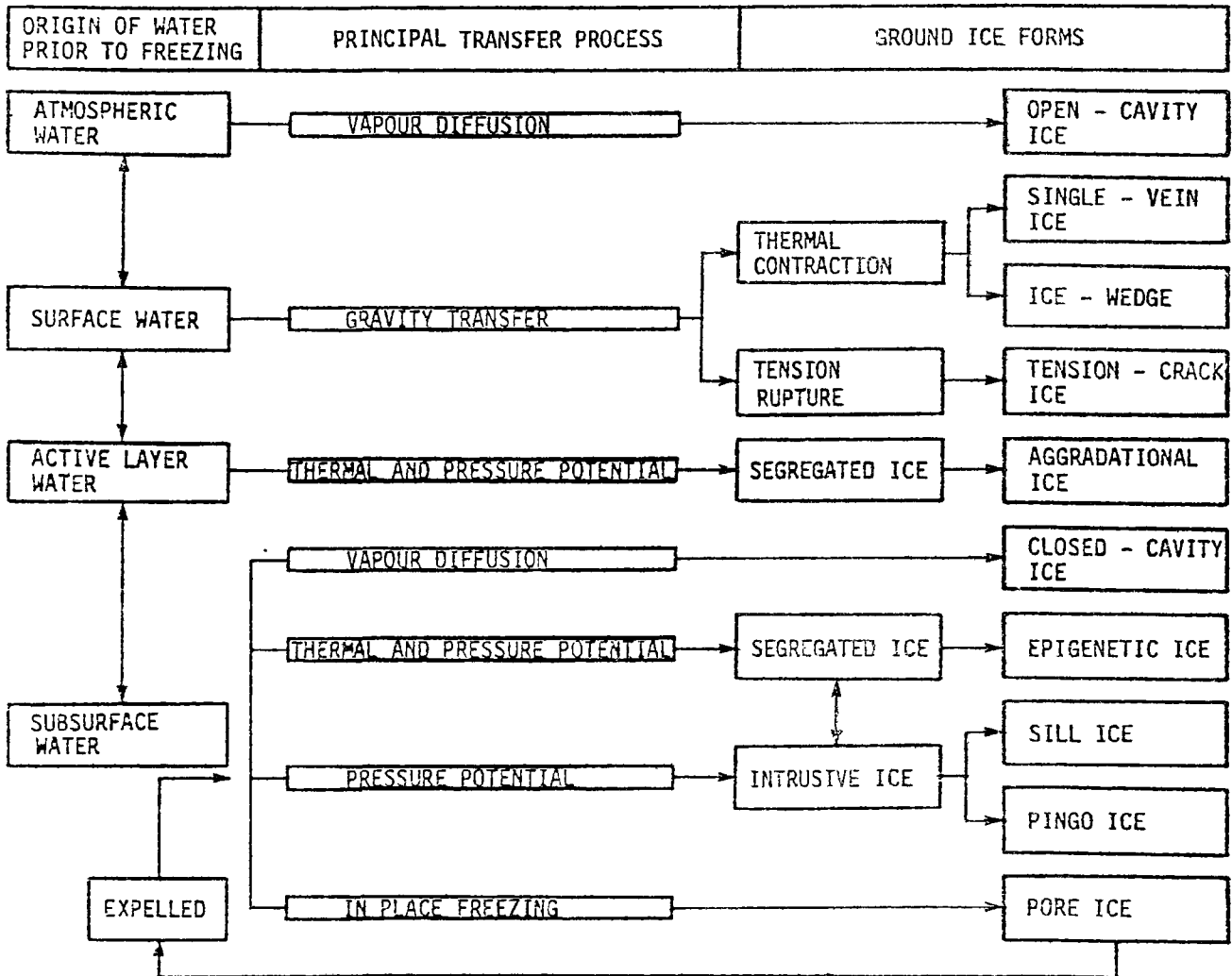


Figure 6 - Classification of ground-ice according to J.R. Mackay (1971a).

It is apparent that there are many ground-ice types. Each ground-ice type, by virtue of its dimensions, distribution and physical properties, may produce a distinct thermokarst form. For example, the melting of segregated ice lenses may produce shallow basin-like features while the melting of large, well developed ice-wedges may produce linear or mound-like relief (Kachurin, 1962b; Czudek and Demek, 1970).

2.3 Thermokarst and Thermal Equilibrium

Thermokarst occurs when the thermal equilibrium of the permafrost is disturbed. Mackay (1971a) has produced a flow diagram which indicates the types of change which bring this about (Figure 7).

The basic factor determining the level of thermokarst activity is climate. Regional climatic warming may produce a thermal inequilibrium and bring about an increase in the depth of the active layer. Equally, an increase in the amplitude of the temperature (TA) may induce an increase in active layer depth.

Precipitation may also be a consideration in the study of thermokarst. The role of snow as an insulator is well known (e.g. Grey, 1970; Sellers, 1965). In years of early and exceptionally high snowfall, the ground surface may be insulated from winter cold and may not cool to the same degree as it would under normal snow conditions. Furthermore, during the following summer, the energy which would have been expended in heating the ground may cause an increase in the active layer depth.

PERMAFROST DEGRADATION

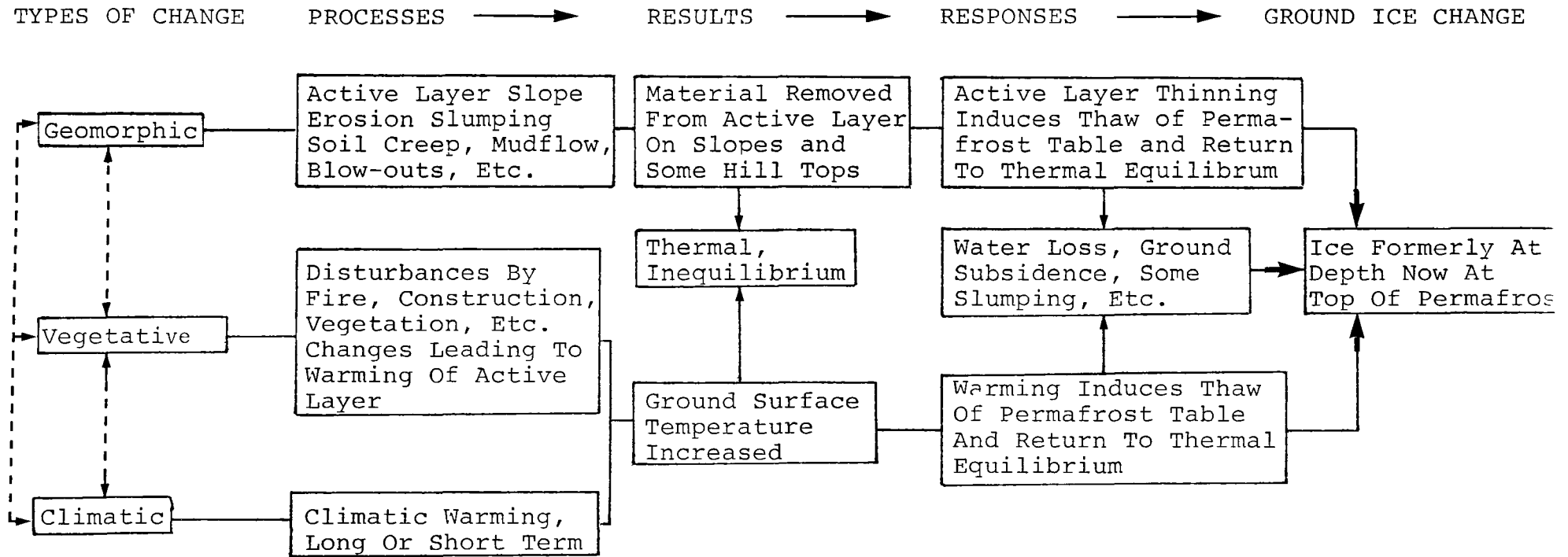


Figure 7 - Factors involved in permafrost degradation (modified from J.R. Mackay, 1971a).

Moisture in the active layer may also influence thermokarst. For example, thermo-erosional wash resulting from the penetration and percolation of snowmelt through the soil and along the permafrost table is thought to be important as it may induce a slow, almost imperceptible melting of the permafrost (e.g. Kachurin, 1962b; Dylík, 1972). The release of water previously held as pore ice leads to a general reduction of relief; the process is termed thermoplanation.

Local changes favouring thermokarst may include changes in vegetation, either natural or man-induced. Vegetation influences the albedo of the ground and affects the net radiation received at the ground surface. In addition, vegetation through evapotranspiration, aids in cooling and insulating the permafrost (e.g. Brown, 1965, 1973; Viereck, 1973). Thus, the destruction or removal of vegetation leads to a thermal inequilibrium and often to a thickening of the active layer.

A local change in the rate of activity of geomorphic processes may also induce thermokarst. Localized slope failure, deflation or an undercutting stream may result in the removal of a portion of the active layer and the subsequent melting of the permafrost.

It is the combined action of these three types of change-climatic, vegetational and geomorphic-either acting separately or interacting with one another, which eventually determines the extent of permafrost degradation.

2.4 Man-Induced Thermokarst and Terrain Inventory Mapping

Disturbance of permafrost terrain by man, and in particular, the destruction or removal of the surface organic net, is an important cause of permafrost degradation and thermokarst (e.g. see Haugen & Brown, 1969). This is on account of the protective, thermal role played by vegetation. For example, Heginbottom (1971; 1973) has documented the effects of a forest fire which occurred near Inuvik in 1968. Apart from the more obvious conclusion that degradation has occurred in the burnt regions, it was found that the cleared fire breaks were subject to more intensive slumping and related thermokarst activity than the burnt areas. Brown, Rickard and Vietor (1969) have reported similarly that the active layer increase associated with a fire break in Alaska was 3.5 times that associated with the actual burnt area (active layer increases were reported at 200% and 60% respectively). The reason for such variation is that fire does not completely destroy the vegetation and the roots remain intact. A bulldozer, on the other hand, removes the root system in total or in sufficient quantity to inhibit rapid recovery.

Mackay (1970) has documented an excellent example which illustrates what happens when 15 cm of the vegetation mat and active layer is removed from terrain possessing a uniform ice content of 50% by volume - a 45 cm subsidence occurs (see Figure 8 and the accompanying notes).

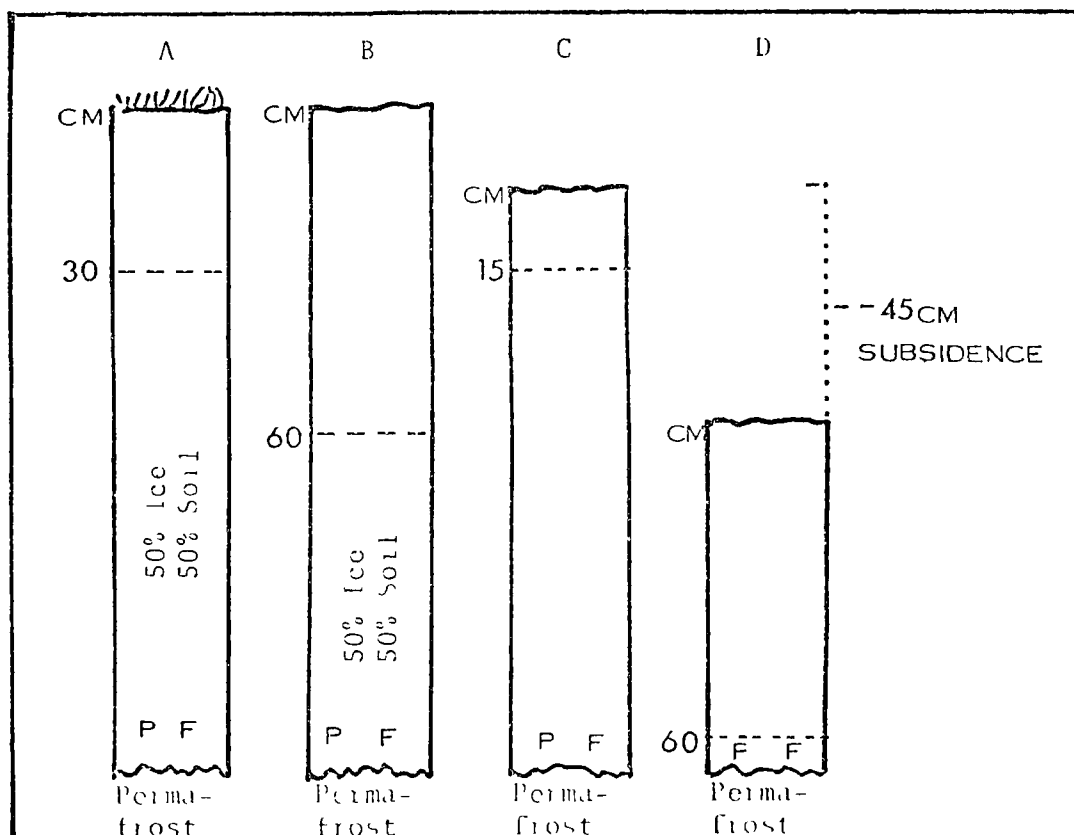


Figure 8 - Diagram illustrating how terrain disturbance can lead to thermokarst development (after J.R. Mackay, 1970). In the equilibrium cases (A and B) the active layer depth is 30 cm and 60 cm for a vegetated and a non-vegetated soil respectively. When 15 cm is removed from a vegetated soil (e.g. by a grader), (C above) the permafrost degrades as the active layer thickens to a new equilibrium depth of 60 cm -the required depth for a non-vegetated soil. This active layer thickening results in a subsidence of 45 cm.

In recent years the impetus for northern development has led to terrain sensitivity and inventory mapping (e.g. Heginbottom and Kurfurst, 1973). The reason for such mapping is that permafrost terrain possessing significant quantities of ground ice may be subject to thermokarst processes upon disturbance. Tests have been conducted on various 'off-the-road' tracked and wheeled vehicles, under different loads and on different terrain units (e.g. Bellamy and others, 1971; Burt, 1970; Muskeg Research Institute, 1970). These tests indicate that the use of wheeled rolligon vehicles cause less damage to the tundra than do tracked vehicles. As such, their use improves the chances of vegetation re-growth following initial disturbance.

Most field investigators seem to agree that the majority of disturbances associated with seismic and other off-road travel, although clearly visible from the air, are minimal when viewed from the ground (e.g. Lambert, 1970; Kerfoot, 1970; French, 1971b; Hodgson, 1974). In addition, most authors suggest that winter seismic activity and winter roads cause less disturbance than summer activity. Kerfoot (1970) has suggested, however, that the recuperative ability of the tundra has been underestimated and Bliss and Wein (1972) have pointed out that, in the High Arctic, once the polar deserts have dried out, summer operations may be carried out with minimal disturbance. In fact, Kerfoot (1972) has suggested that in some instances, summer programs are to be preferred to winter activity. Kerfoot attributes low summer disturbance levels to the fact that the vegetation cover, particularly where it is comprised of shrubs, is more supple in the

summer allowing the vegetation to withstand the passage of vehicles with fewer adverse effects than would occur in winter months.

Man-induced thermokarst is not restricted to seismic lines, fires, or to the passage of vehicles over the tundra. The drilling of wells by oil companies may lead to terrain disturbance, particularly in the vicinity of the well heads and slush pits (e.g. Heginbottom and Kurfurst, 1973; Heginbottom, 1973). Much has been written on permafrost problems including both theoretical (e.g. Lachenbruch, 1970) and field studies (e.g. Isaacs and Code, 1972; McRoberts and Morgenstern, 1974a, 1974b; Nixon and Morgenstern, 1974). Thermokarst has been reported in connection with roads and airstrips (Brown, 1970; Price, 1972, French, 1975b), service utilidors (Copp, Crawford and Girange, 1956; Dickens, 1959), and town construction (e.g. at Aklavik, N.W.T.; see Brown, 1970).

2.5 Thermokarst Landforms

Czudek and Demek (1970) have suggested that thermokarst may act in two distinct ways, either as a downwearing process or as a backwearing process. Each process produces distinctive features. The advantage of such an approach is that it is not necessary to separate the various geomorphic processes. For simplicity, therefore, the subsequent sections describe thermokarst forms under the general headings of thermokarst backwearing and downwearing forms.

2.6 Thermokarst Backwearing Forms

A common backwearing form in the Mackenzie Delta is the ground-ice slump (Mackay, 1966; Kerfoot and Mackay, 1972; Mackay and

Mathews, 1973). These features generally evolve with the retreat of a scarp face consisting of an exposure of ice and an overburden (Figure 9). The exposed ice may be some 5 m high; the entire ice mass may be 15 m or more in thickness and the exposure may be hundreds of metres in length. Mackay has noted that there are three main processes involved in the retreat of such features: 1) the free fall or sliding of the active layer (overburden), 2) erosion, both mechanical and thermal, of the frozen scarp face, and 3) the slumping (partly rotational) of thawed debris blanketing the frozen scarp face. The retreat of the headwall of such features is reported by Mackay (1966) to be 1.5 - 5.0 m per annum and by Kerfoot and Mackay (1972) as 3.5 - 7.0 m per annum.

One of the earliest studies of thermokarst in the High Arctic Islands is that by Lamothe and St-Onge (1961). They described the development of, and the processes acting upon, a small slump feature (backwall 1 to 2 m in height with a total diameter of 40m) on Ellef Ringnes Island, N.W.T. (Figure 10). Headwall retreat of the feature was reported to average 7 m with a maximum of 10 m during the summer of 1960.

Erosion along coastlines in the Arctic can lead to rapid undercutting and coastal retreat, especially where the ground-ice contents are high. Retreat rates of coastlines in the Mackenzie Delta and Alaska are variable and have been reported, depending upon the location, as: 10 m/yr (Lewellen, 1970); 8.6 m/yr (Mackay, 1971b);

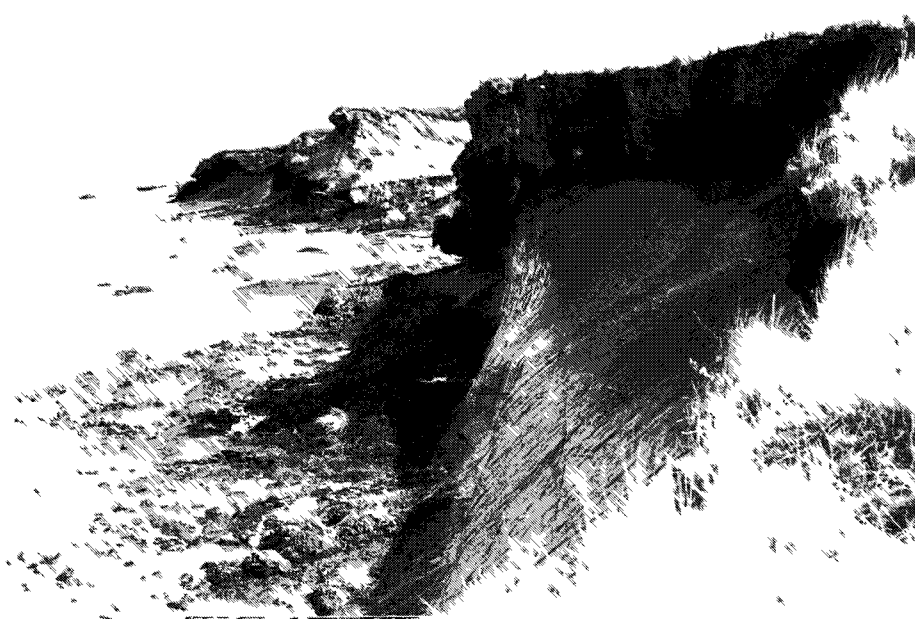


Figure 9 - Photograph of a ground ice slump - District of
MacKenzie, N.W.T.

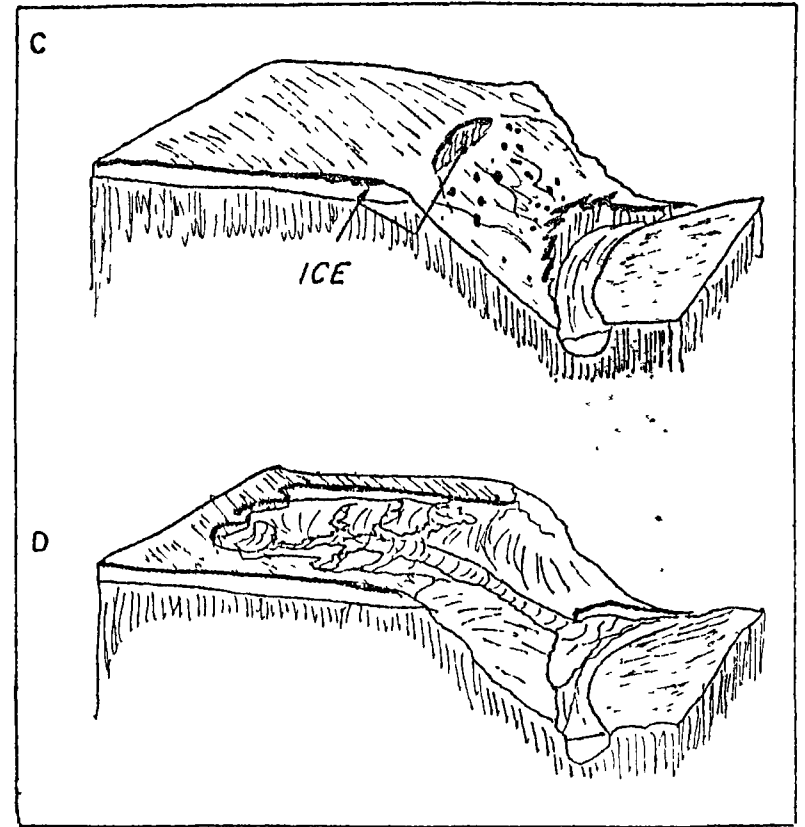
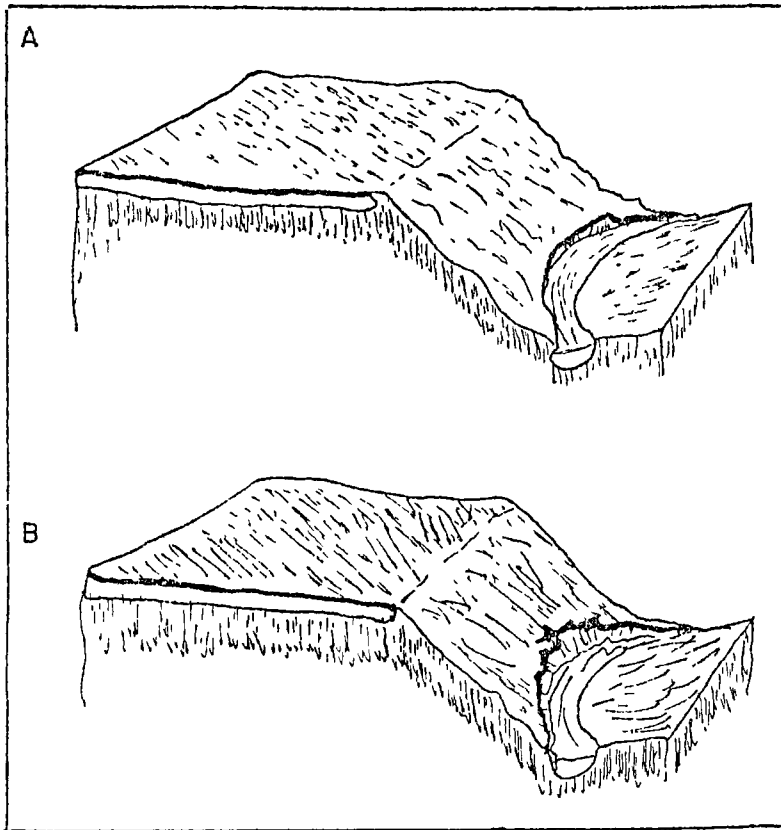


Figure 10 - The evolution of a thermokarst 'hollow' in the High Arctic: (After Lamothe and St-Onge 1961)

A: Valley walls prior to mudflow

C: Gravity fall which exposes the ground ice,

B: Slumping on the slope due to sapping
by the river

D: Mudflow excavating a hollow

5.2 m/yr (Mackay, 1970); 3.1 m/yr (Hume, Schalk, and Hume, 1972); and 3 m/yr (McDonald and Lewis, 1973). However, the values given are not meant to suggest that all arctic coastlines are actively retreating: McDonald and Lewis (1973) found substantial coastal areas where retreat was insignificant and others where deposition was occurring as a result of longshore movements.

Thermokarst backwearing along river banks has been reported by many authors (e.g. Péwé, 1969; Walker and Arnborg, 1963; Dylik, 1969). Czudek and Demek (1970) report that undercutting by streams in Siberia may produce thermal abrasion niches 10 m deep. When the undercut bank eventually collapses, preferential melt occurs along ice wedges producing thaw gullies, which coalesce through time leaving conical isolated mounds.

During the development of thermokarst forms ponded water plays an extremely important role. The high heat capacity of standing water increases the ground temperature below and in the immediate vicinity of the pond, causing further permafrost degradation. For example, in northern Siberia, water-free polygon centres may have active layers which are only 50% as deep as polygon centres which are covered by water to a depth of 20-25 cm (Muskin, 1960, quoted in Czudek and Demek, 1970). Sufficient heat may be stored in some of the larger thaw lakes to inhibit their complete freezing during the winter months. Czudek and Demek (1970) report that lakes greater than 14-16 m in depth do not freeze completely in northeastern Siberia.

In the District of Mackenzie, Brown et al. (1964) report that a lake 800 m in length and 2.1 m in depth developed a talik 65 m in depth.

Thaw lakes are one of the more widespread thermokarst backwearing forms in North America; they range in size from a few metres to several kilometres. The lakes undergo growth along their margins, their dimensions changing constantly, as the permafrost degrades (Hopkins, 1949; Tedrow, 1969). The morphology of these lakes is such that they tend to be oriented with respect to the prevailing winds of an area. There is a disagreement as to the exact orientation process: Black and Barksdale (1948) suggest that the major axes orientate parallel to the major wind direction while Livingston (1954) and Zencovitch (1959) feel that the orientation is along the minor axes. It would appear that a complex relationship exists between the lake orientation, the circulation pattern in the lake, and the wind direction.

2.7 Thermokarst Downwearing Forms

Permafrost degradation from above occurs on flat undissected terrain, mainly on watersheds. The form the feature will take depends upon the amount and type of ice present. For example, Hopkins et al. (1955) have discussed the formation of beaded drainage systems in Alaska, which are essentially downwearing forms. Their formation involves an accumulation of water along ice wedges in the summer which brings about the development of troughs. Ponds ranging from 2.4 - 6.0 m in depth and up to 30 m in diameter form the intersection of the wedges and are joined

subsequently by short, straight, water courses. Thus, the drainage system assumes a beaded form.

The downwearing of ground-ice wedges may progress from beaded drainage into larger and deep forms and ultimately into thermokarst valleys. Soloviev (1973) has traced this development in the Yakutian lowlands of Siberia through several stages (Figure 11). In the initial stage, a thermal disequilibrium occurs and melting commences along ice wedges. Shallow mounds or high centered polygons, sometimes called degradational polygons, develop. Further melting along the polygonal borders together with slumping from the central polygon areas give rise to conical mounds called 'baydjarakhs'. In a secondary stage, baydjarakhs begin to disintegrate and 'sink' systems develop. Through successive linkage enclosed depressions form with steep slopes and uneven bottoms. In the third stage the conical mounds disintegrate; thaw lakes develop and a distinct depression with steep sides and an undulating flat bottom, termed an alas, is formed. Alases reach diameters ranging from 100 m to 15 km and a depth of 30 to 40 m (Czudek and Demek, 1970; Price, 1972; Soloviev, 1973). As degradation of the permafrost continues, the alas or thermokarst lake may disappear, due to infilling or drainage to a lower level alas. If ground-ice conditions are suitable the ridges between adjacent alases are destroyed resulting in the coalescence and formation of thermokarst valleys. Such features are often several kilometres long.

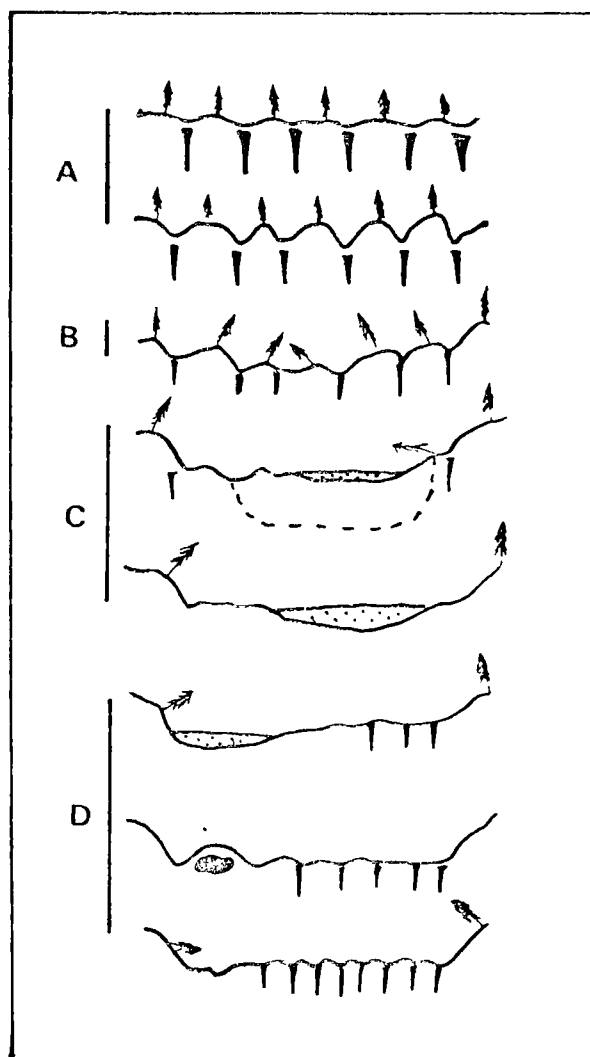


Figure 11 - Stages of downwearing thermokarst and the formation of alas depressions in Siberia (after Czudek and Demek, 1970). A; Undisturbed terrain, B; Initial degradation -grave-yard mounds, C; Drunken forest associated with water movement and ponding, D; the formation of an Alas.

The development of the complete Yakutian sequence as described above is not common in North America. However, Rampton (1974) has identified several thermokarst valleys in the Mackenzie Delta region, and thaw sinks and thermokarst mounds have been reported from Alaska (e.g. Rockie, 1942; Péwé, 1954).

2.9 Summary

Relatively little work has been done on naturally occurring thermokarst in the Canadian Arctic. The majority of the studies that have been undertaken have been concerned with terrain disturbance. As a result, relatively little information is available on rates of activity or growth of thermokarst features in the High Arctic. One aim of this study is to provide such data.

CHAPTER III

SOIL TEMPERATURES, ACTIVE LAYER DEPTHS AND THERMOKARST

3.1 Introduction

Soil thermal disequilibrium which results from regional climatic warming or a positive climatic change may lead to permafrost degradation.

In this chapter temperature and active layer depth data exhibiting spatial and temporal change are presented. These thermal investigations were limited to a heart-shaped amphitheatre, a localized area of badland thermokarst topography, some 0.5 km² in area. It was named the T.S. hollow and is subsequently referred to as such in this thesis (see Figure 12). The objectives of the investigation were to determine the magnitude of spatial and temporal temperature variation within a thermokarst form and, if possible, relate such variation to the rate of thermokarst activity.

The amphitheatre is developed within ice-rich sand and gravel (Figure 13, boreholes C, D, E, and F). Four sites were investigated. Sites 1 and 2 were on the north- and south-facing slopes

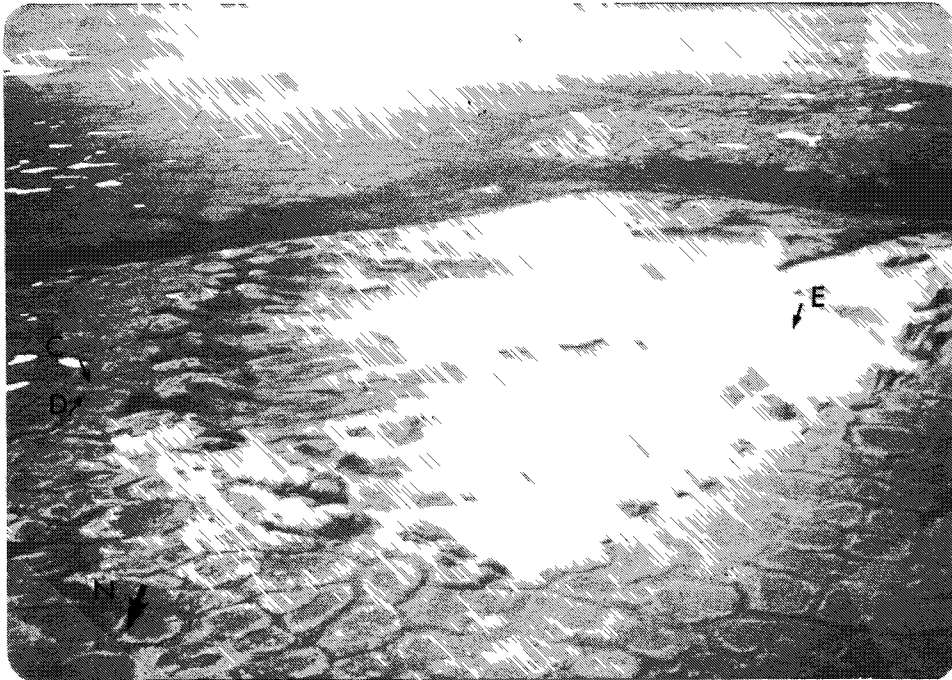


Figure 12 - Oblique air photograph of the T.S. hollow. See Figure 2 for location of this feature. C., D. E - borehole locations.

respectively of a small stream valley; both slopes were inclined at approximately 8 degrees. A difference between the two slopes was the presence of a dark moist soil and earth hummocks, 0.3 - 0.6 m in diameter, on the north-facing slope (site 2) compared with a featureless and somewhat drier soil at site 1. Site 3 was located within the bottom of the amphitheatre, some 6-7 m lower than the surrounding headwall, on a low-angled west-facing slope; soil texture was predominantly silty sand. Site 4, located at the edge of the amphitheatre on an exposed plateau surface, had soil conditions similar to site 3. The upper plateau surface was characterized by ice-wedge polygons some 20-30 m in diameter and limited vegetation (410%). At each of the four sites, soil and surface thermographs (TG1 through TG3) and/or thermocouple rods (R1 through R13) were used to collect thermal data. The latter were constructed of wooden dowelling with thermocouples installed at locations along its length. Readings were taken by means of a potentiometer and were thought accurate to $\pm 0.5^{\circ}\text{C}$.

3.2 Temperature Variation

Daily surface temperature summaries for each of the sites during the summer of 1973 are presented in graphical form and averages for the season are given in Figure 14.

The relatively high maximum temperatures recorded at the top of the T.S. hollow (site 4) are thought to be the result of the prolonged daily radiation period relative to the other slopes. The maximum

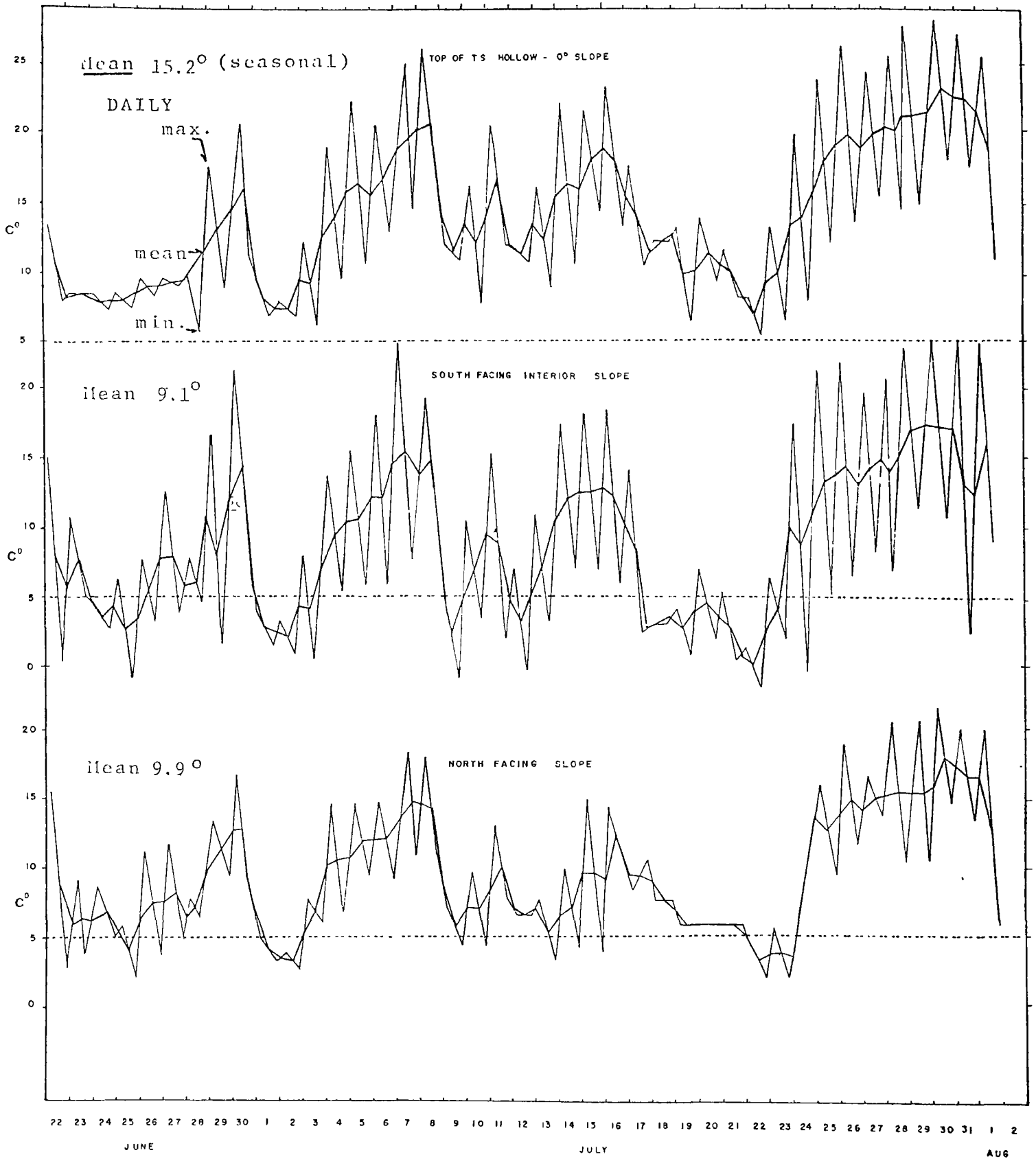


Figure 14 - Daily ground surface temperatures in the T.S. hollow, 1973.

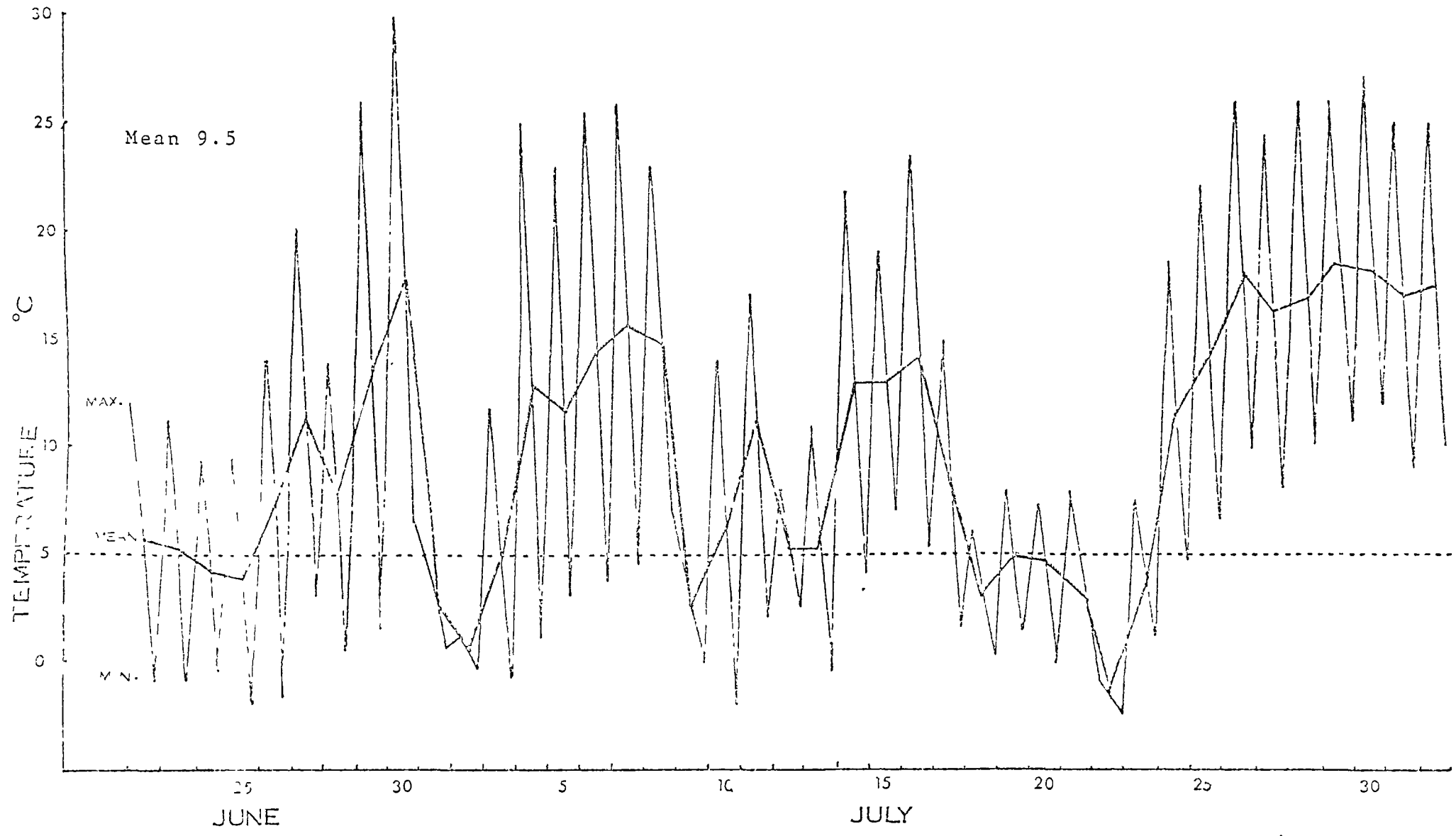


Figure 14 -continued - Temperatures in the central portion of the T.S. hollow

temperatures recorded at the bottom of the T.S. hollow were also high, perhaps due to the sheltered location (relative to the wind). The highest mean daily surface temperatures during the summer of 1973 were recorded at site 4, on the exposed plateau. This was followed by site 3, site 1 and site 2.

This order was unexpected as it was originally thought that the south-facing slope would have a higher average mean temperature than the north-facing slope. Possibly, some of this variation can be explained in terms of other microclimatic factors such as evaporation and localized winds which act to modify the ground surface temperature. Such variables were not measured. Another possible cause for the variation, however, is the difference in the proportion of incoming solar radiation available at each slope for heat storage and sensible heating. For example, Scott (1964) has presented data on the amount of daily heat energy available at the ground surface at 70° latitude. The theoretical heat energy available is as follows:

<u>Slope and Aspect</u>	<u>g calories/cm²</u>
Horizontal	797
Vertical Surface North facing	431
Vertical Surface South facing	489

If Scott's data is accepted and allowances are made for differences in albedo such that the south-facing slope is assumed to have an albedo of 35 and the north-facing an albedo of 10 (albedos

are estimated from tables - Sellers, 1965) and the theoretical energy available for heating is measured equivalent to the available radiant energy, then 388 g calories/cm² ($\frac{431 \times 100-10}{100}$) and 318 g calories/cm² ($\frac{489 \times 100-35}{100}$) are available on the north and south slopes of the T.S. hollow respectively. Indeed, by mid-summer there may be little variation in the incoming solar radiation received by any of the slopes in the study area. For example, Wender and Ishikawa (1974) have found that during periods of maximum declination at a latitude of 69⁰, there is little variance in the incoming solar radiation received on slopes of varying aspects and angles. The same may be expected on slopes in the study area. Thus the measured surface temperatures at each site may well be consistent with the available heat energy.

Subsurface temperatures were measured for sites 1, 2 and 4 by means of soil thermographs and thermocouple rods, at various times throughout the 1972 and 1973 field seasons.

To illustrate subsurface temperature variation, isochrones at 4 hour intervals were constructed from the data collected from 3 soil thermographs and 13 thermocouple rods on July 4 and 5, 1972. The days immediately prior to, and including, the measurement period itself were characterized by few clouds and a lack of precipitation. The wind during the period July 2-5 (inclusive) was variable although winds from the north and west at speeds of between 16-30 km dominated.

The importance of aspect in determining soil temperatures at a specific time is clearly apparent. For example, thermograph

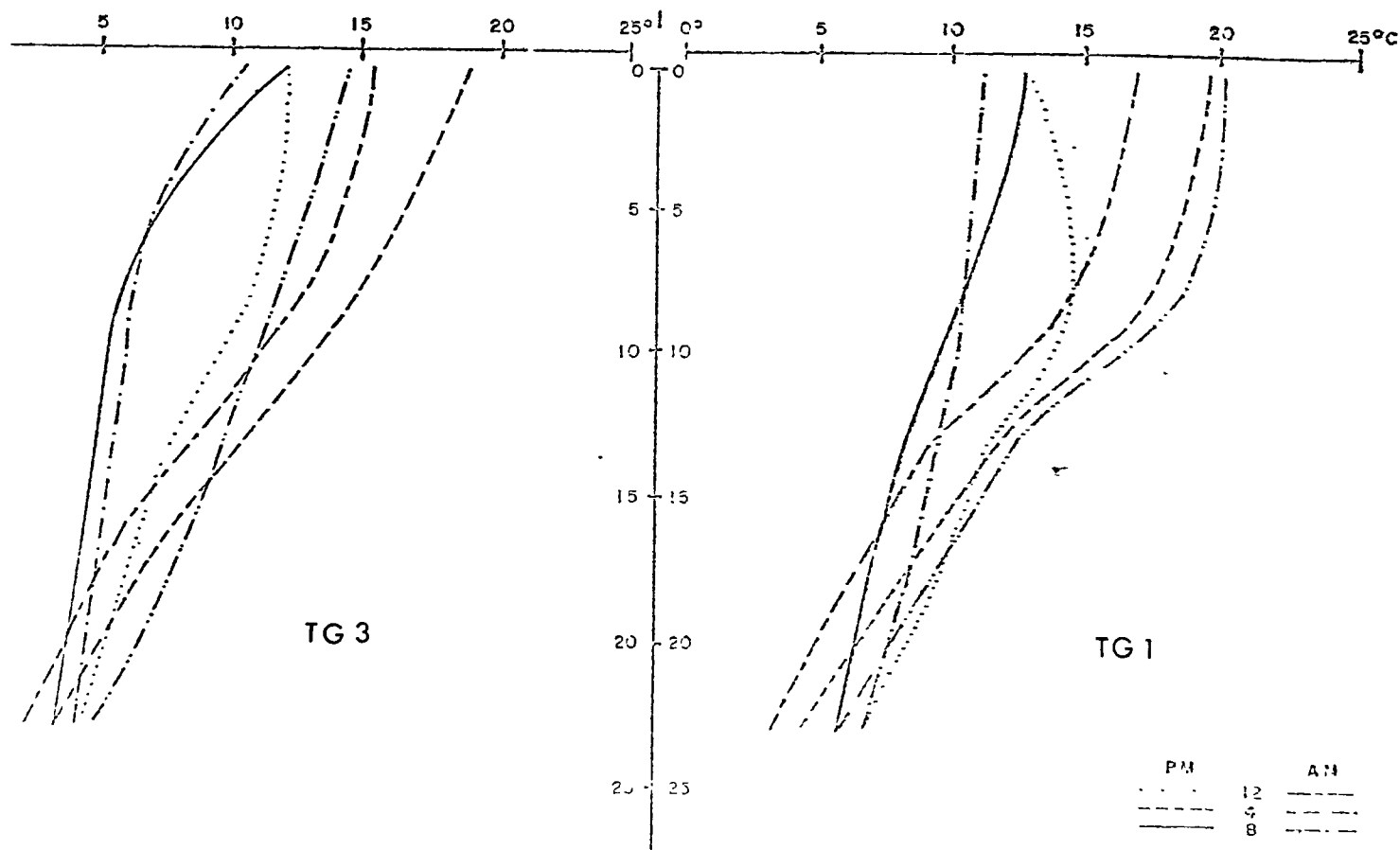
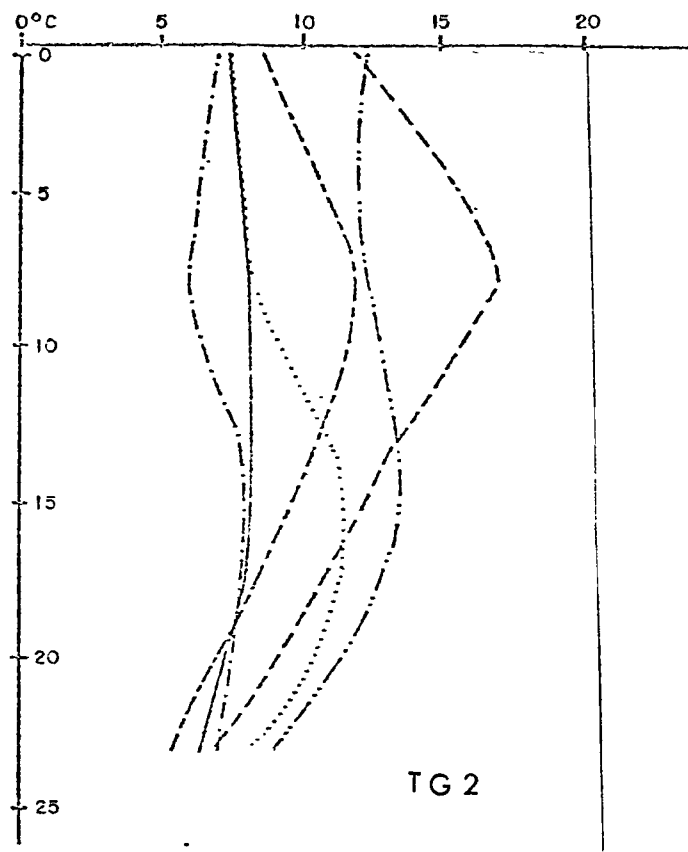


Figure 15 - Soil isochrones at sites 1, 2, 3 in T.S. hollow, July 4-5, 1972.

2 (Figure 15) located on a south-facing slope showed considerable cooling tendencies in the upper few cm by 4 p.m., while thermograph 3, located on the exposed plateau surface had not shown any tendency towards cooling at that time; similarly, thermograph 1 located on the north-facing slope continued to heat until 8 p.m. and beyond.

Temperature variations are not limited to sites of different orientation. Considerable variation occurred over distance of less than 2 m. For example, thermocouple rods 11 and 12 were located on a north-facing slope of 8 degrees; rod 11 was positioned on the shoulders of a fissure polygon while rod 12 was located in the polygonal depression. The range of surface temperatures experienced at each site varied considerably: the temperatures on rod 11 ranged through 12.5°C , and on rod 12 through 15.5°C . The mean surface temperatures were 15.5°C (rod 11), and 17.2°C (rod 12). Considerable temperature variation also existed at depth at the three sites, as is reflected in the shapes of the isochrones (see Figure 16).

Subsurface temperature data are presented in Figures 17-19 for the north-facing slope (site 1), the south-facing slope (site 2) and the top of the hollow (site 4). The mean soil temperatures at the three sites on July 30, 1973 (the date of maximum recorded mean daily temperatures at the 22.5 cm depth) are also indicated. The data suggest that the south-facing slope is the warmest slope at the 22.5 cm depth. This is contrary to what may have been expected on the basis of mean surface temperature (Figure 14). An explanation for this

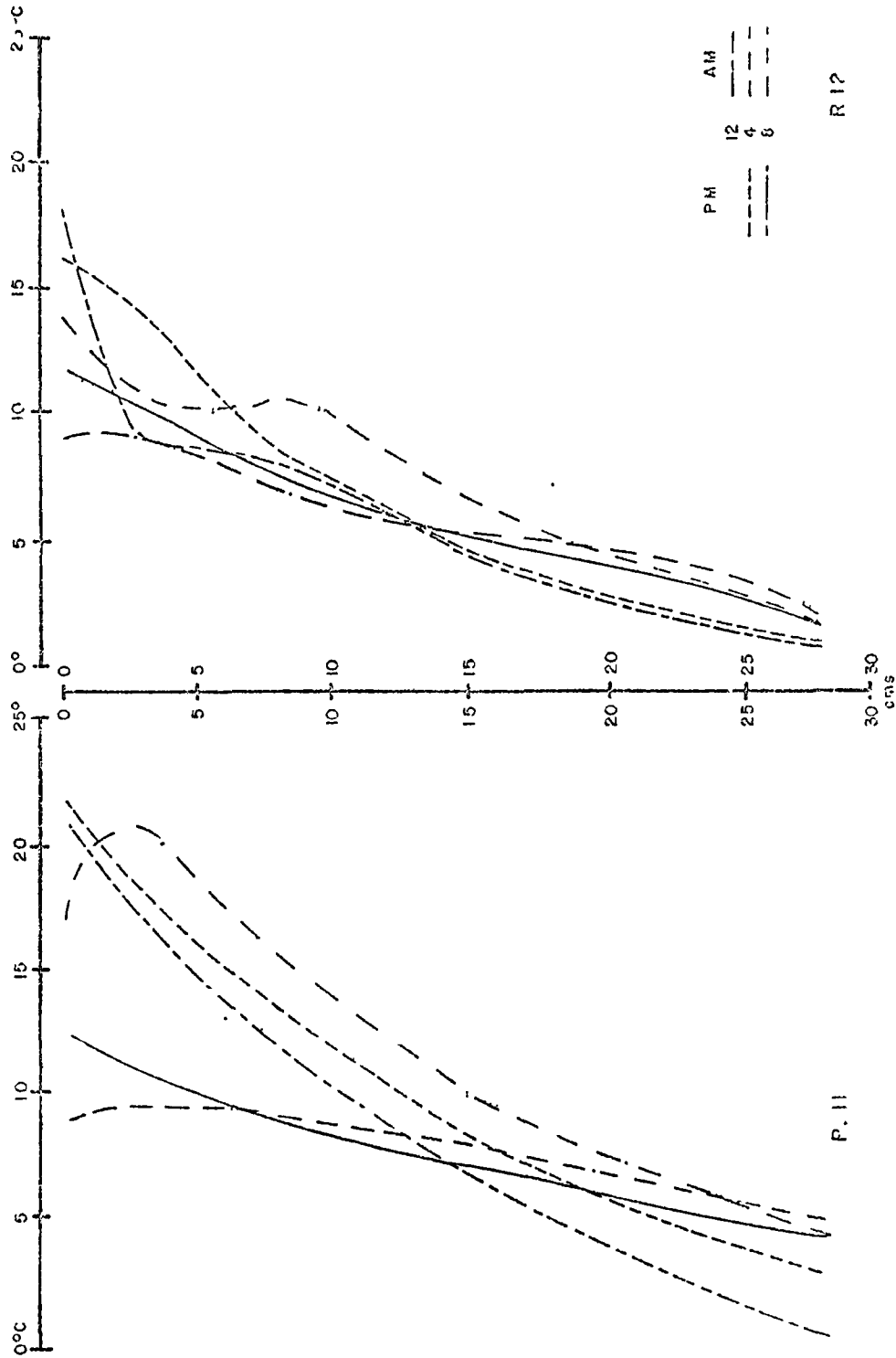


Figure 16 - Soil isochrones for rods 11 and 12, T.S. hollow, July 4-5, 1972.

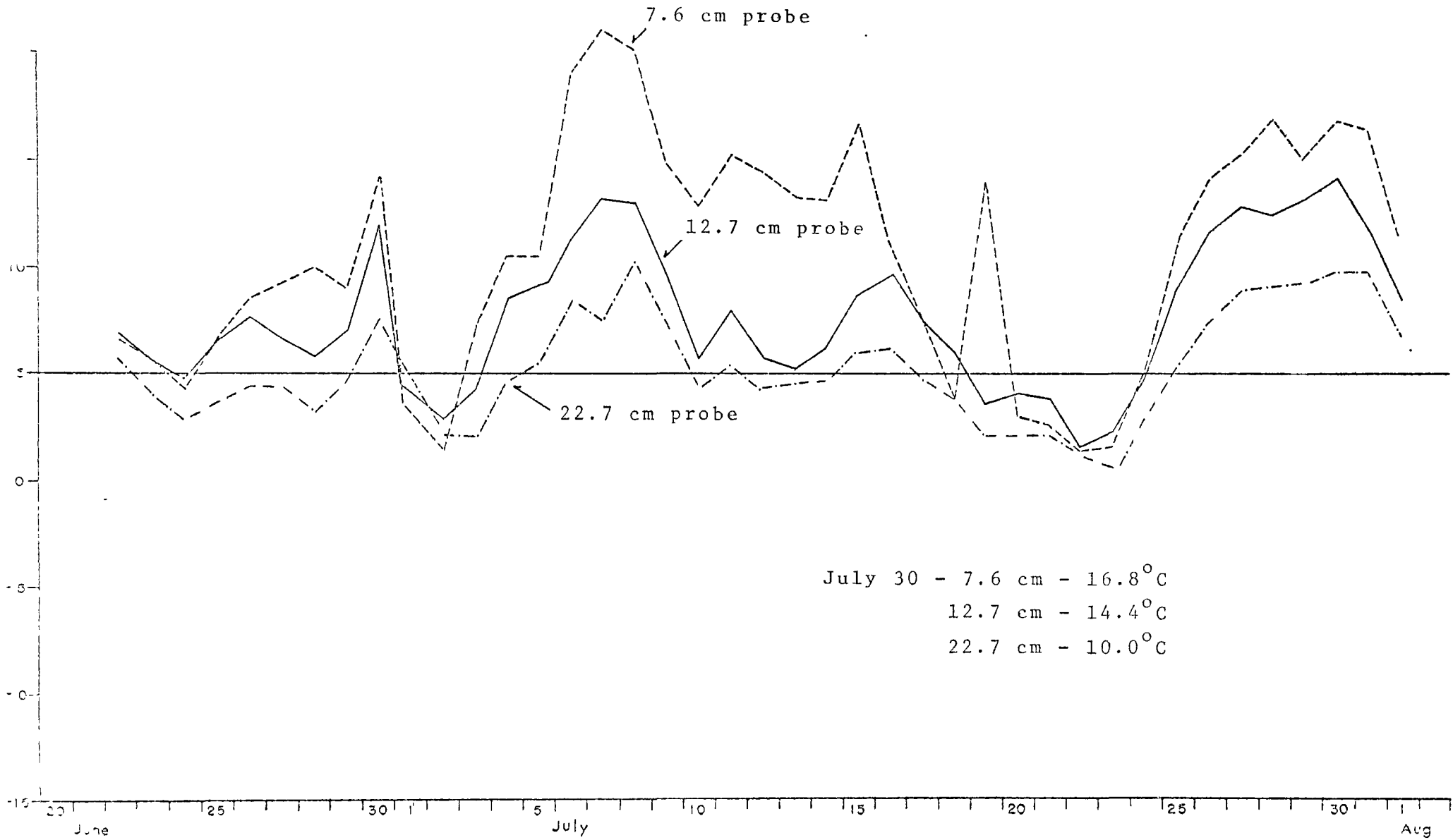


Figure 17 - Soil temperature, site 1, T.S. hollow, June 22 - August 1, 1973.

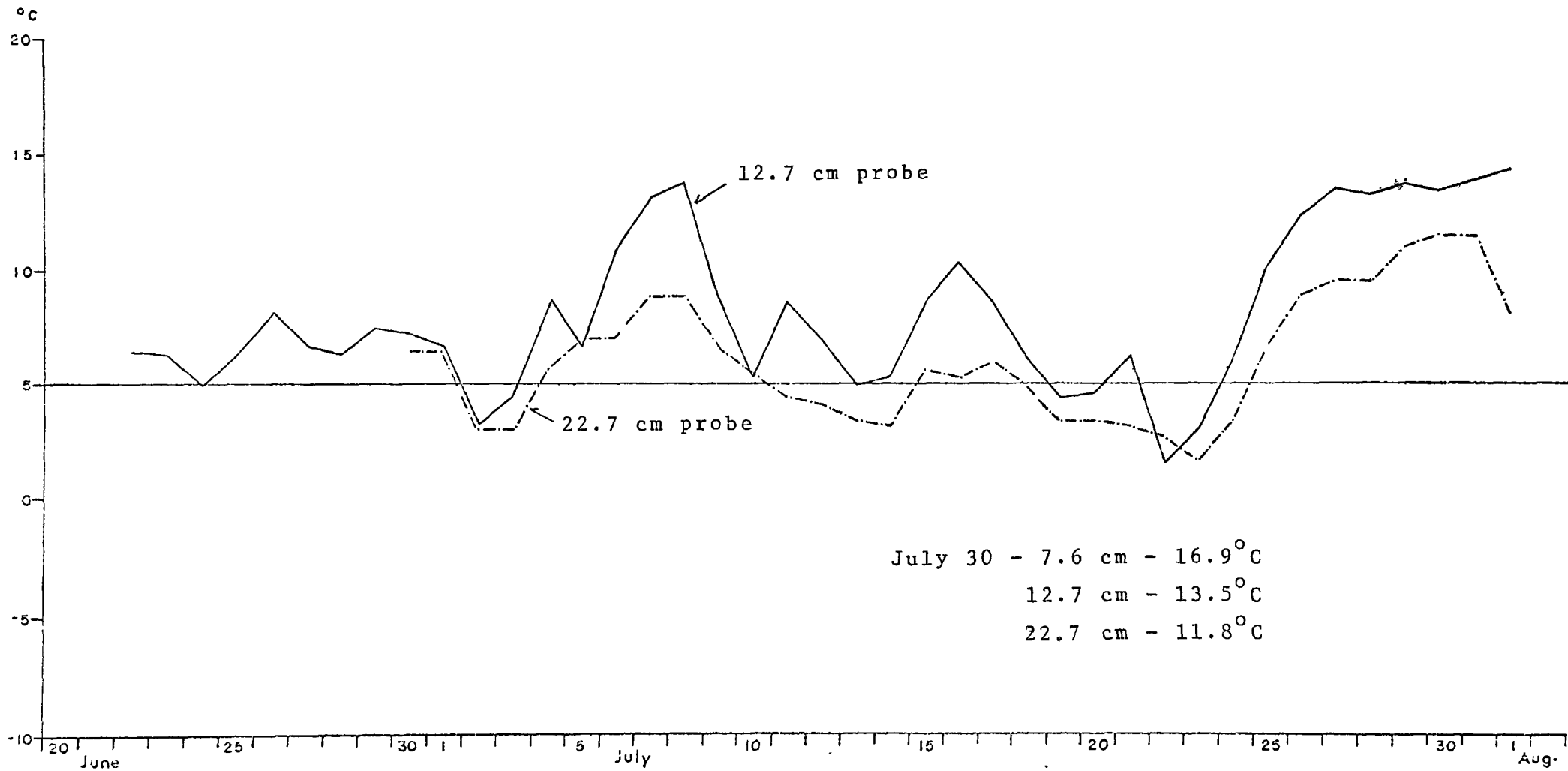


Figure 18 - Soil temperature, site 2, T.S. hollow, June 22 - August 1, 1973.

Mean daily temperatures

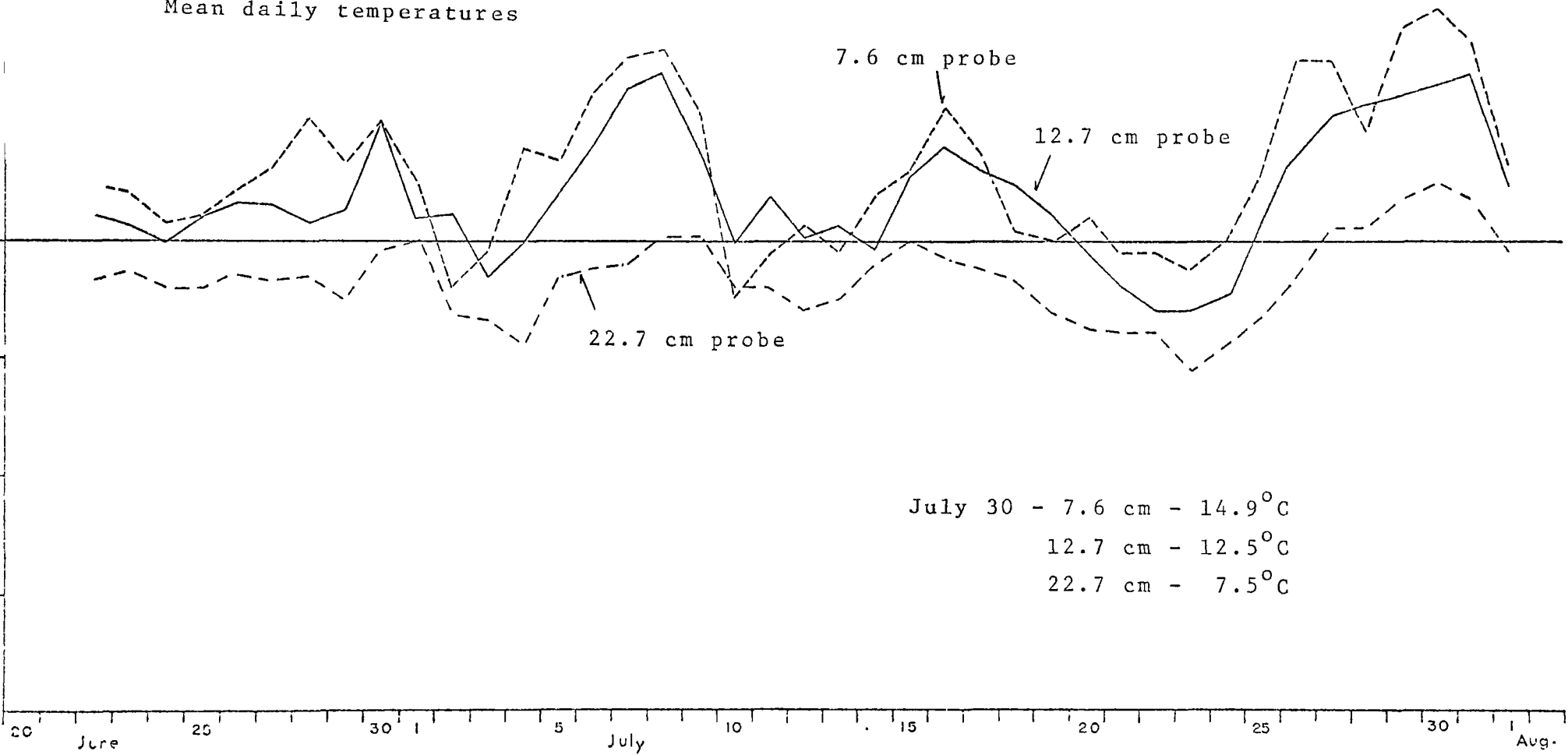


Figure 19 - Soil temperatures, site 3, T.S. hollow, June 22' - August 1, 1973.

apparent contradiction may lie in the variability of the thermal diffusivity among the sites with the soil on the south-facing slope being most efficient at transferring heat energy. Computed diffusivities, confirming this statement, are presented in the following section.

3.2.1. Thermal Diffusivity

Thermal diffusivities for the 16 temperature measurement sites were calculated from the diurnal data where possible, by means of either a cubic spline program (Joynt, 1973) or the time lag equation (Williams and Nickling, 1973). The diffusivities range from .002 to .008 cm^2/sec (Table 3). The majority of this variation is probably due to moisture content diversity among the sites.

3.2.2. Temperature Change 1972 to 1973

Surface temperatures at the three thermograph sites were monitored for the duration of the 1972 and 1973 field seasons. Average values for the daily maximum, minimum and mean have been computed for comparison between 1972 and 1973 data (Table 4). The temperatures recorded during 1972 show limited variation from site to site in comparison to values obtained during 1973. There is only a 1.3°C range among the average daily mean temperatures at the three sites in 1972 compared with a 6.6°C range in 1973. The temperature change (1972 to 1973) was such that the average maximum, minimum, and mean temperatures increased - the exception being the north-facing slope where the average

TABLE 3 - SOIL DIFFUSIVITY VALUES IN THE T.S. HOLLOW

JULY 30, 1972

Location **	Depth cm	Diffusivity * cm ² /sec
TG4	7.5	.003
TG2	7.5	.006
TG1	7.5	.001
R1	7.5	.001
R3	7.5	.005
R4	7.5	.002
R6	5.5	.008
R8	5.5	.004
R9	7.5	.002
R11	5.5	.001

* Diffusivities were calculated from isochrones that were heating or cooling unidirectionally with time.

** TG = Thermograph site

R₁₋₁₁ = Thermocouple rods

TABLE 4 - COMPARISON OF GROUND SURFACE TEMPERATURES AT SITES 1, 2, and 4,
T.S. HOLLOW; JUNE 24 - AUGUST 1, 1972 and 1973, EASTERN BANKS ISLAND (°C)

1972	1973		Change 1972-73
13.3	12.7	North facing slope, maximum	- .6
3.9	7.2	" " " minimum	+3.3
9.4	5.5	" " " range	-3.9
8.6	9.9	" " " mean	+1.3
12.8	13.8	South facing slope maximum	+1.0
3.3	4.4	" " " minimum	+1.1
9.5	9.4	" " " range	- .1
8.1	9.1	" " " mean	+1.0
13.8	19.3	Top of T.S. hollow maximum	+5.5
4.6	11.2	" " " minimum	+6.6
9.2	8.1	" " " range	-1.1
9.2	15.2	" " " mean	+6.0

Note:

Temperatures are mean daily temperatures

maximum temperature dropped 0.6°C . In all cases, the magnitude of the increase of the average minimum temperatures was greater than that of the average maximum temperature.

The most important aspect of the data, as far as this study is concerned, is the increase in the average mean daily temperature from 1972 to 1973. The nature of the increase was such that it acted preferentially. The average mean surface temperature on the north-facing slope increased 1.3°C over the period, that of the south-facing slope by 1.0°C and that on top of the T.S. hollow by 6.0°C . The cause of such preferential variation is unknown, although it is suspected that it is strongly linked to a decrease in the average mean daily wind speed from 22.4 km/hr in 1972 to 12.8 km/hr in 1973.

3.2.3 Summary

Considerable surface and soil temperature variation existed among the sites monitored during the summers of 1972 and 1973. This temperature diversity is probably related to a number of factors including albedo, soil grain size, soil moisture content and soil diffusivity. During the period of observation the total variability of these factors was sufficient to promote differences in surface and soil temperatures (at the 2.5 cm depth) of 3.6°C and 4.3°C between sites less than 2 m apart (e.g. see Figure 16, thermocouple rods 11, and 12).

The range in soil temperature is partially explained by differences in thermal diffusivities at the monitored sites. This suggests that active layer depths may vary significantly from site to site within a spatially limited area.

The highest mean daily surface temperatures during the summer of 1973 were found on top of the feature on the exposed plateau area (site 4). This was followed by the bottom of the hollow (site 3) then the north-facing slope (site 1) and finally by the south-facing slope (site 2). In addition, surface temperature change at the monitored sites was not uniform over time (i.e. between 1972 and 1973). The mean surface temperature of site 4 underwent a temperature increase of 6°C while sites 1 and 2 underwent temperature increases of only 1.3 and 1.0°C respectively.

3.3 Active Layer Depths

The depth of seasonal thawing is of fundamental importance to the study of thermokarst as it directly determines the rate of thermokarst activity and indirectly determines the rate of activity of other geomorphic processes. The depth of the active layer can be determined directly by the use of an auger or a thin metal probe, or it can be determined indirectly by the use of equations which utilize known climatic data and the thermal parameters of the soil.

During the summers of 1972 and 1973 active layer depths were recorded by means of a thin metal probe, wooden dowelling and a shovel. The metal rod was driven into the ground until strong resistance was felt. The depth of penetration was interpreted as being the active layer depth. Three readings were taken at each site and, if all three were in accord, the depth was recorded. If a discrepancy existed, a pit was dug to determine the correct depth. Thirteen 1.9 cm wooden dowels of 1.22 m length were placed at various locations throughout the T.S. hollow, and periodically hammered to the bottom of the active layer throughout the summer.

Initially active layer depths were taken from a wide variety of slopes located some distance apart. This was an attempt to collect data from as wide a range of slopes as possible. The results are presented in Table 5 and illustrate certain basic relationships such as (a) thinner active layers occur within ice-wedge depressions than within polygonal centres (86.4 vs. 109.2 cm) and (b) the presence of a vegetal cover reduces the active layer thickness (compare values, sites (1) and (2) or (3) and (4) (Table 5).

Initially slope orientation was thought to be an important factor in determining active layer depth. However, active layer depths were measured on a number of slopes of 6° with similar vegetation cover but different orientations in the general study area. East and west-facing slopes did not have similar values in spite of equal energy distribution on the slopes as described by Scott (Table 5). This

TABLE 5 - ACTIVE LAYER DEPTHS FROM SELECTED SLOPES WITHIN THE STUDY AREA

(Readings taken August 10, 1973)

Active Layer Site	Layer Depth	Slope Angle	Aspect	Vegetation Percent	Description
1a)	86.4	0°	--	5%	Plateau surface - Sandy till, Ice wedge polygon trough
b)	109.0	0°	--	5%	Plateau surface - Sandy till - Mid-polygon
2)	68.6	0°	--	95%	Valley floor - alluvium, covered by grass
3)	104.2	6°	N.	5%	Sandy till - reading taken between stripes
4)	84.5	6°	N.	70%	Sandy till with Dryas & willow cover in the form of stripes
5)	90.2	6°	W.	5%	Sandy till
6)	109.2	6°	E.	5%	Sandy till - slope covered by earth hummocks
7)	101.6	6°	S.	5%	Sandy till - slope covered by earth hummocks
8)	106.8	10°	S.	5%	Sandy till - slope covered by earth hummocks
9)	99.1	6°	S.	--	Sandy till - no vegetation
10)	99.1	1°	N.	5%	Plateau top - sandy till - no vegetation

variation may result from a number of factors but is attributed to the heterogeneity of the soil as the sites were spaced at considerable distances from each other.

In an attempt to examine the various controls over active layer depths the area in and around the T.S. hollow was chosen for intensive study. It was hoped that such an approach would permit the pin-pointing of specific causes of variation in active layer depth. Active layer depths, together with descriptions of the material, vegetation, and slope angle and aspect, were investigated at over 50 sites at the T.S. hollow. The readings were taken on August 9 and 10, 1973 and probably represent 80-90% of the total thaw depth at each site.

The active layer depths recorded varied from 54.6 cm to 109.2 cm. Clearly this wide range of values is related to variations of surface temperature and microclimate among the sites, as discussed in 3.2. However, there are certain other factors which may cause active layer depth to fluctuate from locality to locality. For example, moisture content and grain size are two of the major determinants of a soil's diffusivity and these factors will influence active layer depth. Thus, average active layer depths for sites in a silty-sandy soil varied between 57.6 - 73.8 cm while in coarse materials values were in excess of 109 cm.

The thirteen thermocouple rods installed in and around the T.S. hollow provided an excellent means of tracing increments in the

active layer through time as the rods were periodically driven to the bottom of the active layer (Table 6). All active layers were assumed to be at zero depth on June 10, 1972.

The data presented in Table 6 indicate that the change of active layer depth varied from locality to locality as did the rate of active layer increase. Spatial variations in (a) the active layer depth and (b) the active layer depth increase are readily apparent. A consistency exists in that (a) and (b) were greater in polygon centres than in polygon borders. The temporal variation in (a) and (b) was not related solely to overall climatic change as the rate of active layer increase actually decreased over time at one locality (i.e. from 2.38 cm/day over the period June 24 to June 28 to 1.70 cm/day over the period June 28 to August 1, rod 4, Table 7) and increased at another over the same time period (1.90 cm/day to 3.60 cm/day, rod 9). These differences are probably related to variations in soil diffusivity and soil moisture content.

3.4 Summary

The data presented in this chapter have several implications concerning thermokarst:

- 1) mean summer ground temperatures in the study area increased between 1972 and 1973 by 1°C to 6°C (Table 4).

This suggests that thermokarst activity was more intense in 1973 than in 1972.

TABLE 6 - THE RATE OF INCREASE OF THE ACTIVE LAYER THROUGH TIME AT

SELECTED SITES IN THE T.S. HOLLOW, 1972

Site No.	Active layer depth, June 24 cm	Daily rate of increase, June 10-24 cm/day	Active layer depth, June 28 cm	Daily rate of increase, June 24-28 cm/day	Active layer depth, July 1 cm	Daily rate of increase June 28-July 1 cm/day	Daily rate of increase June 10-July 1 cm/day
(2)	* 13.97	* .99	* 20.32	* 1.58			
(4)	26.03	1.85	35.56	2.38	40.64	1.70	1.93
(5)	* 15.24	* 1.08	* 20.95	* 1.42			
(6)	19.68	1.40	36.19	4.48			
(7)	17.78	1.27	21.59	.95			
(8)	9.52	.68	* 13.97	* 1.11			
(9)	17.14	1.22	24.76	1.90	35.56	3.60	1.69
(10)	--	--	20.95	--			
(11)	10.16	.72	28.57	4.60	40.64	4.02	1.93
(12)	2.54	* .18	* 15.87	* 3.33	* 29.21	* 4.44	* 1.39
(13)	13.33	.95	24.49	3.62			

Notes - * indicates that the site lies in a polygon depression.

The active layer was assumed to be at 0 cm depth on June 10, 1972.

2) the high variability of surfaces and soil temperatures, moisture contents and accompanying active layer depths throughout the T.S. hollow suggest that thermokarst and other geomorphic processes act differentially within the feature.

CHAPTER IV
GROUND-ICE SLUMPS

4.1 Introduction

In a number of localities in the study area the melting of icy sediments and other ground-ice bodies has led to mudflow activity and the production of shallow semicircular hollows (Figure 20). The scarp face, which outlines the features, results from the rapid removal of material by mudflow into the central hollow as the ground-ice melts out. Sufficient moisture is released by permafrost melting to turn the overlying silts into a plastic or liquid mass, and, in some instances, sufficient moisture exists for fluvial (thermal) erosion to occur. The features are similar to those described by Lamothe and St-Onge (1961) on Ellef Ringnes Island, by Kerfoot and Mackay (1972) in the Mackenzie Delta, and by Code (1973) in the Mackenzie Valley, where they are termed retrogressive failures.

A variety of such features is found throughout the hummocky morainic terrain of eastern Banks Island (French, 1973; French and Egginton, 1973; French, 1974a). Both active and stabilized forms can be identified from aerial photographs together with singular and composite polycyclic features. In places the density of slumps exceeds one per two km². All features are exceedingly shallow with a headwall or scarp face rarely exceeding 1.5 - 2.5 m in height; as such, the features are quite different from those of the Mackenzie Delta where headwalls up to 7 m in height have been reported (e.g. Mackay, 1966).

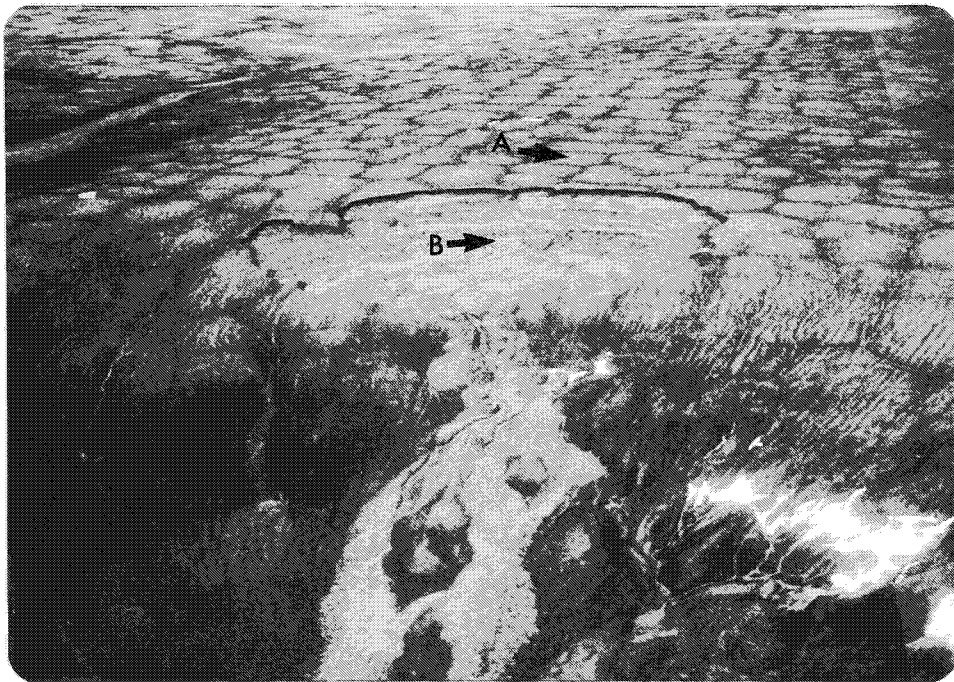


Figure 20 - Oblique air photo showing ground-ice slump number 1 (for location, see Figure 2). Borehole locations A and B (see Figure 13) are indicated.

The development of a ground-ice slump requires an initial exposure of the permafrost and a trigger mechanism or process is necessary. In the study area, many of the features occur in juxtaposition to lakes or streams (Figure 21). In all probability, the streams have exposed the permafrost by meandering and lateral undercutting. Where slumps are found beside lakes it is likely that the features are initiated by wave action or ice-push which may remove a portion of the active layer and expose ground-ice. Several slump features, however, are found in isolation from such obvious trigger mechanisms and likely were initiated by localized slope failures, such as earth flows or active layer glides (e.g. Mackay and Mathews, 1973) that result from high pore-water conditions, which make the slope unstable.

Since ground-ice slumping is one of the most obvious thermo-karst forms present on the morainic terrain of eastern Banks Island, a major objective of this thesis was to examine such features to determine their rates of growth and, if possible, the time required for them to progress through the early stages of initiation to stabilization.

Two active slumps located in the vicinity of the base camp were selected for detailed study. Slump 1 is a large well developed feature some 200 m in breadth located on the upper portion of a valley side slope. Slump 2 is a small feature (less than 30 m in breadth) located along the southwest corner of a lake (Figures 2 and 22). Both

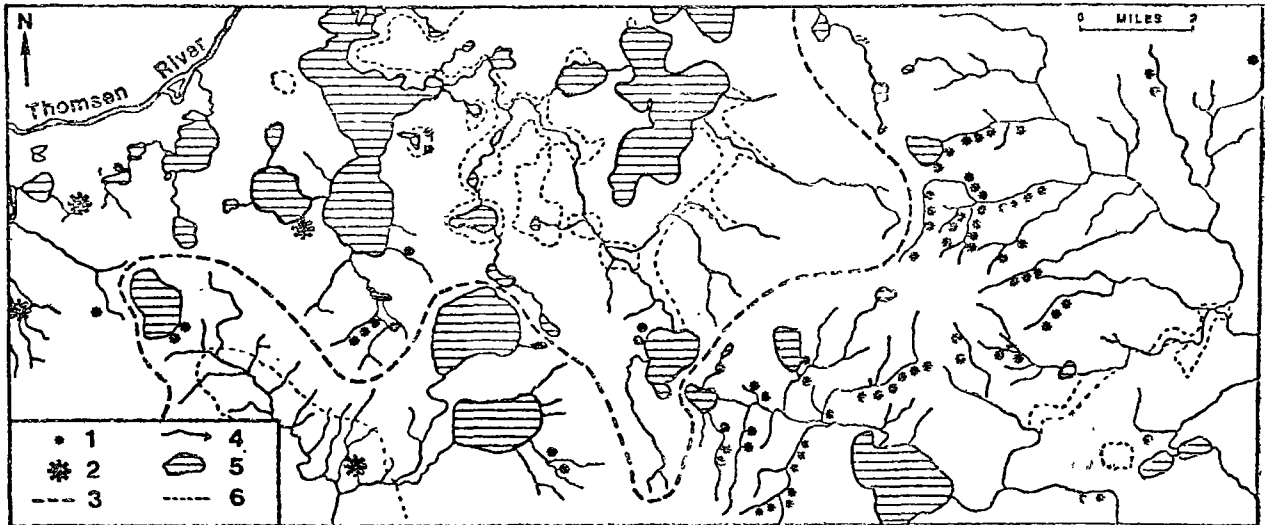


Figure 21- The distribution of ground-ice slumps and other topographic features in the study area. (From French and Egginton, 1973).

Key: (1) Ground-ice slumps, (2) Areas of badland thermokarst terrain, (3) Drainage divide, (4) Streams, (5) Lakes, (6) Abandoned river channels and lake bottoms.



Figure 22 - Photograph of ground-ice slump number 2 (for location see Figure 2). Photograph taken July 6, 1972.

slumps are characterized by an active headwall, with exposed ground-ice, and less active sidewalls where ice exposures are infrequent.

4.2 Rates of Headwall Retreat

Active portions of the headwalls of the two slump features were monitored by the placing of pegs along the top of the feature, such that a marked string could be run between the pegs. Measurements were then taken from the string to the headwall at intervals of 0.3 m. The accuracy of the measurement was ± 5 cm. Approximately 30% and 90% of the headwalls of slump 1 and 2 respectively were monitored by this method.

Average rates of headwall retreat are presented in Table 7. In general, retreat rates of 10 cm/day were typical of the two slumps monitored; however, the rate of retreat was highly variable through time and generally increased or decreased in accordance with ground surface temperature. For example, during the summer of 1972 the mean temperature for each period (see Table 7) decreased through time, as did the rate of retreat. Similarly, the summer of 1973 was characterized by relatively high temperatures and higher rates of headwall retreat, particularly during the latter portions of July and early August.

For active scarp face retreat to continue adequate moisture must be obtained from the melting ice mass or from other sources in

TABLE 7 - AVERAGE RATES OF HEADWALL RETREAT ASSOCIATED WITH GROUND-ICE SLUMPS 1 AND 2

Slump 1								No. of days measured
1973 - Period of Measurement	22/6-27/6	28/6-27/7	8/7-13/7	14/7-25/7	26/7-31/7	1/8-5/8	6/8-12/8	51
Retreat cm/day	6.7	8.0	6.7	6.7	21.7	18.7	22.3	
Average temp. during period (°C)	8.9	12.2	7.1	8.2	16.7	11.6	9.3	
1972 - Period of Measurement	30/6-10/7	11/7-23/7	24/7-3/8	4/8-13/8				43
Retreat cm/day	10.4	9.9	6.7	6.7				
Average temp. during period (°C)	12.1	10.8	10.6	8.3				
Average mudflow action in cm/day	25.0	17.0	14.0					
Slump 2								
1973 - Period of Measurement	22/6-11/7	12/7-24/7	25/7-1/8	2/8-8/8	9/8-13/8			52
Retreat cm/day	4.8	4.8	12.6	15.5	11.2			
Average temp. during period (°C)	10.2	7.5	15.4	13.3	4.6			
1972 - Period of Measurement	12/7-28/7	29/7-12/8						32
Retreat cm/day	11.2	8.2						
Average temp. during period (°C)	6.8	8.0						

order to ensure continual mudflow and material removal. If this is not the case the face is buried and becomes inactive.

Precipitation may promote scarp face retreat directly by encouraging ice degradation through heat transfer or indirectly by inducing mass movement. The increase in the rate of headwall retreat during the period 28/6/73 - 7/7/73 in Slump 1 (Table 7) may be due in part, to an accumulation of 2.5 cm of rain in the five days period prior to July 28; similarly, a high headwall retreat rate was maintained in Slump 1 during the period 6/8/73 - 12/8/73, despite a 2°C drop in temperature from the time period immediately preceding, as a result of 1.25 cm of precipitation which fell on August 8-9.

Headwall retreat even within the same period and under similar climatic conditions is spatially variable. This is illustrated by maps of the monitored portions of Slump 1 and Slump 2 (Figures 3 and 4). This variation may be related to ice content and the nature of the overlying material. Those areas of the slump features with high ice content release sufficient moisture to induce active mudflow and as a result scarp or headwall retreat is relatively fast. The nature of the overlying material may also be an important consideration as silts and clays are easily liquified and removed by mudflow from the vicinity of the retreating headwall; gravels and cobbles are not as easily removed and they may retard headwall retreat.

Borehole data from the vicinity of Slump 1 indicates that high ice content materials (>30% excess ice) exist for only a few metres

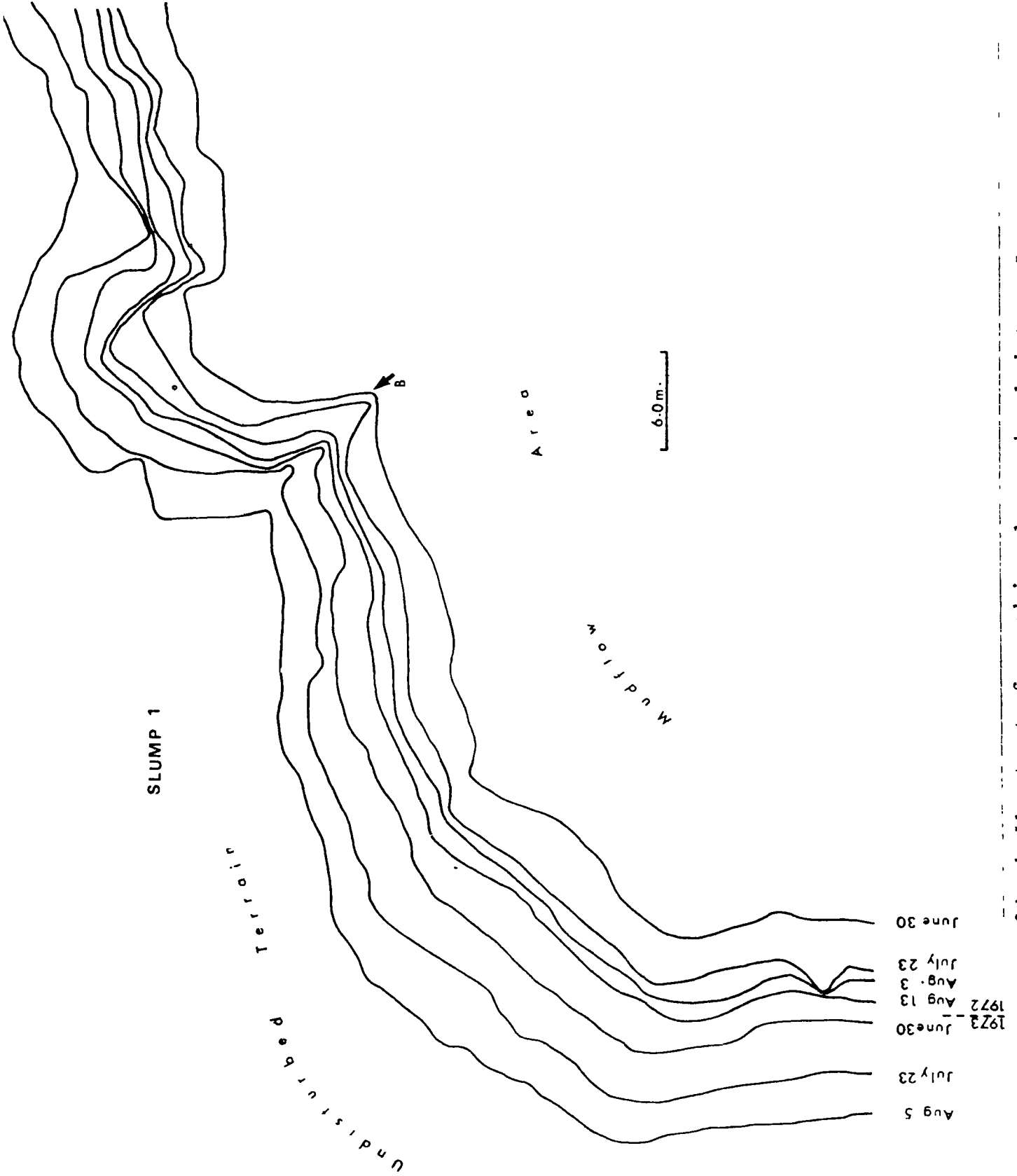


Figure 23 Map showing amount of headwall retreat of ground ice slump number 1, between June 30, 1972 and August 5, 1973

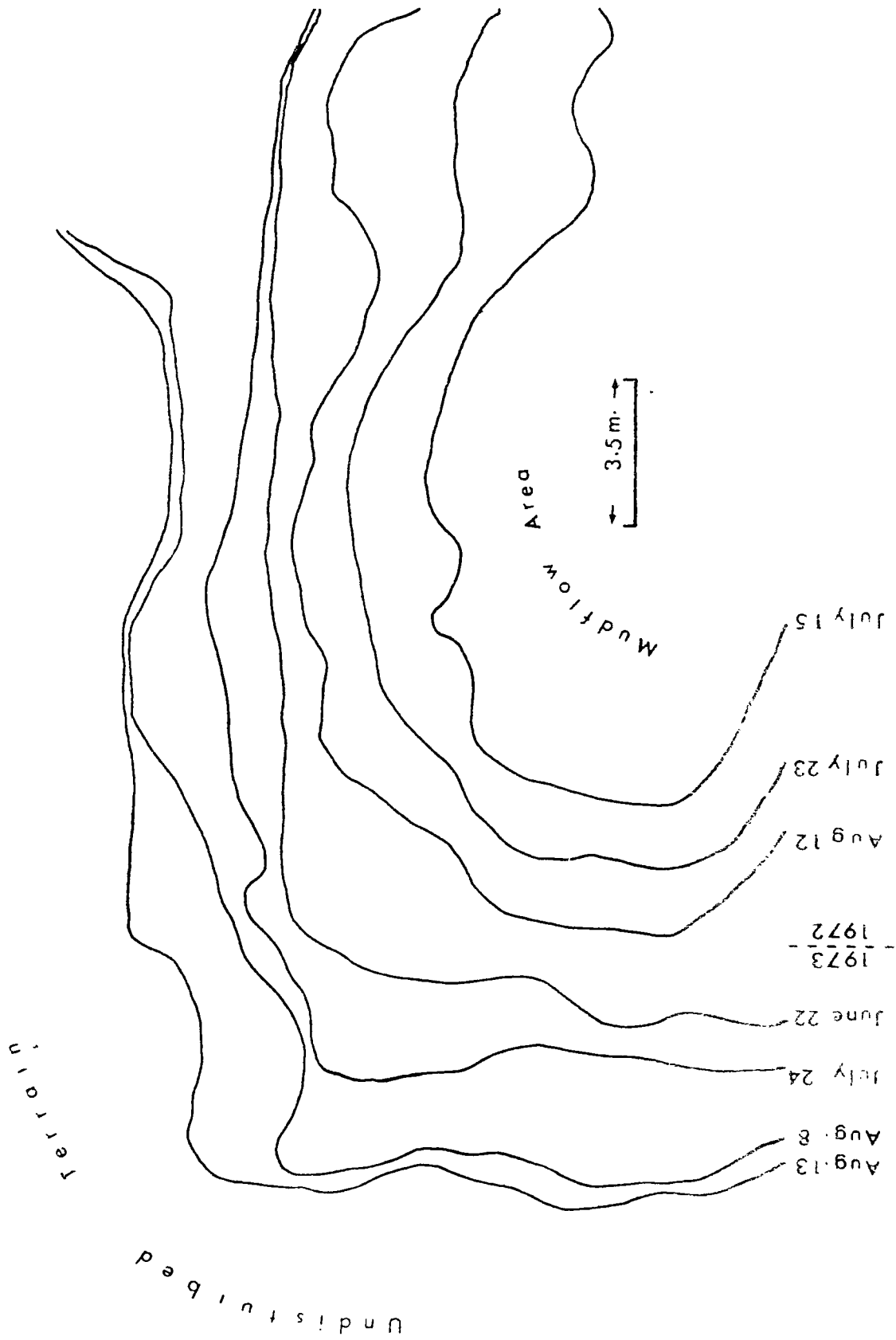


Figure 24 - Map showing amount of headwall retreat of ground ice slump number 2, between July 15, 1972 and August 13, 1973.

below the ground surface (Figure 13). In addition, several ice samples were taken along the ice exposures of Slumps 1 and 2. The excess ice content of the sediments varied greatly from locality to locality with values ranging from 11.2% to 90.8%.

4.3 Nature of Headwall Retreat

During the summer of 1972, 15 vegetated earth clumps near the edge of the retreating headwall of Slump 1 were painted and periodically observed. Observations suggest that the headwalls (1) crumble piece by piece, retreating a few cm at a time or, (2) break into larger pieces some 20-30 cm in diameter and slump into the hollow in a rotational movement or, (3) if sufficiently undercut by the melting of the ground ice, fall forward into the hollow in a sliding motion.

In an attempt to monitor headwall retreat on a continuous basis, a slope retreat recorder was used during 1973. The apparatus was essentially an aluminum spring-loaded arm which moved against the retreating headwall as shown in Figure 25. The arm was counter-balanced and pivoted about a central point, giving the arm a maximum swing of 168 cm. Movement of the arm, due to a retreat, resulted in the movement of a potentiometer (connected to the arm at the central pivot); the resultant change in potential (power supplied by a 12-volt car battery) was recorded on a single event Rustrak recorder. The instrument measured the headwall retreat of Slump 1 to the nearest 1 cm.

The data collected from the recorder in 1973, (Table 8) supported earlier observations concerning the nature of the retreat. Retreat involved the detachment of blocks of between 7-39 cm in width. For example, on July 17, 1973 the recorder arm was slowly pushed away from the headwall as a block began to detach from the headwall and slip into the hollow. A similar slow but rotational movement was detected over the period July 9 to 15.

By far the largest portion of retreat activity (77%) occurred in the 12-hour period, between 8 p.m. to 8 a.m., which receives the lowest solar radiation and which has the lowest temperature. Undoubtedly, this is related to a time lag factor and perhaps, the northerly orientation of the feature. Solar radiation was monitored by a solar radiometer and totalled for the periods between headwall retreat (Table 8). The relationship between solar radiation (k), thawing degree days, and headwall retreat is illustrated in Figure 26. The better correlation between solar input and headwall retreat at 'a point' ($r^2 = .60$) in comparison to thawing degree days and mean headwall retreat ($r^2 = .08$) is not understood. It seems likely, however, that ice conditions at 'a point' were relatively homogeneous in comparison to conditions elsewhere along the headwall.

4.4 Sidewall Retreat

All portions of Slumps 1 and 2 did not possess a well defined scarp face; this is particularly true in the sidewall regions of the



Figure 25 - The recorder used to monitor headwall retreat at Slump 1.

TABLE 8 - A CONTINUAL RECORD OF HEADWALL RETREAT, SLUMP 1, 1973

Date	Time	Movement or Retreat (cm)	Cumulative Retreat (cm)	No. of Hours Between Retreat Periods	Total Solar Input During Period K		
uly	3	23:00	-	0	54:00	30.51	
uly	6	5:00	35.1	35.1	41:00	28.0	
uly	7	22:00	30.5	65.6	30:50	18.05	
uly	9	4:50	2.5*	68.1	20:10	4.34	
uly	10	1:00	22.9	91.0	68:20	28.79	
uly	12	21:20	35.1	126.1	54:55	24.92	
uly	15	4:15	6.4*	132.5	14:45	7.85	
uly	15	19:00	43.2	175.7	36:00	11.37	
uly	17	7:00	-10.2**	165.5	31:00	10.92	
uly	18	14:00	26.7	192.2			
No Record available from July 18 - July 26							
uly	26	17:00	-	192.2(?)	-	-	
uly	27	7:00	24.1	216.3	28:00	15.50	
uly	28	11:00	30.5	246.8	33:40	14.75	
uly	29	20:40	35.1	281.9	21:20	10.1	
uly	30	18:00	22.9	304.8	33:55	15.8	
ugust	1	3:55	39.4	344.2	21:05	8.2	
ugust	2	1:00	22.9	367.1	54:00	21.82	
ugust	4	7:00	33.0	400.1	35:30	12.48	
ugust	5	18:30	17.8	417.9	29:30	8.37	
ugust	7	0:0	17.8	435.7	6:00	1.00	
ugust	7	6:00	20.3	456.0	61:00	17.20	
ugust	9	6:00	7.6	463.6	15:30	2.87	
ugust	9	21:30	17.8	481.4	18:5		
ugust	10	14:30	End of Record				

K = constant x solar radiation ($\text{cal}/\text{cm}^2/\text{min}$).

* The values recorded do not represent retreat per day but a retrogressive rotational movement of the scarp face.

** The value represents a forward falling movement of the scarp face prior to detachment.

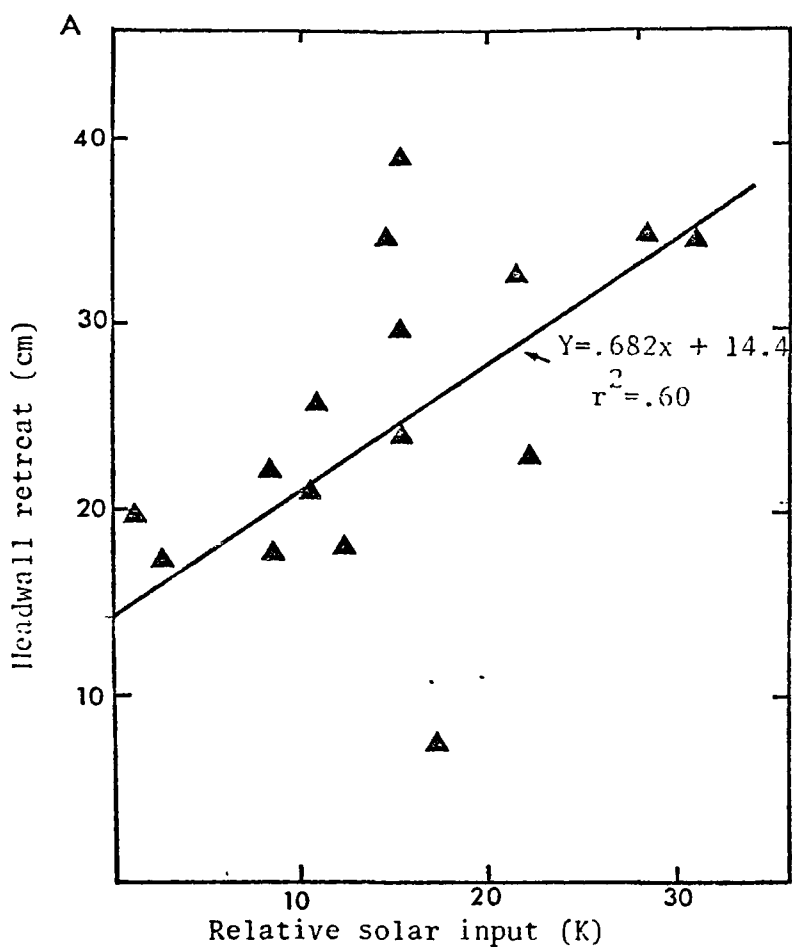
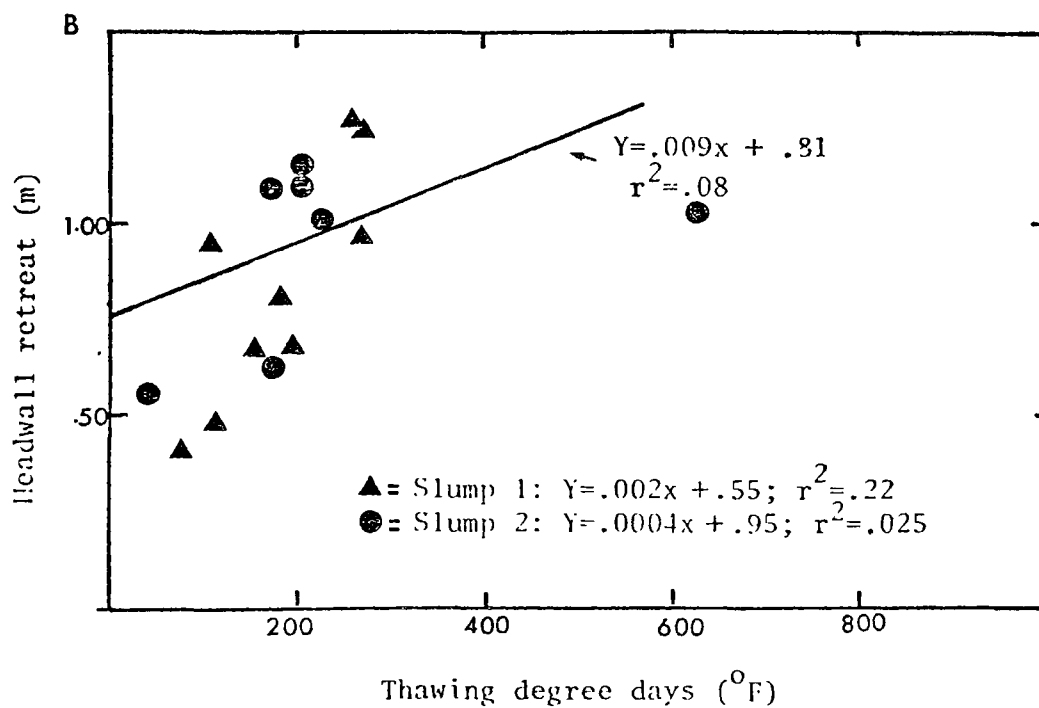


Figure 26 - The relationship between thermal input and headwall retreat associated with ground-ice slumps.
 A) Headwall retreat 'at a point' vs solar input (see Table 8).
 B) Mean headwall retreat vs thawing degree days (see Table 7).



feature where the ice face had become buried. The burial likely results from a lack of slope. As a slump feature broadens, sidewalls are cut perpendicular to the slope which reduces the slope angle that material moving from the sidewall to the central region must move across. In time, therefore, there is insufficient slope to induce rapid mass movement from the sidewall and burial subsequently ensues.

A portion of the sidewall of Slump 1 was monitored by the tagging of hummocks along its periphery (Table 9). The movement of the tagged hummocks was variable; in some cases the distance between the tags decreased, indicative of either a rotational movement of the front inner hummock or the movement of the outer hummock into the hollow; in other instances the distance between the markers increased as the inner hummock moved into the hollow. Of the eight markers remaining on the sidewall on August 12, 1973 the majority showed a substantial change, over the period June 30, 1972 to August 12, 1973, with movement averaging 5.7 cm/year; this movement suggests that the sidewalls of Slump 1 are not yet completely stabilized.

4.5 Growth and Stabilization

The rate of headwall retreat of the active slump features averaged, over a 2 year period, between 10.2 - 8.7 cm/day for each feature (Table 7). The maximum (average) retreat recorded was 6.1m over a 51 day period. The maximum number of thaw days that can

TABLE 9 - HUMMOCK MOVEMENT ASSOCIATED WITH THE SIDEWALL OF SLUMP 1

	June 30/72 d-cm	July 23/72 d-cm	August 13/72 d-cm	August 12/73 d-cm
1	26.5	27.3	26.7	33.2
2	23.5	22.8	23.4	26.0
3	14.5	14.2	13.9	14.0
4	15.5	25.4	25.7	33.4
5	32.7	33.0	33.3	26.2
6	31.2	30.7	33.3	40.2
7	20.5	19.7	20.6	31.4
8	29.0	28.9	31.0	-
9	92.2	92.0	95.0	-
10	60.1	60.2	61.4	-
11	25.7	25.4	27.3	-
12	32.0	32.2	35.2	-
13	29.4	29.5	20.7	-
14	18.8	19.0	20.3	-
15	21.7	22.2	24.1	-
16	30.0	31.0	32.0	-
<hr/>				
1 \bar{x}	31.45	32.15	33.36	
2 \bar{x}	23.49	21.37	25.27	29.2

d - distance measures between adjacent hummocks

1 \bar{x} - mean value 1-6 inclusive

2 \bar{x} - mean value 1-16 inclusive

be expected on this portion of the island is approximately 100 days (climatic records, Johnson Point). If the average retreat values given above are assumed to apply over this period then the maximum retreat that can be expected would be of the order of 8.7 - 10.2 m per annum. These values are of the same order of magnitude as those observed by Lamothe and St-Onge (1961) (average 7 m yr^{-1} and maximum 10 m yr^{-1} on Ellef Ringnes Island), and Kerfoot and Mackay (1972) (average 3.5 m and maximum 7.3 m yr^{-1} on Garry Island).

Stabilization of a slump feature may occur when either all of the ground-ice has melted or when burial occurs. Since the majority of features do not attain widths in excess of 200-300 m and given the average retreat rates observed, it is likely that the majority of slumps become stabilized within 30-50 years of their initiation. This is likely of the correct magnitude since features which appeared to be active on 1948 and 1962 aerial photographs were found to have stabilized in 1972, while others which did not appear on either of the earlier air photographs are active today (French and Egginton, 1973).

Slump 2 illustrates the dynamic nature of these features since it does not appear on either the 1948 or the 1962 aerial photographs (Figures 2a, 2b) and is, therefore, a recent feature. The rapid development of these features is further exemplified by occurrences during the week of August 8, 1973. During this period the central portion of Slump 2 was cleared of debris by mudflow activity (Figure 27) and a 'new' slump (Slump 3) was formed some 200 m along the beach from Slump 2 as the result

of a localized slope failure. A rotational movement accompanied the failure which produced a headwall 1.5 m high and some 20 m in length. The headwall was observed to retreat some 0.85 m from August 8 to August 13, 1973.

4.6 Summary

It would appear that ground-ice slumps are initiated by a trigger mechanism. The development of thermokarst pre-supposes the presence of some disturbing factor(s) which lead(s) to the eventual degradation of the permafrost. In the study area a number of the ground-ice slumps are found in close association with streams and it is envisaged that the streams expose ground-ice through lateral migration. Similarly, a large proportion of the slumps are found in juxtaposition to lakes, which during the periods of high wave activity may so disturb or erode the active layer that slumping occurs. In a few instances slump features are found in isolation from obvious trigger mechanisms and may owe their origins to localized slope failures.

Geomorphic processes are important in the initiation and maintenance of the semi-circular form. They are important not only as trigger mechanisms but also in maintaining thermokarst activity through (1) removal of portions of the active layer thereby inducing permafrost degradation and (2) removal of material from the actively retreating scarp face. Mudflow is the main mode of material transportation



Figure 27 - Photograph of ground-ice slump number 2, taken August 8, 1973. Compare this photograph with that in Figure 22, taken the previous year.

from the central hollows of the slump features investigated. The process keeps the ice clear of debris and ensures the rapid retreat of the headwall. Inadequate or impeded removal leads to burial of the ice face and/or a lower retreat rate.

CHAPTER V
BADLAND THERMOKARST TERRAIN

5.1 Introduction

Several areas of badland terrain are found within the study area. One such area, located 2 km from the Thomsen River and 4 km from the base camp was selected for detailed study; for the purpose of identification it was called the T.S. hollow. The area was also the site around which much of the soil temperature data reported in Chapter III was recorded.

The T.S. hollow is a large heart shaped amphitheatre some 0.5 km² in area (Figure 12). The hollow is characterized by a scarp face, a small stream which drains the feature, several isolated and steep sided mounds, and various thaw ponds both within and surrounding the feature.

The form of this terrain is closely related to a network of large ice-wedge polygons some 20-30 m in dimension. The badlands developed when a small stream, flowing westwards into the Thomsen River, began to downcut through the easily eroded silts and sands. The ice content of the enclosing materials is high ('excess ice' values of between 30-60% are typical; see Figure 13). The retreat was quickest along ice wedges giving rise to isolated mounds (some of which are still visible within the hollow today (Figure 28). The large size, and vertical extent of the ice wedges are probably the most important factors in determining the growth of this feature.



Figure 28 - View of interior of T.S. hollow showing degraded mounds, remnants of old polygon centers, and edge of the amphitheatre. Man provides scale.

In Siberia, Czudek and Demek (1970) have described similar features along the banks of the Lena River which they term 'thermocirques'. In North America, the nearest analogous landform is the nivation hemicycle as described by St-Onge (1964; 1969) on Ellef Ringnes Island.

5.2 Geomorphic Processes

Many geomorphic processes in addition to thermokarst subsidence are operative within the area of thermokarst badland terrain. Attempts were made to monitor some of these processes. Problems arose, however, in that markers which were placed to monitor a specific process were also subject to movement, or exposure from other processes. The extent of the problem varied with the type of markers used and the time period over which the readings were taken.

Nivation and deflation were measured by hammering wooden dowelling to the bottom of the active layer (perpendicular to the slope surface) and measuring rates of exposure. Rates of mass movement were measured relative to dowelling posts. In all cases, the posts may have been subjected to a certain amount of movement resulting from frost heave. The values presented in this section, therefore, should be considered as approximations of actual rates of geomorphic activity.

5.2.1. Scarp Retreat Within the T.S. Hollow

The steep sidewalls of the T.S. hollow are covered by snow for a large portion of the year and, as such, appear dominated by

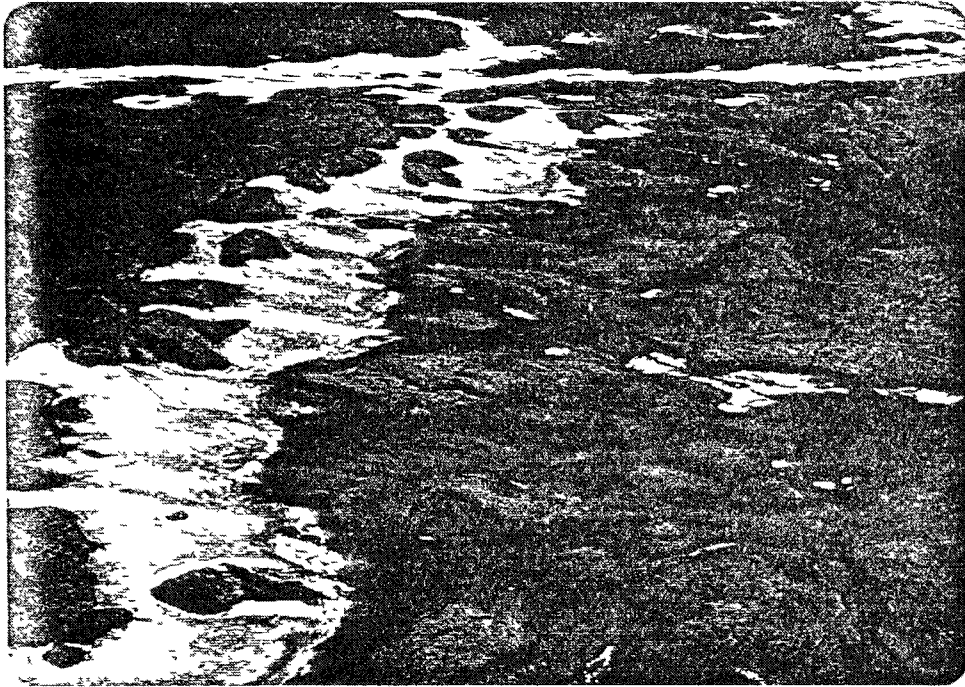


Figure 29 - Oblique air photograph of the T.S. hollow showing snow conditions, June 20, 1972.

nivation (Figure 29). Material is moved downslope both over and under the snow patches.

In order to monitor the retreat of the scarp face, a total of 15 wooden dowels were driven to the bottom of the active layer on August 7, 1972 on two scarp slopes. In both cases, the stakes were placed midway between the top and the bottom of the slope. The amount of the marker stake exposed above the ground surface in the following year was then measured. The data (Table 10) indicate that over the period August 7, 1972 to June 24, 1973 one slope gained 0.21 cm (mean value) due to localized collapse of the slope above, while the other lost 1.36 cm of material (mean value). For the period of June 24, 1973 to August 12, 1973, however, both sites experienced continued denudation as indicated by the stake measurements. During this period, the two slopes were exposed a further 5.17 (8.68 - 3.51) and 8.17 (13.73 - 5.56) cm (Table 10). This removal is clearly associated with mass movement and deflation since all traces of snow on these particular slopes had disappeared by June 24, 1973. Deflation is locally important within the T.S. hollow (Figure 30) and may account for a significant portion of the material removed.

5.2.2. Slope Denudation Within the Central Portion of the T.S. Hollow

The slopes surrounding the remnants of two isolated polygon centres were monitored by driving twenty-four, 60 cm length stakes into the soil until their tops were flush with the ground surface, a method similar to that used by Schumm (1956) (see Figure 31 and Table 11).

TABLE 10 - MARKER STAKE MEASUREMENTS ON TWO HEADWALL SLOPES IN
THE T.S. HOLLOW

	August 7, 1972	June 24, 1973	August 12, 1973
Slope 1	4.76	4.29	10.16
	3.02	5.24	8.89
	1.90	1.59	3.81
	3.65	3.12	7.62
	4.13	1.90	8.89
	5.01	4.92	12.70
	\bar{x} 3.75	\bar{x} 3.51	\bar{x} 8.68
Slope 2	4.61	7.62	19.05
	3.30	3.30	8.26
	3.30	3.30	7.62
	3.30	3.49	8.89
	3.65	3.65	8.89
	2.86	3.97	8.89
	7.93	13.00	33.02
	4.76	5.40	15.24
	\bar{x} 4.21	\bar{x} 5.56	\bar{x} 13.73

NOTE:

Values given are the amount of marker stake exposed above the ground surface (cm).



Figure 30 - Photograph showing effects of deflation in the T.S. hollow. Notebook gives scale.

The stakes were installed on July 5, 1972. At periodic intervals, the stakes were re-examined and the length of the stake protruding above the ground surface was recorded (Table 11). The data indicate accumulation in some areas and it is impossible to relate this to a specific process. However, the burial of the stakes at locations 8 and 22 is related to mass movement and the denudation from the flat mid-portion of the two polygon centres (locations 10 and 20) is likely the result of deflation. Generally, there appears to be a greater removal of material from south-facing slopes than from the north-facing slopes. As the mounds are retreating from all sides a yearly rate of denudation may be determined as 1.92 cm/yr, the sum of the mean retreat rates on all slopes over the period August 12, 1972 to August 12, 1973.

5.3 Mass Movement Within the T.S. Hollow

Two apparently stabilized slump features are located at the southern fringe of the T.S. hollow, on a 2 to 4° slope. The central portion of one slump was monitored by marker stones and buried foil strips similar to the method used by French (1974c).

The marker stones and foil strips were installed along a straight line (marked by a string) between marker rods which were driven to the bottom of the active layer at the time of installation. The tin foil markers were installed by excavating a small pit downslope from the marker string and inserting the foil strips on the upslope side

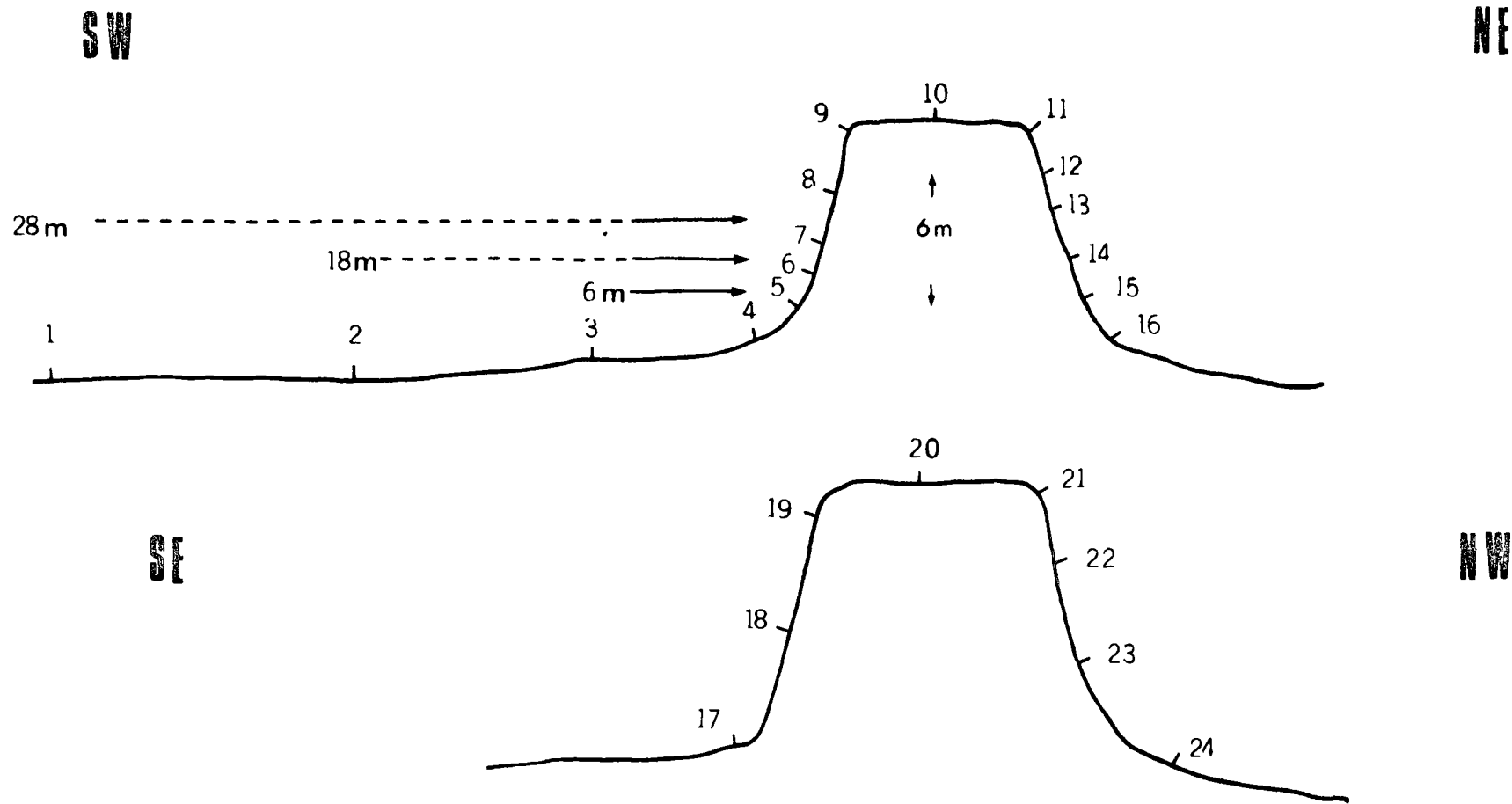


Figure 31 - The location of slope denudation markers in the central part of the T.S. hollow around an isolated, conical mound (degraded polygon centre).

TABLE 11 - SLOPE DENUDATION ASSOCIATED WITH ISOLATED CONICAL MOUNDS IN BADLAND THERMOKARST TERRAIN

(THE T.S. HOLLOW) - ALL READINGS IN cm.

Location No.	July 5/1972	August 12/1972			August 12/1973			Comments	Mean denudation August 12/1972 to August 12/1973
	mean *	upslope	downslope	mean	upslope	downslope	mean		
<u>S.W. facing slope</u>									
1	0.00	0.00	0.16	.08	0.30	0.50	.40		
2	0.00	0.00	1.43	.72	1.00	2.00	1.50		
3	0.00	0.00	0.07	.00	0.50	0.00	.25	Top of stake covered	
4	0.00	0.00	0.00	.00	0.20	0.20	.25		
5	0.00	0.95	0.00	.48	0.50	0.20	.35		
6	0.00	1.59	0.32	.96	0.50	0.00	.25		
7	0.00	0.95	0.00	.48	1.00	2.00	1.50		
8	0.00	0.48	0.00	.24	--	--	--	Mass movement evident	
9	0.00	0.00	1.59	.80	0.00	1.00	.50		
10	0.00	0.32	0.79	.40	1.50	1.00	1.25		
	0.00	.42	.43	.43	.61	.78	.70 - mean		0.27
<u>N.E. facing slope</u>									
11	0.00	0.16	0.32	.24	0.50	0.50	.50		
12	0.00	0.16	0.00	.08	0.50	0.50	.50		
13	0.00	0.00	0.32	.16	0.50	1.00	1.25		
14	0.00	0.16	0.32	.24	0.10	0.40	.25		
15	0.00	0.32	0.00	.16	0.50	0.50	.50		
16	0.00	0.16	0.00	.08	0.00	0.50	.25		
	0.00	.16	.16	.16	.35	.57	.46 - mean		0.30
<u>S.E. facing slope</u>									
17	0.00	2.38	0.16	1.27	1.70	1.00	1.35		
18	0.00	1.59	0.48	1.04	0.80	1.00	.90		
19	0.00	0.95	0.64	.80	5.00	3.00	4.00		
20	0.00	1.11	1.27	1.19	3.50	1.50	2.50		
	0.00	1.51	.64	1.07	2.75	1.62	2.19 - mean		1.05
<u>N.W. facing slope</u>									
21	0.00	0.95	0.64	.80	3.00	1.50	2.75		
22	0.00	0.32	0.16	.24	--	--	--	Mass movement evident	
23	0.00	0.00	0.16	.08	0.00	0.32	.16		
24	0.00	0.00	0.16	.08	0.20	0.40	.30		
	0.00	.64	.56	.60	1.05	.74	.90 - mean		0.30

NOTE: * Markers were placed at 0 cm depth on July 5/1972

of the pit. Great care was taken to repack the pit with all of the material excavated so as to prevent preferential movement within the area of the pit. The markers were installed July 10, 1972 and re-excavated August 12, 1973. The level of accuracy of the initial installation and subsequent remeasurement is considered to be within 0.25 cm (Table 2).

In general, the foil strips buried at the 0.1 - 2.5 cm depth moved faster (mean movement 15.1 and 7.7 cm) than those at 2.5 - 5.0 cm depth (mean movement 13.6 and 6.3 cm) which in turn moved faster than those at 5.0 - 7.7 cm depth (mean movement 12.0 and 5.5 cm). The marker stones, installed to measure surface change, averaged slightly less movement than that of the 0.1 - 2.5 cm foil strips. This may be due to the fact that the marker stones used were relatively large (1.5 - 3.0 cm) and other surface material may have been able to move around the stones without inducing the pebbles to move.

The rates of mass movement recorded are considerably higher than values recorded by other authors on similar low angle slopes: French (1974c) measured rates of movement at Sachs Harbour, southern Banks Island on a 3° slope of 2.5 cm yr^{-1} and Washburn (1973) recorded movements of 1.0 cm yr^{-1} on a 2.5° slope. The high values measured in the badland terrain in this study likely result from high soil moisture contents associated with the melting of ice-rich permafrost.

Rapid mass movements resulting from the exposure of substantial bodies of ground ice were observed within the T.S. hollow. The summer

TABLE 12 - MASS MOVEMENT ASSOCIATED WITH A SHALLOW SLUMP WITHIN THE T.S. FOLLOW

Period	Site	Type of Marker	Depth of Marker cm	No. of observations	Mean movement cm	Maximum movement cm	Minimum movement cm
July 10/1972 - August 12/1973	A	Marker stones	0.0	26	14.8	25.0	10.0
		Foil strips	2.5	5	15.1	19.0	11.0
		Foil strips	5.0	5	13.6	17.0	11.0
		Foil strips	7.7	5	12.0	15.5	9.5
July 10/1972 - August 12/1973	B	Marker stones	0.0	28	6.6	10.0	0
		Foil strips	2.5	3	7.7	9.0	4.0
		Foil strips	5.0	3	6.3	8.5	3.0
		Foil strips	7.7	3	5.5	7.5	3.0

of 1972 was not characterized by any significant rapid mass movements. However, August 1973, was characterized by more intensive activity as a result of higher temperatures and higher precipitation.

For example, a portion of the central amphitheatre as it was viewed on August 8, 1973 is shown in Figure 32. The same area as it was found on August 11, 1973 is shown in Figure 33. The rate of floor movement at this site reached a maximum of 106 cm per day during this period (see Table 13). It appeared that, once the main floor had broken into hummock-like masses, these blocks slid or glided along the permafrost-active layer interface, maintaining their initial identity for several days. Markers were placed upon these hummocks to trace their movement relative to the undisturbed hollow (Location X, Table 13) and to themselves (Location Y and Z, Table 13). The data suggest that the hummocks tend to pile up (i.e. move closer together) through time (this is indicated by negative retreat values, Location Y and Z, Table 13).

During August 1973, rapid movement was also associated with the sidewalls of the T.S. hollow. The permafrost of two portions of the sidewall became exposed between August 1 and August 13, 1973 revealing two ice wedges.

During the latter part of August both ice wedges underwent melting and retreat, causing a crumbling of the adjacent sediments. The more active of the two exposures (Figure 34) was monitored by



Figure 32 - Photograph showing active layer slumping in the interior of the T.S. hollow, August 8, 1973.

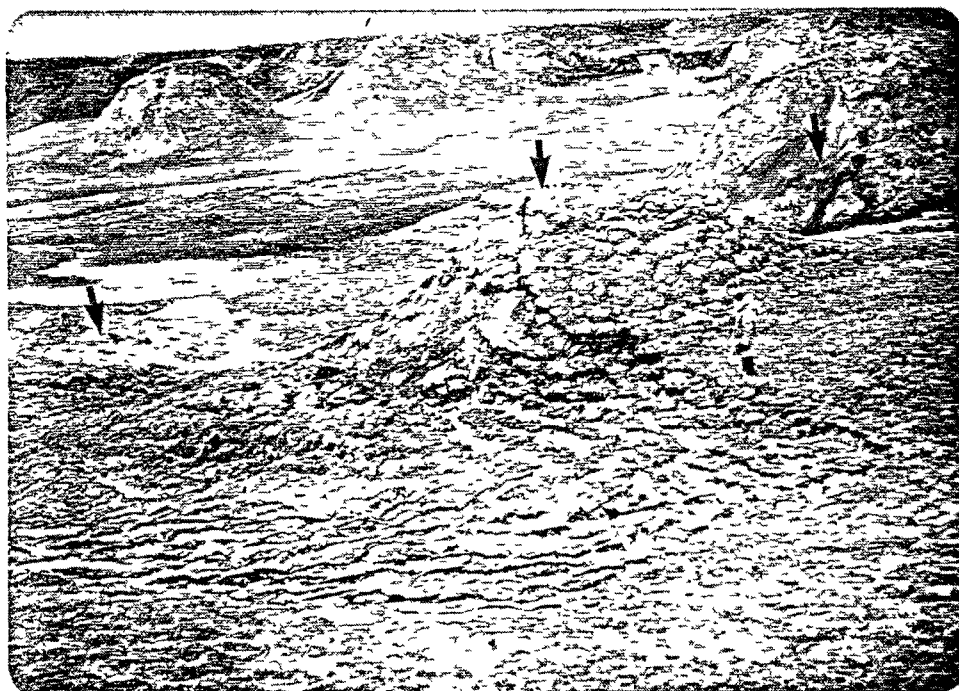


Figure 33 - Photograph of same feature as in Figure 32 but taken August 10, 1973

TABLE 13 - RAPID MASS MOVEMENT AND THERMOKARST ACTIVITY IN THE T.S. HOLLOW

	Location No.	Length of measurement period (1973)	Number of measurements	Mean retreat recorded cm	Maximum retreat cm	Minimum retreat cm	Average daily cm/day
1) Active layer glide, T.S. hollow (see figures 41-42)	A	August 8-11	19	161.4	343.1	17.8	53.8 cm/day
	A	August 11-12	19	155.9	297.4	7.6	155.9 cm/day
	B	August 8-11	18	181.2	233.6	86.4	60.4 cm/day
	B	August 11-13	18	44.5	158.4	7.6	44.5 cm/day
	X	August 8-11	8	258.6	319.0	166.5	86.2 cm/day
	Y	August 8-11	8	- 7.71	- 36.0	- 1.0	- 2.57 cm/day
	Z	August 8-11	8	- 16.79	- 33.5	- .5	- 5.6 cm/day
2) Permafrost degradation on headwalls, T.S. hollow (see figure 43)	I	August 7-11	8	24.0	49.53	7.6	6.0 cm/day
	I	August 11-13	8	1.75	7.62	0	.9 cm/day
	F	August 7-11	42	94.8	256.7	0	23.7 cm/day
	F	August 11-13	42	5.8	45.8	0	2.9 cm/day

Note - Values given for locations Y and Z are negative as the values represent the movement of a hummock as it slides along the permafrost active layer interface relative to the movement of other hummock.

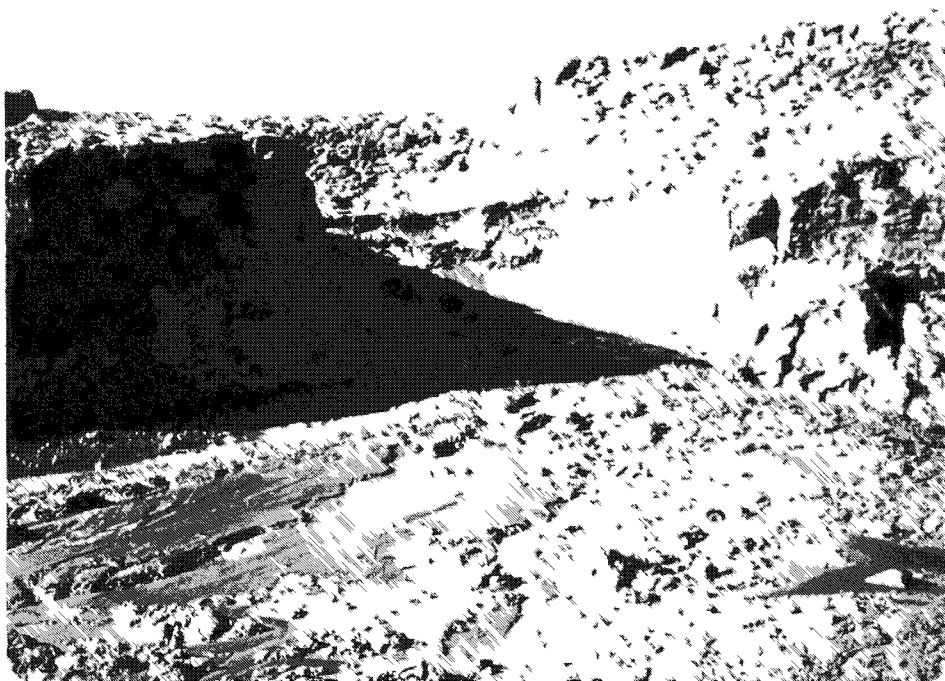


Figure 34 - Photograph showing headwall retreat of the T.S. hollow at locality where ice became exposed, August 8, 1973.

marker stones and stakes located in the vicinity of active retreat (Table 13, locations I and F) and tagged hummocks, which recorded movement of material from the top of the scarp face into the active retreat zone. A maximum retreat of 256.7 cm (64.2 cm/day) was recorded immediately above the exposed ice-wedge face although mean retreat rates within this active zone ranged between 0.9 cm/day and 23.7 cm/day.

The hummocks located immediately above the retreating exposure were prone to movement, as the slope on which they were located progressively steepened. Two types of movement were inferred; i) that where the distance between consecutive hummocks increased due to a sliding action and (ii) that where the distance between consecutive hummocks decreased as a result of a slumping or rotational movement. Movements as large as 27 cm (5.4 cm/day) were recorded (Table 14).

Often, the volume of water released when the permafrost in the sidewalls degraded was of sufficient quantity to exceed the liquid limits of the sediments. This resulted in mudflows, which moved materials away from the retreating scarp face, and ensured the continual exposure of the ice face.

5.3 The Significance of Thaw Ponds to Thermokarst Badland Development

Two types of ponds can be recognized in the area adjacent to the T.S. hollow: 1) shallow, semi-permanent ice-wedge junction ponds (Figure 35) and (2) deep, permanent 'thaw ponds' (Figure 36).

TABLE 14 - HUMMOCK MOVEMENT ASSOCIATED WITH HEADWALL SLUMPING ABOVE AN ICE EXPOSURE

(Location I and F, Table 13)

Measurement No.	August 8/1973: Distance between hummocks, cm*	August 13/1973: Distance between hummocks, cm*	August 8-13/1973: Change in distance between hummocks, cm*
1	43.0	64.5	21.5
2	28.0	32.0	4.0
3	37.0	44.5	6.5
4	38.5	43.0	5.0
5	48.5	39.0	- 9.5
6	42.5	57.0	13.0
7	60.5	63.0	3.0
8	44.5	51.0	7.0
9	42.0	47.5	5.0
10	54.5	43.0	-11.0
11	37.0	38.5	1.5
12	55.0	43.0	-12.0
13	71.0	44.0	-27.0
14	45.0	48.0	3.0
15	59.0	55.0	- 4.0

* Distance measured was the distance between markers on two adjacent hummocks.

The latter are characterized by a pond floor which is substantially lower than the surrounding ground surface.

Standing water bodies appear to be of major significance in the development of the T.S. hollow as they are instrumental in the initial degradation of the ice-wedges surrounding the feature. Observations indicated that mean daily temperatures at the bottom of the water bodies are warmer than those of the ground surface in the immediate vicinity of the pond (e.g. see Table 15). Numerous workers (e.g. Black, 1969; Czudek and Demek, 1970; Brown, Johnson and Brown, 1964) have suggested that higher temperatures associated with standing water bodies may lead to accelerated thermokarst activity along their periphery.

The terrain surrounding the T.S. hollow is pitted with numerous small ponds, located at the junction of fissure polygons. It would appear that these ponds modify the soil microclimate and cause the underlying ice wedges to degrade. This process may be aided by surface and active layer drainage along ice-wedge depressions, which leads to thermal erosion. Both of these factors lead to preferential thaw along ice wedges and give the limit of the badland topography its serrated nature.

5.4 Summary

In addition to permafrost degradation (i.e. thermokarst subsidence), a number of other processes are operative within the T.S.



Figure 35 - A shallow, semi-permanent ice wedge junction pond located near to the base camp.



Figure 36 - A deep permanent thaw pond located adjacent to the T.S. hollow on upland terrain.

TABLE 15 - COMPARISON OF TEMPERATURES IN AN ICE-WEDGE JUNCTION
(THAW) POND AND ADJACENT HIGH CENTRED POLYGON. SUMMER 1973

Date	Surface temperatures, °C, high-centered polygon				Pond temperatures, °C			
	MAX.	MIN.	MEAN	RANGE	MAX.	MIN.	MEAN	RANGE
July 8	22.2	8.9	15.6	13.3	18.9	12.8	15.9	6.1
9	11.1	3.9	8.5	7.2	15.6	6.7	11.2	8.9
10	7.8	1.7	4.8	6.1	7.8	5.6	6.7	2.2
11	17.8	5.0	11.4	12.8	14.4	8.3	11.4	6.1
12	7.8	4.4	6.2	3.2	13.9	8.3	11.1	5.6
13	13.3	1.1	7.3	12.2	11.1	6.7	8.9	4.4
14	20.0	5.2	12.6	14.8	15.6	8.9	12.3	6.7
15	18.9	8.9	13.9	10.0	15.6	11.1	13.4	4.5
16	21.1	6.7	13.9	14.4	15.6	8.3	12.0	7.3
17	16.7	4.4	10.6	12.3	15.6	10.0	12.8	5.6
18	7.8	5.2	6.0	2.6	14.4	8.3	11.4	6.1
19	9.4	1.1	5.3	8.3	13.3	5.6	9.5	7.7
20	8.3	3.3	5.8	5.0	10.0	6.7	8.4	3.3
21	10.0	2.2	6.1	7.8	10.6	6.7	8.7	3.9
22	4.4	0.0	2.2	4.4	8.3	4.4	6.4	3.9
23	4.4	1.1	2.7	3.3	7.2	3.9	5.6	3.3
24	14.4	3.3	8.9	11.1	11.7	3.3	7.5	8.4
25	17.8	6.7	12.2	11.1	15.6	6.7	11.2	8.7
26	23.3	8.9	16.1	14.4	17.8	10.0	13.9	7.8
27	24.4	11.1	17.8	13.3	20.0	12.2	16.1	7.8
28	23.3	14.4	18.9	8.9	21.1	15.6	18.4	5.5
29	23.9	10.0	17.0	13.9	20.0	15.6	17.8	4.4
30	26.1	11.1	18.6	15.0	20.0	13.3	16.7	6.7
31	23.3	5.6	8.9	17.7	20.0	15.6	17.8	4.4
August 1	13.3	5.6	9.5	7.7	18.9	10.6	14.8	8.3
2	19.4	4.4	11.9	15.0	16.7	10.0	13.4	6.7
3	20.6	8.3	14.5	12.3	16.8	13.3	15.0	3.4
4	17.8	7.8	12.8	10.0	15.6	11.1	13.4	4.5
5	13.9	8.3	11.1	5.6	13.3	11.1	12.2	2.2
6	24.4	7.8	16.1	16.6	15.6	11.7	13.7	3.9
\bar{x}	16.2	6.1	11.2	10.1	15.0	9.4	12.2	5.6

hollow. Deflation is active on the steep scarp face, while slow and rapid mass movements dominate the central portion of the amphitheatre.

CHAPTER VI

CONCLUSIONS

6.1 Thermokarst

Thermokarst landforms are widespread throughout the study area reaching a density of one per two km². These landforms are related to trigger mechanisms. On Banks Island, the presence of thermokarst pre-supposes the presence of factors which disturb the thermal equilibrium of the permafrost. For example, the majority of ground-ice slumps and areas of badland thermokarst terrain are located along lakeshores (e.g. Slumps 2 and 3) or streams (e.g. the T.S. hollow). It appears that such features are initiated by localized scour or undercutting which removes a portion of the active layer and induces degradation. Other ground-ice slumps are located at a distance from obvious trigger mechanisms and may owe their initiation to localized gullying or slope failure (e.g. Slump 1).

Ground-ice slumps are related to the ice-rich nature of the underlying materials. Once these features are initiated the headwalls continue to retreat either by a crumbling action or through the detachment and slumping or sliding of blocks. Retreat rates are related to climatic factors and either increase or decrease with changes in solar radiation, temperature, and precipitation. The average retreat rate for two slumps, over a two year period, is of the order of 9.0 m per year, similar to values obtained on the mainland and elsewhere.

As the slump headwall retreats material is removed from the central hollow by mudflow. If material is not removed from the base of the headwall the slumps will stabilize as the icy sediments become buried. The sidewalls of the slumps usually stabilize before the headwall since they soon develop to the point where insufficient slope exists at the base of the headwall for rapid material removal.

In areas underlain by high ice content silts and sands, and which possess well developed ice wedges, badland thermokarst terrain may develop. One such area investigated (the T.S. hollow) showed considerable spatial and temporal variation in soil thermal properties and microclimate. Surface and subsurface soil temperature was monitored at four locations. The warmest site was the flat surface immediately adjacent to the badland terrain followed by the central amphitheatre, the south-facing slope and lastly, the north-facing slope. In addition, summer temperatures generally warmed from 1972 to 1973 but the temperature increase was not uniform: the mean surface temperature increased by 1.3°C on the north-facing slope and by 6.0°C on top of the hollow. Microclimate is important to thermokarst development as those sites in the T.S. hollow with the highest temperatures experienced the most intensive thermokarst activity.

The development of badland thermokarst terrain is not tied solely to climatic considerations but also to geomorphic processes which act to expand the feature. The central portion of the T.S. hollow is being reduced by mass movement (6-15 cm/yr) while the headwalls are retreating through nivation and deflation.

An examination of the climatic records at Sachs Harbour indicates that 1973 was an exceptionally warm year (Table 2). Therefore, the rates of thermokarst activity during 1973 are not representative of 'average' conditions. The average 1972 headwall retreat rate recorded for the ground-ice slump (9.1 cm/day) may be more typical than the 1973 rates (Table 10).

Years of rapid thermokarst activity (i.e. 1973) appear to be significant to the overall development of badland thermokarst terrain. Rapid retreat occurs along ice-wedges and initial retreat may result in continued future activity once ice-rich sediments are exposed. In addition, higher than average temperatures encourage thermokarst subsidence within the central amphitheatre and increased activity within and around thaw ponds.

Although periods of relatively high temperatures are important in the development of the badland terrain, the frequency of such events must be considered before an overall assessment can be made. At present there is insufficient geomorphic and climatic data for such an evaluation to be made.

6.2 Limitations of the Study and Future Considerations

The major limitation of this study is its short duration. Longer studies are necessary if more meaningful average values of geomorphic activity are to be obtained. Additional instrumentation is also

required if the data are to be representative of a wide range of conditions (e.g. high and low rates of activity).

Active thermokarst forms need to be investigated over long periods of time to establish average rates of activity. Microclimate is an important consideration since thermokarst is more active on warmer slopes. The asymmetric nature of stream valleys and the presence of ground-ice slumps in the study area may be related to local and regional microclimatic conditions.

The thaw ponds found at the junction of ice-wedge polygons are ubiquitous throughout the study area and warrant further study. Information is required on their rate of development, on the movement of water from pond to pond along ice-wedge depressions and on the significance of these features to the development of badland thermokarst terrain.

Further work is also required on fluvial processes and deflation. Deflation has been viewed as insignificant in the western High Arctic (e.g. Pissart, 1966). However, the present study has shown that the process can be quite significant, at least within limited areas. Furthermore, French (1972) has emphasized the indirect importance of wind action in N.W. Banks Island. Data are required on the intensity of the deflation process from other areas of Banks Island. Similarly, relatively little data are available on fluvial processes on Banks Island and in the western Arctic in general; both long-term studies

and general surveys are required. Gullying is tied to thermal erosion and appears to be the initiator of several thermokarst landforms within the study area.

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