A STUDY OF PERMAFROST TERRAIN DISTURBANCES, ARCTIC CANADA

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"Since I began to know the North, its beauty, freedom and friendliness have continually grown upon me. They were there from the first but my eyes were holden and I would not see them, for even in that clear air I walked wrapped in the haze of my bringing-up . . .. Certainly it would take keen eyes to read between the lines of McClure's narrative of hardship and heroism the soft beauty and homelikeness of Banks Island as I see it."

(Vilhjalmur Stefansson, 1921)

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ACKNOWLEDGEMENTS

In order to work successfully in the Arctic, one must rely upon other people and organizations.

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CHAPTER I

INTRODUCTION

1.1 Aims and Objectives

The search for new lands, as well as the finding of mineral resources and hydrocarbons has promoted interest in Arctic development. Unfortunately many of these activities tend to produce either physical or ecological disturbance (e.g. Babb and Bliss, 1974a; Brown and Grave, 1979; Mackay, 1970). The effect of any given surface disturbance is difficult to predict as terrain responses are subtle and vary from area to area. In general, compaction of the ground surface alters the thermal transfer properties of the soil while removal of surface vegetation alters the albedo. In most cases both these changes lead to an increase in heat flux in summer, thereby increasing the depth of thaw (e.g. Mackay, 1970). Depending on controlling factors such as the ground ice content, the increase in thaw may either be a few centimeters and of little practical consequence or may lead to gullying, thermokarst development, and landslides (e.g. see Brown and Grave, 1979; Heginbottom, 1974). Prediction of the physical consequences of terrain disturbance is difficult therefore.

Within this general context, the thesis aims to assess the importance of terrain disturbances associated with oil and gas exploration. A modified form of the geoecological mapping approach (Everett et al., 1978) was used to assess terrain sensitivity at a number of disturbed localities. In addition, terrain disturbances in the vicinity of Sachs Harbour, on southwest Banks Island were examined in order to provide information as to the nature and rate of man-induced thermokarst, and also to enable comparisons to be made between the types of terrain disturbances associated with oil and gas activities as opposed to other economic activities.

1.2 Study Areas

1.2.1 Fieldwork

Three areas were examined during the 1980 summer field season (figure 1). Two were wellsites, one on the northwest corner of King Christian Island and the other in the Parker River area of northeast Banks Island. The third locality was the community of Sachs Harbour on southwest Banks Island.

Panarctic Oils Limited, Calgary, provided access to the two wellsites. The King Christian Island Dome Wallis A-73 (77°52'N; 102°25'W) was an operating well at the time of the visit on July 27, 1980. Then, between July 30 and August 4, the abandoned Banks Island Chevron Parker River J-72 wellwite (73°31'N; 115°52'W) was examined. This well had been drilled during the winter of 1978-1979. In addition, en route to King Christian Island,

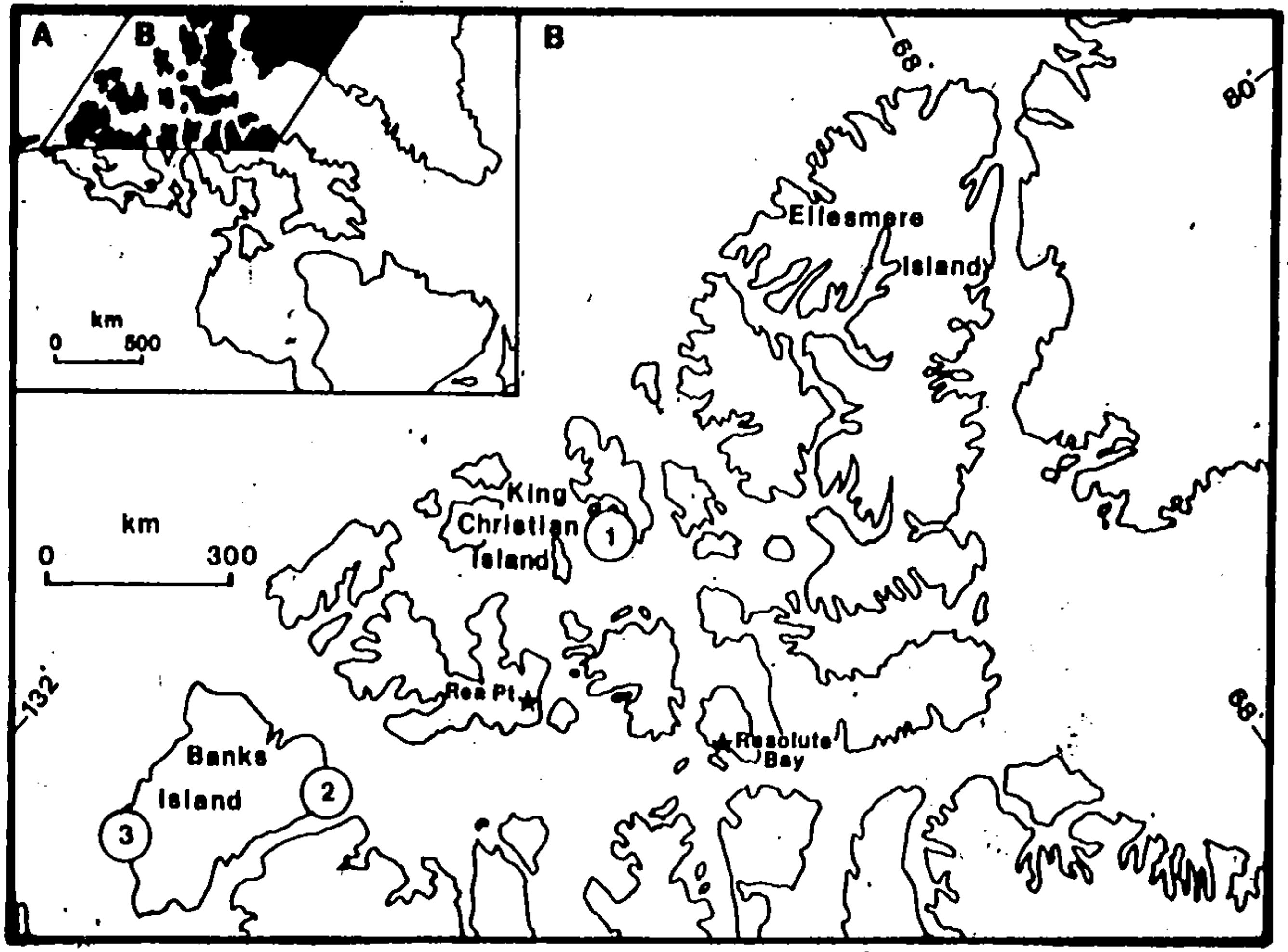

Figure 1. Location map of the study areas in the Canadian Arctic. 1) Dome Wallis A-73 wellsite, northwest King Christian Island; 2) Chevron Parker River J-72 wellsite, northeast Banks Island; 3) Sachs Harbour, southwest Banks Island.

observations were made of terrain conditions at Stokes Range, Northern Bathurst Island. Between August 5 and August 15, studies of the terrain disturbances in the vicinity of Sachs Harbour (71°59'N; 125°17'W) were undertaken.

Air photo coverage of the three areas is variable, ranging from standard arctic coverage on King Christian Island and northeast Banks Island to relatively good sequential coverage of the Sachs Harbour area (table 1).

1.2.2 Dome Wallis A-73 wellsite, King Christian Island

King Christian Island lies within the central part of the Sverdrup Basin, a physiographic region of little relief, developed on poorly consolidated, slightly deformed Mesozoic sedimentary rocks. Geologically the island is: ". . . . a broad, ovate, north-westward trending structural depression . . . flanked by a closed anticline on the eastern coast, and by eastward-dipping beds along the western coast" (Balkwill and Roy, 1977, p. 1) (figure 2). The two most widespread rock types occurring at the surface are sandstones and shales of the Deer Bay and Christopher Formations respectively.

The area is underlain by continuous and thick permafrost approximately 400 m thick (Brown, 1972, 1978). Well developed thermal contraction polygons are present (figure 3). Typical active layer depths usually do not exceed 50 cm (Babb and Bliss, 1974b; Bliss, 1975).

TABLE 1

AIR PHOTO COVERAGE OF THE THREE STUDY AREAS

	Air photo		Date	Scale
King Christian Island	A-16751	176-178	1960	c. 1: 60,000
Parker River	A-17053	50-52	29/7/61	c. 1:101,000
	A-17683	5-6	6/7/62	c. 1:101,500
Sachs Harbour	A-15980	64-65	14/7/58	c. 1: 59,500
	A-17381	41-42	29/8/61	c. 1:102,000
	A-18646	4-6	18/8/64	c. 1: 11,400
	A-20917	79-84	3/9/68	c. 1: 4,800
	A-22953	47-54	5/8/72	c. 1: 7,000
	A-24088	43-48	26/6/75	c. 1: 5,700
	A-25222	6-13	23/7/79	c. 1: 7,300

Figure 2. Oblique air photograph, King Christian Island, showing dipping sedimentary strata. Note the degree of fluvial dissection of the landscape. Photo: July 27, 1980.

Figure 3. Oblique air view of thermal contraction cracks developed on sandy substrata, King Christian Island. Permafrost is continuous and probably exceeds 400 m in thickness. Photo: July 27, 1980.

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No climatic station exists on the island; data from the Isachsen Weather Station on Ellef Ringnes Island are believed representative. Maximum air temperatures are approximately +15°C, while minima fall to -50°C. Mean temperature is approximately -20°C (table 2). Usually the island is snow-covered from September to late June; the period of summer thaw lasts from early June to late August.

The island is best described as a polar semi-desert with less than 20% cover of scattered vascular plants: Puccinellia vaginata, Arenaria rubella, Papaver Radicatum, and Saxifraga caespitosa predominate (Bliss, 1975); similar terrain and vegetation occurs on parts of Southern Cameron (figure 4). Soils are poorly developed, arctic regosols being most common. The geotechnical characteristics of the Christopher Formation shales are described as follows: " . . . low permeability, retains water in summer, swelling clays, slopes undergo extensive solifluction, poor fill material" (Balkwill and Roy, 1977).

Earthflows occur widely throughout the island both below and above the marine limit (Hodgson, 1977). These result from the saturation of material during snow melt and/or heavy or extended rainfalls during the summer. Failures are confined to the active layer, the permafrost table acting as a lubricated slip place. During the

TABLE 2

CLIMATOLOGICAL DATA FOR SELECTED WESTERN ARCTIC STATIONS

Month	Mean Air Temperature (°C)	Precipitation (mm)	Number of Frost-Free Days
Isachsen (78°47'N; 103°32'W)			
J	-34.2	7.6	0
F	-34.6	7.6	0
M	-33.2	12.7	0
A	-25.9	5.8	0
M	-14.3	14.5	0
J	- 1.6	23.6	1
J	+ 2.9	14.0	12
A	- 0.2	29.0	4
S	- 6.7	4.1	1
O	-21.2	18.8	0
N	-28.9	2.8	0
D	-32.0	3.6	0
	Mean: -19.2°C	Mean: 12.0 mm	Total: 17
Sachs Harbour (71°59'N; 125°17'W)			
J	-32.4	1.0	0
F	-33.2	9.1	0
M	-30.8	3.0	0
A	-14.2	2.0	0
M	- 6.7	16.5	6
J	+ 1.5	5.8	2
J	+ 7.9	1.5	29
A	+ 2.5	10.1	11
S	+ 1.4	26.4	7
O	- 8.8	53.1	0
N	-17.6	4.3	0
D	-30.2	7.1	0
	Mean: -13.4°C	Mean: 11.7 mm Total: 119.9 mm	Total: 55

Source: AES Records, 1976.

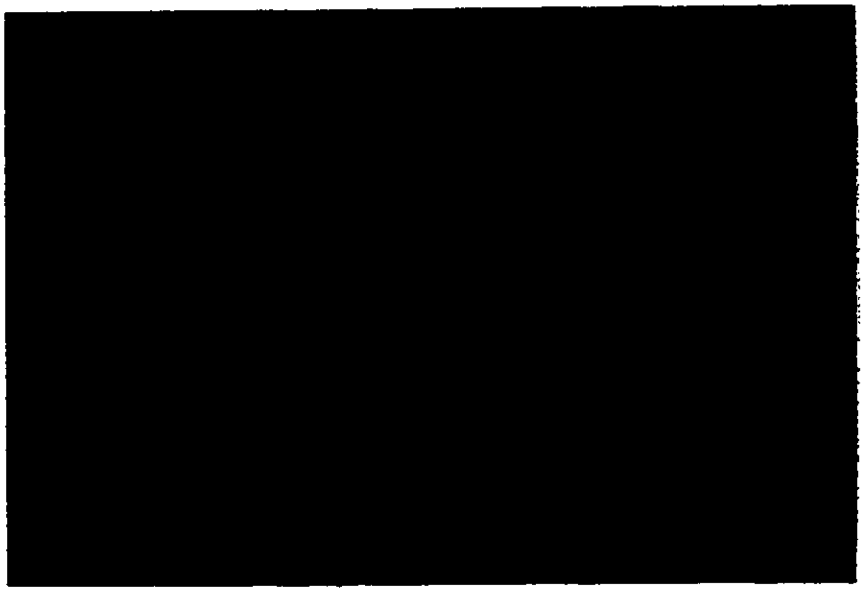

Figure 4. Typical polar desert vegetation developed on sandy well-drained surface, southern part of Cameron Island. Puccinellia vaginata is the dominant species with scattered Oxaria digyna. Photo: July 27, 1980.

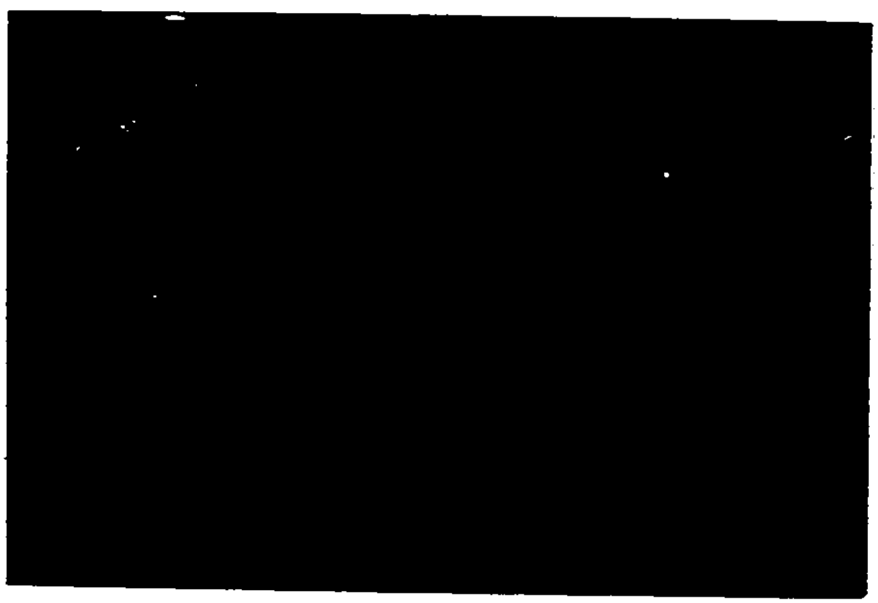

Figure 5. Oblique view of terrain underlain by shale of the Christopher Formation, northwest King Christian Island. Note the numerous mudflows which occur on this terrain. Photo: July 27, 1980.

summer of 1980, numerous earthflows were observed in varying localities (figure 5). "The low angle upon which such movement takes place, and the remarkably intact and apparently stable surface of the adjacent tundra makes the prediction of such events virtually impossible" (French, 1978a, p. 12).

The Dome Wallis A-73 well is located on the north-western corner of the island, within 0.5 km of the coast, at an elevation of 5.4 m above sea level. The site is a shallow interfluve between two northwest-southeast flowing rivers (figure 6).

1.2.3 Chevron Parker River J-72 wellsite, northeast Banks Island

The Parker River wellsite on northeast Banks Island lies roughly at the boundary between two distinct physiographic regions: 1) the morainal belt constituting the principal drainage divide of the island, and 2) the Devonian Plateau (Fyles, 1962). The area lies at the maximum known limit of the last classical Wisconsinan ice sheet (Prest et al., 1968; Vincent, 1978, 1980a). The terrain is an undulating upland surface dissected by tributaries of the Parker River (figure 7). In this area of northern Banks Island, the landscape is transitional between high Arctic polar desert and low Arctic tundra.

The climatic conditions can be extrapolated from those at Sachs Harbour (table 2). Mean annual temperature is probably in the order of -15°C, and the number of

Figure 6. Air photo of Dome Wallis A-73 area, showing wellsite location and major terrain features (NAPL A16751-178).

Figure 7. Typical landscape and vegetation in the vicinity of the Chevron Parker River J-72 wellsite, northeastern Banks Island, July 30, 1980.

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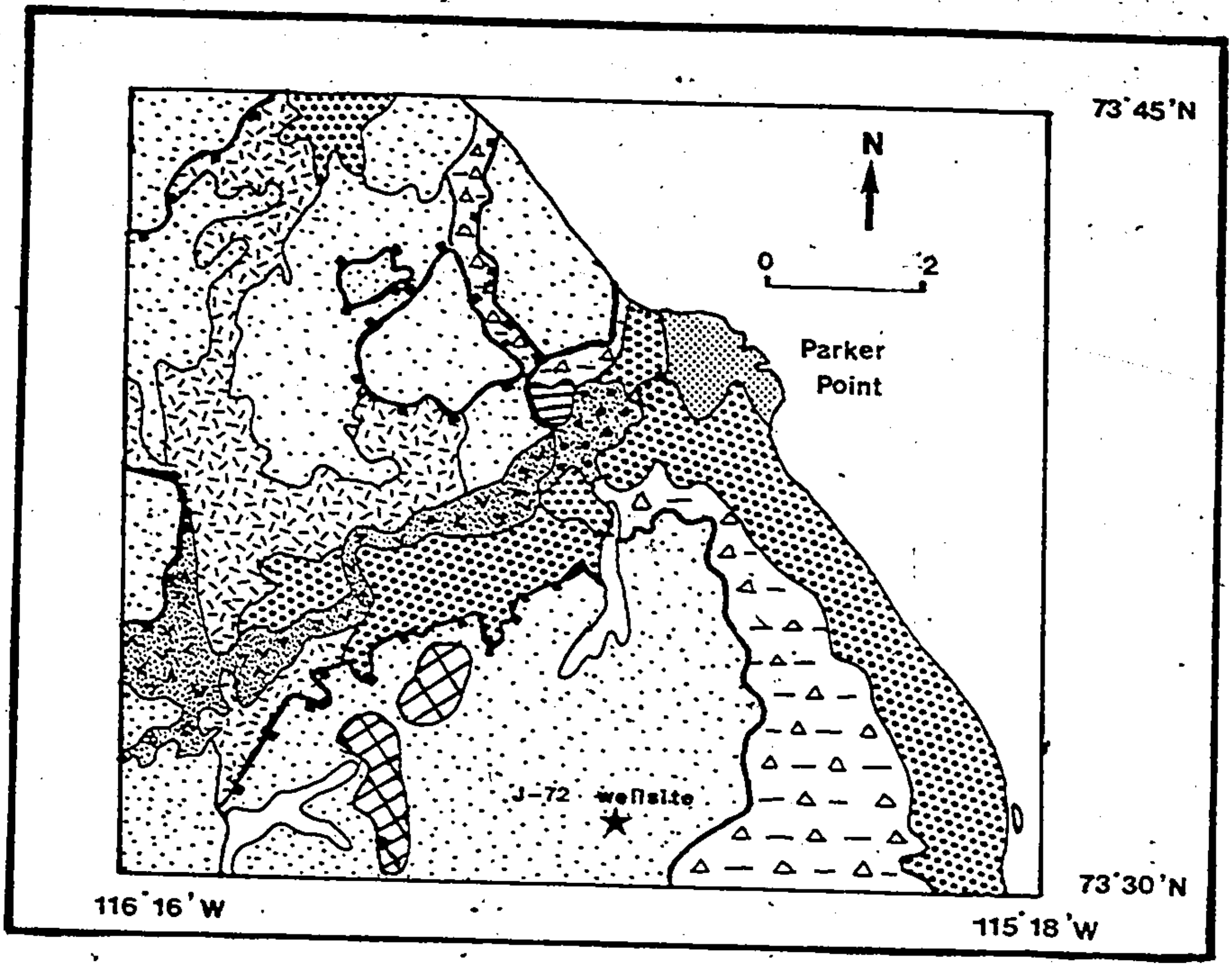
frost-free days is approximately forty. Precipitation is assumed to be as little as that experienced at Sachs Harbour, i.e. c. 100 mm per annum.

Vegetation on Banks Island comprises some 350 species of which a large proportion are endemic (Kuc, 1974; Porsild, 1950, 1955; Savile, 1961). Vegetation is generally of low stature: in poorly drained areas such as valley bottoms, it forms a continuous meadow tundra while in well drained and xeric sites the vegetation cover is discontinuous. Many soils of northern Banks Island have high Arctic affinities. They are hence designated as polar desert rather than tundra soils (Tedrow and Douglas, 1964). In well drained localities, they are characterized by a relatively thick active layer; depths in excess of 70 cm were measured during field work in 1980.

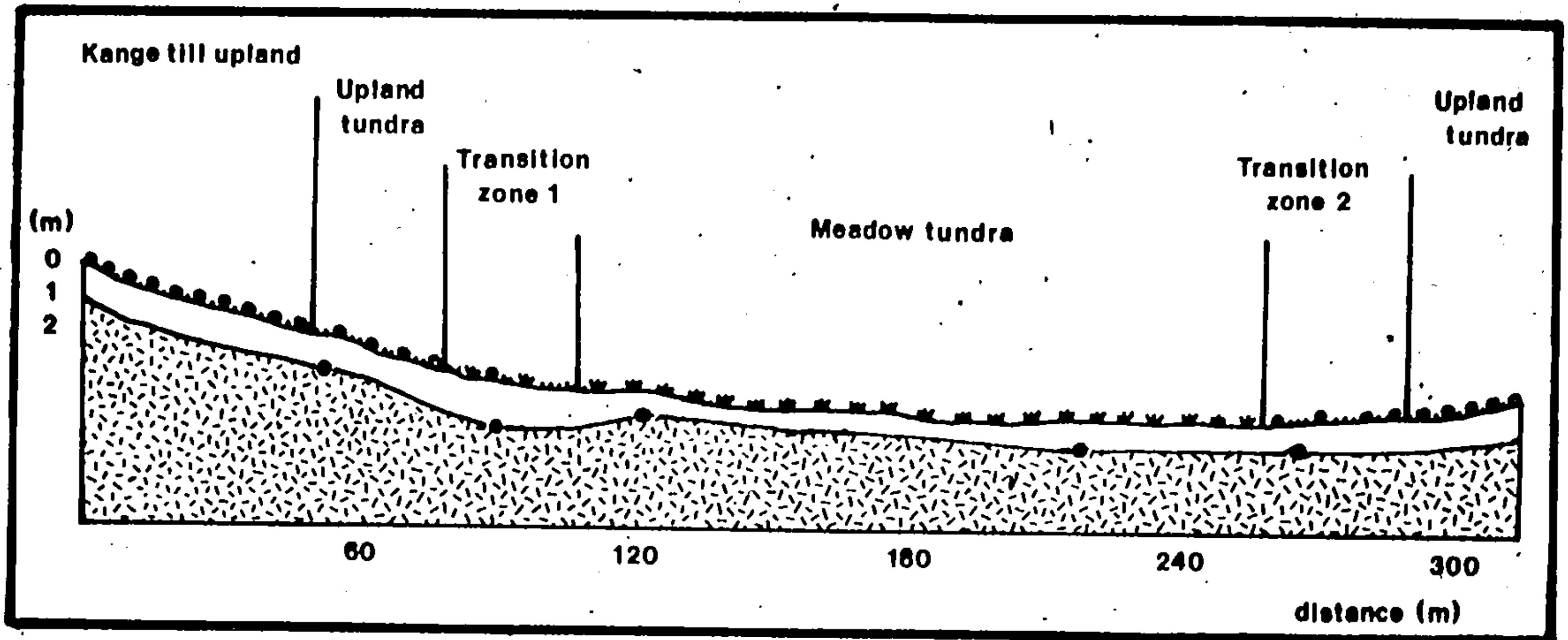
Surficial materials have been mapped by Vincent (1978); sandy gravelly till from an early pre-Wisconsin glaciation veneers the area (figure 8). The description of a typical slope-soil catena sequence best explains the material, vegetation and slope assemblages. Till mantles the polar semi-desert uplands, and the relatively steep-sloping upland tundra (figure 9). Ice wedge polygons are not apparent from air photographs (figure 10). Nevertheless, field observations at Johnson Point (French, 1974a) reveal high but variable ground ice amounts related to ice wedges and massive icy sediments.



Legend

Area of hummocky moraine
Limit of ice advance and/or till deposition
Limit of submergence by glacial Lake Parker
Fluvial sediments
Littoral sediments
Offshore and nearshore sediments
Glaciofluvial sediments
Ice-contact sediments
Jesse till, Amundsen glaciation
Kange till, Thomsen glaciation
Pre-Mercy Bay Member of the Weatherall Formation, Upper Devonian
Lake

Figure 8. Distribution of surficial materials in the vicinity of Chevron Parker River J-72, northeast Banks Island (after Vincent, 1978; 1980a, b).



Kange till upland:	gravels and silty sand, semi-polar desert, 5-15% vegetation coverage (<u>Saxifrage-Phippsia</u>--<u>Dryas</u>--lichen patina).
Upland tundra:	more fines; 5-15% vegetation cover (mosses--grasses--smaller vascular plants).
Transition zone 1,	between gravelly tundra and meadow tundra: stripes end; 85% vegetation cover.
Meadow tundra:	luxuriant vegetation, cover 60-90% (moss hummocks--sedges).
Transition zone 2,	between meadow tundra and gravelly tundra: stripes begin; 30% vegetation cover (<u>Dryas</u>--Willow-<u>Saxifrage</u>--grasses).

<u>Legend</u>

- gravels } Kange till
- fines (silty sands) } Kange till
- • thaw depth, measured
- — thaw depth, extrapolated

Figure 9. Schematic diagram of a typical profile in the vicinity of Chevron Parker River J-72 wellsite

Figure 10. Air photo of part of northeast Banks Island showing the location of the Chevron Parker River. J-72 wellsite (NAPL A 17683-5).

The Chevron Parker River J-72 wellsite is located approximately 15 km inland from Passage Point (figure 10). The site is gently inclined towards the northwest and is drained by two small creeks.

1.2.4 Sachs Harbour, southwest Banks Island

Sachs Harbour is the only permanent settlement on the island. There are approximately 150 inhabitants. Figure 11 shows the spatial distribution of the settlement, the airstrip, the lake which supplies the village, and the road 'network'. Three major terrain units can be recognized: 1) the Sachs Harbour ridge, 2) sloping terrain to the south, and 3) gently sloping terrain to the north. The Sachs Harbour ridge represents a major ice margin recognized by Vincent (1978) and is composed of coarse sandy and gravelly materials. The village is located on the lower south-facing slopes. Above the village, slopes are steep (15-20°) and support relatively sparse vegetation with non-sorted solifluction stripes which surround gravel 'outcrops'. On the upland tundra north of the Sachs Harbour ridge, slopes, usually gentle (2-5°), extend towards the Kellett River. Non-sorted polygons and thermal contraction cracks are widespread.

Information on Sachs Harbour is relatively plentiful and includes both qualitative and quantitative information (French, 1974b, 1975a, 1975b, 1976a, 1976b) as well as surficial geology and bedrock geology maps (Thorsteinsson

Figure 11. Air photo of Sachs Harbour. Note the terrain disturbance adjacent to the airstrip. Photograph was taken in 1964, 3 years after initial disturbance (NAPL A 18646-5).

and Tozer, 1962; Vincent, 1978). Climatic data have been recorded since 1955; representative data are presented in table 2. Due to its exposed location, winds are unusually strong (e.g. mean velocity of 5.4 m/sec. in 1967). Air photo coverage is good by Arctic standards; coverage at three or four year intervals since 1961 is available (table 1).

Typical undisturbed terrain on the Sachs Harbour ridge is shown on figure 12. Due to the coarse nature of the materials, thaw depths are thick, often being in excess of 1 m on steep south-facing slopes. Hummocky *Dryas* tundra is the most widespread community on the ridge and immediately to the north (figure 13). In lowland areas near the coast, vegetation consists of wet grassy tundra, sometimes heavily disturbed (figure 14). Due to human activity, these southerly slopes are often organic rich. Surface temperatures are often high therefore but thaw depths are relatively shallow. Particularly luxurious tundra grass communities with *Eriophorum* sp. (Cotton Grass) commonly develops (figure 15). On the gravel ridge and exposed uplands, lichen moss communities together with scattered *Dryas* and *Salix* sp. occur.

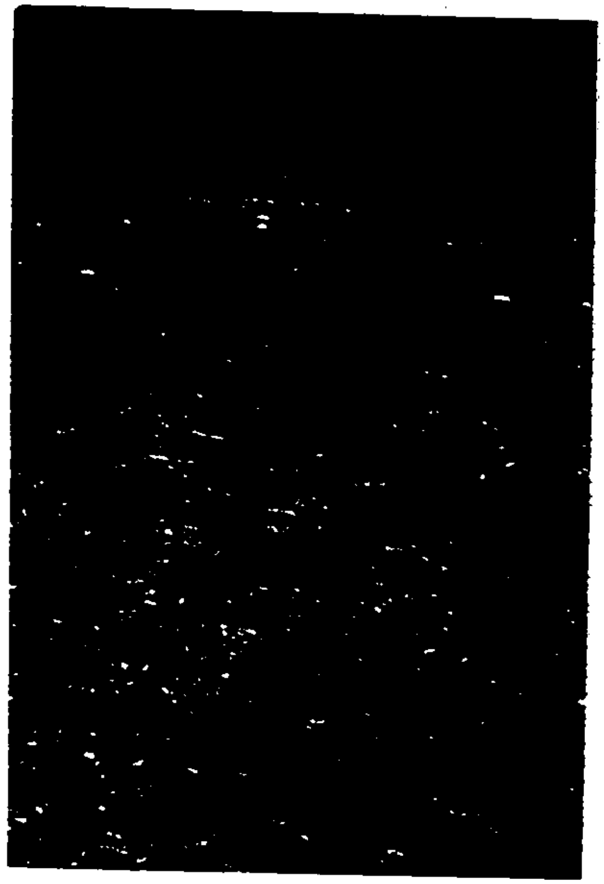


Figure 12. Typical undisturbed terrain, immediately south of the airstrip. Note the gravelly material and the hummocky *Dryas* vegetation.

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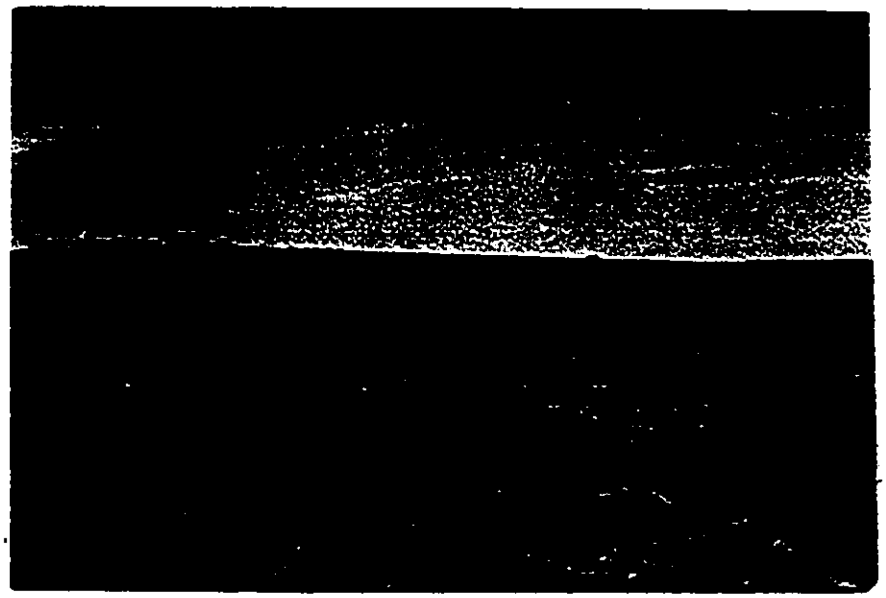

Figure 13. Discontinuous hummocky Dryas tundra. Note the thermal contraction cracks in the unvegetated areas.

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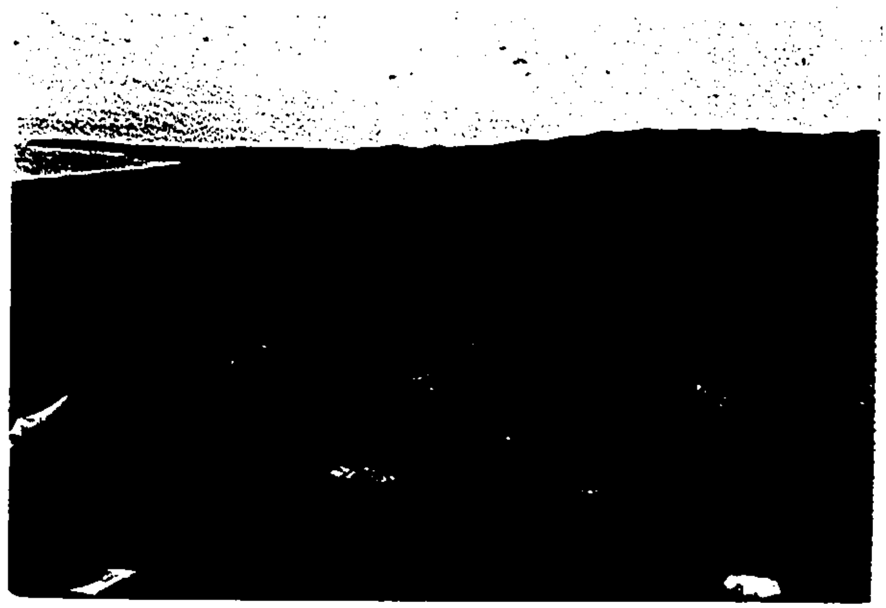

Figure 14. Grassy tundra typifies the lower south-facing slopes of the Sachs Harbour ridge. View looking west from the village.

Figure 15. Near dwellings, disturbed terrain is often organic-rich and Eriophorum sp. communities proliferate.

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CHAPTER II

REVIEW OF LITERATURE

2.1 Controls over Terrain Disturbances

The studies of terrain disturbance in the Arctic range from the effect on the vegetation cover (e.g. Bliss and Wein, 1972) to the physical and thermal effects (e.g. Beattie et al., 1973; Brown and Grave, 1979; French, 1975a; Mackay, 1977b). The degradation of permafrost is thought to be greater in the low than in the high Arctic where the difference between surface and permafrost temperature is greater (Babb and Bliss, 1974b). Recently, H. M. French (1980a) has concluded that: " . . . the nature, speed and controls over thermokarst development are now reasonably well known." Nevertheless, many aspects need further investigation. For example, the U.S. Permafrost Committee of the Polar Research Board of the National Academy of Sciences concluded that little is known about rates of heat transfer in the thermokarst process (Ad hoc Study Group on Permafrost, Polar Research Board, 1974).

The controls over permafrost terrain disturbance can be summarized under a number of headings.

2.1.1 The ground thermal regime

Permafrost is a thermal state where materials remain frozen for more than one year (Brown and Kupsch, 1974). Ground temperatures vary with depth at different times of the year. This variation is a function of the surface heat balance, the heat flow from the earth's interior and the thermal properties of the earth material. Ground surface temperatures are approximately 3 to 4°C higher than air temperatures.

Soil temperatures in permafrost areas are highly variable, as they are affected by local variations in snow cover, vegetation, drainage, and soil composition. For example, Brown (1970a, 1972) has found that in high Arctic regions, ground temperatures can be 5° to 10°C lower at 10-30 cm depth than in low Arctic regions. Furthermore, summer soil temperatures measured on the Beaufort Plain of western Banks Island are high compared with other Arctic areas, reflecting the high thermal conductivity and low heat capacity of these materials (French, 1970). Soil temperatures also vary seasonally; during the fall freeze-up, temperatures cool from the surface downwards, as air temperatures drop, during which time freezing also takes place from the permafrost upwards. During the major part of the freeze-up period, much of the active layer lies within the freezing boundary, or 'zero curtain'.

2.1.2 Water (ice) content

There are a number of ground ice types; in his classification J. R. Mackay (1972) proposes ten categories. Three types are important in terms of thermokarst (French, 1979). Pore ice or ice cement exists in varying quantities in all rock types; segregated ice varies from ice lenses a few centimeters thick to massive ice bodies; and, wedge ice occurs as the result of the thermal contraction of the ground. Pihlainen and Johnston (1963) have established field methods to describe ground ice both visually and quantitatively.

The amount of moisture may reflect the grain size of the material. Usually soils with high ice contents are fine-grained; these are the frost susceptible soils, i.e. ". . . soils in which significant detrimental ice segregation occurs when the requisite moisture and freezing conditions are present" (Brown and Kupsch, 1974, p. 12). As a rough guide, soils with more than 10% by weight of particles smaller than 20μ are usually frost susceptible and will support ice lense growth. In soils with greater pore space, water migrating to the freezing plane freezes in situ. Upon thawing and in unconsolidated sediments, liquifaction may occur.

The liquid content of a soil is defined on a dry weight basis. A field sample, e.g. 200 g is first weighed and then dried until its weight becomes constant. It is then reweighed and the weight of the moisture lost is expressed as a percentage of the dry weight, accurate to 0.1% (Krynine and Judd, 1957). In the field it is possible to weigh the sample and air dry it. Since ice contents may vary considerably within a few centimeters, it may be unrealistic to adopt more sophisticated weighing and drying techniques (e.g. French, 1976a, p. 75). Ice contents are considered high when values range within 50-150%.

Excess ice is defined as the volume of supernatant water to the volume of saturated sediment, i.e. " . . . the ice in the ground that exceeds the total pore volume that the ground could have under natural unfrozen conditions" (Brown and Kupsch, 1974). Basically, it is the excess ice which determines the degree of subsidence (figure 16), thus, its assessment is absolutely necessary in any terrain disturbance investigation.

The variable nature and distribution of ground ice prevent accurate prediction unless site specific conditions are known. For example, a study performed on the variability of ground ice at selected sites in the Mackenzie valley (Heginbottom and Kurfurst, 1977) indicated three factors to be particularly significant: 1) soil texture, 2) slope aspect, and 3) surface drainage. In fact it was obvious that (a) the higher the silt content, the greater the water content, (b) south-facing slopes

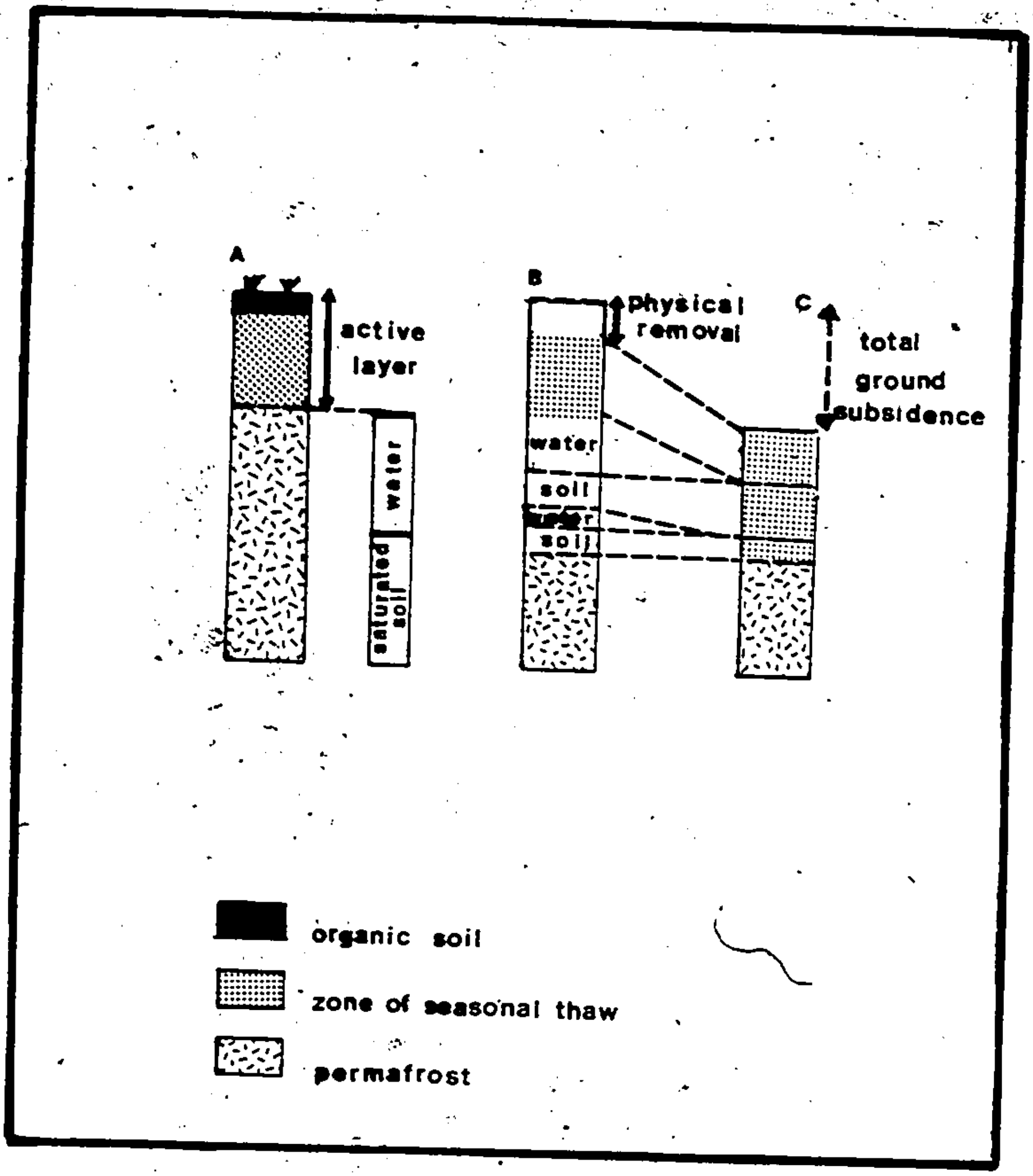


Figure 16. Diagram illustrating how disturbance of a soil containing 50% excess water may lead to ground subsidence (Mackay, 1970). A) Before disturbance; B) Immediately after disturbance; C) Long term result.

were drier than north-facing and contain less ice and, (c) significant differences in ice content exist between poorly and well-drained areas.

Excess ice contents need to be evaluated quantitatively. "Visual estimates of excess ice are deceptive since a body of sediment may not necessarily contain excess ice even though it may contain visible ice lenses, since the sediment between the lenses may not be saturated with ice and upon melting all water would be retained in the voids" (French, 1976a, p. 77). Field procedures consist of filling a container with frozen sediment and allowing it to thaw. The volume of supernatant water (excess ice) is expressed as a percentage of the total saturated sediment. Values in the 70-80% range are considered exceptionally high.

2.1.3 Vegetation

Vegetation is perhaps the most complex terrain factor controlling the extent, distribution, and thermal regime of permafrost (French, 1976a). In fact, it is so closely interwoven with other terrain factors that it seems difficult to single out the role of vegetation alone (Brown, 1966). Vegetation has both a direct and an indirect influence on permafrost. It modifies the thermal regime by shielding the underlying permafrost from solar radiation, thereby decreasing air circulation, retaining moisture, and intercepting rain. It also provides cooling of the soil by evapo-transpiration (Benninghoff, 1952) while protecting it from the penetration of cold. "This insulating property is probably the single most important factor in determining the thickness of the active layer" (French, 1976a, p. 60). As vegetation plays a direct role in the heat transfer mechanism between the ground and the atmosphere, any change will cause variations in active layer thickness.

The role of vegetation varies for different latitudes: " . . . the significance of vegetation in governing the occurrence of permafrost in soil decreases the more the earth surface mean annual temperature is depressed below the freezing point" (Benninghoff, 1963, p. 11).

The complexity of vegetation was reported, for example, by T. A. Babb and L. C. Bliss (1974b), from the high Arctic where the plant cover/active layer depth relationship appears non-causal. Due to severe growing conditions, the development of a strong insulative cover is inhibited and active layer thickness appears related to moisture conditions. This is supported by simulation of active layer sensitivity (Goodwin and Outcalt, 1974). It is clear that plant cover does not act simply as an insulation barrier to sensible heat flow. Experiments show that, while removal of the vegetation and peat layer from low Arctic tundra increases active layer thickness by 50 to 100% (e.g. Brown et al., 1969), replacement of the same material as a mulch decreased it by 40% only (Babb and Bliss, 1974b). Obviously, " . . . a complex of variables, of which radiation balance and insulative capacity of the organic layer are only components, is involved" (Babb and Bliss, 1974b, p. 552).

Studies in the U.S.S.R. have shown that under a vegetation cover, the summer average monthly temperature of the soil at a depth of 15 to 40 cm is frequently lower than the ground surface temperature; also that the depth of thawing is less by a factor of 1.5 to 3.0 or more, than in areas where vegetation has been removed and where the organic matter has been minimized. "This effect of vegetation increases with the bulk, height and density of the vegetation cover and with the amount of organic matter deposited in and on the soil" (Tyrtikov, 1964, p. 79).

Different types of vegetation cover have different effects on the underlying ground. Many investigators have found that, of all ground cover types, spaghnum and peat retard thawing the most. This is because these organic materials have a low thermal conductivity especially when dry. During summer, they effectively insulate the underlying soil; during winter, they are good conductors of cold since the water (ice) content is high.

Clearly, vegetation has an effect on the temperature of the soil and therefore a similar effect on the permafrost;

in fact, it was shown to influence climate, terrain, and drainage (Brown, 1963). Its removal, or even its disturbance may cause permafrost degradation.

2.1.4 Material properties

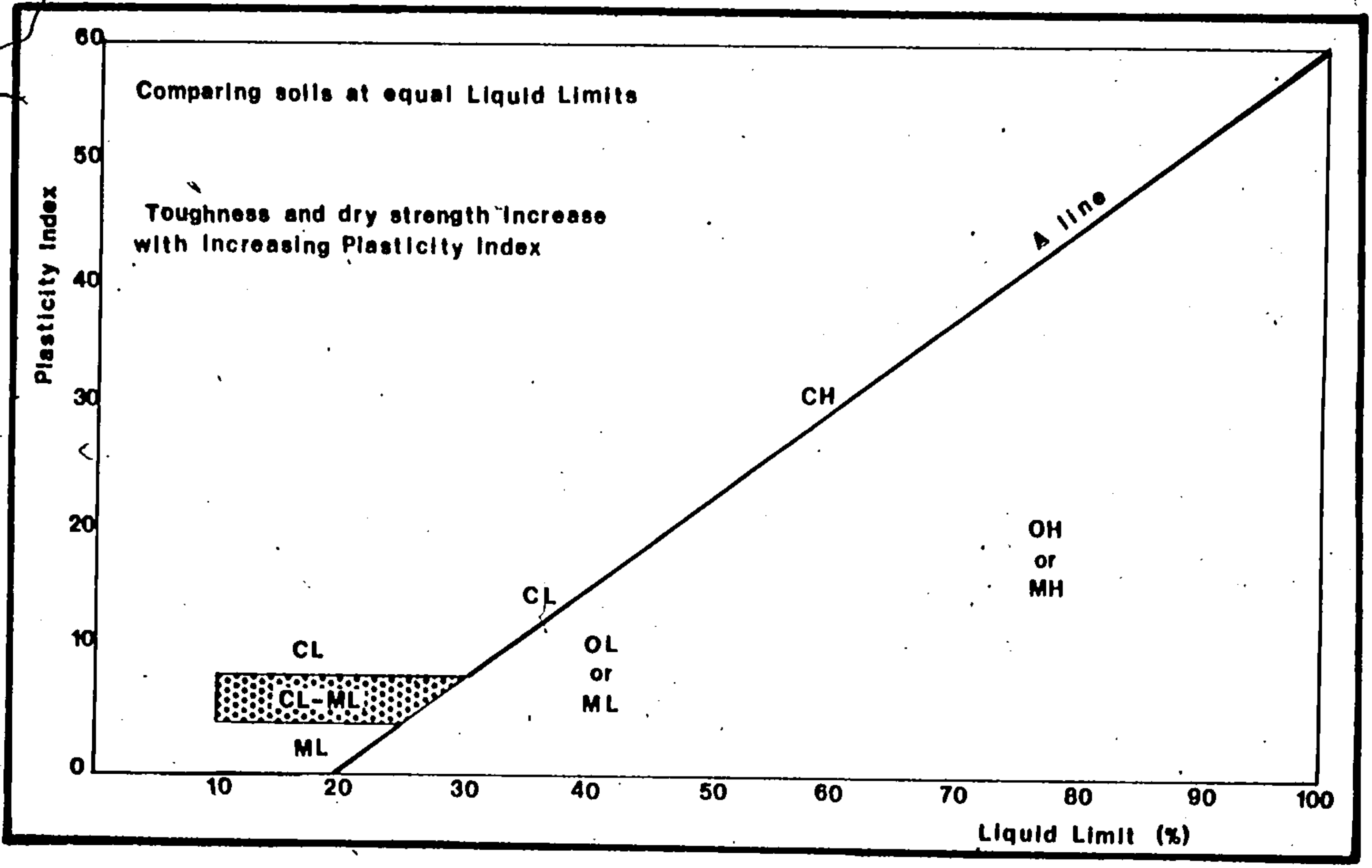
The control of subsurface material is probably not as complex as that of vegetation; it affects the thermal regime of the ground simply by its physical or thermal properties, namely soil or rock reflectivity, conductivity, diffusivity, specific heat, and moisture conditions. Bare soil or rock are known to have the greatest influence on ground temperature as they reflect a large percentage of the solar radiation they receive. For example, albedo values of 12 to 15% for rocks and of 15 to 30% for bare soil are typical (Brown, 1970b). As a result, the thermal conductivity of silt is half that of coarse-grained soils and several times less than that of rock. Intakes of precipitation, evaporation rates, and the presence or absence of moisture are all important as they modify these properties. For example, in loose gravelly or sandy soils a quick adjustment of soil temperatures to prevailing climatic conditions can occur (French, 1970).

Soil and rock type are characterized by specific thermal properties, which are reflected by soil moisture conditions and directly influence active layer thickness. Other factors being equal, the active layer is thinner under fine-grained soils.

The determination of the Atterberg Limits, which are a measure of the plasticity and liquidity of a sediment, are of importance in determining terrain sensitivity (French 1975a, p. 136). For example, if, upon thawing, the natural (ice) content of the frozen soil exceeds its liquid limit, liquifaction is possible for certain saturated fine-grained soils.

Atterberg Limits pass through four stages: liquid, plastic, semi-solid, and solid. Determination of both the Liquid and the Plastic Limits can be easily performed in the laboratory. The Liquid Limit ($LL = \frac{\text{water content}}{\text{mass of dry soil}} \times 100$) is a measure of the minimum amount of water necessary for the sediment to experience flow. The Plasticity Limit ($PL = \frac{\text{water content}}{\text{mass of dry soil}} \times 100$) is reached when the sediment becomes capable of being permanently deformed without breaking. The difference between LL and PL is the Plasticity Index (PI) within which the soil has plastic properties.

In this context, the determination of the Plasticity Index serves two purposes. First, it provides a qualitative assessment of the soil's sensitivity to increasing water content. Second, it can be used with the plasticity chart (figure 17) to determine the soil nature. The appropriate liquid limit and plasticity index for a given soil are plotted on the chart. The so-called A line is given by $PI = 0.73\,(LL-20)$. Basically clays are above while silts



Source: U.S. Corps Engineers, 1953.

Figure 17. Plasticity chart for classification of fine-grained soils

are below the A line. In the shaded area this rule does not apply and a double classification must be used, e.g. the association of any of the three following main soil types: inorganic silts or very fine sands, inorganic clays, organic clays and silts.

2.1.5 Other factors

Relief, or more precisely slope orientation and angle, influences the amount of solar radiation reaching the ground surface. Generally, in the continuous permafrost zone, the active layer is thinner and the permafrost thicker on north-facing slopes. Nevertheless, local climatic conditions may overrule. French (1970), reports from northwest Banks Island that due to dominant southwesterly winds which increase evaporation and latent heat loss during summer, the active layer is thinnest on southwest-facing slopes. Similar conditions can occur on a micro scale, for example, variations in snow accumulation may modify these patterns on and between peat mounds (Brown, 1970a).

Snow cover influences the heat transfer between the air and the ground and hence affects the distribution of permafrost (Brown, 1970a, p. 25). Critical factors are snowfall regime and the length of time snow remains on the ground. In the discontinuous permafrost, snow is often a major control in the existence of permafrost. For example, at Schefferville, a snow depth of 16" is critical in the development of permafrost (Nicholson and Granberg, 1973). In the continuous permafrost zone the active layer is usually thinner at snowbank localities. The relationship is not always simple though, as the effect of snow on the ground thermal regime is determined by the net balance of frost penetration and thawing. For example, snow accumulation in the autumn inhibits winter frost penetration while snow remaining long into spring delays thawing. It has been shown that snow has the effect of temporarily decreasing near-surface ground temperatures in the active layer. At Schefferville, variations in snow cover caused temperature variations greater than those resulting from vegetation cover (Brown, 1970a, p. 26).

Water bodies may alter the thermal regime of perennially frozen soil. Under deep lakes which do not freeze to the bottom, sub-lake taliks develop. Their depth depends on factors such as: " . . . lake area, shape, depth, bottom configuration and water temperature, the mean ground temperature and its past thermal history: the nature of the soils and disturbances induced by nearby lakes" (Mackay, 1962, p. 33).

2.2 Terrain Disturbance Studies

The study of terrain disturbances in permafrost areas is new; for example, less than ten years ago, few quantitative reports existed on the effects of man's activities in permafrost areas (Haugen and Brown, 1970). Types of disturbance vary from those involving large areas such as those caused by fire and agriculture, to those related specifically to northern development. The latter include buildings, roads, airstrips, borrow pits, seismic lines, etc. Natural disturbances also exist, e.g. lake drainage, frost heaving, fire, and thermokarst. A problem is to distinguish the long-term effects of man-induced disturbance from naturally occurring processes.

2.2.1 Thermokarst processes

Surface disturbance of permafrost terrain especially leading to the compaction and/or destruction of the surface organic layer may result in an increase of summer thaw depth and melt of the permafrost. If the permafrost is ice-rich, this can lead to subsidence and instability, a process termed "thermokarst" (e.g. French, 1976a, p. 105-133; Washburn, 1980, p. 268-276).

Thermokarst processes involve both a thermophysical and a geomorphological aspect. That is, the rise in temperature thaws any ground ice while the surface subsides as water is released and soil material compacts (thaw consolidation). Ground subsidence inevitably leads to further thawing as the active layer is lowered. Although both thermal erosion and thermokarst subsidence play a role in permafrost degradation, the latter is much more important, at least in regions of low precipitation.

While thermal erosion, or lateral permafrost degradation (backwearing) necessitates sufficient drainage, thermokarst subsidence, or permafrost degradation from above (downwearing), can occur in flat undissected terrain (Mackay, 1970). The former produces thaw lakes, thermo-erosional niches, and ground ice slumps, the latter, especially in areas of well-developed ice wedges, may ultimately produce a new, lower surface with closed depressions and hummocky terrain (e.g. Czudek and Demek, 1970). It was reported from Alaska that " . . . the top level of the hummocks is not uniform--an indication that many of them have also undergone subsidence" (Rockie, 1942, p. 129). Furthermore, local surface collapse inevitably creates a change in external conditions (e.g. snow accumulation, moisture regimes) such that the thermal regime is modified and permafrost degradation occurs.

Variables influencing thermokarst include: 1) the natural water content, 2) the insulating qualities of the vegetation, 3) the depth of summer thaw, 4) the thermal conductivity of the material, and 5) the slope angle and aspect. As terrain responses are subtle, the effect of any given surface disturbance is difficult to predict. It follows that site-specific investigations are necessary.

Thermokarst processes are probably underestimated in North America. Once they are initiated, they are difficult to arrest and their effects are long lasting. According to French (1979, p. 153): ". . . stabilization only begins 10-15 years after the initial disturbance and probably is not complete until 30 years or more have passed."

Thaw slumps are reported widely from the Canadian Arctic (e.g. French and Egginton, 1973; Lamothe and St-Onge, 1961; Mackay, 1966). They are said to resemble those of temperate regions, though, because there is no surface of rupture, the features characteristic of rotational slides (e.g. lunate tension cracks) are absent (Mackay, 1966). The actual process is best described by French and Egginton (1973, p. 205):

> The erosion takes place through the thermal melting of the ground ice, which causes a crumbling and slipping of the overlying silts into the hollow that then liquify into mud through the addition of the melted ground ice. Excavation, therefore, is by mudflow and/or solifluction, and, occasionally, if there is sufficient moisture, fluvial (thermal) erosion occurs forming a network of small channels within the hollow.

Thaw slumping is a particularly rapid process: rates of headwall retreat of 7-10 m per annum were recorded while their stabilization is not complete until 30-50 summers after their initiation (French and Egginton, 1973).

2.2.2 Causes of thermokarst

The following discussion summarizes the major causes of thermokarst as described in the literature. More general surveys can be found, for example, in French (1979).

Controls over thermokarst may be either geomorphic, vegetational or climatic. Each may lead to permafrost degradation (figure 18). A more systematic treatment of the more important causes is presented below.

2.2.3 Fire

Fire occurs frequently in forest and forest-tundra regions, usually due to lightning. Of short duration, the long-term effects remain to be evaluated (Brown and Grave, 1979). Though generally considered a naturally occurring phenomena, it is discussed here as it is frequently compared with other forms of man-induced disturbances. The degree of its influence depends on the vegetation and soil conditions, and on the rate of burning. In the tundra zone fire is not as common due to the wet ground conditions and the low proportion of woody species. Following a fire, thermal and moisture regimes often undergo considerable change. The active layer may increase (e.g. Brown et al., 1969; Mackay, 1977; Wein and Bliss, 1973) due to the absorption of more energy into the soil through darker surfaces (table 3). If all the vegetation is destroyed by fire, provided the moss roots are unharmed, active layer depth will not vary. The incidence of skin-flows may also increase following fire (Rowe et al., 1975; Wein et al., 1975).

More serious are the effects of bulldozing of fire guards where the vegetation and peat cover are removed;

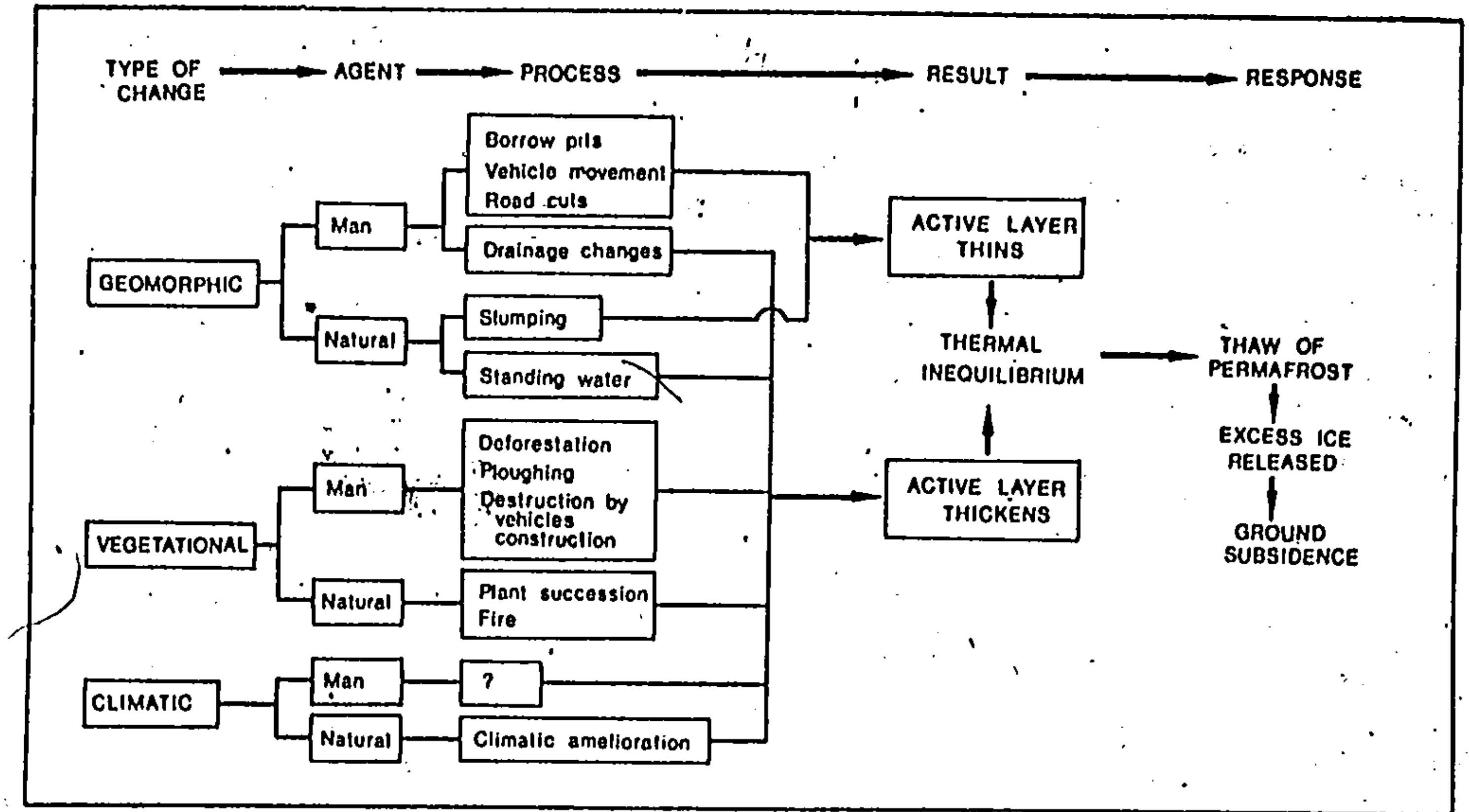


Figure 18. Diagram illustrating how geomorphic, vegetational and climatic changes may affect thermokarst (French, 1979; p. 149).

Notes

[1]"Due to rapid regrowth of Eriophorum as: fire removed all the litter, some of the peat, but only charred *Eriophorum vaginatum* subspecies *spissum* tussocks" (p. 1,100).

[2]"Due to the thermokarst process the fire had buried the surface by 20 cm" (p. 110).

[3]"The increase in thaw depth is a minimum and not a maximum, because any subsidence from ice (water) losses would not be registered" (p. 428).

[4]"The charred organic surface, being very dark, absorbed more short wave energy and the active layer depth increased by 35 to 50% in June and as much as 25% (more) by late autumn. The same thermal regime was found in burns several years old" (p. 845).

TABLE 3

ACTIVE LAYER DEPTH INCREASES FOLLOWING A FIRE

Approximate Location	Time Span Between Fire and Survey	Active Layer Increase		Ground Subsidence	Source
lat 69°30'N	1 month	>50%		-	Haag & Bliss (1974)
	2 years	early summer late summer	50% 25%[1]	-	Bliss & Wein (1972)
	8 years	50-55%		20 cm [2]	Czudek & Demek (1970)
lat 68°30'N	2 years	depressions ridges	185%[3] 393% 166% 185% 136% 152%		Mackay (1970)
lat 68°30'N	3-4 years	early summer late summer	60%[4] 65%	-	Wein & Bliss (1973)
lat 68°30'N	2 years	60-80%			Heginbottom (1971)

Peat removed at all sites.

the active layer thickens rapidly and subsidence occurs. For example, the Inuvik fire of 1968 was subject to detailed study (Heginbottom, 1971) and active layer changes have been monitored from 1968 to 1976 (Mackay, 1977). The active layer thickened rapidly during the first four or five years and then the rate of increase diminished. It was found that thaw depth aggradation followed an exponential decay curve with absolute changes being similar under the depressions and under the ridges.

Further complications arise when two disturbances are combined. Observations have shown burned areas, when wet, to be more sensitive to vehicle traffic than control areas (Wein et al., 1975).

2.2.4 Agriculture

Perhaps the most common cause of man-induced thermokarst on a large scale is the clearance of the surface vegetation for agricultural or construction purposes (French, 1976a, p. 129). In Alaska, the clearing of vegetation in the late 1920's resulted in mounds and pitted surfaces (Rockie, 1942). The relationship between ground ice and ground subsidence was apparent: " . . . the severity of surface pitting decreases more or less proportionally as the depth to the upper surface of the ice mass increases" (Rockie, 1942, p. 134). Later, Péwé (1954) directly linked the thermokarst topography with the melting of the underlying ice wedges. The mounds generally form within two or three years of the initial clearing, and ultimately the fields must be abandoned or reduced to pastures.

2.2.5 Buildings

"It has been said that 'to keep one's home level in Fairbanks, one must level it every year.' This may or may not be an exaggeration, but certainly, it has some basis in fact" (Rockie, 1942, p. 134).

The effect of a heated building on the thermal regime of the permafrost is considered similar to that of vegetation stripping or road construction (Lachenbruch, 1957). Therefore, coarse-grained sediments of low frost susceptibility should be selected. Methods now being used include 1) the 'active method', whereby permafrost degradation is promoted in areas mainly of discontinuous permafrost and 2) the 'passive method', whereby fill is placed over the permafrost to prevent thermal change. The thickness of the fill required can be calculated given the thermal conductivity of the materials and the mean air and ground temperatures at the locality (e.g. Ferrians, Kachadoorian and Greene, 1969). Problems arise when the appropriate thickness is not calculated correctly (figure 19). Also, where possible, space should be provided for the circulation of air between the ground and a heated building so as to minimize the heat transfer.

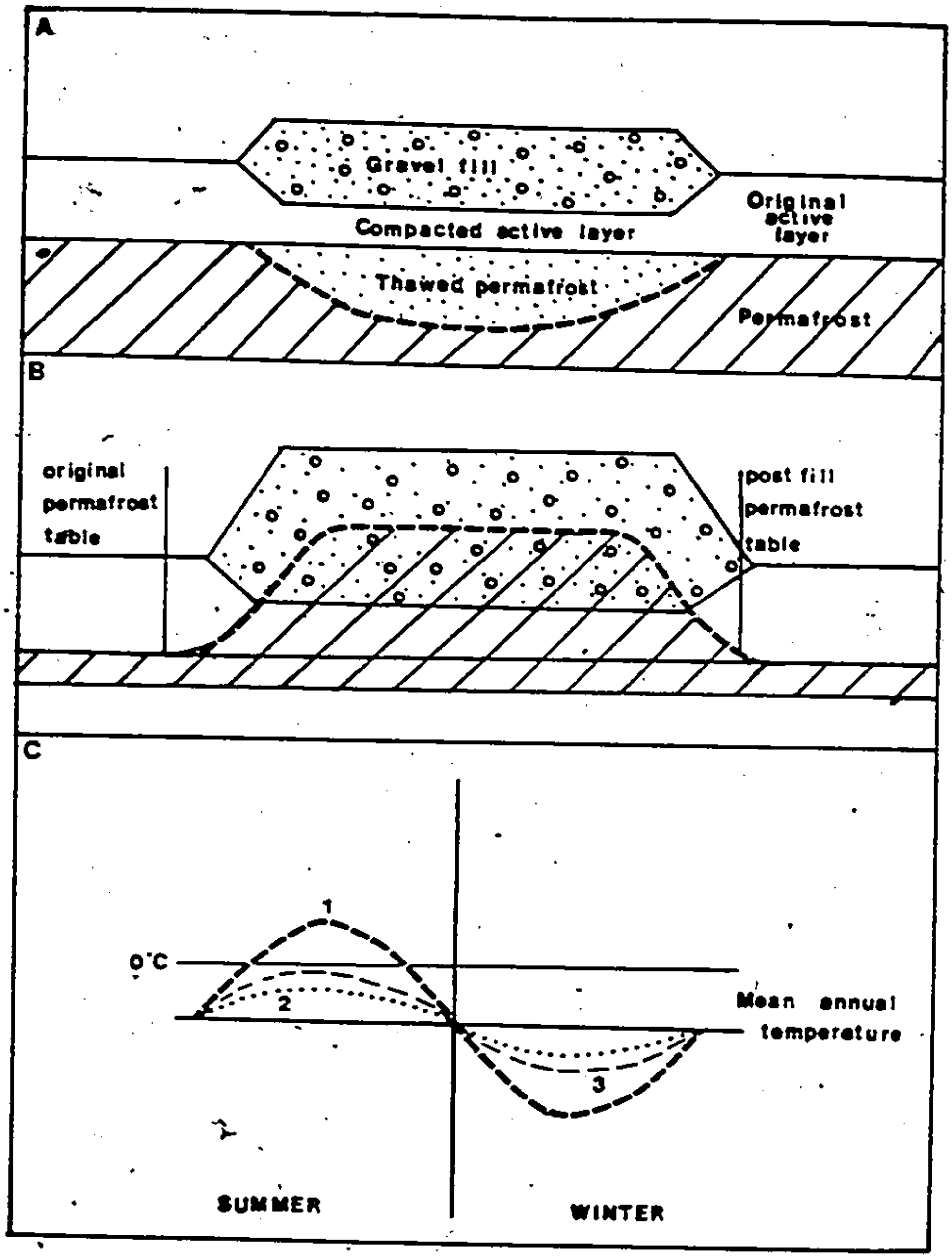


Figure 19. Diagram illustrating the effects of different thicknesses of fill on active layer thickness and ground thermal regime (Ferrians et al., 1969). A) Too little fill; B) Too much fill; C) Thermal regimes: (1) effect of too little fill upon the thermal regime; (2) effect of too much fill upon the thermal regime; (3) original temperature at the permafrost table.

2.2.6 Vehicle movement

Most studies have been concerned with the effects of off-road vehicles on vegetation (Radforth and Burwash, 1977). In addition to vegetation disturbance, compaction of the underlying material may result. Observations show that soil bulk densities and temperatures are higher, thaw depths greater, and moisture contents lower along vehicle tracks that in adjacent undisturbed terrain (Gersper and Challinor, 1975). In another example, 'wet spots' were observed on scraped surfaces in the high Arctic and attributed to the frequent application of pressure by the passage of vehicles on ice-rich ground (Price et al., 1974).

The distinction should be made between the disturbance caused by off-road vehicles and that associated with summer roads. In winter transportation problems are minimized since the ground is frozen. Monitoring of active layer and of road surface elevation of a snow road near Inuvik showed, during the first year, a 43% mean decrease in plant cover while no significant variation in surface elevation or active layer thicknesses was recorded (Younkin and Hettinger, 1978). Nevertheless, continued monitoring is needed to assess long-term effects. In another case, where all vegetation and most peat was removed during construction, active layer depth increased from 33 cm in the undisturbed area to 55 cm while the ground surface subsided 15 cm (Haag and Bliss, 1974).

The most important factors controlling the degree of permafrost disturbance are the amount of traffic, the vegetation type, and the soil stability. In the case of long-term impact, soil depth, drainage, slope, and the presence of coarse materials all play a role (Sparrow et al., 1978). The time of year and the type of vehicle are also significant (Rickard and Brown, 1974). Nevertheless, precise data are not always available as environmental conditions vary due to time of year, snow and plant cover, and the micro-relief.

Recommendations may be summarized as follows: vehicle traffic should be restricted to winter where precautions should be taken to minimize damage (e.g. avoid sloping terrain, the use of low-pressure tire vehicles, etc.). Summer travel should be on roads, the route of which has been selected so as to avoid ground ice bodies. Due to the gently sloping nature of the tundra and the aridity which characterizes many arctic regions, the potential for damage in many areas may be essentially aesthetic (French, 1978b).

2.2.7 Wellsites

Oil and gas exploration involves the construction of sumps, the disposal of waste drilling fluids and the search for aggregate for use at rig sites. Government land use permits require most operations to be confined to winter. Thus, sump construction and/or containment of waste drilling fluids become major concerns (French, 1978c).

A study of the disturbance adjacent to an abandoned wellsite drilled on the Alaskan North Slope in 1949 revealed that hummocky thermokarst topography associated with the melt of ice wedges is still active (Lawson et al., 1979). It was concluded that the most intense and lasting disturbances were due to bulldozing, fuel spills, and vehicle trails. Moreover, "The effect of surface disturbance on surface and subsurface materials and processes in the Arctic is poorly understood" (Lawson et al., 1978, p. 53).

In a survey of terrain problems associated with abandoned wellsites in Canada (French, 1978c, 1980b), it was concluded that approximately 30% experienced problems related to sumps and/or the containment of waste drilling fluids. Least problems were associated with one-season winter drilling operations. Two-season winter drilling, in which the sump is left open during the summer, and one-season summer drilling operations usually present more problems.

2.2.8 Linear facilities

Linear facilities include railways, roads, hydro lines, seismic lines, and pipelines. Their construction may involve considerable terrain disturbance. For example, in the late 1960's, both thermokarst subsidence and thermal erosion were reported from portions of the Tuktoyaktuk seismic lines where bulldozers had crossed areas of high ice content (Watmore, 1969). In the Mackenzie delta, summer bulldozing for a seismic line resulted only in a slight increase in active layer depth; native species reinvaded rapidly (Bliss and Wein, 1972).

'Ground swelling' (i.e. differential subsidence) under railway beds was reported and described from the U.S.S.R. (Datskii, 1950). In fact, the construction of railways may require the application of various techniques as they cover large areas where permafrost conditions may be variable. Attention should be given to both soils and drainage conditions and to the availability of sufficient fill, which becomes a critical factor.

In northern Canada, the projected gas pipelines are of immediate concern. For land use impact: "The right-of-way for northern pipelines is significantly wider than in conventional conditions, both on the stage of working on project specifications and in preparing working drawings" (Spiridonov, 1972).

Research for route selection for the Mackenzie transportation corridor as well as the construction of the Trans-Alaska pipeline provide an abundance of observations, data, and maps on the effects and sensitivity of the tundra to man-induced disturbances (Everett et al., 1978; Johnson and Rowe, 1977). The experience gained has led to many recommendations. For example, in the case of a warm oil pipeline, installation above ground is required to allow heat dissipation through the air. By contrast, gas pipelines must be buried, and this may create frost heave problems, especially in the discontinuous permafrost zone (e.g. Williams, 1979). Additional problems may also arise; for example, when pipelines cross rivers or creeks they may be subject to ice damage (Ferrians et al., 1969). As with most linear facilities, ". . . the correct selection of the route is practically impossible without comprehensive study; and the losses due to mistakes incurred by the absence of needed information would be considered higher than the cost of research" (Spiridonov, 1972). At the present time, cost seems to be the most limiting factor, while construction techniques are related to the soils and permafrost conditions encountered along the route.

2.3 Terrain Sensitivity Mapping

2.3.1 History of mapping in permafrost regions

Early geomorphological maps (e.g. St-Onge, 1965) serve as a necessary stepping stone to the development of the applied aspects of geomorphology. The first applied maps were those sponsored by the Geological Survey of Canada and the Department of Indian Affairs and Northern Development, when selection of the Mackenzie Valley Transportation corridor was undertaken in the early 1970's. These are the 1:250,000 Terrain Classification and Sensitivity Maps which illustrate land response to disturbances in relation to surficial geology (e.g. Hughes, 1970). Terrain Disturbance Susceptibility Maps were also elaborated at a larger scale for smaller areas (e.g. Kurfurst, 1973), and terrain sensitivity photomosaics were prepared by J. C. Sproule and Associates, under contract to Indian and Northern Affairs (Sproule, 1972-1974).

In the mid 1970's, a Terrain Classification and Evaluation Map was conceived as a pilot study for integrating both data collection and presentation, using a multidisciplinary approach (Barnett et al., 1975, 1977). By the late 1970's many of these terrain maps existed, other examples being those by D. A. Hodgson (1978); D. A. Hodgson and S. A. Edlund (1977); and, P. J. Kurfurst and J. J. Veillette (1977). The Trans-Alaskan Pipeline Project provided an opportunity for 1:12,000 maps showing the landforms expected in a 3.5 km wide corridor along the proposed route (Kreig and Reiger, 1976). Finally. K. R. Everett et al. (1978) produced a geoecological terrain sensitivity map of coastal tundra in Alaska which brings together a combination of soils, vegetation, and landform data.

Current trends are that more detailed site specific investigations and the refinement of the geoecological mapping approach are to be expected (French, 1980a).

2.3.2 The geoecological approach

Susceptibility and sensitivity imply the response of a given terrain type to impact. As such, they are highly subjective concepts. For example, a sparsely vegetated range may generally be said to be less sensitive to disturbance as vegetation has a small thermal protection role but it can also be said to be highly sensitive if it is considered as the range for ungulates (Barnett et al., 1977). Therefore, it is essential for terrain characterization to identify the regional differences which are significant to the intended user.

Most often data for maps are drawn both from air photo interpretation and from field observations. Barnett et al. (1975) suggest a minimum working scale of 1:250,000, while Webber and Ives (1978) argue that a scale smaller than 1:10,000 is of little practical value. Obviously, the larger the scale, the more the map is applicable with precision; scale selection remains often influenced by the available photographic and topographic maps, and by the time and money available.

Basically, two different approaches can be recognized: the geobotanical and the geoecological. The former is the most widely used (e.g. Barnett et al., 1975), the latter the most recent (e.g. Everett et al., 1978). Generally, in the geobotanical approach, surface material is considered the key element of potential disturbance while in the geoecological approach, a terrain sensitivity map is produced bringing together a number of different combinations of soil, vegetation, and landform data.

Other approaches include those of T. A. Babb and L. C. Bliss (1974b) where emphasis is on soil and vegetation susceptibility to disturbance. However, criteria to determine the sensitivity groupings are obscure; and the scale used (1:2.85 million) is not useful.

Synthetic terrain sensitivity maps at a scale of 1:1,000,000 have been produced for the Mackenzie Valley (Van Eyk and Zoltai, 1975). These incorporate mapping by Kurfurst (1973) among others, and show surficial geology and terrain sensitivity based on ground ice, slope, material, and insulating cover. Other approaches include the TAPS (Trans-Alaska Pipeline System) landform classification system. This provides a soil and terrain conditions data bank which helps produce photomosaic maps at a scale of 1:12,000, together with geological and geotechnical characteristics (Kreig and Reiger, 1976). In the U.S.S.R., terrain sensitivity is estimated on the basis of previously existing geocryological maps (e.g. engineering-geological maps, regionalization maps according to type and intensity of thermokarst, thermal erosion, and frost heaving). Furthermore, systematic photogeologic mapping of areas under development is presently being conducted (Brown and Grave, 1979). In North America, Mackay (1972) has suggested that research into the origin of ground ice could contribute to a more economical terrain disturbance mapping scheme. An initial start has been made in this direction (e.g. Pollard and French, 1980).

Perhaps the best example of the geobotanical approach is that produced for the Cornwallis, Bathurst, Eastern Melville, and adjacent islands of the Canadian Arctic Archipelago (Barnett et al., 1975, 1977). Here, surficial materials are considered significant elements of the terrain when potential for disturbance is being considered. Therefore, they form the nucleus around which other terrain factors are grouped. For a rational assessment of the problem it is believed information is needed on (a) surficial materials, e.g. ice content, texture, engineering properties, (b) topography and landforms, (c) geomorphic processes, (d) drainage, (e) vegetation, e.g. percent coverage, and composition, (f) summer temperatures and moisture balance in the soil, and (g) wildlife. The data are gathered either from integrated studies or from aerial photography, supplemented by ground reconnaissance with shallow drill cores.

The geoecological scheme (Everett et al., 1978) emphasizes both the biophysical and the geotechnical properties of the terrain.

The philosophy behind this approach is based on the similarity between the vegetation, soil, and landform boundaries. In areas underlain by permafrost, existing landforms provide a maximum interrelation between soils and vegetation. This is probably a reflection of the harsh arctic environment, where plant, animal, and soil development are governed by limiting factors, microclimatic differences, and competition between species. Under certain local climatic conditions, or terrain and landform characteristics, soil formation and vegetation colonization will be a function of the severe environment and of any limiting factor. For example, underlying a high-centered polygon, soils will be cold, wet, and mottled (e.g. Pergelic Cryaquoll or Humic Cryic Gleysol), a reflection of the reducing environment. The vegetation will be that of relatively poorly-drained areas, e.g. Carex aquatilis, Saxifraga oppositifolia. Nevertheless boundary delineation remains subjective as terrain properties are highly variable even within a given landform unit. For example, the moisture content at the edges of a low-centered polygon and in the center may vary. The difference may be sufficient to host different plant species.

Soil and vegetation maps are combined with geomorphic units. A master map is elaborated from which derived maps are available, depending on the user's needs. The information upon each landform unit must be manipulated in response to factors such as season, type of disturbance, frequency of impact. As such " . . . perhaps the most complex of all the derived maps developed to date involve terrain sensitivity" (Everett et al., 1978, p. 363). This is due to the interdependence of many of the variables and to the absence of unifying theories or concepts on terrain sensitivity.

CHAPTER III

WELLSITE DISTURBANCES

3.1 Introduction

In recent years, disturbances associated with oil and gas exploration have changed in nature and extent. In the 1960's and early '70's, important problems related to seismic operations and to transportation aspects (e.g. Bliss and Wein, 1972). Today, mainly because of the strict application of the Territorial Arctic Land Use Regulations and the co-operation of industry, major concern has turned to sump construction, the disposal of waste drilling fluids, and vehicle movement around wellsites (French, 1978a, p/ 12; 1980b). This present chapter examines terrain disturbance at two wellsites in the Arctic islands.

3.2 Dome Wallis A-73 Wellsite, King Christian Island

3.2.1 Site layout

The well was commenced on May 16, 1980. At the time of the visit, terminal depth had nearly been achieved (c.3669 m) (figures 20 and 21). The well was directionally drilled and the mud system being used was a barite/bentonite mixture.

Access to the site was by helicopter from the King Christian Island airstrip located on the southeast

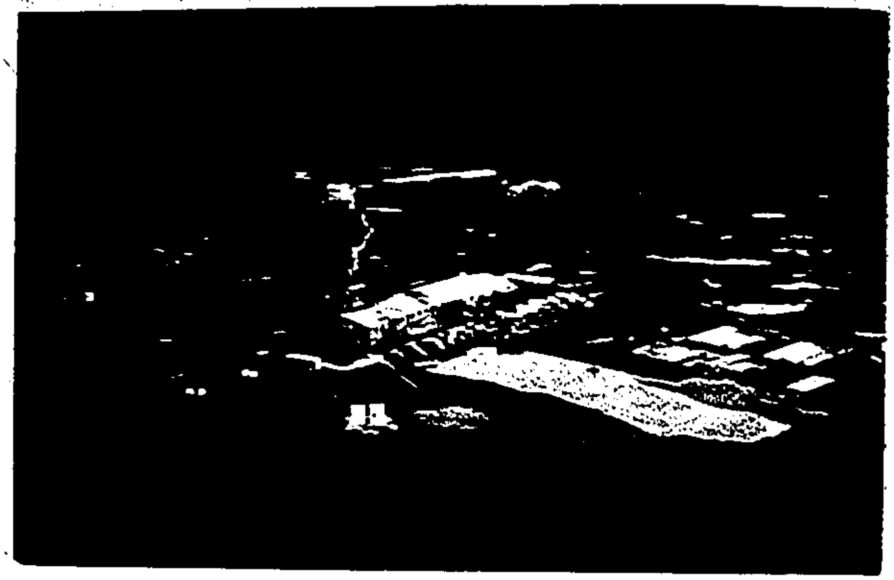


Figure 20. Oblique air view of the Dome Wallis A-73 wellsite, King Christian Island, July 27, 1980. Note the melt-out of the sump wall adjacent to the bladder farm and the wet nature of the surrounding disturbed tundra.

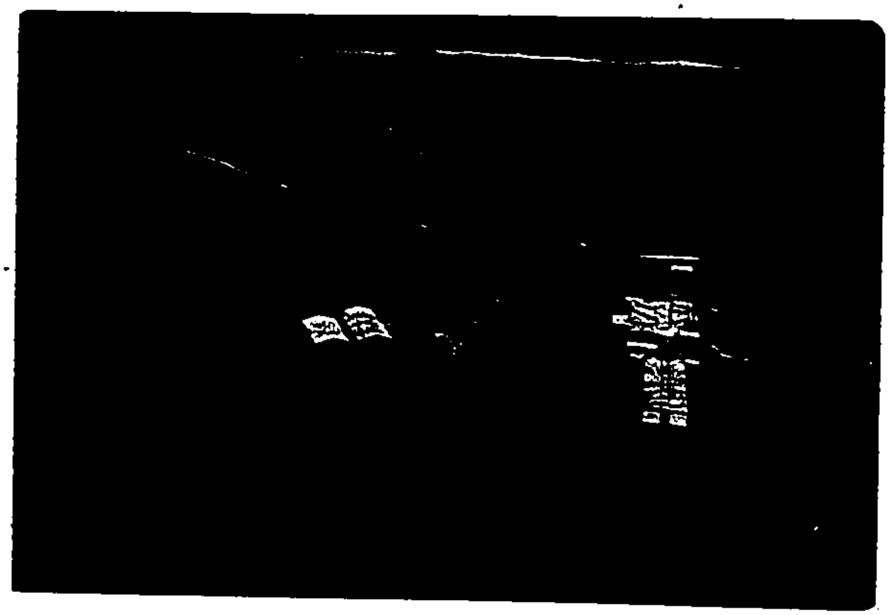


Figure 21. Living quarters, Dome Wallis A-73 wellsite, July 27, 1980. Note the rutting which has occurred following vehicle movement in early spring. At the time of visit, movement was restricted to the catwalk and access to the site was by helicopter.

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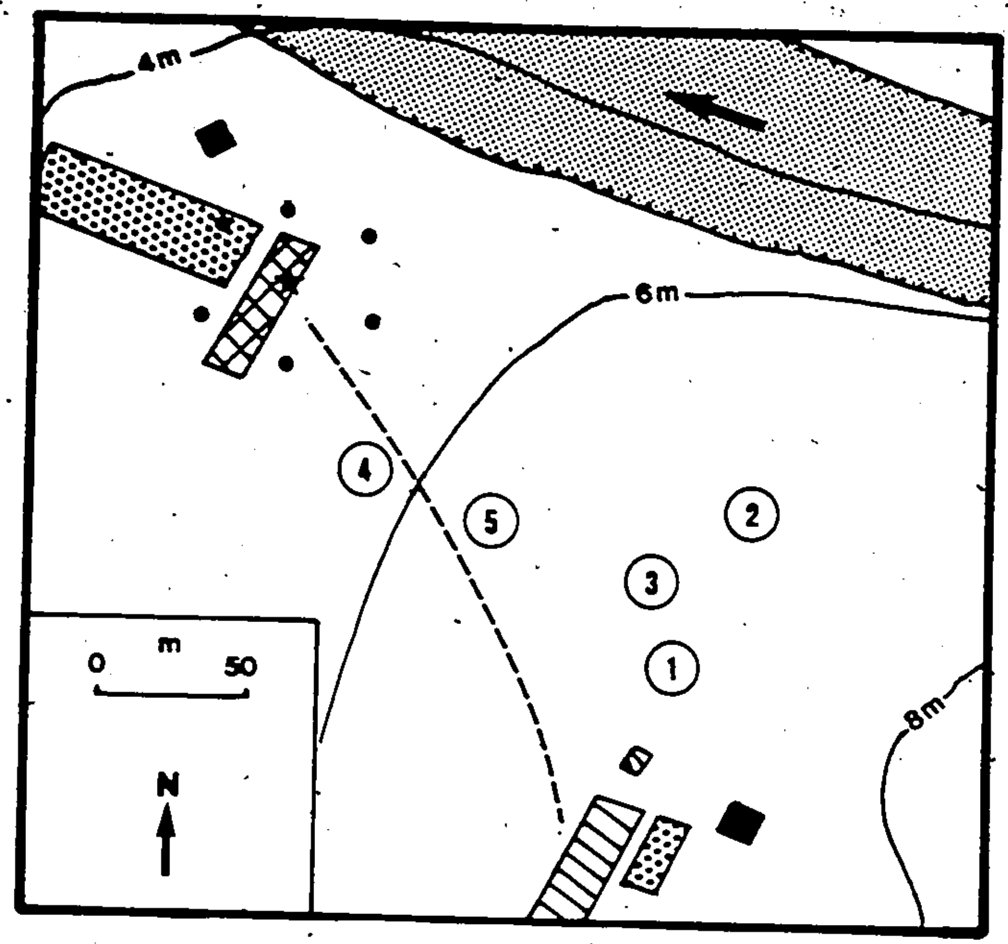
corner of the island. The site plan is given as figure 22. The living quarters and the rig lie approximately 0.25 km from each other. The main sump is at right angles to the rig pad and measures 90 x 25 m. At the time of the visit, approximately 2 m of freeboard still remained (figure 23). The lease area is gently inclined with a relative relief of approximately 4 m. The area actually covered by installations (i.e. rig, main sump, living quarters, camp sump, burn pit, and flare pit) is small, approximately 5,000 m^2, distributed over the lease area of approximately 85,000 m^2. The camp site lies approximately 7 m above sea level while the rig and the main sump are between 4-5 m above sea level.

3.2.2 Terrain conditions

In the spring of 1980, surficial drilling around the well, undertaken by Alterra Survey Limited, revealed the presence of siltstone with ice contents varying from nil, to layers of ice, approximately 0.3 m in thickness (table 4).

In July 1980, investigations of active layer conditions and surficial materials at a number of sites, revealed thaw depths varying from 30 cm in undisturbed hummocky terrain to 50 cm in wet disturbed areas (figure 24). However the thermal regimes of sites 2 and 3 are similar indicating that in the disturbed site, vehicle movement has not resulted in a significant increase in



Source: Alterra Surveys Ltd., April 1980.

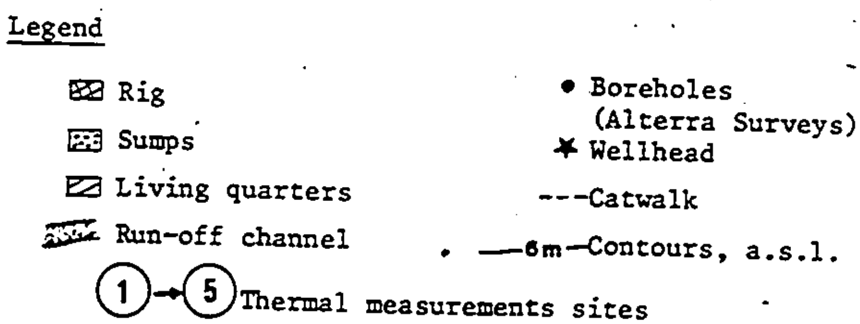


Figure 22. Dome Wallis A-73 site plan, King Christian Island.

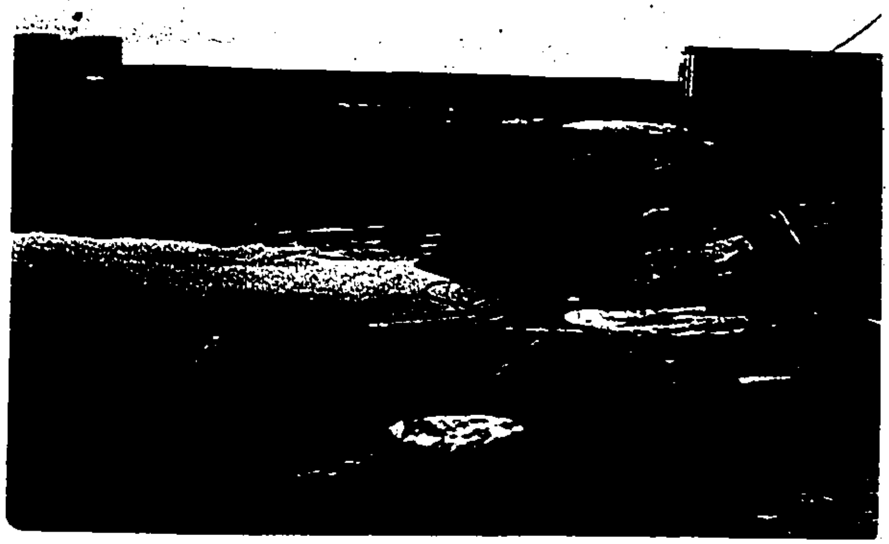


Figure 23. Main sump, Dome Wallis A-73 wellsite, July 27, 1980. Sheeting and boards reduce melt-out of the sump wall adjacent to the rig.

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TABLE 4

SURFICIAL DRILLING DATA OBTAINED BY ALTERRA SURVEYS LTD., FROM BOREHOLE DRILLING IN A 30 m RADIUS OF DOME WALLIS A-73 WELLHEAD APRIL 10, 1980

Borehole	Drilling Data	
A	0' - 3'	Siltstone (no ice)
	3' - 4'	Ice
	4' - 43'	Siltstone (no ice)
B	0' - 43'	Siltstone
C	0' - 13'	Siltstone with small ice lenses
	13' - 43'	Siltstone (no ice)
D	0' - 8'	Siltstone (no ice)
	8' - 13'	Siltstone with small ice lenses
	13' - 18'	Siltstone (no ice)
	18' - 28'	Siltstone with small ice lenses
	28' - 43'	Siltstone (no ice)
E	0' - 15'	Siltstone (no ice)
	15' - 16'	Ice
	16' - 43'	Siltstone (no ice)
F	0' - 15'	Siltstone with small ice lenses
	15' - 43'	Siltstone (no ice)

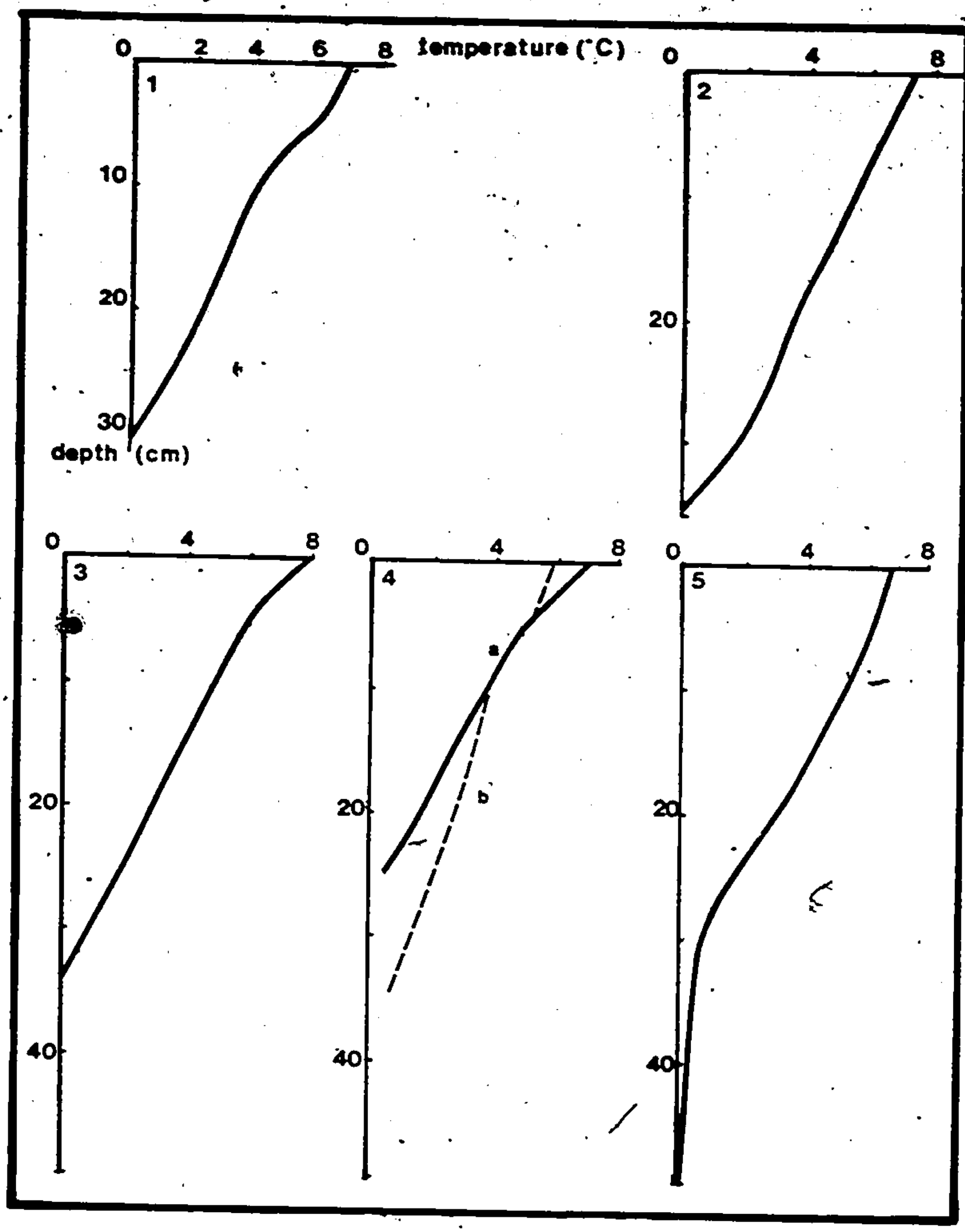

Figure 24. Active layer thermal regimes adjacent to Dome Wallis A-73 wellsite, King Christian Island, July 27, 1980.
Site 1: Undisturbed, hummocky terrain (dry).
Site 2: Undisturbed depression (wet).
Site 3: Vehicle track (dry).
Site 4: Churned up area (a) wet; (b) dry.
Site 5: Disturbed area, flat (wet).

thaw. The limited role which the surface organic layer plays in controlling the thermal regime of the active layer in polar desert environment has been commented upon earlier by Bliss (1975).

Although no obvious relationship was established between ground-ice content, surficial material, and vegetation, excess ice contents were found to be variable. For example, samples of the icy sediment exposed in the main sump's wall contained 55-70% excess ice (figure 25). Although such an ice body was not revealed by the Alterra Surveys Limited investigations, this ice body was exposed throughout the sump and appeared to be widespread. Given the silty nature of the overburden, it must be concluded that the Dome Wallis wellsite is underlain by highly sensitive terrain.

3.2.3 Extent and nature of terrain disturbances

Several reasons explain the considerable amount of surface rutting around the wellsite. First, the ice-rich nature of the silty sediments inevitably leads to muddy conditions. In mid summer, walking between the installations was only possible by 'catwalks' (figure 26), and a helicopter pad had to be installed for normal access to the site. Certain areas showed evidence of water saturation of the active layer. Liquification, consequent upon repeated trampling by foot, was easily obtained.

Figure 25. Massive ice exposed in the sump wall at Dome Wallis A-73 wellsite, King Christian Island. The origin of this ice is uncertain; it may be beach-fast or sea ice buried beneath silty colluvium. Photo: July 27, 1980.

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Second, vehicle movement in the early thaw period probably led to the destruction and removal of the surface organic layer as well as to soil compaction. In the case of excessive movement, rutting has occurred (figure 27).

Melt-out around the sump is related to the presence of the massive ice body. Polyurethane sheets, which line the sump walls, operated to reduce the degree of melt-out. However, given the unconsolidated nature of the over-burden, its thinness (<1 m), and the fact that the A-73 well was a summer operation, degradation of the sump walls is inevitable (e.g. see French and Smith, 1980, for thermal conditions adjacent to sumps).

A number of compaction values were made at various localities around the rigsite. These are tabulated in table 5. Modal shear strength values of undisturbed terrain were 0.42 kg/cm² while those for disturbed terrain were significantly higher, ranging between 0.47 and 0.70 kg/cm². However, the fact that thermal regimes in both disturbed and undisturbed sites were approximately the same (see figure 24) indicates that the increase in thermal conductivity associated with this increase in compaction is not significant. In all probability, the more important control over the thermal regime is the preservation, albeit dead, of any surface organic materials, together with the local moisture conditions.

Figure 26. Extensive vehicle rutting, as shown here, adjacent to the Dome Wallis A-73 wellsite was probably caused in early spring. Gullying along tracks was minimal on account of the gently sloping terrain. Photo: July 27, 1980.

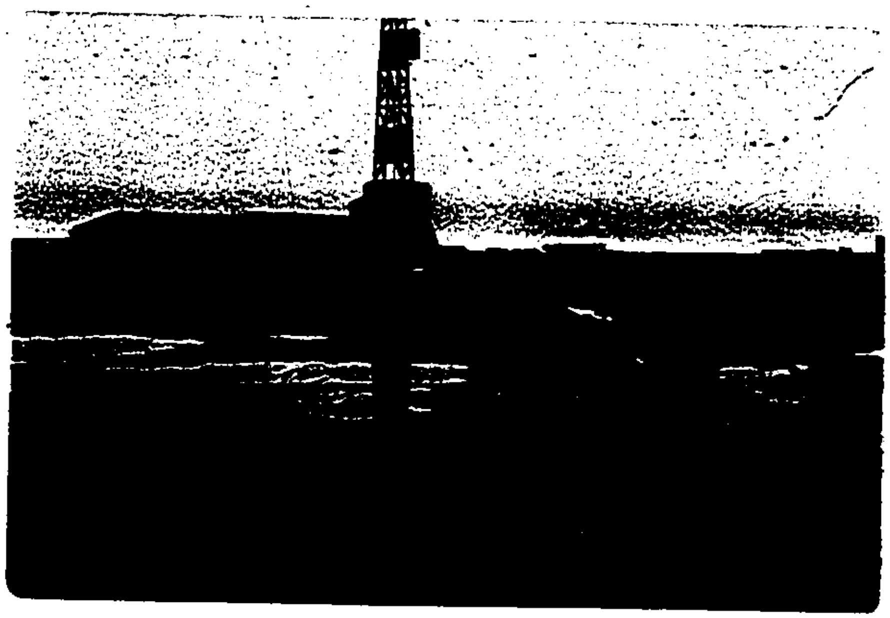

Figure 27. Local site conditions at Dome Wallis A-73 wellsite, July 27, 1980. Silty colluvium, derived from Christopher Shales, underlies the site.

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TABLE 5

ACTIVE LAYER AND TERRAIN CONDITIONS ADJACENT TO DOME WALLIS A-73 WELLSITE, KING CHRISTIAN ISLAND (JULY, 1980)

Site No.	Site Description	Active Layer Depth (cm)	N	Shear Strength: Range (kg/cm^2)	Shear Strength: Modal Value (kg/cm^2)
1	Undisturbed hummocky terrain; clayey silt	31	7	0.26–0.63	0.42
2	Undisturbed, depression; clayey silt	35	4	0.06–0.19	0.10
3	Vehicle track, dry; silt	36	4	0.53–0.84	0.70
4	Churned up area; silty dry	between tracks 42 under track 28	7	0.03–1.19	0.70
5	Flat disturbed area, wet; silty clay	58	3	0.42–0.49	0.47

3.2.4 Discussion

The terrain at the Dome Wallis A-73 wellsite is characterized by a relatively high sensitivity. The major variables known to influence sensitivity, namely fine-grained unconsolidated material and high ice contents, are present at the site. Given the shallowness of summer thaw, it may be concluded that the terrain is particularly sensitive to physical disturbance, either by removal or compaction of surficial material.

Vegetation is a complex controlling factor in the high Arctic where the plant cover/active layer depths relationship is non-causal (Babb and Bliss, 1974b). Since severe growing conditions inhibit the development of a strong insulative cover, active layer thickness appears related to moisture conditions. Measurements of the thermal regime at a number of both disturbed and undisturbed sites show this effect (see figure 24). Furthermore, data indicate that disturbed terrain is usually cooler at the surface and warmer at depth than adjacent undisturbed terrain. This is probably due to the lowering of surface albedo following disturbances, combined with the latent heat loss caused by evaporation of surface moisture released by the degrading permafrost.

Given the high sensitivity of the terrain as discussed above, and given the nature of the well drilling operations, some degree of terrain disturbance is to be expected. Since the Dome Wallis A-73 well is a summer operation, it is a 'worst case' situation. In response, the company has adopted several methods to minimize disturbance. For example, catwalks and platforms connect the various installations minimizing movement over the tundra. Also, polyurethane sheeting has been installed to prevent sump melt-out. On the other hand, vehicles moved around the lease when the ground was thawed, resulting in a high degree of rutting and vehicular disturbance. This probably occurred in late spring. At that time, air temperatures were probably still below freezing and vehicle movement was allowed under the Arctic Land Use Regulations. However, snow removal may have led to an increase in albedo and an artificial acceleration of the amount of thaw. Late spring is a critical period therefore, since frozen ground cannot always be inferred, given the mean air temperatures.

Compared with other sites visited during the summer of 1980, the Dome Wallis site possesses a high sensitivity to disturbance. For example, at the Stokes Range wellsite on northern Bathurst Island, the underlying bedrock is a consolidated sandstone, there is little ground ice, and vegetation is virtually non-existent. As a result, terrain sensitivity is low (figure 28). The area is well-drained and the abandoned wellsite is located on a felsenmeer, or block field surface. Disturbance was minimal. For example, the construction of the airstrip

Figure 28. Typical felsenmeer surface adjacent to the Stokes Range wellsite, northern Bathurst Island, July 27, 1980.

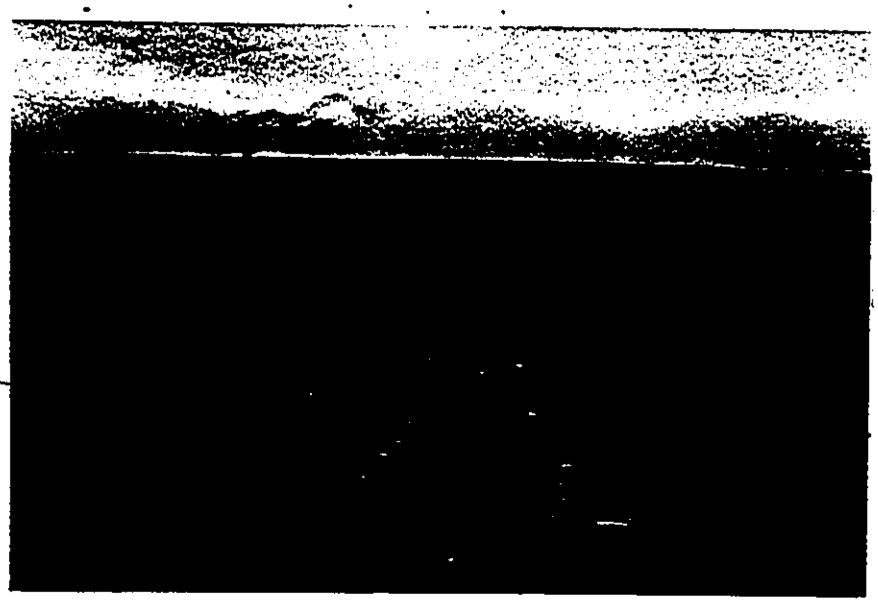

Figure 29. Stokes Range wellsite, northern Bathurst Island. In such a non-sensitive area, the construction of an airstrip produces minimal disturbance.

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produced virtually no disturbance (figure 29).

3.3 Chevron Parker River J-72 Wellsite, Northeast Banks Island

3.3.1 Site layout

The wellsite was drilled during the winter of 1978-1979. Since it was spudded on January 13, 1979 and drilling was completed by May 22, the whole operation was conducted while the ground was still frozen. Total depth achieved was 3,010 m.

Access to the wellsite was by winter road (figure 30) from the Hercules landing strip at Passage Point. The site plan (figure 31) shows that the rig and living quarters lie relatively close, approximately 0.15 km distant.

3.3.2 Terrain conditions

Typical terrain of the area adjacent to the wellsite (see figure 9) consists of a till covered upland surrounded by extensive slopes at angles ranging from 2 to 20°. Areas of meadow tundra occupy poorly drained depressions. The lease area exhibits a transition from upland tundra on the upper slope to meadow tundra on the lower slope and near the creeks (figure 32). Average thaw depths were found to be 64 cm under undisturbed ground, both bare and vegetated while in disturbed areas, active layers vary between 50 and 60 cm deep. As at Dome Wallis A-73, these values indicate the minimal insulative role played by the vegetation.

Figure 30. Access to Chevron Parker River J-72 was by winter road from the airstrip at Passage Point some 15 km away. Damage is minimal, in some areas the route of the winter road is not apparent. Photo: July 28, 1980.

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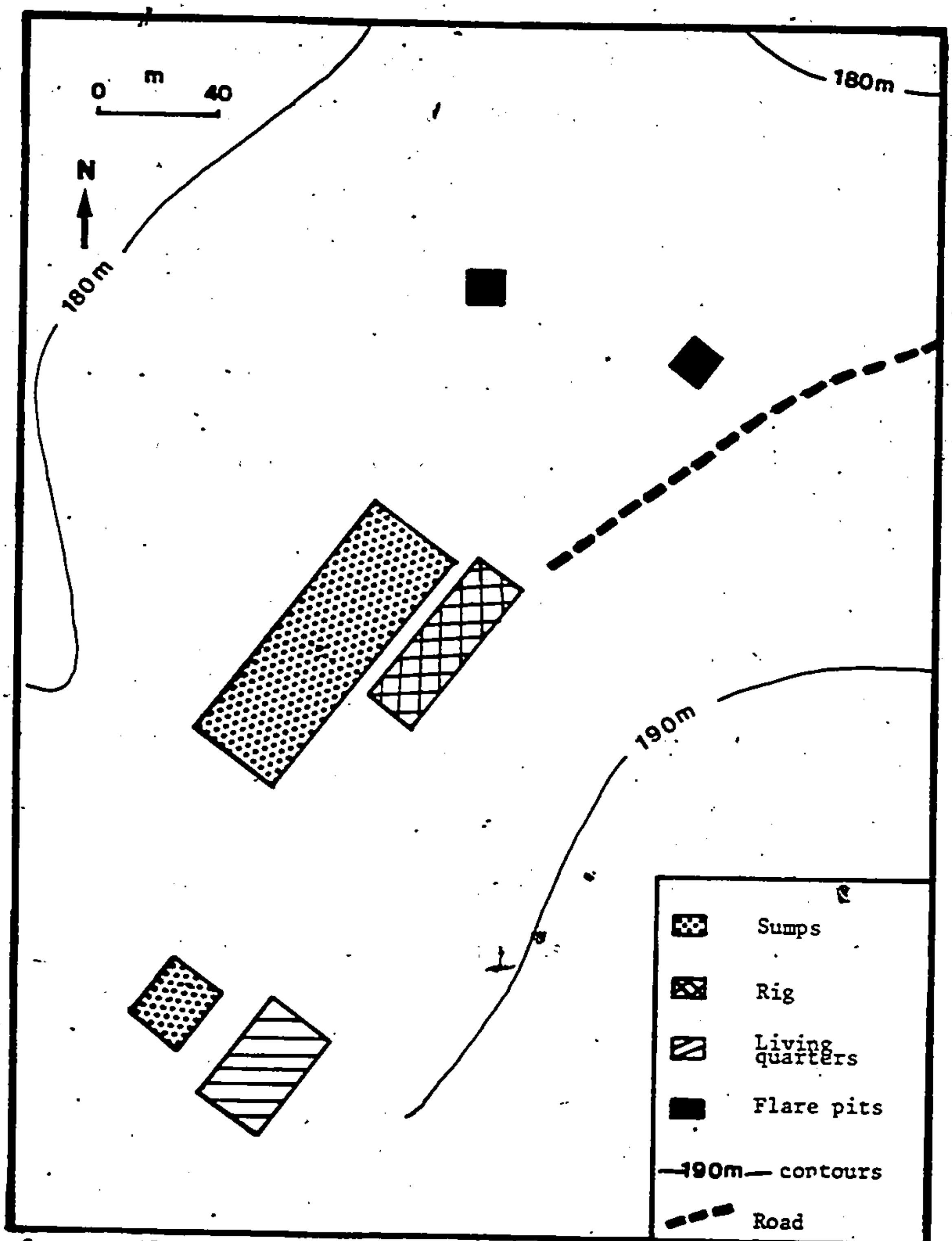

Source: Alterra Surveys Ltd., November 1978.

Figure 31. Site plan of Chevron Parker River J-72.

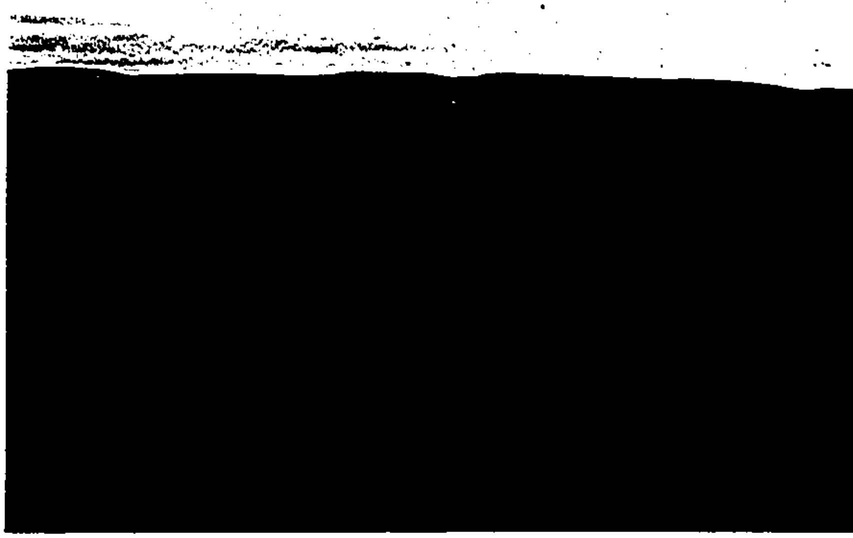

Figure 32. General view of terrain adjacent to Chevron Parker River wellsite, northeast Banks Island, July 28, 1980.

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Soil shear strength values were found to be relatively low, as compared to those recorded on King Christian Island. For example, values in the order of 0.17 to 0.28 kg/cm² in undisturbed areas and 0.28 to 0.39 kg/cm² in disturbed areas were measured. These values indicate 1) the low degree of cohesion of the underlying sediments resulting from their sandy nature, 2) the relatively small increase in compaction which has resulted from vehicle movement and other activities. The latter is probably a reflection of the nature of the winter well drilling operations.

Field investigations did not reveal high ice contents in the underlying sediments. Only in valley bottoms does terrain of relatively high sensitivity exist, due there to the higher water contents and the presence of vegetation.

3.3.3 Extent and nature of terrain disturbances

A terrain disturbance map was compiled in the field by tape and Brunton survey (figure 33). The approach and classification of terrain types was based upon the application of 1) the geoecological mapping approach (e.g. Everett et al., 1978) and 2) the identification of specific types and degrees of disturbance. In total, three undisturbed terrain units and seven disturbed terrain units were recognized. Additional symbols were provided for landscape elements, both natural (e.g. stream channels)

Legend

1. Undisturbed terrain

   a. silty gravelly sand
      < 25% vegetation cover
      <2° slope

   b. silty gravelly sand
      c. 25-35% vegetation cover
      c. 2.5° slope

   c. slope colluvium, solifluction

2. Disturbed terrain

   a. sump infill area

   b. borrow pits area
      (>15 cm removed)

   c. vegetation dead

   d. vegetation mostly dead;
      some recovery (mostly *Salix*)

   e. surface scuffing

   f. covering of vegetation

   g. excess sump material

3. Symbols

slope convexity
slope >5°
seismic shot holes
standing water bodies
alluvial fans
natural stream channel
base line
well head
scarp

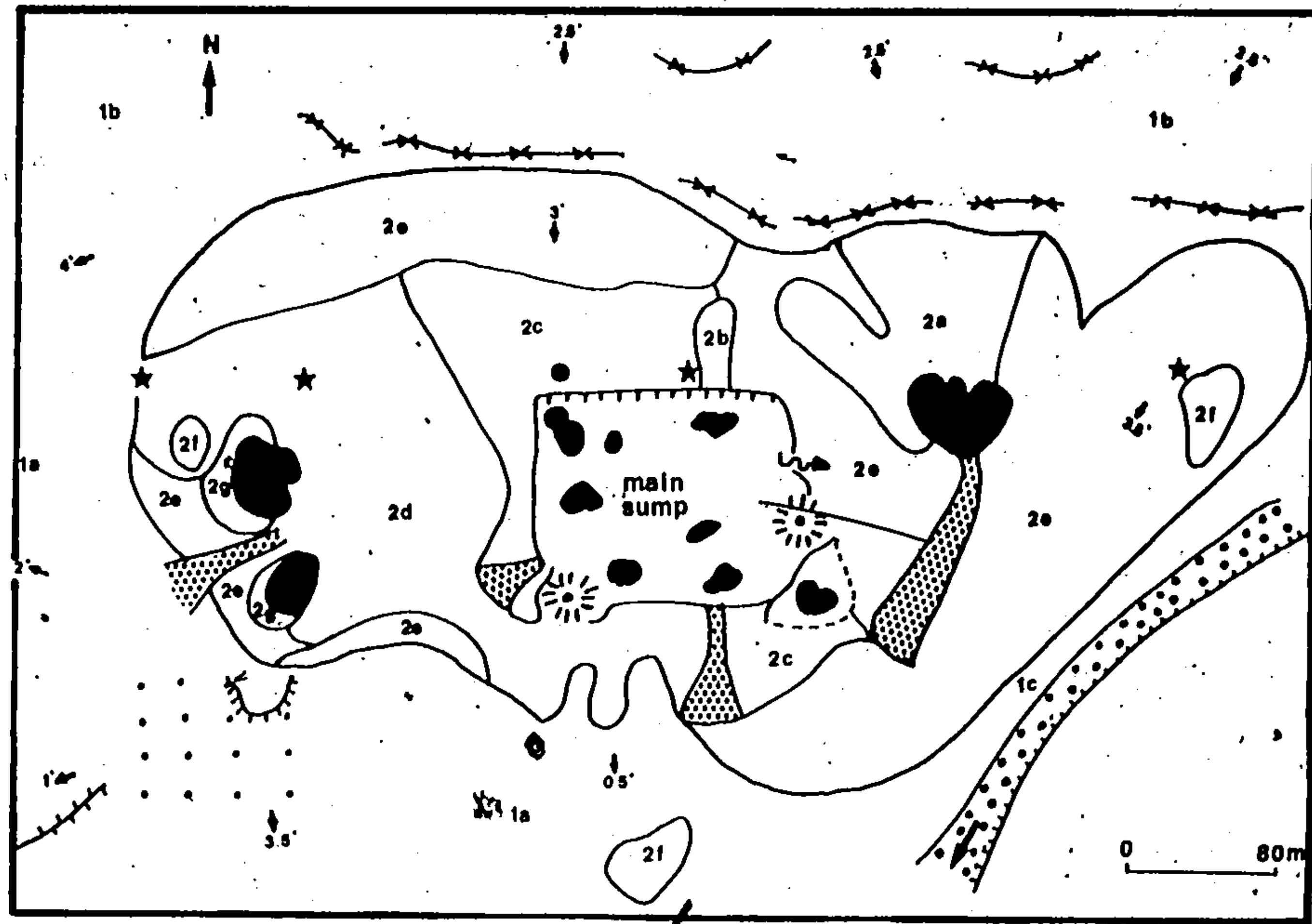

Figure 33. Map showing extent and nature of disturbance around Chevron Parker River J-72, abandoned wellsite, northeast Banks Island. Date of survey: August 1-2, 1980. (Legend is on opposite page.)

and man-made (e.g. seismic shot holes). Natural units were classified according to surficial material, percent vegetation cover, presence or absence of patterned ground, and slope. Disturbed areas were classified according to either the degree of damage to vegetation (e.g. surface scuffing, vegetation dead) or to the nature of the disturbance (e.g. borrow pit area). The scale of the mapping was 1:2,500.

This mapping revealed the extent of disturbed terrain to be limited to the areas adjacent to the wellsites and living quarters. The largest disturbed area consisted of surface scuffing where only slight compaction has occurred (figure 34). More heavily disturbed areas were those immediately adjacent to the well head and north of the main sump. The latter probably reflects the area where the excess sump material was placed. No evidence of rutting was observed and the sump infill had compacted well. There was no evidence of spillage of waste fluids upon the tundra.

Additional disturbance was produced during the site rehabilitation operations (figure 35). These were essentially borrow pit areas where surficial materials were scraped and vegetation killed (figures 36 and 37).

3.3.4 Discussion

The area possesses relatively low susceptibility to terrain disturbance. Thaw depths are naturally deep and differences in depth between disturbed and undisturbed

Figure 34. Disturbed area in vicinity of Parker River J-72 wellsite showing light scuffing and disturbance. Organic material (Salix sp.) unharmed in places as regrowth is apparent. Photo: August 2, 1980.

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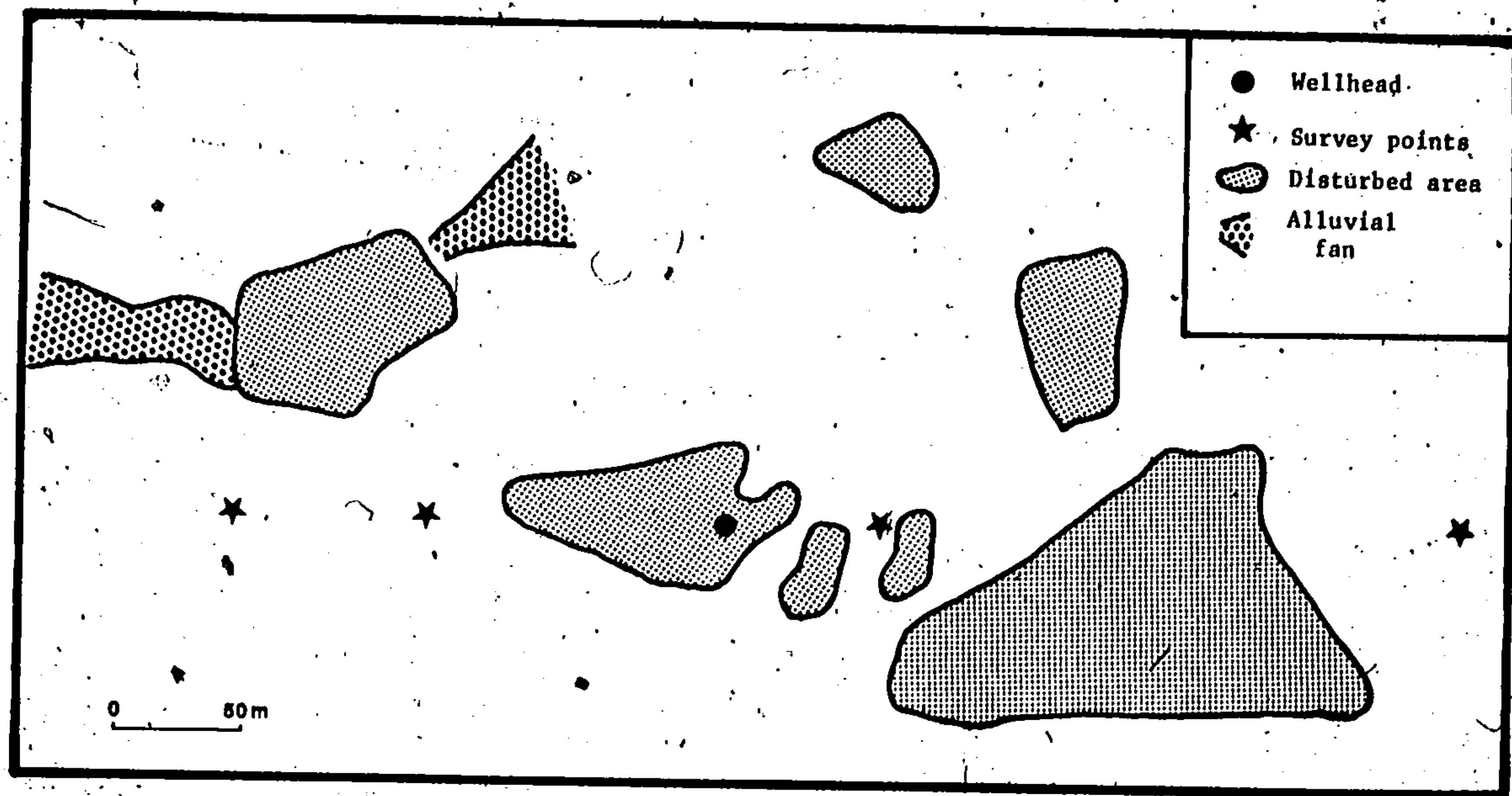

Figure 35. Extent of terrain disturbance initiated by the clean-up operations at Chevron Parker River J-72 (August 3, 1980). Compare with figure 33.

Figure 36. Infilling of depression left in main sump, Chevron Parker River J-72 wellsite. Photo: August 3, 1980.

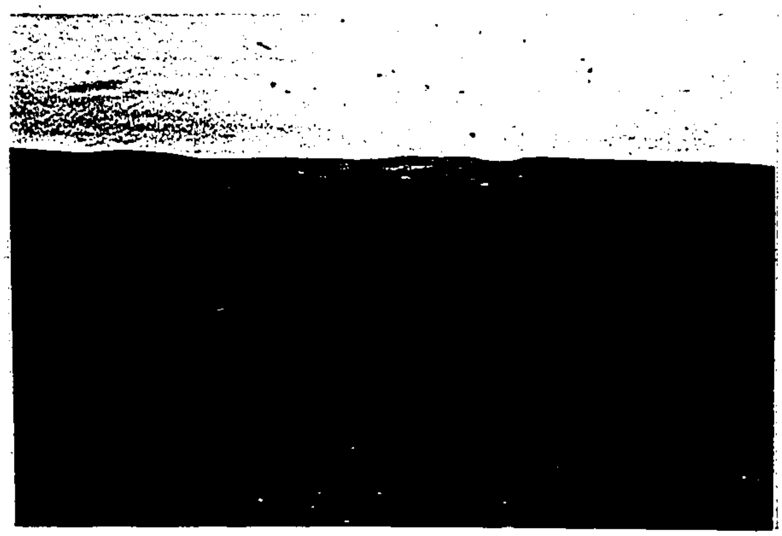

Figure 37. General view of clean-up operations, Chevron Parker River wellsite. Wellhead marked by the sign. Photo: August 3, 1980.

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sites virtually non-existent. Furthermore, soil shear strength values do not indicate severe compaction of the ground during disturbance. The lack of evidence for ground ice bodies and a high ice content also point to a low terrain sensitivity. Finally, the sparse vegetation cover (5-15%) plays a weak insulative role; its disruption does not lead to significant increase in thaw depths.

Most disturbances are essentially physical, that is, removal and/or disruption of surficial material and of vegetation. However, the sandy gravelly nature of surficial materials, the lack of high ice contents, and the gentle slope all combine to minimize subsequent terrain disturbance. Areas affected by disturbance are restricted to the lease area and, apart from the sump, the major terrain damage occurred during site rehabilitation.

The major conclusions emerging from these observations are as follows: 1) In terms of degree of disturbance, summer drilling, as represented by Dome Wallis A-73, presents more problems than winter drilling, as represented by Chevron Parker River J-72. 2) As discussed above, terrain sensitivity is higher at the King Christian Island site, where unconsolidated shales with high ice contents underlie the site, than on northeast Banks Island where the surficial materials are sandy tills with low ice contents. The degree of disturbance at the Chevron Parker River J-72 is small in comparison to that at Dome Wallis A-73.

There are several observations of relevance to the Territorial Arctic Land Use Regulations. First the Dome Wallis site illustrates that terrain damage, especially rutting, can occur in late spring. This is a critical period and the necessity of close control of operations at that time of year is highlighted. Second, the Banks Island site illustrates that disturbance can occur during clean-up, particularly associated with minor sump infill operations in late summer. The advantages of site rehabilitation must outweigh the extra disturbance caused, before such work is authorized.

CHAPTER IV

TERRAIN DISTURBANCES AT SACHS HARBOUR

4.1 Local Terrain Conditions

General information concerning the Sachs Harbour area has already been presented in Chapter I. In this chapter, information related to terrain disturbances is presented.

4.1.1 Surficial materials

Interpretation of the glacial history of Banks Island has recently been clarified. Southwestern Banks Island was overriden by an ice sheet in early Wisconsin times (Vincent, 1980b, p. 217). A major ice margin, dated from the Amundsen glaciation (Vincent, 1978, 1980a) lies in the vicinity of Sachs Harbour where it forms a ridge c. 300 m high on which the airstrip is located (see figure 11).

Coastal sections indicate the nature of the sediments which underlie the settlement of Sachs Harbour. Till is overlain by sand which is in turn covered by colluvium. The colluvium is a solifluction layer, rich in gravels and derived from the Sachs Harbour ridge. The sands are fine to medium, yellowish, and well stratified, probably of distal outwash origin. The till, characterized by a blue clayey matrix, contains striated Paleozoic erratics, probably derived from the Shaler Mountains of Victoria Island.

4.1.2 The airstrip

The airstrip, built obliquely across the crest of the Sachs Harbour ridge, is underlain by gravelly, sandy sediments. Borehole data (French, 1975a) indicate variable ground ice conditions. For example, in undisturbed terrain north of the airstrip, natural liquid content varies from 30-1,874% with excess ice values of 10-95% (coarse sand and foliated ice respectively). On disturbed terrain adjacent to the airstrip natural water content varies between 40 and 129% while excess ice occupies 35 to 60% of the total sediment volume (sand and gravel and fine sand respectively). The ground ice conditions suggest that " . . . the overall volumetric ground loss upon thawing of the ice-rich sediments and the ice wedges may be as high as 20-25%" (French, 1975a, p. 136). Natural water (ice) contents were found to exceed the liquid limits. Upon thawing, therefore, these sediments become extremely mobile and adjust to any ground surface changes that may occur through the release of excess water. Ground ice conditions as well as Atterberg limits are given in table 6.

Consistency limits for sediments within the disturbed terrain adjacent to the airstrip at Sachs Harbour are

TABLE 6

GROUND ICE AND CONSISTENCY LIMITS FOR SELECTED SEDIMENTS, ADJACENT TO SACHS HARBOUR AIRSTRIP

Location	Sample Number	Material	Excess Ice (%)	Natural Water Content (%)	Liquid Limit (%)	Plastic Limit (%)	Plasticity Range (%)
Undisturbed terrain (S of airstrip)	A3	silty sand		27	23.5	18.1	5.4
	A4	sand & gravel		26	25.0	20.7	4.3
Disturbed terrain (S of airstrip)	C2	fine sand	60	129	19.0	13.7	5.3
	C3	fine sand	35	86	20.6	15.8	4.8
	C4	sand & gravel	35	40	25.9	18.8	7.1
Airstrip shoulder	D1	fine sand	30	41	18.1	17.5	0.6

Source: French (1975a), tables 2 and 3.

plotted on the plasticity chart (figure 38). These samples are described as inorganic silts and clays and/or very fine sands. All possess low plasticity and thus are highly sensitive to disturbance.

Adjacent to the airstrip, a network of ice wedge polygons is widely developed and particularly visible on air photographs (see figure 11).

Undisturbed active layer depths are provided by measurements taken in various upland tundra areas adjacent to the airstrip (figure 39a). Thaw depths are approximately 70 cm under vegetated areas and 80 cm under unvegetated areas. These data indicate that vegetation is an important thermal insulator in these upland tundra sites. However surface and ground temperatures are highly variable and appear dependent on angle and aspect of the slope. For example, highest surface temperatures are recorded on steep south-facing slopes.

4.1.3 The settlement

The townsite is underlain by colluvium, a product of mass-wasting from the Sachs Harbour ridge. Ground thermal regimes at a number of typical undisturbed sites in the townsite are given in figure 39b. Thaw depths vary between 60 and 70 cm for areas with vegetation cover greater than 50%. As such, thaw depths are less than on the sloping terrain of the Sachs Harbour ridge.

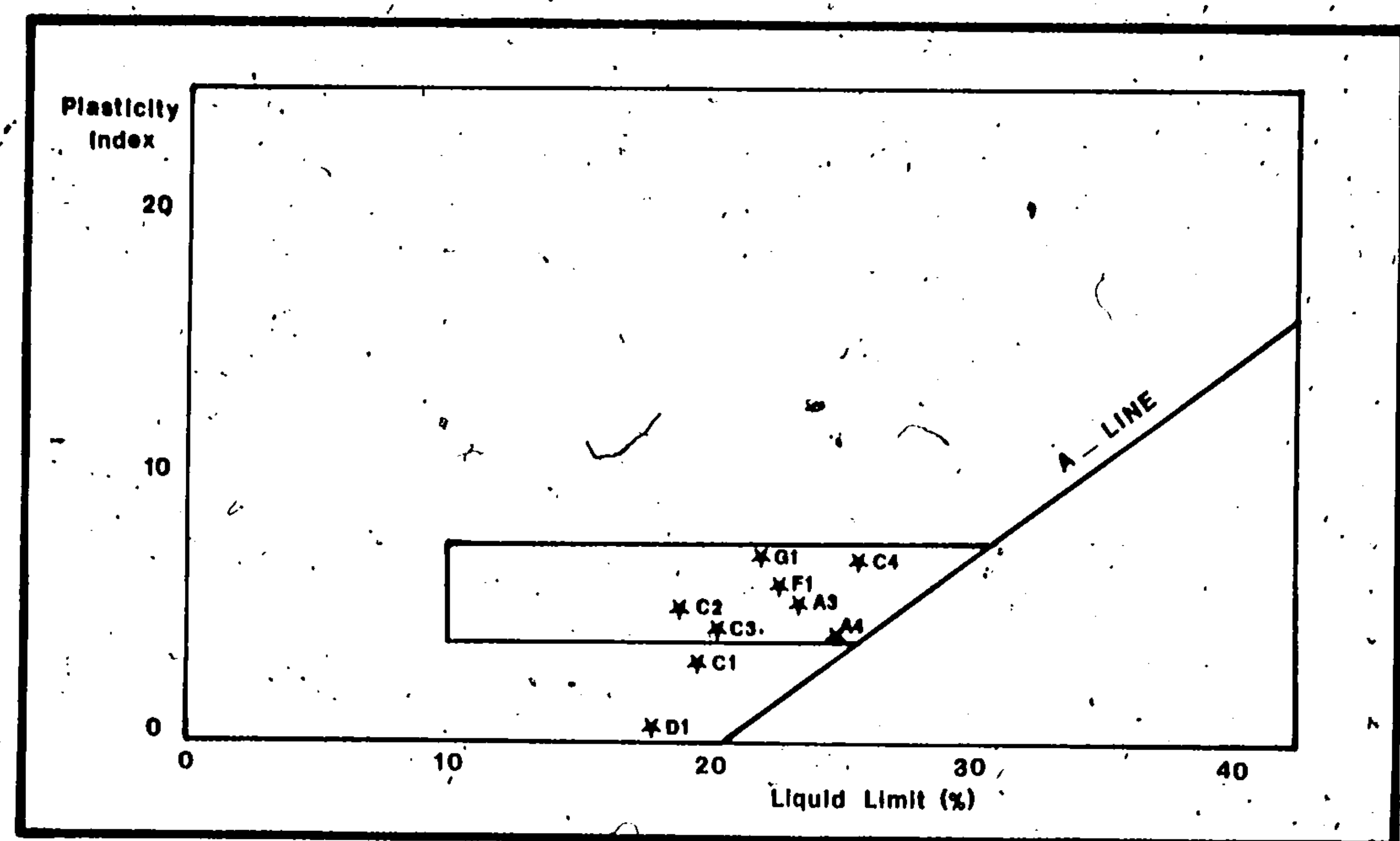
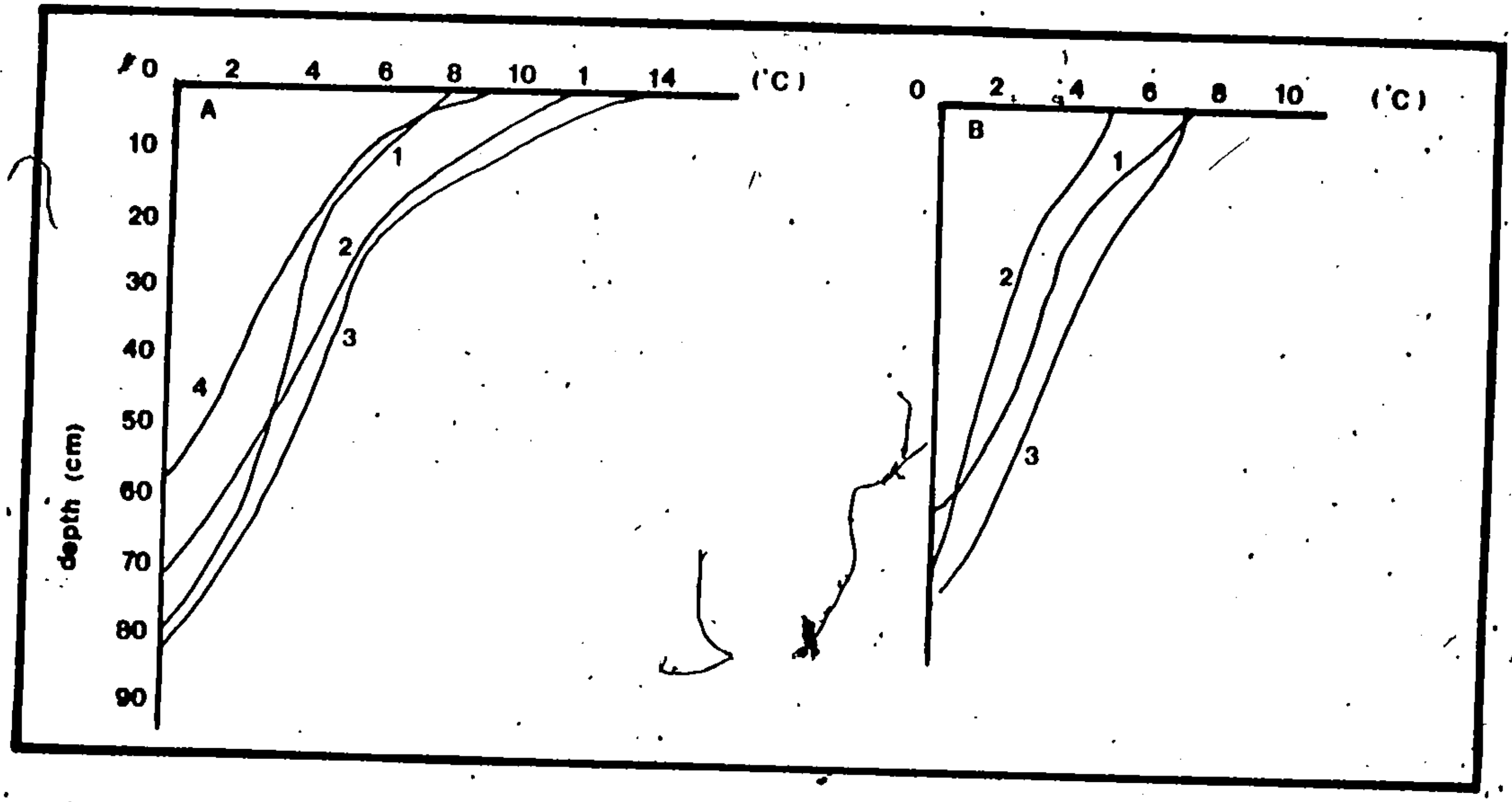


Figure 38. Plasticity chart showing consistency limits of sediments adjacent to the Sachs Harbour airstrip (French, 1975a). Most samples occur in the boxed area and require a double classification (see figure 17).



A) Upland tundra

1. Upland tundra with non-sorted polygons.
2. Upland tundra with no patterned ground.
3. Upland tundra with non-sorted stripes.
4. Well vegetated tundra (90-95% vegetation).

B) South-facing slopes

Sites are characterized by % vegetation cover:
1. 95% (Eriophorum, Salix, grasses).
2. 75% (Salix, some grasses).
3. 45% (Eriophorum, grasses, Dryas).
(Note how the greater is the vegetation cover, the shallower is the active layer.)

Figure 39. Thermal regimes at 7 undisturbed sites typical of: A) Upland tundra adjacent to the airstrip, and B) South-facing slopes on which the settlement is built (Survey; August 6, 1980).

The area thought most sensitive to disturbance occurs at the western limit of the settlement (see figure 14). This area possesses 'wet' tundra characteristics: vegetation is abundant, soil material is fine, and the ridge topography favours the accumulation of large snowbanks immediately upslope. This area however, has been one of the most heavily disturbed since vehicles frequently traversed the area between 1970 and 1975 in order to reach the town dump situated approximately 600 m to the west of the settlement.

4.2 Nature and Extent of Airstrip Thermokarst

4.2.1 Introduction

The major man-induced disturbance in the Sachs Harbour vicinity is that associated with the construction and maintenance of the airstrip. This was built between 1959 and 1962 and is located obliquely across the crest of the Sachs Harbour ridge. While the west end of the strip lies upon the crest, the east-end is aligned southwest-northeast. As a consequence, grading of the airstrip was required to eliminate the east-end depression. For this purpose, as well as for the initial construction, approximately .05 km² of adjacent terrain was disturbed as material was removed during 1959 and 1962 (French, 1975a).

Maps of the airstrip and adjacent disturbed terrain, including the townsite of Sachs Harbour, for 1964, 1968, 1972, 1975, and 1979 may be used to trace the history of terrain deterioration and recovery. From these maps, information such as the total disturbed surfaces associated with the airstrip, and the surface area covered by standing water bodies is compiled. These data are presented as table 7. Also, the evolution of the pattern of ice wedge thaw depressions is mapped to evaluate the speed of morphological stabilization. Finally, disturbances of different ages may be recognized; this provided the opportunity for thermal measurements to be undertaken in the field in 1980, so as to determine, within a time context, the nature and rate of thermal stabilization.

The five maps produced from air photos are presented as figures 40 to 44. Measurement errors are not believed to be excessive as disturbed surfaces were determined to the 0.01 cm^2 on the map, and exact scales were used to operate the transformations. A legend common to the five maps describes both the natural units of the terrain and the disturbed terrain (table 8). Classification of the disturbed terrain was spatial, i.e. disturbances were termed 'at-a-point', 'linear', or 'spatial', rather than genetic, e.g. disturbances associated with the construction of the airstrip, with vehicle movement, etc.

TABLE 7

TABLE SHOWING SURFACE AREAS COVERED BY STANDING WATER BODIES AND THE TOTAL AREA DISTURBED ADJACENT TO THE SACHS HARBOUR AIRSTRIP, 1964-1979*

Year	Disturbed surfaces (km^2)	Surface Covered by Standing Water Bodies			
		Total (km^2)	% of total area disturbed	North of airstrip (km^2)	South of airstrip (km^2)
1964	0.67	-	-	-	-
1968	0.81	0.157	19.8	0.063	0.093
1972	0.80	0.129	10.4	0.054	0.075
1975	0.74	0.026	1.9	0.010	0.016
1979	0.76	0.045	3.4	0.019	0.026

*Note the general decrease of standing water bodies. Data obtained from air photographs.

The mapping of 'disturbed' as opposed to 'undisturbed' terrain was somewhat subjective. Terrain was regarded as disturbed where it was clearly visible material had been removed and/or vegetation disrupted. Because the scales of the air photographs are different, ranging from 1:5,000 to 1:100,000, certain inconsistencies may be present.

4.2.2 Early development, 1961-1964 (figure 40)

Hummocky thermokarst topography appeared within three years of the initial disturbance (see: French, 1975a, p. 137; 1976a, p. 131). The 1961 air photographs, although at a small scale, indicate small thermokarst ponds developed on the southern edge of the airstrip. By 1964, man-induced thermokarst terrain covered 0.67 km². The length of vehicle tracks and other linear disturbances, also associated for the most part with the airstrip, totalled 15.5 km. Spatial disturbances are mostly restricted to upland tundra areas with variable vegetation covers, slope angles, and surficial materials.

The 1964 air photographs also show a number of linear, through-like depressions. These are thought to be due to preferential thawing along the line of ice wedges. Their plan appears consistent with a random orthogonal pattern. While thermokarst ponds and mounds typify much of the borrow pits area, the ice wedge thaw depressions

Legend

A. Disturbed terrain

1. **Spatial**
   - airstrip and shoulders
   - ramps
   - standing water bodies
   - borrow pits, including small thermokarst mounds, 3-5 m maximum diameter, 1 m high

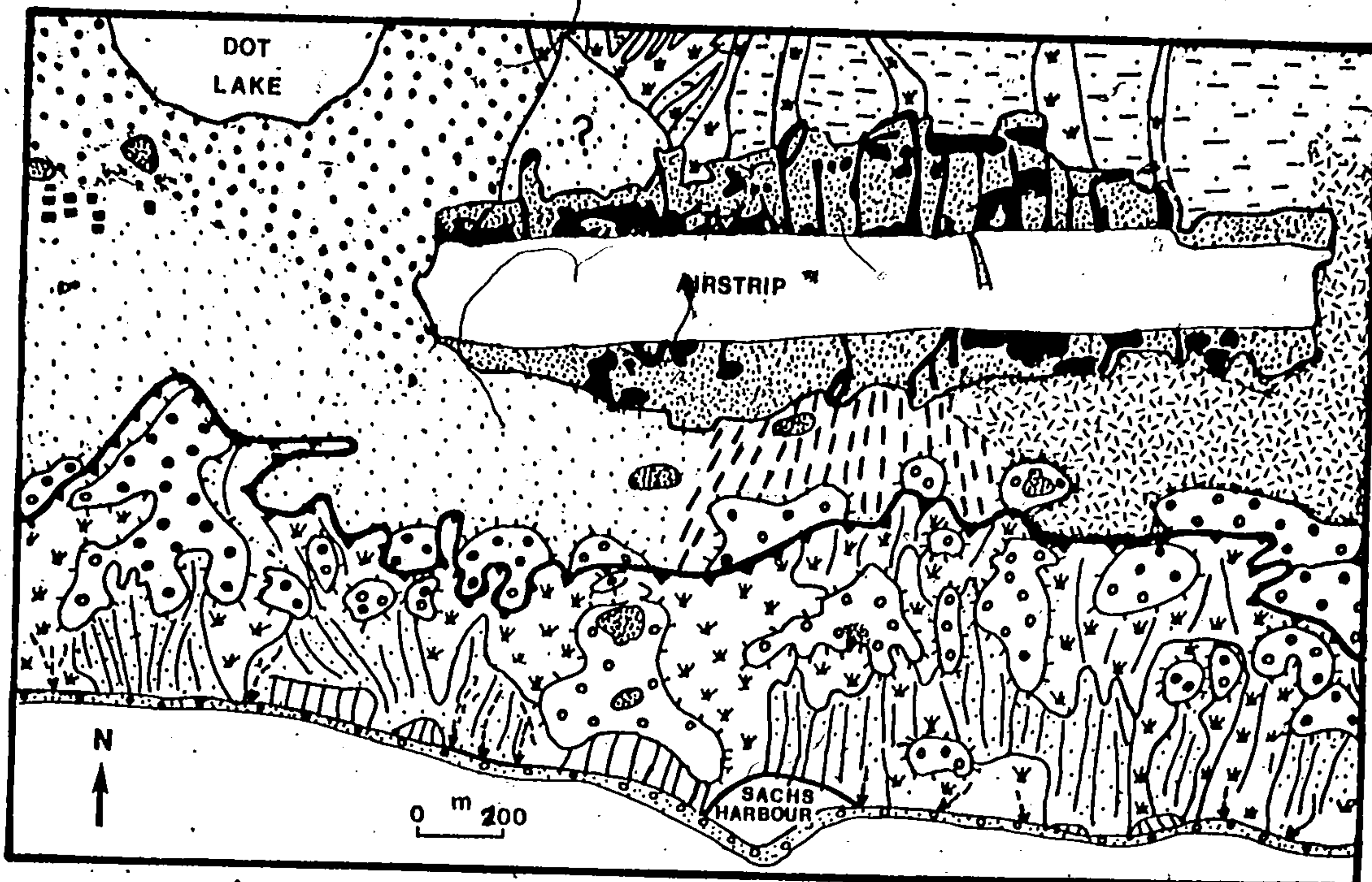
2. **Linear**
   - culvert gully erosion
   - ice wedge thaw depression

B. Undisturbed terrain

1. **Spatial**
   - sandy and gravelly surfaces, little vegetation, well-drained
   - well-vegetated tundra
   - relatively well-vegetated tundra with non-sorted stripes
   - relatively bare tundra with non-sorted stripes
   - beach sands and gravels
   - upland tundra, non-sorted polygons
   - upland tundra, non-sorted stripes
   - upland tundra, thermal contraction cracks
   - upland tundra, thermal contraction cracks and mass-movement
   - upland tundra, no evidence of mass-wasting or patterned ground
   - bedrock?
   - water bodies

2. **Linear**
   - south edge of Sachs Harbour ridge
   - slopes greater than 15°
   - gullies

3. **At-a-point**
   - ▲ owl-perch



Source: NAPL A 18646-5.

Figure 40: A physiographic map of Sachs Harbour airstrip and townsite, 1964.
Date of photo: 8/8/64.

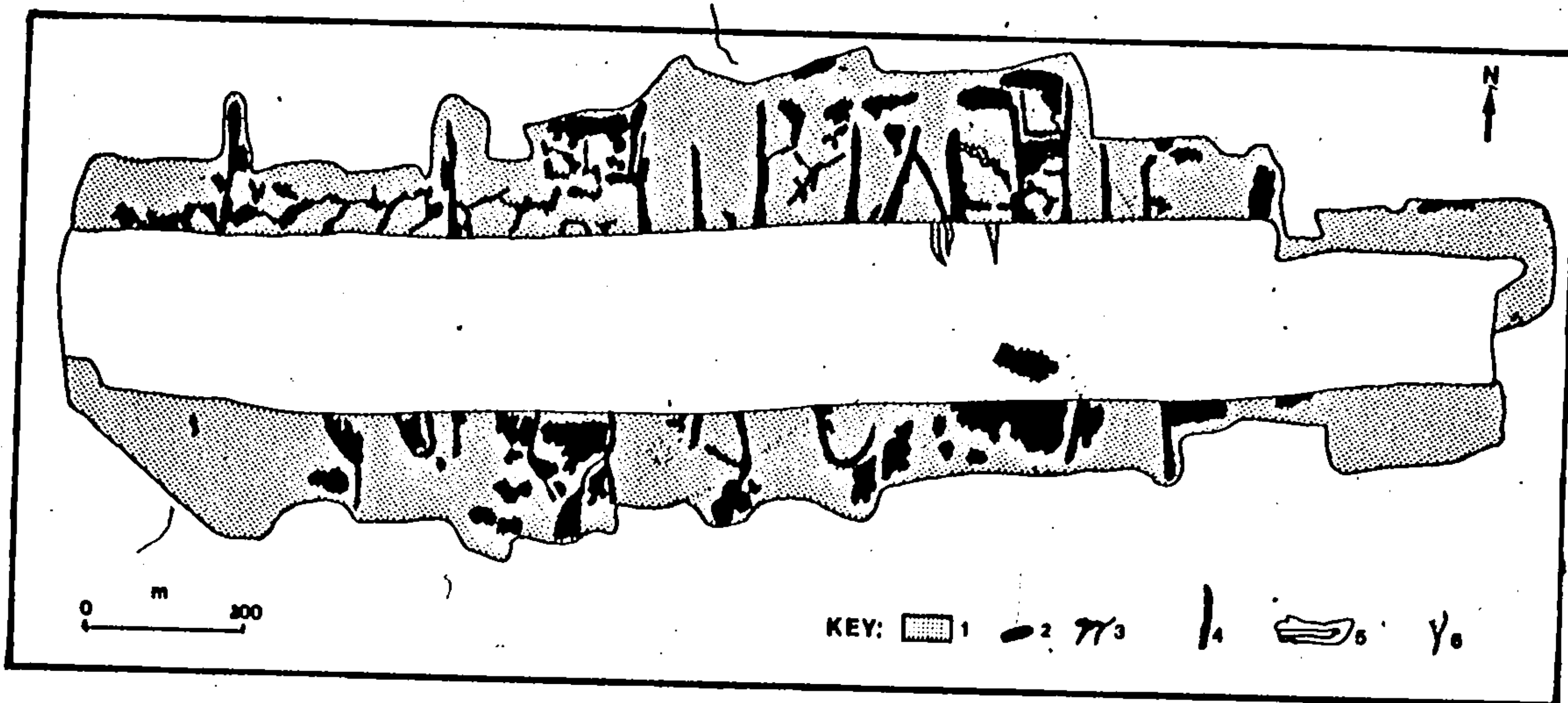
are apparent only in the northwest portion of the disturbed area adjacent to the airstrip.

Also noticeable on the 1964 air photographs is a gully in the east-end airstrip depression. This has been caused by water accumulating in the borrow pits on the higher south side of the airstrip, overflowing across the strip in the spring. In subsequent years, air photos reveal this gully to be a recurrent problem, related to the fact that the airstrip was not properly aligned across the crest of the Sachs Harbour Ridge.

4.2.3 Extent in 1968 (figure 41)

In 1968, the disturbed terrain adjacent to the airstrip increased by 20% to 0.81 km^2, as further aggregate was sought to grade the airstrip. This increase reflects the paucity of suitable aggregate deposits which constitute a thin veneer to the Sachs Harbour ridge.

The same features were present in 1968 as were observed in 1964, with minor modifications: 1) The ice wedge thaw depressions, northwest of the airstrip, appear more integrated than before; the crude random orthogonal pattern can be better recognized. Adjacent undisturbed areas reveal similar contraction crack patterns and support the interpretation that these linear features reflect the preferential thawing along ice wedges. 2) Standing water bodies promoted by thermokarst subsidence and, to some extent, thermal erosion, have increased in size and



Source: NAPL A-20917/79, 81, 83.

Figure 41. Disturbed terrain at Sachs Harbour airstrip, 1968. 1) Borrow pits; 2) Standing water bodies; 3) Ice wedge thaw depressions; 4) Ramps; 5) Airstrip and shoulders; 6) Culvert gully erosion. Date of photo: 3/9/68.

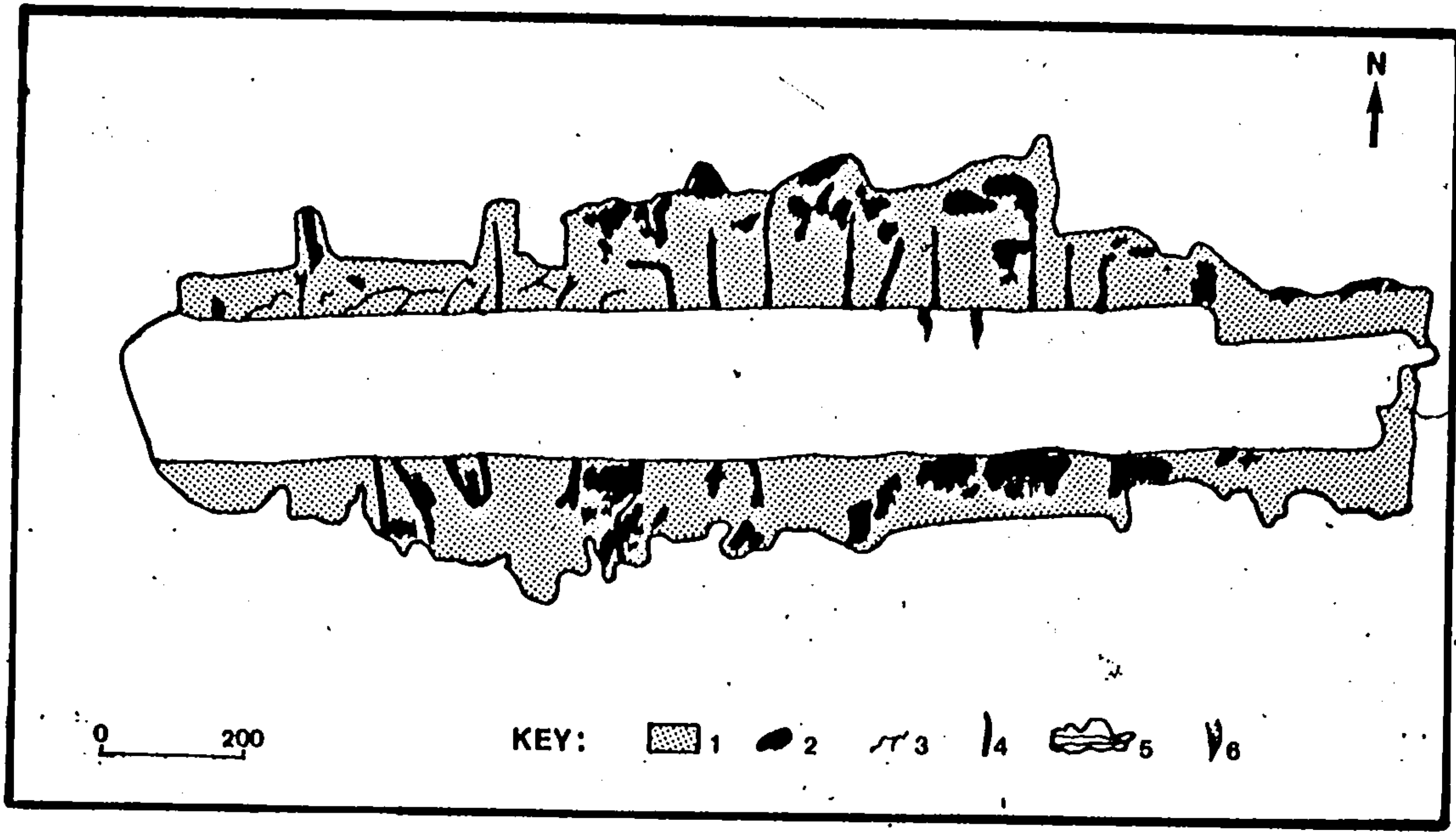
number, particularly in the terrain south of the airstrip. At this time, 19.8% of the disturbed terrain is occupied by water bodies of which 12.7% occur south of the airstrip.

4.2.4 Extent in 1972 (figure 42)

In 1972, the thermokarst ponds and mounds, as well as the ice wedge thaw depressions, remain essentially unchanged since 1968. Nevertheless, their dimension and number decreases; also, the number of standing water bodies occupies 0.129 km² or 10.4% of the disturbed area, the majority being on the southern edge of the airstrip. Finally, the linear depression pattern does not appear to be as distinct as in previous years. Post-construction disturbances are known to have occurred between 1968 and 1972 and these may have modified the pattern.

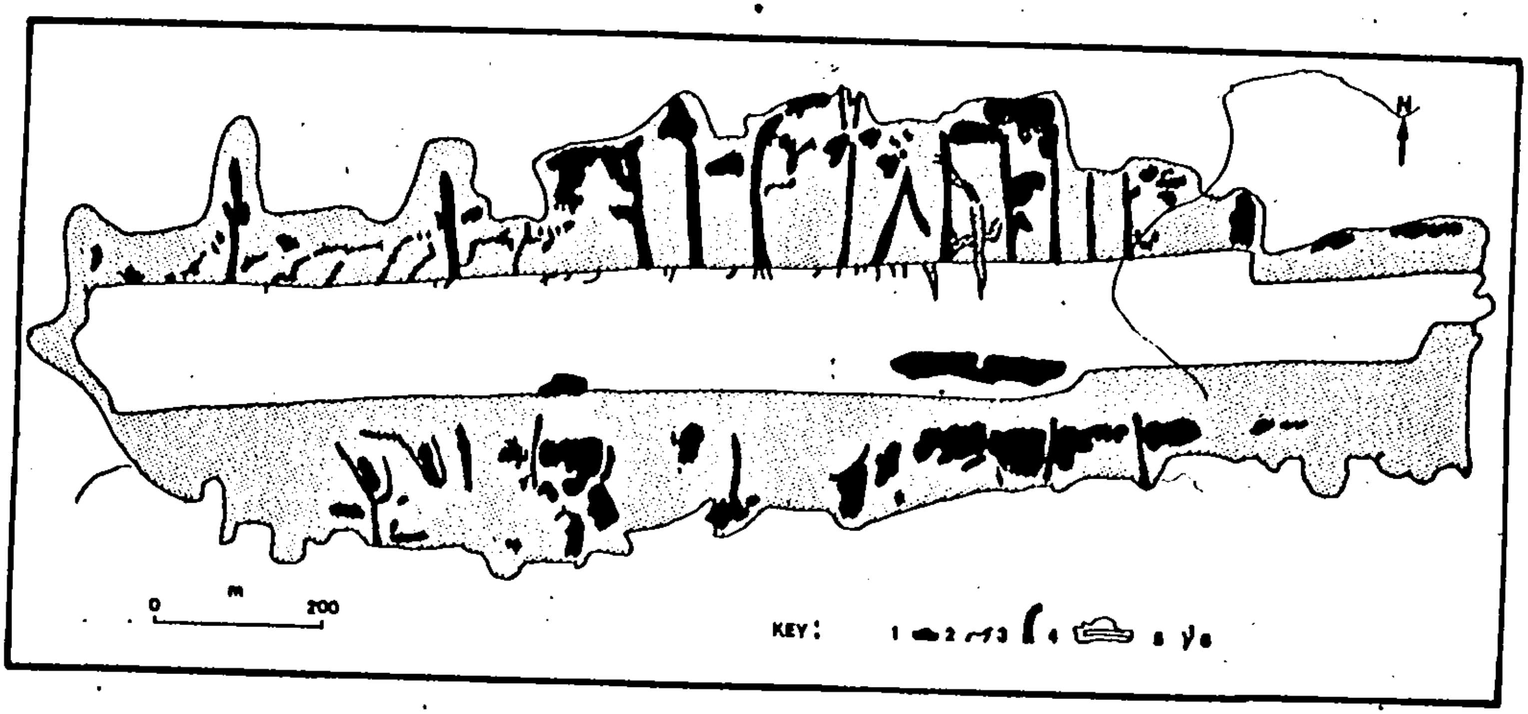
4.2.5 Extent in 1975 (figure 43)

In 1975, the disturbed area associated with the airstrip totals 0.74 km², a 7.5% decrease from 1973 (table 7). This may indicate a certain amount of terrain stabilization associated with plant recolonization. The standing water bodies now occupy only 0.026 km² or 1.9% of the disturbed area. On the other hand, water bodies are now present on the airstrip itself and others have appeared northeast of the airstrip. Gullying within the borrow pits north of the airstrip now forms an organized network. Further gullying has developed just west of



Source: NAPL A-22953/50, 52.

Figure 42. Disturbed terrain at Sachs Harbour airstrip, 1972. 1) Borrow pits; 2) Standing water bodies; 3) Ice wedge thaw depressions; 4) Ramps; 5) Airstrip and shoulders; 6) Culvert gully erosion. Date of photo: 5/8/72.



Source: NAPL A-24088/45, 46, 47.

Figure 43. Disturbed terrain at Sachs Harbour airstrip, 1975. 1) Borrow pits; 2) Standing water bodies; 3) Ice wedge thaw depressions; 4) Ramps; 5) Airstrip and shoulders; 6) Culvert gully erosion. Date of photo: 26/6/75.

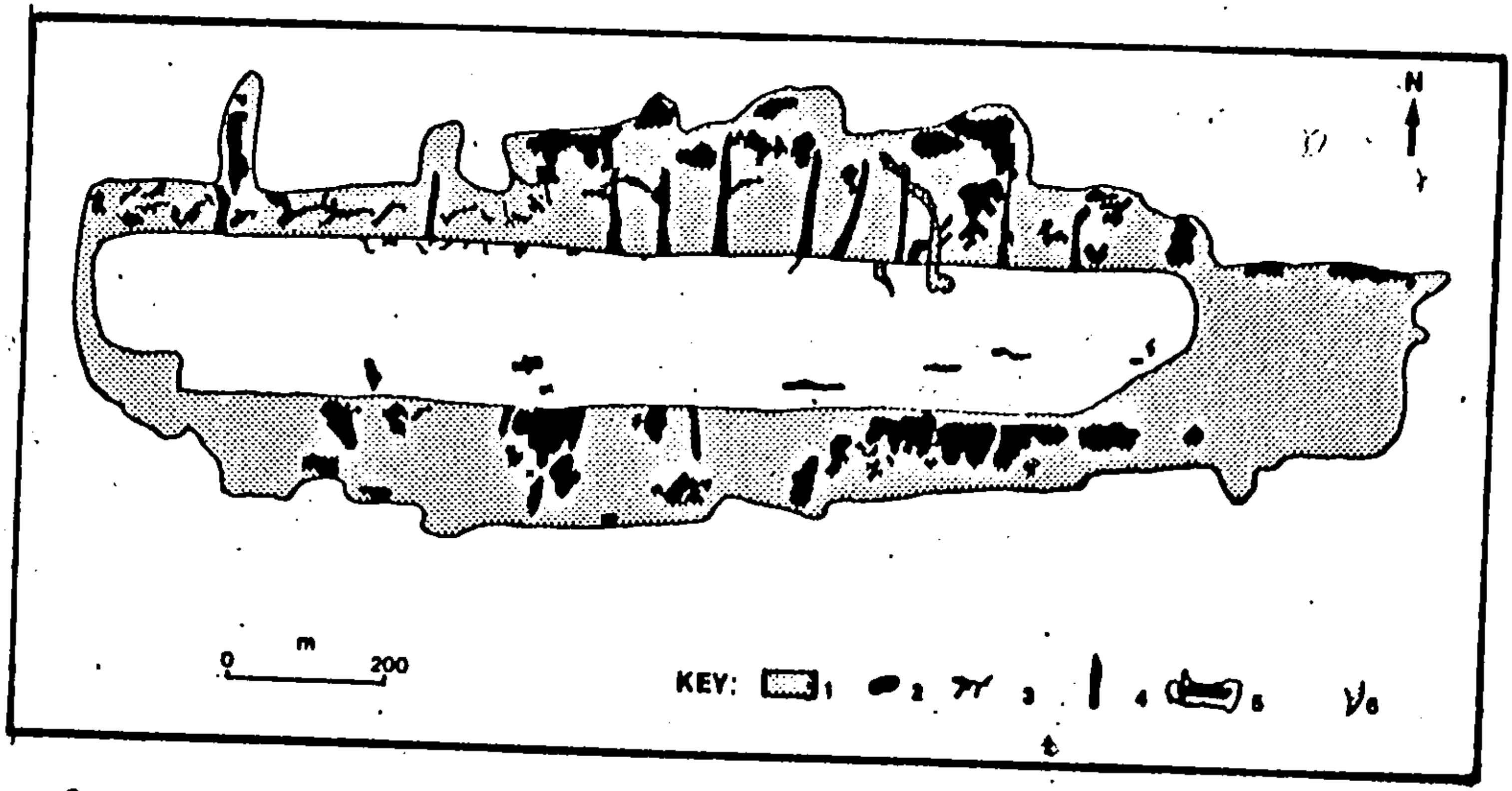
the airstrip as water collects in depressions, accentuating thawing and subsidence. Small gullies now erode the north shoulder of the airstrip and form small natural integrated drainage channels.

4.2.6 Extent in 1979 (figure 44)

In 1979, the disturbed terrain amounts to 0.76 km², basically similar to that for 1975. The surface covered by thermokarst ponds has slightly increased since 1975, reflecting both (a) the fact that thermal stabilization is still incomplete, and (b) recent borrow pit activity. The pattern of the ice wedge thaw depressions does not appear to have changed since 1972.

4.2.7 Current situation, 1980

Field observations in the summer of 1980 enable the pattern of terrain disturbance and recovery, as described earlier, to be further refined. In particular, the effects of additional disturbance caused by ongoing construction activity during 1980 were briefly examined. Commencing in the spring of 1980, the airstrip is being extended towards the east, from 3,000 to 5,000' in length, requiring approximately 200,000 m³ of aggregate. The borrow pits are located approximately 10 km to the west, utilizing ice-contact material associated with the Sachs Harbour ridge. A 'haul road' has been constructed along the crest of the ridge to transport the material from



Source: NAPL A-25222/7, 8.

Figure 44. Terrain disturbances at the Sachs Harbour airstrip, 1979. 1) Borrow pits; 2) Standing water bodies; 3) Ice wedge thaw depression; 4) Ramps; 5) Airstrip and shoulders; 6) Culvert gully erosion. Date of photo: 23/7/79.

the borrow areas to the airstrip.

During the summer of 1980, several important morphological changes occurred in the airstrip thermokarst terrain. These included the elimination of the recurrent gully at the east-end depression. A culvert, 30 cm in diameter, was replaced by a 120 cm diameter culvert to prevent the runoff waters from collecting on the south side of the airstrip and then overflowing onto the strip. Also, various standing water bodies on the shoulders of the airstrip itself were infilled as a result of renewed airstrip grading. They are still numerous elsewhere, however, especially on the northern side of the airstrip (figure 45). Field observations also indicate the ice wedge thaw depression pattern continues to be well developed (figure 46).

4.2.8 Thermal stabilization

Field work in 1980 included the examination of the degree of thermal stabilization at various disturbed sites. The previous air photo analysis served as a basis and enabled a time control to be placed upon the disturbed sites observed in the summer of 1980. Based on 1) air photo interpretation (e.g. extent of standing water bodies) and 2) the amount of recolonization and size of *Puccinellia vaginata*, as observed in the field, three ages of disturbances were recognized. These were: 1) 16-21 year old thermokarst terrain. This occurs in the northwest and southwest disturbed areas and is associated

Figure 45. Standing water body, typical of the disturbed area adjacent to the airstrip, August 1980.

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Figure 46. Ice wedge thaw depression, north side of the airstrip. Width is approximately 1 m. Note the revegetation (*Puccinellia vaginata*), August 1980.

COLOURED PICTURES

with the initial construction of the airstrip. 2) 8-16 year old thermokarst terrain. This occurs also in the northeast disturbed terrain adjacent to the airstrip and is related to airstrip maintenance and subsequent aggregate searching. 3) Recent (i.e. less than three year old) disturbed terrain. This is associated with a) material which has been excavated from the Sachs Harbour ridge, just east of the settlement, b) 1979 construction at the east-end of the airstrip, and c) borrow pits where material is presently being excavated for the airstrip extension. Ground thermal regimes were measured in these disturbed sites of different ages (figure 47).

As thaw depths are often a function of the amount of material removed, it is useful to compare the thermal regimes on the basis of their temperatures at 20 cm. At these depths, ground temperature is a more direct reflection of long-term trends.

In thermokarst areas initially disturbed between 1959 and 1964, the mounds possess a relative relief of approximately 40 cm. Thermal measurements between the mounds reveal thaw depths of about 120 cm while ground temperatures at 20 cm are between 8.5° and 10°C. Within these same borrow pit areas, measurements taken between the mounds show thaw depths varying between 75 and 100 cm. At a depth of 20 cm, temperatures are between 7.0° and 7.5°C. This may indicate that the varying thaw depths

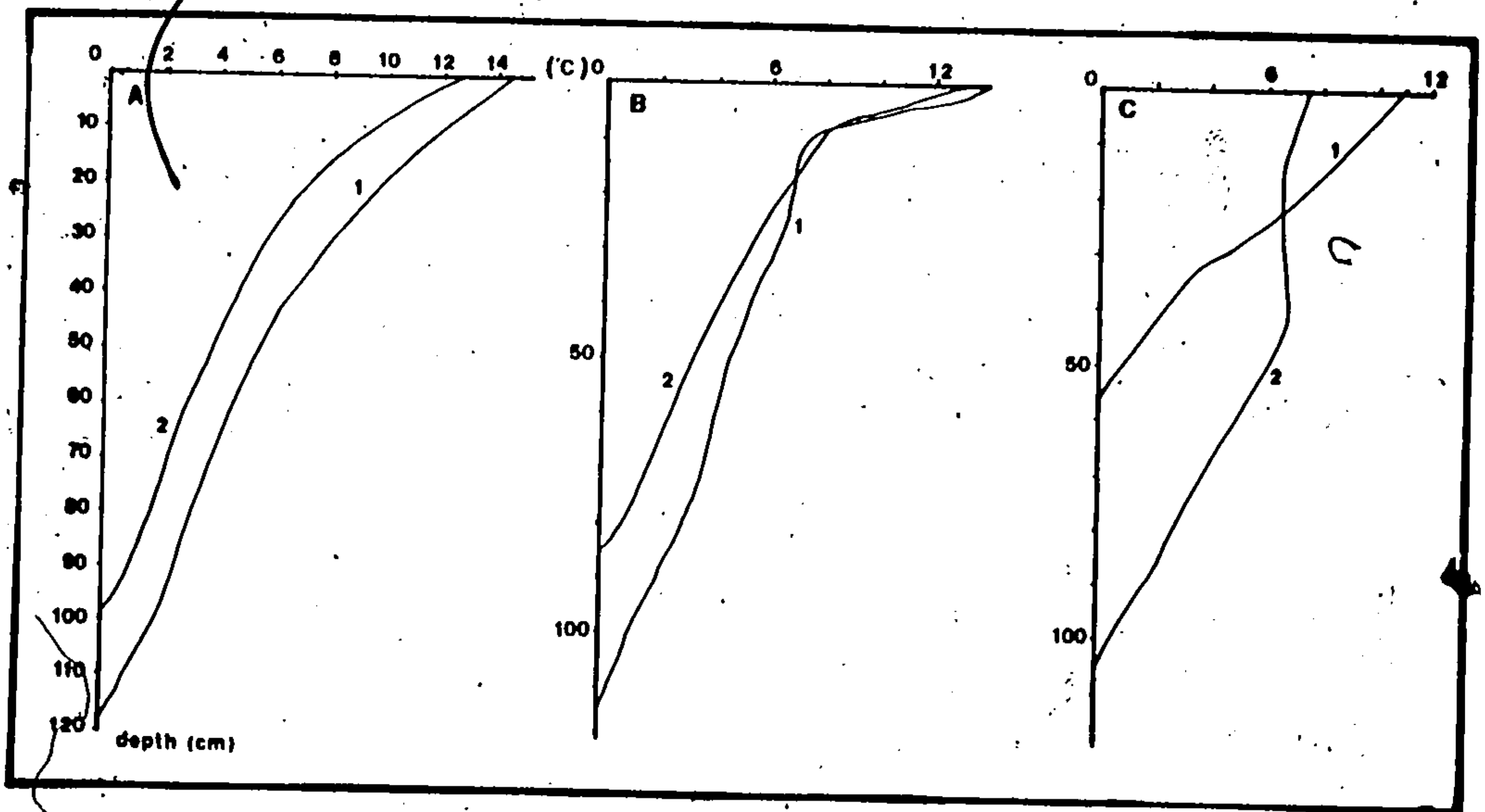

Figure 47. Typical thermal regimes on disturbed sites of: A) 16-21 year old, B) 8-15 year old, and C) less than 3 year old (1) hummocks, (2) depressions.

are merely a reflection of the physical removal of material. Furthermore, thermal stabilization is incomplete since melting is still active; standing water bodies are still numerous in this area. Under vegetated areas, thaw depths were approximately 70 cm, while under unvegetated areas they were approximately 80 cm (figure 39a). Furthermore, under heavily vegetated areas (90-95% vegetation) depths of thaw were approximately 55 cm (figure 39b). It is evident, therefore, that thermal stabilization is still incomplete in disturbances 16-21 years old.

In areas more recently disturbed (i.e. 8-16 year old disturbances) thaw depths vary within an even wider range (see figure 47). Here again, measurements taken under depressions show, on average, shallower thaw depths than those taken under mounds. At a depth of 20 cm, temperatures range from 5° to 8°C under mounds and from 5° to 6°C under depressions. At 40 cm depth, temperatures are between 4° and 6°C under mounds and 4° and 5°C under depressions.

For still younger disturbances (i.e. less than three year old), thaw depths are even more variable. They range between 25 and 90 cm beneath mounds and between 75 and 120 cm beneath depressions (figure 47). Not only do the ground thermal regimes under these recent disturbances lack uniformity from site to site, but the general shape of the temperature curves deviate from the control sites (see figure 39).

It can be concluded therefore, that the older disturbed terrain shows a greater degree of thermal equilibrium than the youngest disturbed terrain. In this context, it may be recalled that compaction, and/or destruction of vegetation leads to a significant increase in thaw depth (see Chapter II). Comparison of thaw depths under unvegetated undisturbed terrain with those under the oldest disturbances shows the latter to be still in thermal disequilibrium. However, by comparison, it can also be clearly shown that the youngest disturbances show the greatest degree of disequilibrium. These data support the generalization made by French (1979) that thermal stabilization begins only 10-15 years following the initial disturbance and is not complete before 30 or more years have elapsed.

4.3 Terrain Disturbance in the Townsite

During the 1980 summer, several terrain disturbance maps were made for those areas most affected by disturbances within the townsite. As for the wellsite studies, disturbances were described and classified on the basis of vegetation damage (e.g. vegetation covered, in the case of built areas; vegetation mostly dead, where vehicles have frequently traversed the tundra). Gullying was also observed.

One area mapped in detail is presented in figure 48, and illustrates the nature of terrain disturbance.

Legend

1. Disturbed areas

- Thermokarst area; churning up of earth along ice wedges
- Built-up area, vegetation-covered; some vehicle tracks, no rutting, some revegetation, mainly *Festuca rubra*
- Areas of severe rutting (along vehicle tracks), little vegetation
- Areas of densely spaced vehicle tracks
- Vegetation dead, some revegetation (grasses and cottongrass)
- Vegetation mostly dead, some vehicle tracks
- Man-induced gullying, gullies usually developed along vehicle tracks and branching out along ice wedges, or developed along drainage channels and branching out along vehicle tracks and/or ice wedges. Width varies from 2 to 12 m, depth from 0.5 to 4 m
- Man-induced gullying, gullies usually inactive

2. Undisturbed areas

- Slight depression, south-facing slope; 95% vegetation cover (grasses, cottongrass, some *Salix*)
- Area with thermal contraction cracks, south-facing; some melting along ice wedges, 75% vegetation cover (mostly *Salix*, some grasses)
- Area with no ground pattern, south-facing, 40-50% vegetation cover (grasses, cotton grass, *Dryas*, some *Salix*)
- Beach sands and gravels

3. Buildings and other features

- Buildings, approximate
- Buildings, to size
- Water tank
- Ice cellar
- Road

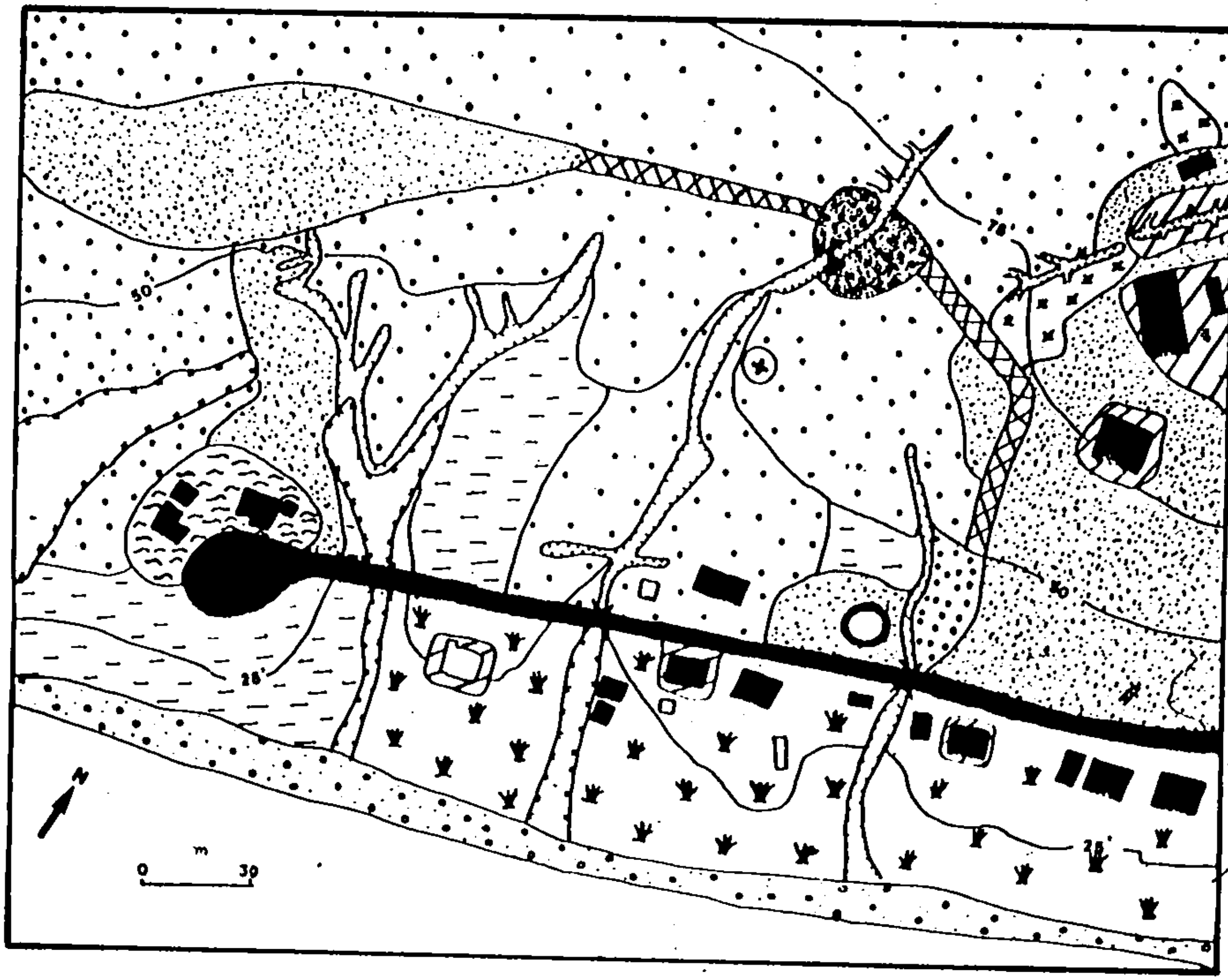

Figure 48. Disturbed terrain within the Sachs Harbour townsite, August 1980.

The most extensive damage appears associated with rutting along vehicle tracks. This is concentrated in two areas: (a) where vehicles have crossed the tundra on their way to the town dump, and (b) where vehicles have descended the sloping terrain between 'Government Row' and the main road. These vehicle tracks have promoted gullying, which in turn has been favoured by the gentle slope on which the settlement is built.

The local topography is conducive to the development of snowbanks upslope from the village (French, 1975b) and in the lee of the Sachs Harbour ridge. These snowbanks provide spring meltwater which is channelled through existing vehicle tracks, exposing ice wedges. The latter are then subject to both thermal and fluvio-thermal erosion. After initial erosion, these gullies " . . . become the natural sites for further activity . . ." (French, 1975b, p. 463).

The importance of gully erosion on sloping terrain consequent upon vehicle rutting needs emphasis since such disturbances are not confined only to sites of oil and gas exploration in the Arctic.

CHAPTER V

Conclusions

Conclusions drawn from the present study relate to an understanding of thermokarst processes and the effectiveness of the Territorial Land Use Regulations. The observations presented in this thesis contribute to the literature describing the impact of Arctic oil and gas exploration. In addition, the nature of terrain disturbances linked with a northern community, such as Sachs Harbour, may be of interest to those involved in northern settlement planning. The limitations of the present study, however, must preface any discussion of these conclusions.

5.1 Limitations

The wellsites studied were chosen on logistical rather than academic considerations. As a result, the observations made at the two wellsites are not necessarily typical of all wellsites. In the case of the community studied, Sachs Harbour is essentially a prosperous hunting community and as such may not be typical of northern settlements. Vehicle traffic over the tundra by snowmobile, motorcycle or truck and airstrip utilization is probably heavier than elsewhere. Furthermore, the site of the village, on a well vegetated south-facing slope underlain by ice-rich unconsolidated deposits, is susceptible to severe terrain damage. Snow banks, immediately upslope of the settlement, promote the formation of wet grassy tundra, highly sensitive to disturbance. The disturbed sites are nevertheless of interest because of their variety of 1) geographic locations, 2) terrain sensitivities and 3) different times of year at which they were created.

As the fieldwork was undertaken during summer, no data on winter conditions were collected. Extrapolation of conditions from summer to winter and from one season to another is difficult. In general, one can say that terrain disturbance in winter is less severe than in summer as the frozen tundra is generally snow covered and therefore less sensitive to disturbance.

One indication of the degree of disturbance of a given site is the change in the ground thermal regime. This relatively direct approach was used in the field. Disturbed sites were compared with undisturbed sites. Measurements recorded were then selected to be representative of each site. A better sampling design would now be possible in view of the limited time available at each site. At Sachs Harbour, the "spot" nature of the observations was supplemented by sequential air photo analysis of the development of terrain disturbance.

A further limitation concerns the climatic data: As the two wellsites are not in the vicinity of weather stations, extrapolations had to be made. This is not ideal although the discussion of these data is not detailed. At Sachs Harbour, a weather station has existed since 1955, approximately 1 km west of the airstrip.

A final limitation relates to applying the geoecological mapping approaches. In spite of the fact that this approach was used in northern Alaska at a scale of 1:100,000 it would appear that the site specific nature of terrain disturbances described in this study, is not conducive to such a general mapping procedure. In essence, this was because disturbed terrain occurred only within one landform unit; in addition the main terrain variable of the geological approach was slope angle which was generally uniform. As a result, it was thought more appropriate to classify disturbed terrain on the basis of the damage to vegetation and the cause of the disturbance.

5.2 Thermokarst processes

This study provides information as to the nature and rate of man-induced thermokarst in the Arctic Islands. The air photo analysis at Sachs Harbour indicates that an irregular topography of hummocky terrain and standing water bodies is created very soon after the initial disturbance. Field observations suggest that this irregular topography is influenced by the melt of underlying ice wedge networks. Data presented support the conclusion of French (1979) that the thermal stabilization of disturbed ground begins approximately 10-15 years after the initial disturbance and that the stabilization probably takes between 3 and 4 decades. The instability associated with recent disturbances is shown by 1) the difference in thermal regimes between disturbed and undisturbed terrain, and, 2) the lack of uniformity of thaw depths from site to site.

A further conclusion relates to the control which site specific factors exert over the thermokarst process. For example, as illustrated by the King Christian Island wellsite, plant cover in the High Arctic is sparse. As a consequence, the plant cover / active layer depth relationship is non-causal. On the other hand, on southern Banks Island, the plant cover is linked with thermal regimes, i.e. vegetation plays an important role as a thermal insulator. Also, at Sachs Harbour, angle and aspect of slope were important; for example, highest surface temperatures were recorded on steep south-facing slopes.

5.3 Land Use Regulations

First, an obvious conclusion is that the degree of terrain disturbance is directly related to both the sensitivity of the site and to the time of year at which the disturbance occurred. For example, thawing of the ground surface was caused at the King Christian Island wellsite, a high ice content area and a summer operation, while only superficial damage was observed at the Banks Island wellsite which is underlain by sandstone bedrock. It is therefore, very important to assess the sensitivity of a site before a Land Use Permit is issued; different sites will require a different set of terms and conditions. For example, if the area is deemed highly sensitive, only winter operations may be allowed.

Site rehabilitation, as illustrated by the Parker River wellsite, was found questionable since additional disturbance was caused by the clean-up operations. One might question, therefore, whether site rehabilitation is necessary to the extent currently practised.

The territorial Land Use Regulations were set up in 1970 at a time of rapidly increasing oil and gas exploration-related activities. Since then, some techniques and equipment have changed (e.g. drilling fluids, vehicles) and perhaps some of the terms and conditions set need to be amended. Without the existing regulations, damage may have been more severe than at present (e.g. thermokarst development at Sachs Harbour); in some cases damage even with the Territorial Land Use Regulations could be less severe (e.g. spilling of drilling fluids over the tundra instead of containment in a sump, when the walls are ice-rich).

A final point concerns the application of the Regulations. Perhaps they are effective in most cases but not always correctly applies. The key to this problem lies in further applied research and monitoring of performance.

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ABSTRACT

Physical disturbances adjacent to two exploratory oil and gas wellsites in the high Arctic, the King Christian Island Dome Wallis A-73 and the Banks Island Chevron Parker River J-72 are described and compared with those occurring at the community of Sachs Harbour, on southern Banks Island. Conclusions drawn lead to a better understanding of the impact of man-induced disturbances, and in particular the nature and speed of thermokarst. It was found that the controls over thermokarst include 1) moisture and ice content, 2) vegetation, 3) material properties (e.g. texture), 4) slope angle and aspect, and that they vary from site to site in importance. Also thermal stabilization of thermokarst terrain was found to begin only ten to fifteen years following the initial disturbance and to be complete after thirty or more years had elapsed. Disturbance is also a function of terrain sensitivity and the time of year of the disturbance. For example, the Parker River wellsite, drilled in winter presented little physical disturbance. On the other hand, the King Christian Island wellsite, drilled in summer and of high sensitivity, showed great amounts of terrain disturbance. The effectiveness of the present Territorial Arctic Land Use Regulations in minimizing terrain disturbance, in particular site

rehabilitation, should be questioned as they influence the overall degree of disturbance in the Arctic.

RESUME

Des perturbations de terrain associées à deux puits de prospection pétrolière dans l'Arctique (le site de forage Dôme Wallis A-73 de l'île King Christian et celui de Chevron Parker River J-72 de l'île de Banks) sont décrits puis comparés à celles qui surviennent à Sachs Harbour au sud de l'île de Banks.

Les conclusions conduisent à une compréhension plus complète de l'impact des perturbations causées par l'homme, en particulier la nature et la vitesse du processus thermokarstique. Les facteurs qui contrôlent le thermokarst sont variables d'un site à l'autre mais il ressort que les plus importants sont: 1) l'humidité et le contenu de glace de sol, 2) la végétation, 3) les propriétés du matériel, 4) l'angle de l'orientation de la pente. De plus, il semble que la stabilisation thermique du terrain thermokarstique ne débute que 10 ou 15 ans après le début des perturbations et que l'équilibre ne se réalise qu'après 30 ans ou plus.

Les perturbations sont aussi fonction de la sensibilité du terrain et de la saison. Par exemple, le site de Parker River, foré en hiver montre peu de perturbations alors que le site de l'île King Christian, foré en été et particulièrement sensible est beaucoup plus perturbé.

On peut s'interroger sur la pertinence des lois actuelles (Territorial Arctic Land Use Regulations), dont la portée influence le degré de perturbation dans l'Arctique, en particulier la restoration des sites de forage.