# A GEOECOLOGICAL INVESTIGATION OF PALSAS IN THE SCHEFFERVILLE AREA

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## ABSTRACT

The term palsa is a Fennoscandian word for a peaty hillock or mound having a permafrost core composed of alternating layers of segregated ice lenses, and organic or mineral soil. This dissertation presents results of a study on the morphology, ecology, cryotic structure, and thermal regime of 6 palsas sites in the Schefferville area and offers a new categorization of these features based on their cryotic structure. Eighteen palsa sites were located within a 35 km radius of Schefferville and six of these sites were investigated in detail. Palsas ranged from 5.6-59.0 m in length and up to 1.1 m in height. Most were located in valleys formed by the strong ridge-valley topography of the Labrador trough. Analysis of plant macrofossils suggests a successional change from hydrophilic species 10-15 cm below the palsa surface to relatively xerophilic species on the palsa surface. The transition zone between these vegetation associations indicates when the peat surface was heaved above the water table and thus, the initiation of the palsa. Surface vegetation on the palsas is used to indicate stage or category of development. Lichens and shrubs combined with small amounts of bare peat suggest a stable palsa. Large areas of bare peat on the surface of palsas resulting from erosion indicates degradation. Healthy sedges on the palsa surface indicate aggrading conditions. Ground ice within palsas ranged from small discontinuous ice lenses within peat to large lenses at the peat mineral soil contact and within the mineral soil. The depth of snow on the palsa surface varied on both a temporal and spatial basis. Active layer depths were not greatly affected by the depth of winter snow. Climatic parameters, such as heating degree days and bright sunshine hours, were found to predict maximum active layer depths more accurately than Stefan's equation. This dissertation shows that palsas with both organic and mineral soil cores are common permafrost features in the Schefferville area and within a relatively small area palsas exist at different stages of development.

RÉSUMÉ

Le terme palse, d'origine finno-s[illegible] désigne une butte ou un monticule tourbeux et pergélisolé formé d'une alternance d'hori[illegible]s de glace de ségrégation et d'horizons de matériel organique ou minéral. En plus de prés[illegible]nter l[illegible] résultats d'une étude portant sur la morphologie, l'écologie, la structure in[illegible]erne cyroge[illegible]que cryogénique et le régime thermique de palses localisées dans 6 des 18 sites que l'on t[illegible] à moins de 35 km de Schefferville, le present mémoire propose un critère de di[illegible]férent[illegible] palses fondé sur la structure cryogénique. Les palses étudiées avaient une longue[illegible] à 59 m et jusqu'à 1,1 m de hauteur. Elles se trouvaient pour la plupart dan[illegible]s de la fosse du Labrador. L'analyse des macrorestes végétaux montr[illegible]e[illegible]es xérophiles en surface à des plantes hydrophiles 10 ou 15 cm sous [illegible] La localisation de la zone de transition est reliée à la périoue d'émergence [illegible]pport à la nappe phréatique, c'est-à-dire à sa formation initiale. Le type de végé[illegible]on e[illegible]ce indique le stade de développement de la palse. Une surface de lichens et d'arbust[illegible]uée de tourbe nue indique une stabilité de développement. On associe une surface caractérisée par de grandes zones de tourbe à une dégradation et, à l'inverse, l'aggradation se traduit par une relative abondance de carex. La glace dans les palses se trouvait soit en petites lentilles discontinues dans la tourbe ou en couches plus épaisses dans le sol minéral ainsi qu'au contact entre ce dernier et la tourbe. Bien que l'épaisseur du manteau nival à la surface des palses montrait une variation à la fois spatiale et temporelle, il a été impossible d'y associer une variation de l'épaisseur de mollisol. Il a été déterminé que l'utilisation de paramètres climatiques comme le nombre de degrés jours de chauffe et le nombre d'heures d'ensoleillement donnait de meilleurs résultats que l'équation de Stefan quant à l'estimation de l'épaisseur maximale du mollisol. Le présent mémoire démontre que les palses à coeur minéral ou tourbeux constituent de fréquentes manifestations de pergélisol dans la région de Schefferville et que des palses rapprochées peuvent présenter des stades de développement différents.

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# PREFACE

This dissertation is based on a compilation of three original manuscripts, two of which are already published. The Faculty of Graduate Studies and Research require that the following three paragraphs appear in full at the beginning of a dissertation adopting this approach.

"The candidate has the option, subject to the approval of the Department, of including as part of the thesis the text, or duplicated published text (see below), of an original paper or papers. In this case the thesis must still conform to all other requirements explained in Guidelines Concerning Thesis Preparation. Additional material (procedural and design data as well as descriptions of equipment) must be provided in sufficient detail (e.g. in appendices) to allow a clear and precise judgement to be made of the importance and originality of the research reported. The thesis should be more than a mere collection of manuscripts published or to be published. It must include a general abstract, a full introduction and literature review and a final overall conclusion. Connecting texts which provide logical bridges between different manuscripts are usually desirable in the interests of cohesion.

It is acceptable for the thesis to include as chapters authentic copies of papers already published, provided these are duplicated clearly on regulation thesis stationary and bound as an integral part of the thesis. Photographs or other materials which do not duplicate well must be included in their original form. In such instances, connecting texts are mandatory and supplemental explanatory material is almost always necessary.

The inclusion of manuscripts co-authored by the candidate and others is acceptable but the candidate is required to make an explicit statement on who contributed to such work and to what extent and supervisors must attest to the accuracy of such claims, e.g. before the oral committee. Since the task of the Examiner's is made more difficult in these cases, it is in the candidates interest to make the responsibilities of the authors perfectly clear. Candidates following this option must inform the Department before it submits the thesis for review." (Guidelines Concerning Thesis Preparation, McGill University, Faculty of Graduate Studies and Research.)

This dissertation is divided into four chapters; chapter 1 introduces the subject, defines the study objectives and summarizes background literature relevant to the study. Chapter 2 is divided into two distinct sections, each section comprising a published manuscript. These two papers are combined into one chapter because there are a number of overlapping discussions. Chapter 3 comprises a manuscript that, at the time of submission, was in the review process. This manuscript is presented as a separate chapter because it is based primarily upon empirical analyses. Chapter 4 discusses the three manuscripts and attempts to draw together their conclusions into an integrated statement.

The literature described in each of the manuscripts summarizes background information relevant only to the problems addressed. Accordingly, an expanded literature review is presented in chapter 1 to put these papers, and this research, into a broader context.

The candidate is the primary author and the supervisor (Dr. Wayne H. Pollard) second author, of all three papers. The research is solely that of the candidate: the field, laboratory, and statistical analyses were the work of the candidate as well as the original drafts of the manuscripts. Dr. Pollard offered helpful advice on various phases of the field program, revisions to the texts, and helped in the formulation of conclusions from the raw data. Moreover, his help in arranging equipment and funding and support in the field made much of the research possible. His role thus remained that of thesis adviser.

Each manuscript presents conclusions relating to the focus of that paper that stand alone and will not be repeated. Because the general subject of the papers is similar, several conclusions can be drawn from the three works. These are discussed in a separate chapter.

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## CHAPTER 1: INTRODUCTION AND BACKGROUND TO THE STUDY

### 1.1 GENERAL STATEMENT

Permafrost is defined as ground (soil or rock) that remains at or below 0°C for at least two years (Permafrost Subcommittee 1988). This is a recent area of research and has only been considered a separate field of study since the late 1940's. The term "permafrost" was proposed by Muller (1943, P.3) as a convenient short form for the phrase "permanently frozen ground".

Permafrost is a thermal condition influencing approximately 20-22% of the earth's land surface, including 50% of Canada and the USSR and up to 80% of Alaska. In Canada, the permafrost region is divided into 4 zones based on its location and distribution: (1) continuous, (2) discontinuous, (3) alpine and (4) submarine permafrost (Brown 1978).

In North America, considerable research has been carried out on various continuous permafrost phenomena such as pingos and ice wedges; however, the landforms of the discontinuous permafrost zone have generally received less attention. The peatland areas of Canada cover up to 2,000,000 km$^2$ and overlap a great deal with the discontinuous permafrost zone. A consequence of this is the development of a series of unique peaty surface features ranging from small hummocks to palsas and peat plateaus.

The term palsa is derived from the Finnish word used to describe peat hummocks in wetlands with a frozen core (Seppala 1988a). Confusion has arisen in the literature concerning the definition of palsas and other types of frost mounds. A number of reviews have been published in recent years (e.g. Pissart 1985, Seppala 1988a; and Washburn 1983), however a disturbing aspect of these reviews is a lack of consensus on the landform defined by the term palsa. This discrepancy usually revolves around the process-form relationship and the difference between traditional descriptive geomorphology and modern process geomorphology. The question, "what defines a palsa, its form or the process that led to this form?" is at the heart of this controversy. In this study a palsa is "a peaty permafrost mound possessing alternating layers of segregated ice and peat or mineral soil material" (Permafrost Subcommittee, 1988, p.60).

Palsas are often regarded as the most conspicuous and reliable surface indicator of permafrost in the discontinuous zone; however, in recent years, features resembling palsas have also been reported in the continuous permafrost zone (Washburn 1983). Palsas are not the only type of frost mound found in the discontinuous permafrost zone. Recently, confusion between palsas and frost blisters has caused controversy in the permafrost community. Frost blisters are morphologically similar but genetically different frost mounds that can be mistaken for palsas unless detailed process or structural studies are undertaken.

Palsas are widely reported throughout most of the discontinuous permafrost zone of Canada and extensively in western Quebec (Allard and Seguin 1987a; Lagarec 1982). However, in only two instances have palsas been reported in the Schefferville area (Jahn 1986; Waterway *et al.* 1984) but to date there has been no detailed study of their occurrence. A recent paper by Lagarec and Dewez (1990) suggested that palsas are absent in this area. It follows therefore, that there is an immediate need for a study concerned with palsa occurrence in the interior of Nouveau Quebec. This research project was conceived in response to this need.

## 1.2 STUDY OBJECTIVES

Palsas constitute an interesting but little studied permafrost phenomenon in the central part of Northern Quebec. Thus the general objectives of this research were to investigate the occurrence of palsas in the Schefferville area and to describe their distribution, setting, surface and internal characteristics. An additional objective was to examine seasonal variation in external variables such as snow cover and air temperature, to develop a better understanding about aggradational and degradational processes acting on palsas in this region.

Attention focused upon four problems associated with palsa occurrence near Schefferville:

(1) Do palsas posses typical geographic location and site-specific

characteristics?

(2) What is the range in palsa size, shape, morphology and vegetation cover?

(3) What is the range in internal structure of palsas in this region and what can be inferred from biostratigraphic differences?

(4) What are the environmental conditions acting on palsas?

These problems are addressed in these manuscripts. Accordingly, the specific aims of paper one are to describe the morphology and setting of palsas in the Schefferville area and to describe the near surface characteristics of these palsas. As peat is an essential constituent of palsa structure and the palsas studied are composed primarily of peat and organic silt, an attempt is made to relate the vegetation cover and structure, including biostratigraphy, as a means of inferring palsa evolution. A secondary aim of this paper is to examine the ground ice and thermal regimes of these palsas as an integral component of any process oriented permafrost study.

The primary aim of the second paper is to develop a cryogenetic classification of palsas using surface and subsurface data to categorize site-specific permafrost conditions. Since thermal regime and surface condition of these palsas are strongly affected by winter conditions, a secondary aim of this paper is to describe how winter conditions can also play a role in their cryogenetic classification.

The third paper focuses on the dynamic relationships between the thermal regime of palsas and environmental factors that directly affect seasonal temperature patterns. The aims of the third paper are: 1) to describe the spatial and temporal variation in snow cover in a palsa fen and its influences on active layer development, 2) to document active layer development and relate it to proxy environmental data collected at the Schefferville airport. Least squares regression equations are developed to predict maximum active layer depths and are compared with results of analytical equations and 3) to describe the internal temperature of palsas and relate this to winter and summer conditions. This paper attempts to provide a better understanding of the annual variations in the thermal regime of discontinuous permafrost by using palsas in the Schefferville area.

## 1.3 APPROACH

This is primarily a field investigation supported by limited laboratory and empirical analyses. It follows therefore, that the research design and methodology focused on the collection of setting and process data that will help provide better understanding of the factors influencing the distribution, formation and degradation of palsas.

A number of standard field techniques were used to collect data on the physical and thermal characteristics of palsas. Some of these techniques are described in the manuscripts presented in chapters 2 and 3, however the brief discussion about techniques is presented here to emphasize the integrated nature of this project.

Initially study sites were identified from aerial photographs. Using a limiting radius of 35 km a total of 18 sites were identified. Subsequent field reconnaissance identified six sites that could be readily accessed by either all terrain vehicle, snowmobile or truck depending on conditions of mine roads.

Peat samples were obtained using a CRREL permafrost coring kit or were cut from the sides of the palsa using a saw. The stratigraphic sequence of organic, mineral and ice material provided detailed information on sequence and chronology of palsa formation processes. These core samples were used to determine ice content and type and biostratigraphic sequence. Core holes were instrumented with multi-thermistor cables calibrated to 0.1°C as outlined in Judge (1973). Ground thermal regime data is of utmost importance when studying permafrost features as the determination of permafrost is based on the grounds thermal condition. A YSI needle probe and Fluke multi-meter were used to obtain instantaneous surface peat and snow temperatures which provided information on ambient air temperatures and rates of freeze and thaw of the palsas. A Mount Rose snow sampler was used to measure snow depth and density which control to a great degree how winter conditions affect the thermal regime of the palsas. Surface vegetation cover was based on four 1 $m^2$ selected quadrats in order to determine relative age and condition of palsas. Plant macrofossil data were obtained using the method described by Lowe and Walker (1984). These data provided information regarding chronology of vegetation colonization of the wetland surface prior to palsa formation. Unfrozen peat depths in fens surrounding the palsas were obtained with a 3 m steel probe pushed through the peat until mineral soil was reached. Active layer development was monitored using a steel probe pushed into the surface. This data helped to identify permafrost bodies and quantify rates of thaw. Tree age was determined by removing a cross section of the tree just above the root crown which was sanded and examined under 10x magnification. This determined how long the wetland surface was above the water table and thus the minimum age of the palsa.

## 1.4. STUDY AREA

The study area is situated in the Labrador Trough geologic structure that is approximately 80 km wide and cuts through the Canadian Shield in a northwest-southeast direction from just south of Schefferville, to Ungava Bay, a distance of roughly 700 km. The younger interbeded metamorphosed sedimentary and volcanic rocks of Proterozoic age were laid down in an arm of the Tyrell Sea which inundated this area in Pre-Cambrian time. Subsequent folding and faulting of the sediments has given variable, often steep dips to the bedding planes which strike predominantly northwest-southeast, and have led to the formation of numerous faults and fissure zones. These act as aquifers within the unfrozen bedrock. Leaching of silica by groundwater and deposition of iron compounds in solution locally enriched the iron formations to high-grade ore. The bedrock is porous and poorly cemented in these leached zones. A consequence of this process are the large iron deposits mined by the Iron Ore Company of Canada from 1956 to 1984.

The Labrador-Ungava area, with only minor exceptions, experienced extensive glaciations during the last 100,000 years and especially during the maximum of the Wisconsinan glaciation, at about 18000 years B.P. (Ives, 1979). Some believe the ice sheet grew from a depression in the highlands of eastern Labrador (Flint, 1971), however most researchers (Bryson *et al* 1969, Ives, 1979) believe that this sector of the Laurentide Ice Sheet was concentric, with a centre near Kivivic Lake, 40 km north west of Schefferville. Moreover, it is thought that a remnant ice sheet persisted well into the Holocene, and based on radio-carbon dates, disappeared approximately 6000 years B.P.. There remains much confusion concerning the deglaciation of this area, as indicated by other dates for ice disappearance ranging from 16330 to 3830 years B.P. (Ives, 1979).

These glaciations are important for three reasons; (1) they modified the existing landscape, (2) they exerted a limiting time frame for soil development and paludification, and for (3) permafrost aggradation into the peatlands. One of the most obvious landscape modifications was the rearrangement of drainage patterns. Former river valleys became choked with debris and new lakes formed. Many large melt-water channels are cut into existing synclinal structures. This provided the starting point for the present disorganized drainage patterns which are also characterized by the widespread occurrence of peatlands. The overburden of glacial till has low permeability and is usually less than 1 m deep and often absent at higher elevations.

The climate of the Schefferville area is controlled by the Canadian high pressure and the Icelandic low pressure zones which produce a prevailing air flow from the northwest which is particularly strong in winter. Wind speeds of 15-25 m $s^{-1}$ are common in most winters.

Schefferville winters are more severe than most other areas at the same latitude. The coldest month is January with a mean monthly temperature often below -22°C (Figure 3.2.2) and extreme minimum temperatures of -45°C. Winters months are usually accompanied by relatively high wind speeds. Summers are characterized by cool, cloudy and rainy conditions, however hot air inclusions from the southwest combined with prolonged periods of dry sunny conditions produce maximum summer temperatures exceeding 30°C.

Snow fall is usually quite variable and ranges between 200-600 cm $yr^{-1}$ (Figure 3.2.1b) Snow cover is continuous by early October and remains until May. By the end of May the snow is usually gone in woodland areas, while in the more exposed areas snow is completely absent by the beginning of May. Mean annual rainfall is

Maximum rainfall occurs in July and can exceed 100 mm.

Vegetation influences the amount of radiant energy absorbed or reflected by the surface (during the snow free period), it also protects the underlying soil from the effects of wind and reduces wind speed because of its higher friction coefficient as compared to bare soil. Vegetation also affects snow accumulation and the moisture exchange between the underlying soil and overlying boundary layer.

The Schefferville area can be considered to be an ecotone between boreal forest and open tundra. Therefore, within this zone a wide range of vegetation and permafrost conditions occur. The vegetation complex found in any area depends on its topographic setting which strongly influences exposure and moisture availability. The landscape is dominated by open lichen woodland grading into lichen heath at higher elevations and spruce-moss forest in the low wet areas. Sedge meadows and patterned fens occur frequently in the poorly drained topographic lows, while alpine tundra covers the higher well-drained areas.

There are two forest types in this area; spruce-feather moss forest and spruce-lichen woodland. The spruce-feather moss forest have closed canopies and are found in moist relatively nutrient-rich sites. The dominant trees are black spruce (*Picea mariana*) and white spruce (*P. glauca*) often mixed with balsam fir (*Abies balsamea*). These forests have thick moss and shrub cover. The spruce-lichen woodlands have an open canopy and are usually found in drier nutrient-poor sites. Both black and white spruce are common with larch (*Larix laricina*) often being the dominant species. Shrubs are not as common as in the spruce-feather moss forest while the ground cover usually consists of a thick cover of caribou lichen (*Cladonia* spp.).

A transition zone between the spruce-lichen woodland and the higher elevation tundra zone usually consists of wind stunted trees and shrubs (krummholz) which can be very thick. The tundra vegetation found on the higher ridges of the area consist of low lying wind stressed vegetation such as lichen and various *vaccinium* species.

Poorly drained areas with surfaces underlain by peat are found in most topographic depressions of this area. Their size ranges from a few $m^2$ to several $km^2$. Patterned fens (string bogs) are the most common varying from minerotrophically rich fens in areas enriched from runoff from dolomite substrate to poor fens at other sites. The strings are dominated with small larch, black spruce and ericaceous shrubs, while the flarks are dominated by sedges and mosses. Small sedge meadows without patterns are also common and originate from infilled lake basins. It is these sedge meadows where palsas are usually found.

The soils of the Labrador-Ungava are strongly influenced by their glacial origin, with glacial till being the most common substrate on which these soils develop. The depth of overburden on the slopes varies, depending on drainage, aspect, and angle of repose. The mineral soils vary from coarse grained sand and gravel, associated with morainic and glaciofluvial deposits, to fine grained silt and clay deposited in lacustrine and marine environments. Following deposition, soil development has superimposed pedological variation.

Most of the soils in this area are generally acid with low nutrient content, the exception being in areas underlain by dolomite where the soils are much richer in calcium and magnesium (Waterway *et al.* 1984). Podzolization occurs mainly in freely drained soils while gleying is dominant in wetter areas usually between the topographic highs where drainage is impeded. Since the frost table is at, or near, the surface for much of the year the soil is water logged for much of the summer thus gleying is dominant. When the frost table deepens or disappears, the podzolization process becomes dominant in the same profile. Nicholson and Moore (1977) suggest that the Schefferville soils lie in an area of weakening importance of podzolization and increasing importance of gleying.

### 1.4.1 STUDY SITES

A total of 18 palsa sites were identified based on aerial photograph analysis and 6 of these were investigated in the field. At site 1, also called the Goodream site, two palsas occur in a fen situated in a small valley lying between two till covered bedrock ridges at an elevation of 718 m a.s.l.. Both palsas are bound on three sides by standing water ranging from <0.5 to >2.0 m deep. On the fourth side a thin floating mat of peat occurs dominated by *Carex* spp and *Sphagnum* spp.. The largest palsa is 28.0 m long, 15.0 m wide and 1.1 m high (heights are measured relative to the water table). It is oval-shaped with its long axis trending northeast-southwest and appears to be degrading by block failure along its western perimeter, similar to those described by Salmi (1968) As well, patches of bare peat are exposed on the surface and large cracks up to 15 cm wide and 30 cm deep traverse the entire palsa

At site 2, on the west side of Ferriman ridge, (hence, referred to as the Ferriman site) one palsa occurs in a fen at 750 m a.s.l. in a topographic setting similar to the Goodream site. This palsa is surrounded by a deep (>2.0 m) 'moat'. It is circular in plan shape with a diameter of 12.0 m and a height of 0.7 m. The presence of cracks, up to 10 cm wide 40 cm deep, traversing its entire surface along with thermokarst depressions, indicates that this palsa is also degrading

Site 3, the Laroche palsa site, contains two oval palsas located in a fen in a small valley at 661 m a.s.l. with a bedrock ridge on the east and till covered bedrock on the west. The till surface is marked by non-sorted circles The fen surrounding these palsas is dominated by *Carex* spp. vegetation with the water table located 5 cm below the surface vegetation mat. A small pond (50 m in diameter) lies to the northwest of the palsas. The largest palsa is 58.7 m long (along a northwest-southeast axis) and 21.6 m wide, with a height of 1.0 m.

The fourth site, referred to as the Newf site, contains nine palsas ranging from 5.6 to 21.0 m in length, 2.4 to 12.0 m in width and 0.5-0.8 m in height The surface of the fen surrounding the palsas consists of a thin *Carex* spp and *Sphagnum* spp. floating peat mat. This site is topographically different from the previous sites There is no definite valley, but rather gently sloping open lichen and feather moss forests surrounding the peatland. There are no large open water bodies, only small pools ($2m^2$). The palsa studied is 17.4 m long, 8.0 m wide and 0.8 m high.

Sites 5 and 6 contain small permafrost peat mounds that constitute a minimum expression acceptable to meet the definition of a palsa. At site 5, (site 2 in paper 1) three small palsas occurred in a minerotrophic fen situated in a setting similar to site

1. This fen is drained by a small creek flowing to the southwest. One palsa was examined with a length of 10 m. and a width of 4.5 m and a height of 0.77 m above the water table. Water approximately 1.5 m deep surrounded the palsa on three sides. This palsa was approximately circular in shape and appeared to be geomorphologically stable as there was a continuous vegetation cover and no block failure was occurring.

Site 6 (site 3 in paper 1) contained three "embryonic" palsas that were completely surrounded by standing water > 1.5 m deep. This is a weakly minerotrophic fen (Waterway *et al.* 1984) and is bound by a gentle slope covered by lichen forest Again, only one feature is discussed. It was circular in shape with a diameter of 1.5 m and a height of 0.59 m above the water table. The term embryonic is used because this mound appears stable and at a threshold stage in palsa development because no block failure was evident and a continuous vegetation cover was present.

## 1.5 PALSA LITERATURE

### 1.5.1 MORPHOLOGY AND STRUCTURE

Palsas are peaty permafrost mounds between 0.5-7.0 m high and less than 100 m in diameter. They can be dome-shaped or have flat profiles and are often dissected by open cracks. The internal structure usually consists of alternating layers of segregated ice and peat or mineral soil (Lundqvist 1969; Permafrost Subcommittee, 1988; Seppala 1972, 1988a; Thie 1974). However, there are those who feel peat is not an essential constituent for a palsa (eg. Jahn 1986; Pissart 1985). These features have been incorrectly termed mineral or minerogenic palsas; however, Lagarec's (1982) term mineral cryogenic mound is more accurate in the genetic context. Allard *et al.* (1987) suggest that these mineral cryogenic mounds may be palsas whose surface peat has been removed by wind deflation or they are formed by other processes dissimilar to those of palsas.

Several researchers have classified palsas according to their morphology and size (e.g. Jahn 1986; Pissart 1985). A commonly used classification (Pissart 1985) groups palsas into 5 different morphologic categories: 1) dome-shaped, circular to oval with heights of 0.5-7 m and 15-150 m long, 2) string form, elongated forms running normal to slope with lengths 25-100 long and not exceeding 2 m in height, 3) esker or ridge form; elongated forms running parallel to slope with lengths 50-500 m and between 2-6 m in height, 4) palsa plateau; extensive features covering areas from a few hundred m to several km with heights between 1.0-1.5 m and 5) palsa complex; complicated shape covering a significant area that appear to be an amalgamation of many different palsas at varying stages of development in the same peatland. These descriptive modifiers should not be used as specific types of palsas but simply morphologic variations.

### 1.5.2 ORIGIN

The topic of palsa process or formation is another area of terminological confusion. In Hart's (1986) discussion of the theory and philosophy of pure and applied geomorphology he states "the study of present day processes is almost certainly the most important single theme in modern geomorphology for it lies at the core of pure geomorphology." (p.88). Seppala (1988a) emphasises the importance of process with reference to palsa studies, he states " considerable confusion has arisen because a number of students ... began to use this very specific descriptive term (palsa) in a preconceived genetic context. This was of course a dangerous procedure, since a necessary precondition for the use of genetic terminology is that the genesis of both the classic palsa and the comparable feature being examined in another region must be known." (p.249). Hence, there is support from both general discussion about the philosophy of geomorphology and existing research that the study of palsas should first and foremost be concerned with process and landform origin.

Washburn (1983) presents a comprehensive summary of palsa characteristics derived in the literature. In this review he suggests two possible origins of palsas, 1) aggradational forms due to permafrost aggradation at an active layer/permafrost contact zone, and 2) degradational forms which are due to disintegration of an extensive peaty deposit. This multigenetic description of palsas is not consistent with Hart's (1986) and Seppala's (1988a) focus on process. That is, if a specific process produces specific form then two entirely different processes or mechanisms of formation should define two distinct forms. Whereas Washburn (1983) describes two different processes that can result in one form.

This is not the only debate on palsa origin. The following summarizes various descriptions of palsas to shed further light on the terminology problem.

Akerman and Malstrom (1986) describe various types of mounds in northern Sweden that have been labelled palsas. Included are mounds that are composed of mineral soil and ice, and lacking a surface peat layer, labelled mineral palsas. Other mounds that appear to be degrading pingos have also been labelled palsas. Some of the features that have been labelled palsas have internal cores of injection ice and secondary layers of segregated ice. The presence of injection ice suggests that these features are similar to the frost blister described by Pollard and French (1983) and Pollard (1988) and Van Everdingen (1982). In another paper, Jahn (1986) suggests that palsas may result from both aggradation and degradation of permafrost. In the latter, melting of ground ice causes thermokarst and where the ice has not melted a mounds remains. These positive relief forms were labelled palsas. Seppälä (1988b) described two types of frozen peat mounds in the northern Ungava region of Quebec. The first type was formed when a creek eroded a peat deposit leaving islands of exposed peat. The second type of mound was the result of melting ice wedges leaving high isolated centred polygons. One of the main goals of the Seppälä paper was to show that these mounds were not palsas, since their origin did not fit the "classical palsa"

Brown (1980) described "incipient palsas" in north central Alberta that consist of domes 15-30 cm high, 3-8 m in diameter and have a core of permafrost. These features were covered with dead sedges similar to the type found living in the surrounding fen. Since no information was given on the internal structure, it can not be determined if these are indeed palsas. However, if the positive relief is the result of segregated ice lenses then it is possible that these were newly forming or aggrading palsas.

### 1.5.3 INTERNAL STRUCTURE

This introduces the importance of the investigation of the internal structure in the identification of palsas and other frost mounds. Outcalt and Nelson (1984) suggest that in the absence of stratigraphic information, a specific mound's origin may be difficult to determine. In situations where the internal structure was known to include injection ice the authors labelled the mounds as palsas strictly on the basis of duration and shape. Similarly, mounds in the Brooks Range of Alaska containing free water and massive ice cores were reported as palsas by Brown *et al.* (1983) On the basis of origin, these mounds probably should not be considered palsas but a type of seasonal frost mound termed frost blister (Pollard, 1988). From these examples we can see that without direct observation of formation or stratigraphy one can not assign the mound origin and thus should not use the specific term palsa, but rather use the more generic term, frost mound.

In general, the internal structure of a palsa usually includes layers of peat and mineral soil interbedded with segregated ice lenses, ice crystals and pore ice. The formation of various forms of ice give the palsa its vertical displacement above the surrounding peatland (Allard, *et al.* 1987; Lundqvist, 1969, Seppala, 1986, 1972, Zoltai and Tarnocai, 1971). For example, Allard and Seguin (1987a) present shallow profiles of four palsas from the eastern coast of Hudson Bay where no ice was documented in the peat, however, large ice lenses up to 100 mm thick and reticulate ice veins 2-4 mm thick were found in alluvial silt and sand immediately below the peat layer. In another study, Kershaw and Gill (1979) cored several palsas in the Macmillian Pass area of the NWT. In this case, ice lenses were very common in the surface peat layer, some being as large as 25 cm thick and 55 cm long but no ice was documented in the underlying mineral soil Zoltai (1972) cored several palsas in central Manitoba and Saskatchewan in which thin ice lenses (< 1 cm thick) were found in the peat with larger lenses (≥ 10 cm thick) in the fine grained mineral soil beneath the peat. Lagerback and Rodhe (1986) describe palsas in northern Sweden, where a variety of ice types were found in the underlying mineral soil However, in only one of these palsa was ice lenses found in the peat layer.

These examples highlight some of the variations in cryotic structure of palsas but the majority and thickest ice lenses are found at the peat-mineral soil interface or entirely within the mineral soil. Ice lenses are generally thin or completely absent from the peat. The reason for this may be the change in the slope of the thermal gradient with depth during freezing. In the uppermost peat layers the thermal gradient is quite steep. As the thermal wave penetrates the palsa it becomes attenuated with depth. Thus, the thermal gradient becomes less steep. When the thermal gradient is gentle, unfrozen water migrates to the freezing front, accumulates in layers normal to the direction of heat flow and freezes to form an ice lens. Thus, to a large extent the location, distribution and size of ice lenses depends on the relationship between the freezing rate (air temperature) and properties of the surface peat and soil moisture content.

### 1.5.4 VEGETATION COVER

Seppala (1988a) provides a general summary of the vegetation associations commonly found on palsas. From an ecological point of view, palsas are raised dry peat islands in an otherwise flat fen dominated by hydrophilic vegetation and pools of open water. Fens are normally characterized by seasonal frost, one reason for this is the presence of a vegetation cover that tends to trap winter snow and thus insulates the ground from extreme cold temperatures. By contrast, palsas have raised surfaces which due to their greater exposure, have little or no snow cover and therefore experience much cooler ground temperature conditions. This situation is an important factor maintaining the permafrost core of the palsa. It also influences the vegetation cover that normally develops on the palsa surface.

In general, vegetation on palsas is dominated by xerophilic mosses, lichens and low shrubs (Allard and Seguin, 1987a; Lundqvist, 1969; Railton and Sparling, 1973). Palsas in northern Manitoba and Saskatchewan usually have significant cover of Black spruce and Larch (Thie 1974; Zoltai 1972; Zoltai and Tarnocai 1971). It has been suggested by these authors that under these conditions permafrost forms because of thinner snow cover in the winter and shade conditions during the summer. In most other palsa regions, the lack of vegetation is given as the reason for thinner snow cover in winter. This suggests that winds in northern Manitoba and Saskatchewan play a less significant role. Zoltai and Tarnocai (1971) use vegetation associations to classify two types of palsas: (1) Black spruce-feather moss type and (2) Black spruce-*Cladonia* type. The latter has shorter and wider spaced trees and a thick ground cover of *Cladonia* lichen.

Zoltai (1972) uses a similar scheme to classify four stages of palsa development: (1) young incipient palsas which have very little relief and include dense Black spruce trees in a otherwise treeless fen, (2) young palsas which are < 20 cm high and have open stands of black spruce with Labrador tea and leather leaf shrubs with sporadic lichen ground cover, (3) mature palsas, similar to young palsas except they are > 1 m high and (4) over mature palsas which are similar to mature palsas but also have thermokarst depressions and collapsing edges.

Railton and Sparling (1973) in a study of the ecology of palsas in northern Ontario suggest that changes in fen vegetation from hydrophilic sedges (e.g. *Carex*) to a less hydrophilic moss (e.g. *Sphagnum fuscum*) to lichen is one of the main causes of palsa growth. However, one could argue that this change in vegetation on the palsa surface is a result of changing conditions brought about by palsa growth (heave) rather than a cause of it. That is, after initial heave has raised the peat above the fen surface the moisture content of the surface peat is lowered. This decrease in moisture content permits lichens and xerophilic mosses to colonize the palsa surface. Lichen growth on the palsa surface results in a higher albedo which reduces heat penetration and can induce continued growth in a positive feedback system. The feedback system is enhanced by the lower thermal conductivity of the drier surface peat.

### 1.5.5 AGE

Several ages of palsas have been reported. Allard and Seguin (1987a) suggests that palsa inception on the east coast of Hudson Bay occurred around 1900-1200 years B.P. This is based on a series of pollen diagrams and $C^{14}$ dates of peat samples taken approximately 10 cm below the palsa surface. Based on air photo analysis, Brown (1980) suggests that the palsas in west central Alberta may be less than 25 years old. Thie (1974) used dendrochronology of buried trees found in palsas to suggest an age of 600 years B.P. for palsa inception in northern Manitoba. Jahn (1986) carried out $C^{14}$ analysis on peat found 70 cm below mound surface in the Schefferville area. He obtained a date of 3230 years B.P. which he believed represents the age of the palsa. Kershaw and Gill (1979) dated volcanic ash found in the palsas of Macmillian Pass to suggest an age of 1220 years B.P..

The dating of palsas is somewhat problematic as outlined by Vorren (1972), Allard and Seguin (1987a) and Seppala (1988a). The problem lies in the sampling for dating. It is possible to sample material from any position within an organic layer and to obtain a range of dates. However, to obtain an accurate $C^{14}$ age of a palsa the depth of the organic sample is crucial. Material from the base of the palsa indicates the period of initial peat accumulation. If this data is combined with dates from other depths, then peat accumulation rates can be determined, but this does not provide a date of palsa inception. The clearest indication of the age of palsas should be obtained by dating the transition layers between the uppermost hydrophilic and lower most xerophilic peat. This indicates when the surface ecological conditions changed following initial heave of the fen surface. Because this peat has been raised above the fen surface it is dryer and plant species that can tolerate these conditions will gradually colonize the palsa surface. Problems may arise when wind deflation, rain-splash, thermokarst and block failure create an unconformity in the vegetation profile.

### 1.5.6 PALSA EVOLUTION

The wide range in dates of palsas inception seems to introduce the concept of sequential evolution of palsas. This has already been discussed above with reference to palsas in central Manitoba and Saskatchewan (Zoltai 1972). Allard and Seguin (1987a) have documented aggrading or growing palsas in the same general area of degrading palsas. While Lundqvist (1969) found both thawing and growing palsas in the same fen in northern Sweden.

Seppälä (1982) suggests a complete cycle of development from inception to collapse. The formation of palsas begins when local snow cover is thin and winter frost penetrates so deeply that it fails to thaw completely the following summer and thus, meeting the definition of permafrost. During succeeding winters, snow is still thinner because of snow redistribution over a slightly raised area. Subsequent winter freezing penetrates deeper and may cause heave due to ice lens development. The peat surface becomes dryer and its thermal conductivity is reduced. This reduces summer active layer development. When the aggrading permafrost reaches the basal mineral soil, larger ice lenses may develop and under exceptional conditions palsa can reach heights of 7-10 m. Degradation of the permafrost core is induced by numerous process, including wind deflation of the palsa surface and block failure along its edges. As these processes continue, the horizontal and vertical dimensions of the palsa are reduced. Ultimately there is very little remaining to identify the former position of the palsa. From such areas new palsas may reemerge after a new phase of peat development and low snow years. In this progression Seppala (1982) includes 7 stages, from an open fen and embryo stages to young, mature, old collapsing, fully thawed and finally new palsa formation.

It seems apparent that some sort of cyclic progression does take place. How close this follows Seppala's model can only be assessed after long term process studies are completed.

### 1.5.7 THERMAL REGIMES

The presence or absence of palsas, and thus permafrost, depends on the temperature of the ground. There is limited annual thermal regime data for palsas. Allard *et al.* (1987b) documented the thermal regime of a palsa near Kuujjuarapik on the east coat of Hudson Bay. Here it was found that the mean soil temperature was -4.5°C. The uppermost peat temperatures had a temperature amplitude of 32°C (-22 to 10°C) while below 150 cm the soil was always colder than the freezing point and did not drop below -8°C. Lundqvist and Mattsson (1965) document the annual thermal regime of a palsa in northwestern Norway. In this study, the upper most peat had an annual temperature amplitude of 26°C (-16 to 10°C) while at a depth of 4m below the surface only varied 0.5°C around -1°C isotherm. In a recent paper, Seppala (1990) noted that permafrost can occur during specific winters where snow depth is 30 cm or less in February. Under those conditions up to 70 cm of frost can form which is enough to allow an ice lens to remain throughout the summer.

### 1.5.8 CLIMATIC CONTROLS

A characteristic of the discontinuous permafrost zone is the localized formation of islands of permafrost where frost penetration is sufficiently deep to prevent complete ground thaw during the subsequent summer. This is the result of a combination of cold winter temperatures, thin snow cover (on palsa surface) and the thermal properties of the soil By studying the discontinuous permafrost zone we may develop a better understanding of the variables in the physical environment that may be sensitive to climate change. Since features such as palsas can be in a delicate thermal balance, their formation, presence and degradation may be used as an indication of past and present climatic environments (Brown, 1980). In fact, palsas are often regarded as one of the best and most conspicuous indicators of permafrost in the discontinuous permafrost zone (Akerman and Malstrom, 1986). In this zone palsas are islands of permafrost in an otherwise permafrost free region.

Table 1.5.1 gives some mean annual temperatures (MAT) that have been cited in associated with palsas. Clearly, palsas are located in the discontinuous permafrost zone whose boundaries has been related to areas with mean annual temperatures of 0 to -5°C (Brown and Péwé, 1973). Mean annual temperature is not the only climatic characteristic of palsa regions Lundqvist (1962) described palsa distribution in areas with 200-210 days below 0°C. Ashman (1977) delimited palsa regions as areas having temperatures below -8°C for 120 days. Ashman (1977) also described summer conditions where the mean air temperatures in the summer months was +11 to +12°C. Precipitation has also been used to describe palsa regions. Ashman (1977) again described annual precipitation in Norway ranging from 325-400 mm, the majority of which occurs during mid to late summer. While in winter months precipitation is less than 100 mm. Railton and Sparling (1973) delimited palsa regions as areas with less than 120 cm of snowfall. Harris (1982) defined "active palsa zones" using freezing and thawing indices. The freezing index for palsa areas ranged from 1000-7500 degree-days annually, with 300-2300 thawing degree-days annually.

| MAT°C | REGION | SOURCE |
|---|---|---|
| -5, -6 | eastern Hudson Bay | Allard & Seguin 1987a |
| -7 | Brooks Range, Alaska | Brown, *et al* 1983 |
| 0 | west central Alberta | Brown 1980 |
| -1 | Enontekio Finnish Lapland | Seppala 1976 |
| -0.5 | central Manitoba & Saskatchewan | Zoltai 1972 |
| -1.2 | northern Manitoba | Zoltai and Tarnocai 1971 |
| -4.5 | Richman, northern Quebec | Heim 1976 |
| -2,-3 | Norway | Ashman 1967 |
| -4,-4.5 | James Bay, Quebec | Dionne 1978 |
| -2,-3 | Atlin, British Columbia | Seppala 1980 |
| -1.9 | Iceland | Freidman *et al.* 1971 |

**Table 1.5.1.** Mean annual temperature of regions where palsas have been identified.

It is clear that a variety of delimited factors have and are being used to characterized palsa regions. However, to that end, it is quite apparent that broad generalizations can be made but much more empirical and theoretical research should be carried out to better delimit the critical factors that affect the growth and decay of palsas.

# CHAPTER 2: RESULTS-PALSA MORPHOLOGY AND STRUCTURE

## 2.1 BACKGROUND TO PAPER ONE

This chapter presents the findings from two papers concerned with palsas in the Schefferville area. The first paper discusses three palsa sites, one of which was included in future study (Goodream palsa). The research focused on size, setting, morphology, summer ground temperatures and soil moisture content, near surface biotic and cryotic structure of the palsas and snow distribution in the major vegetation zones of the area. This paper provides an introduction to palsas in this area by discussing readily observable characteristics of these phenomena and, identifies work needed, some of which is addressed in the papers two and three.

This paper represents approximately 10% of the field work carried in this study. The results presented are considered valid; however, following more intensive field work the classification of the palsa at site three seems less sound. It was first thought that the small palsa at site three was "embryonic". However by comparing this site to others in the area this conclusion has to be reworked.

The vegetation species on the surface of the palsa represent a relatively dry environment. The presence of a small shrub (*Betula*) indicates that this surface has been above the water table for a sufficient period of time to allow relatively xerophilic species to colonize the peat surface. Analyses of the 1948 and 1977 air photos showed that the three palsas that are currently visible were part of a single larger palsa. It appears that at some time following 1948, degradation of the permafrost core was initiated. Thermokarst hollows and block failure eroded much of this feature. This resulted in the three small features that were evident in 1987. Thus, the small mounds at site three are degrading rather than embryonic palsas.

**2.2 CUMMINGS, C.E AND POLLARD, W.H 1989. AN INVESTIGATIONS OF PALSAS IN THE SCHEFFERVILLE AREA, QUEBEC. MUSK OX, SPECIAL ISSUE 37. PROCEEDINGS OF THE SECOND ANNUAL STUDENT CONFERENCE ON NORTHERN STUDIES, OTTAWA, NOVEMBER 1988. PP. 8-18.**

### 2.2.1 INTRODUCTION

Palsas are widely reported throughout most of the discontinuous permafrost zone of Canada (e.g. Brown 1968, 1975; Kershaw and Gill 1979; Railton and Sparling 1973; Thie 1971; Zoltai 1972; Zoltai and Tarnocai 1971). There is, however, only a limited body of literature referring to palsas in the Labrador-Ungava area (e.g. Allard and Seguin 1987; Allard *et al.* 1987). This probably reflects a lack of specific research rather than an absence of these landforms. Palsa features have been identified near Cartwright, on the east coast of Labrador (Brown 1975) and on the east coast of Hudson Bay (Lagarec 1982). More recently, Seppala (1988) documented rock pingos in northern Quebec near Asbestos Hill. While these reports are by no means inclusive, they do suggest that a variety of frost mounds, including palsas, are present in Labrador-Ungava.

The term palsa is a Fennoscandian word meaning mound or hillock rising out of a bog with a frozen core (Seppälä 1972). There is confusion in the literature between palsas and other frost mound phenomena (e.g. frost blisters). In many cases descriptive qualifiers have been combined with the term palsa to define a wide variety of morphologically similar landforms, for example, "elongated and string form", "longitudinal", and "conical" palsas (Akerman and Malstrom 1986, Ashman 1976, Wrammer 1972). Furthermore, there have been an increased number of reports describing palsas characterized by frozen mineral-soil cores rather than frozen peat exclusively (Akerman 1982, Forsgren 1968, Lagerback and Rodhe 1986)

Palsas are a slow-growing form of perennial frost mound that occur predominantly within the discontinuous permafrost zone. However, Washburn (1983) has described perennial frost mounds that resemble palsas in the continuous permafrost zone. Palsa formation requires three factors: (1) a thick insulating layer of peat, (2) cold winter temperatures combined with a thin snow cover, and (3) standing water to provide moisture for ice segregation. The dynamics of palsa formation are still uncertain; however, most researchers suggest that ice segregation is the dominant process responsible for their growth, (e.g. Akerman 1982; Brown 1973; Seppala 1972, 1982, Zoltai and Tarnocai 1971). Once elevated above the surrounding terrain, the surface peat of a developing palsa becomes drier and insulates a portion of the underlying frozen material from complete summer thaw. This progressive rise in elevation increases exposure of the mound surface to winter winds which reduce the thickness of snow cover. Many researchers (e.g. Nicholson 1976, Outcalt and Nelson 1984; Seppala 1972) have suggested that reduction in snow cover is a major factor influencing the distribution of permafrost in the discontinuous permafrost zone In many cases palsas and peat plateaus form islands of sporadic permafrost in a dominantly permafrost-free environment.

Palsas are often regarded as one of the most obvious and reliable surface indicators of permafrost in the discontinuous zone (Brown 1973, Rapp and Annersten 1969). This discussion focuses on a number of palsas in the Schefferville area and the use of palsa distribution to describe site-specific permafrost conditions.

### 2.2.2 STUDY AREA

Schefferville is located at 54° 50'N, 66° 40'W, approximately 525 km north of Sept-Iles (Figure 2.2.1). It is situated in the Labrador Trough, which is characterized by a strong ridge and valley topography aligned in a northwest-southeast direction. Peatlands are found in many topographic depressions of the Labrador-Ungava region. The Schefferville area was overridden by a thick ice sheet during the last 100,000 years. This was particularly true during the maximum of the Wisconsian glaciation about 18,000 years B.P (Ives 1979). Most researchers (Bryson *et al* 1969; Ives 1979) believe that the eastern centre of Laurentide ice was over Kivivic Lake, 40 km northwest of Schefferville. Radiocarbon dating suggest initiation of peatlands approximately 6000 years B.P. (Grayson 1957).

The mean annual air temperature for Schefferville is -4.9°C with a maximum

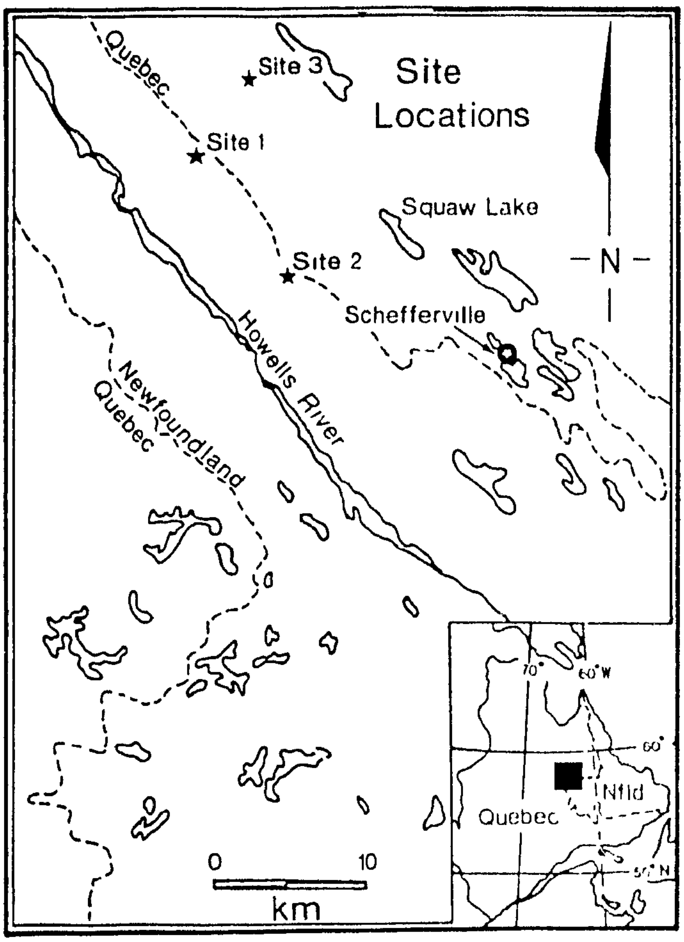



**Figure 2.2.1.** Study area map showing location of study sites.

mean annual temperature of -2.7°C and a minimum mean annual temperature of -7.9°C, (personal communication, D. Barr, McGill Subarctic Research Station). Brown (1973) states that in areas bounded by the -1 and -4°C mean annual isotherm, permafrost is restricted to the drier portions of peatlands. However, in the Schefferville area the ridges are the areas where permafrost is most widespread (Nicholson, 1979).

Studies investigating snow conditions for four areas characterised by distinct vegetation associations found that in the Schefferville area, including; (1) lichen forest, (2) open peatland, (3) peatland-lichen forest transition and (4) spruce bog, have shown that open peatlands have the lowest average snow depth (24.6 cm, Figure (2.2.2). This is well below the critical snow depths of 76 cm and 50 cm needed for permafrost formation suggested by Nicholson (1976) and Harris (1982), respectively.

### 2.2.3 STUDY SITES AND METHODOLOGY

The three palsa sites were located in the immediate vicinity of Schefferville (Figure 2.2.1). Site 1 was 250 m northeast of Goodream Lake (NTS map 23J/14, reference 202 881), site 2 was 325 m south of Hematite Lake (NTS map 23J/14, reference 266 803) and site 3 was 2 km west of Lake Militiere (NTS map 23J/14, reference 249 941).

Field work was undertaken in June and September, 1987. Ground temperatures were obtained using thermistor cables (Yellow Springs Instruments 44033 thermistor beads calibrated to 0.1°C). Cable construction is outlined in Judge (1973) As well, a Yellow Springs Instruments needle-probe and multimeter were used to obtain instantaneous temperatures during excavations. Active layer measurements were carried out using a 1.5 m steel probe. The laboratory component focused on analysis of moisture contents and macrofossils of peat samples obtained by shallow excavations. The macrofossil data was obtained using the method described by Lowe and Walker (1984).

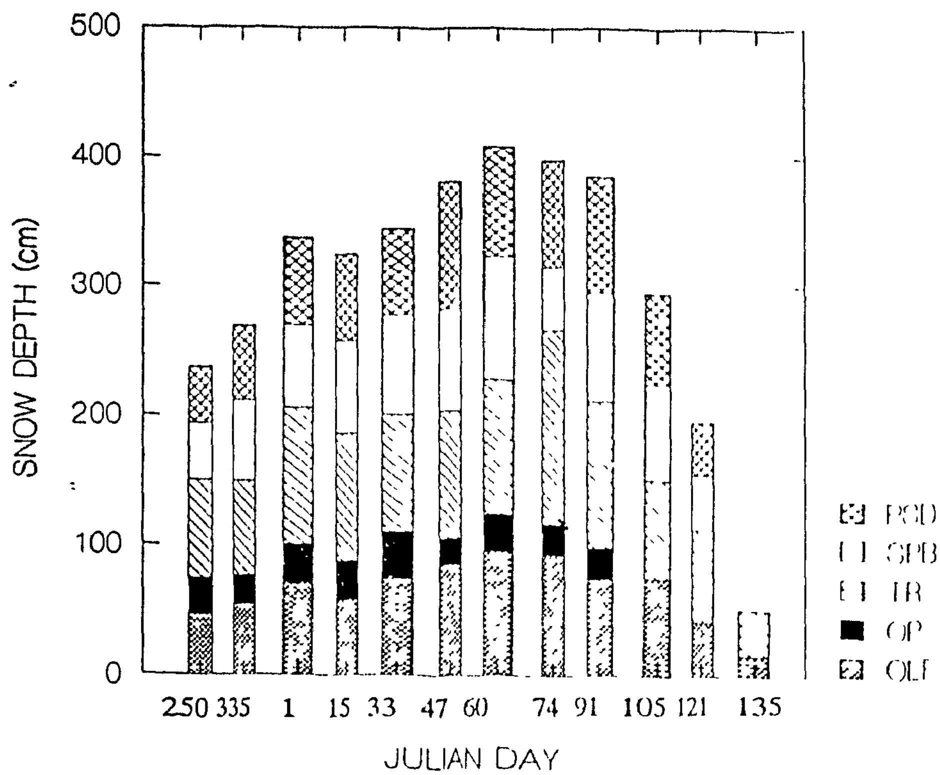



**Figure 2.2.2.** Snow course data for Schefferville, 1986-87: OLF) open lichen forest; OP) open peatland; TR) transition zone between peatland and lichen forest; SPB) spruce bog; PSD) snow drift site. Open peatland has a thinner snow cover and period of snow accumulation.

### 2.2.4 OBSERVATIONS

The following discussion summarizes the setting and morphology, vegetation characteristics, internal structure, shallow ground thermal regimes and moisture contents of the palsas.

#### 2.2.4.1 Setting and morphology

All three palsa sites are located within a 23 km radius of Schefferville Quebec. The palsas occur in peatlands within the tundra-forest ecotone. At site 1, two palsas occur within a minerotrophic fen (Waterway *et al.* 1984) situated in a small valley located between two major drainage divides. This fen is drained by a small creek flowing to the southwest. Both palsas are surrounded by water ranging from <0.5 to >2 m deep. The largest palsa has a length of 28 m, and a width of 15 m and was 0.78 m above the water table (Figure 2.2.3). This oval-shaped palsa (long axis trending northeast southwest) is experiencing block failure along its perimeter (Figure 2.2.4). As well, there are patches of bare peat exposed on its surface. In theory these patches alter the radiation balance through the reduction of albedo (Petzold and Rencz 1975) and result in increased absorption of solar radiation and therefore increased thawing of the permafrost core.

At site 2, three small palsas occur in a minerotrophic fen situated in a setting similar to site 1. This fen is drained by a small creek flowing to the southwest. The palsa examined has a length of 10 m, a width of 4.5 m and a height of 0.77 m above the water table (Figure 2.2.5) Water approximately 1.5 m deep surrounds this palsa on three sides. This palsa is roughly circular in plan shape and appears to be geomorphologically stable since there is a continuous vegetation cover and no block failure was occurring.

Site 3 contains three "embryonic" palsas that are completely surrounded by standing water > 1.5 m deep. This is a weakly minerotrophic fen (Waterway *et al.* 1984) and is surrounded by a gently sloping lichen forest. One feature is discussed, it is circular in shape with a diameter of 1.5 m and a height of 0.59 m above the

**Figure 2.2.3.** Large palsa, site 1.

**Figure 2.2.4.** Block failure along perimeter of large palsa, site 1.

water table (Figure 2.2.6). The term embryonic is used because these mounds appear stable and at a threshold stage in palsa development, as no block failure was evident and a continuous vegetation cover is present. The presence of a permafrost core could not be confirmed within the time frame of this study. However, a permafrost core was documented in previous years (personal communication with D. Desrochers, McGill University)

**2.2.4.2** Vegetation characteristics:

Since peat is an essential constituent of palsa structure and the palsas studied are composed primarily of peat and organic silt, an attempt was made to relate the surface vegetation cover and biostratigraphy, as a means of inferring palsa evolution.

An inventory of vegetation growing on the palsas and stratigraphic analysis of macrofossils identified in peat samples was undertaken. No dates have been obtained for the organic samples; however, by noting the abundance of each species at depth, a relative colonization sequence can be developed. The term macrofossil refers to identifiable fossils preserved in sediment (Birks and Birks, 1980). Macrofossils are used in this study rather than pollen because the latter is easily transported over long distances by wind and water and thus, reflect the local environment. Peat macrofossils are usually found *in situ*, and therefore are reliable indicators of site-specific environmental conditions (Vorren and Vorren 1976).

Lichens and ericaceous shrubs constitute 80% of the surface cover of the palsa at site 1 (Table 2.2.1). As well, bryophytes indicative of drier conditions (e.g. *Sphagnum fuscum*) are also present. This suggests that this palsa has remained above the water table for a period sufficient to permit the colonization and development of xerophilic species. Species indicative of hydrophilic environments such as *Carex* and *Scirpus* which are found immediately below the surface, suggesting a much wetter environment. Wet arctic and alpine species such as *Sphagnum girgensohnii* (Crum and Anderson 1981) and hydrophilic species such *Carex* are encountered at a depth of 25 cm. The presence of a permafrost core undoubtedly plays a major role in

| Species | Percent of identifiable sample | Depth below surface (cm) |
|---|---|---|
| *Cladonia rangiferina* | 70 | 0 |
| *Ledum groenlandicum* | 5 | 0 |
| *Betula michauxii* | 5 | 0 |
| *Dicranum scoparium* | 5 | 0 |
| *D leioneuron* | 5 | 0 |
| | | |
| *Scirpus* spp. | 45 | 15 |
| *Carex* spp. | 45 | 15 |
| *Polytrictum* spp. | 5 | 15 |
| *Sphagnum fuscum* | 5 | 15 |
| | | |
| *Sphagnum girgensohnii* | 40 | 25 |
| *S ceoillifolium* | 40 | 25 |
| *Carex* spp. | 10 | 25 |
| *Scirpus* spp. | 10 | 25 |
| | | |
| *Carex* spp. | 90 | 35 |
| *Drepanocladus exannulatus* | 10 | 35 |
| | | |
| *Carex* spp. | 95 | 45-55 |
| *Drepanocladus* spp. | 5 | 45-55 |
| | | |
| *Fontinalis* spp. | 100 | 65 |

**Table 2.2.1.** Surface and Subsurface macrofossils, site 1.

Figure 2.2.5. Palsa site 2.

**Figure 2.2.6.** Three embryonic palsas, site 3.

| Species | percent of identifiable sample | Depth below surface (cm) |
|---|---|---|
| *Cladonia* spp. | 100 | 0 |
| | | |
| *Carex* spp. | 45 | 10 |
| *Scirpus* spp. | 40 | 10 |
| *Betula* spp. | 10 | 10 |
| *Kalmia* spp. | 5 | 10 |
| | | |
| *Carex* spp. | 85 | 20 |
| *Sphagnum riparium* | 15 | 20 |
| | | |
| *Carex* spp. | 100 | 30 |
| | | |
| *Carex* spp. | 70 | 40-60 |
| *Drepanocladus exannulatus* | 20 | 40-60 |
| *D fluitans* | 10 | 40-60 |

**Table 2.2.2.** Surface and subsurface macrofossils, site 2.

determining which species colonize this environment. As expected, hydrophilic species, such as *Drepanocladus exannulatus* and *Fontinalis*, are found in the deeper sections of the palsa at site 1. This vegetation grouping reflects a wetter environment before any significant vertical displacement associated when palsa growth took place.

The surface of the palsa at site 2 has a thick lichen cover and ericaceous shrubs are absent (Table 2.2.2). This suggests that the palsa surface has been elevated above the water table for a substantial period of time, as lichens usually do not colonize extreme hydrophilic environments. Below the surface are both minerotrophic and weak minerotrophic (e.g. *Drepanocladus exannulatus* and *Sphagnum riparium* respectively) indicator species (Table 2.2.2). This suggests a

| Species | Percent of identifiable sample | Depth below surface (cm) |
|---|---|---|
| *Sphagnum girginsohnii* | 80 | 0 |
| *Carex* spp. | 20 | 0 |
| *Betula* spp. | 1 plant | 0 |
| | | |
| *Carex* spp. | 70 | 10 |
| *Scirpus* spp. | 20 | 10 |
| *Drepanocladus exannulatus* | 10 | 10 |
| | | |
| *Carex* spp. | 60 | 20 |
| *Sphagnum riparian* | 20 | 20 |
| *S subsecundum* | 15 | 20 |
| *Drepanocladus* var *kneiffii* | 5 | 20 |
| | | |
| *Sphagnum fimbriatum* | 80 | 30 |
| *Carex* spp. | 20 | 30 |

**Table 2.2.3.** Surface and subsurface macrofossils, site 3.

period of rapid heave which raised the peat surface from below the water table to a considerably drier environment.

Surface species on the embryonic palsa at site 3 suggest a wet arctic and alpine environment that can also support shrub growth (Figure 2.2.3), as displayed by the presence of *Sphagnum gigensohnii* and *Betula* spp. (Crum and Anderson 1981). Below the surface are indicators of a wet minerotrophic environment. Macrofossils of plants typical of saturated surfaces (e.g. *Carex* and *Sphagnum riparium*) were found in the deeper portions of this palsa.

**2.2.4.3.** Near-surface internal structure:

The near-surface stratigraphic characteristics of the palsas described in this study are based on a series of shallow manually excavated sections into each palsa (Figure 2.2.7). During excavations water filled the pits making deeper investigation impossible, hence only near surface references are made. The peat in this area is approximately 3 m deep (personal communication A. Heyes, McGill University). All three palsas are composed mainly of fresh peat underlain by decomposed peat and organic-rich silt was found only at considerable depth. Fragments of wood (6 cm in length) were preserved within the frozen peat at sites 1 and 2. At sites 1 and 3 approximately 50 cm of thawed fibrous peat were documented. At site 1, the peat is underlain by 20 cm of ice-rich humic peat containing thin horizontal ice veins and lenses. These range from 1-2 mm thick discontinuous veins to ice lenses up to 2-3 cm thick. Below 70 cm the stratigraphy is characterized by frozen organic-rich silt with reticulate ice veins. At site 2, the stratigraphic sequence is characterized by 40 cm of thawed peat underlain by nearly 10 cm of massive frozen peat with pore ice and visible ice crystals. This layer is underlain by 10 cm of organic-rich silt containing horizontal ice lenses and reticulate ice veins. Site 3 has a zone of icy peat and organic-rich silt 5-7 cm thick beneath a layer of thawed peat. The lowest part of the section at site 3 is composed of a 5 cm thick zone of frozen peat and organic-rich silt with pore ice and ice coatings on wood fragments. All three palsas contain a gradational sequence from fresh fibrous peat near the surface to black organic-rich silt at depth. Ground ice occurred as ice lenses and reticulate ice veins up to 2-3 cm thick. The permafrost core contained pore ice and ice coatings through its entire sequence.

**2.2.4.4.** Near surface ground thermal regime and moisture contents

The temperature and moisture content profiles are based on readings taken between August 29 and September 3, 1987 (Figure 2.2.8). The maximum palsa soil temperature recorded at this time was +8.6°C at a depth of 2 cm in the palsa at site 3 (September 3). The minimum temperature recorded was -1.9°C at 60 cm on

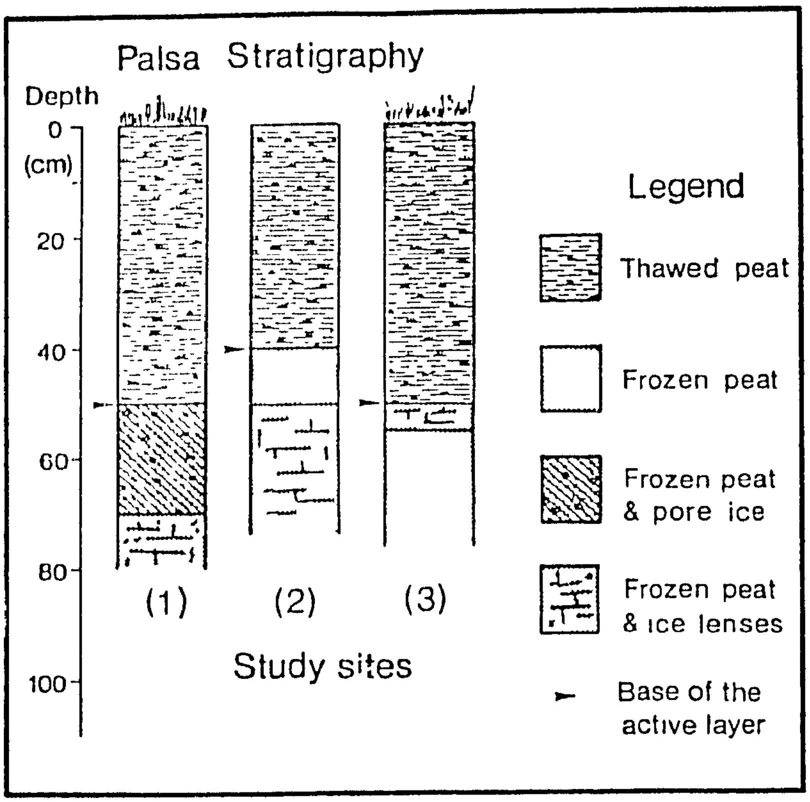



**Figure 2.2.7.** Stratigraphy of palsas at sites 1, 2, and 3.

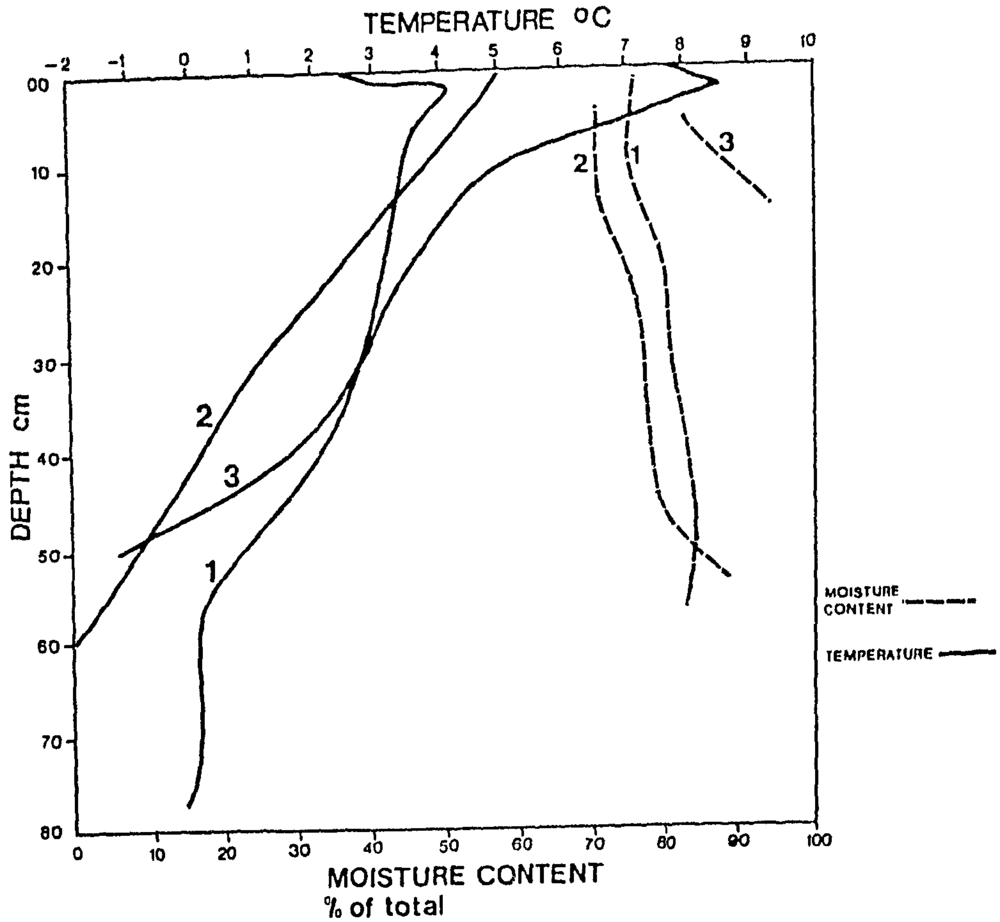



**Figure 2.2.8.** Ground thermal regime and moisture content of palsas at sites 1,2, and 3 (August 19-September 3. 1987).

September 2 in the palsa at site 2. The upper 2 cm of peat at sites 1 and 3 were cooler than the underlying 32 cm. This is probably due to the effect of ambient air temperature in the upper-most peat layers; however, this effect became attenuated below this point because of the insulating properties of peat and the short-term nature of the temperature perturbation. Site 2 had a temperature difference of 7°C from the surface to 60 cm depth.

All three palsas studied are frozen below the water table throughout the study period. The relationship between moisture content and thermal regime is not clear. Moisture content graphs for sites 1 and 2 display slight changes from the surface to the frost table. However, below the frost table the moisture content for site 1 dropped from 89 to 72% (at depths of 48 cm to 64 cm) and increased from 75 to 91% (at depths of 46 cm to 51 cm) for site 2. These are considered to be a function of moisture content variation during freezing and subsequent unfrozen water movement following freezing.

### 2.2.5 CONCLUSION

Within a relatively small area near Schefferville three palsa sites were identified. The settings of all palsas are in peatlands within geologically controlled topographic depressions. These valleys create conditions ideally suited for palsa development, including: (a) collection of cold air during winter (Tout 1964), (b) lacustrine sediments deposited on valley floors that inhibit drainage thus enhancing peat development and increase frost susceptibility (Brown 1973), and (c) funnel winds parallel to valley walls (Tout 1964), thus reducing local snow thickness.

The three palsas appear to reflect three different stages of development: (1) mature-degrading (site 1), (2) mature-stable (site 2), and (3) immature-embryonic (site 3). The actual mechanics of aggradation and degradation were not investigated; however, this does support the concept of cyclic palsa development put forth by Seppala (1982). Further work is needed to confirm the suggested developmental stages documented in this study.

The vegetation displays the successional changes of species that colonize the drier peat following heave of a developing palsa above the surrounding water table (Vorren and Vorren 1976). Railton and Sparling (1973) suggest that formation of palsas may depend on changes in albedo with species-dominance changes from *Sphagnum* spp. to *Cladonia* spp.. The lichen-dominant vegetation on the surface of palsas at sites 1 and 2 would appear to support this theory. However, it could also be argued that the change in vegetation is a direct consequence of changing moisture conditions on the surface of palsas rather than a cause of palsa development. This could occur as the palsas rose above the water table allowing the surface peat to drain and moisture contents to decrease thus permitting colonization of xerophilic lichen species. However, this sequence has not been documented and is highly speculative.

The thermal regime of the palsas demonstrates that the ambient air temperature quickly affects the temperature of the upper peat layers. These near-surface responses are lagged and become less significant at greater depths. The warmer ground temperatures are restricted to the uppermost peat layers throughout the summer. This is the result of the lower thermal conductivity of the dryer upper-most peat layer during summer (Farouki 1981). These observations provide strong support for the premise that peat is an essential component of palsas particularly in areas of discontinuous permafrost.

### 2.2.6 RECOMMENDATIONS FOR FUTURE WORK

The topographic setting in the Schefferville area is favourable for palsa occurrence. More aerial photographic analyses and fieldwork are needed within this environment to quantitatively document setting requirements needed for palsa formation and the sensitivity of palsas to subtle environmental changes. This should then be followed by detailed investigation of peatlands in the area to further document permafrost distribution (in the form of palsas) in the discontinuous permafrost zone. With increasing concern over climate warming due to increases in greenhouse gasses, palsas may prove to be useful indicators of climate change. Thus, a greater understanding of their current distribution should be documented.

There are very few reports on the age of palsas in the literature (e.g. Ashman 1967; Salmi 1972; Vorren and Vorren 1976). Radiocarbon dates of materials found within palsas do not indicate the age of the palsa itself, rather, they identify the age of the peat at that particular level. The clearest indication of palsa age can be obtained by dating the transition layers between the lowermost hydrophillic and upper most xerophilic peat. This transition zone can be identified using macrofossil assemblages which display site-specific hydrologic conditions through indicator species. Hence, a knowledge of macrofossil assemblages is needed before accurate dating of palsas can be carried out. This type of data will also yield relative values on amount and rates of vertical displacement and peat accumulation under different moisture regimes.

Gold and Lachenbruch (1973) state that the seasonal range in thermal conductivity of peat is an important parameter of permafrost development in the discontinuous permafrost zone. However, very little work has been carried out measuring actual thermal conductivities of peat at different depths in palsas. Therefore, detailed profiles of thermal properties of the peat and mineral soil in palsas should be carried out.

Snow density and depths have been recognized as playing an important role in palsa formation. However, no detailed snow thickness data have been published with regard to palsa occurrence. These data would increase the knowledge of winter thermal fluxes between the atmosphere and palsa surface, and help document the influence of snow thickness on palsa growth and decay.

## 2.3. BACKGROUND TO PAPER TWO

The second paper "Cryogenetic categorization of peat and mineral cored palsas of the Schefferville area", is based on field work carried out in February and from April to September, 1989. This paper presents the main body of field research undertaken in this research project. The primary objective of this research was to categorize stages of palsa development using a cryogenetic scheme based on field observations and air photo analyses.

The data presented in this paper focuses on surface vegetation cover, peat depths on and off the palsas, detailed core logs and the analysis of the relation between snow depth and ground/snow interface temperature. The main conclusion of this paper is that both stable and degrading palsas can be found in the same general area.

Although similar conclusions are made in the first paper, a different emphasis is used in paper two. Here the terms mature, immature and embryonic are replaced by aggrading, stable and degrading. It is felt that these terms better describe the permafrost conditions and therefore provide a more useful framework for categorization. The terms mature, immature and embryonic incorrectly suggest a relative age or sequential development between stages. This, in fact, may not be the case, as climatic conditions may intervene at any point in a palsas development and interrupt the natural cycle.

The presence of palsas at different stages of development in one area is discussed in both papers, however these ideas are much better defined in the second. The embryonic palsas described in paper one are dropped from the study and replaced by a similar stage of feature observed at a new site (Newf site).

At the Newf site, the largest palsa is categorized as stable but also found in this fen are features that suggest that both aggradational and degradational forms are present. In this case, the aggradational forms are small up-warpings in the fen surface ranging from 1-10 m in length and up to 30 cm above the water table (Figure 2.3.1 a). They appear similar to features described by Allard *et al* (1987) and Brown a

b

**Figure 2.3.1.a** Aggradational palsa at the Newf site. The palsa surface is covered with dead or dying *Carex* and *Scirpus.* **b** Site of degraded palsa at the Newf site. July 1989.

(1980). Of significance is the vegetation on the surface of these small mounds which consists of dead sedges (*Carex* and *Scirpus*) similar to those found in the surrounding wet fen areas. Allard *et al.* (1987) suggests that very small palsas are a result of thin snow cover; however, at the Newf site these features were covered with at least 0.8-1.2 m of snow in 1989, but information from previous years is not available.

Also at the Newf site, 5 m from the aggrading palsa, is an area of wet disrupted peat, healthy sedges, small tufts of *Sphagnum fuscum*, and dead *Betula* shrubs (Figure 2.3.1 b). This area is bordered by a discontinuous moat of standing water. The presence of healthy sedges suggest that this area remains at or near the water table for the entire summer period. The small tufts of *S. fuscum*, disrupted peat and dead shrubs suggest that this area was raised above the water table for a significant period in the recent past. It is postulated that this is the remnants of a degraded palsa. Thus at the Newf site there appears to be aggrading, stable, and degrading palsas as well as the remnants of former palsas.

## 2.4 PAPER TWO: CUMMINGS, C.E. AND POLLARD, W.H., 1990. CRYOGENETIC CATEGORIZATION OF PEAT AND MINERAL CORED PALSAS IN THE SCHEFFERVILLE AREA, QUEBEC. PERMAFROST-CANADA. PROCEEDINGS OF THE FIFTH CANADIAN PERMAFROST CONFERENCE. NORDICANA COLLECTION NO. 54. LAVAL, CANADA 95-102.

### 2.4.1 INTRODUCTION

Palsas are a common permafrost landform occurring throughout most of the Canadian subarctic (e.g. Brown 1968, 1975; Kershaw and Gill 1979; Railton and Sparling 1973; Zoltai and Tarnocai 1971). Several studies on coastal Labrador-Ungava have been concerned with palsas (e.g. Allard and Seguin 1987a, 1987b; Brown 1975; Dionne 1984; and Lagarec 1982), but very little work has been published concerning palsas in the central Labrador-Ungava region (Cummings and Pollard 1989). This paper presents observations on surficial and internal characteristics of palsas occurring at four locations in the Schefferville area of Quebec and Labrador.

### 2.4.2. BACKGROUND

The term palsa is a Fennoscandian word referring to a mound or hillock with a frozen core found in a bog or fen (Seppälä 1972). But in the current North American permafrost literature, palsas are defined as peaty permafrost mounds possessing a core of alternating layers of segregated ice and peat or mineral soil (Permafrost Subcommittee 1988). This is the definition adopted in this study. Implicit in this definition is the genetic distinction between palsas and other types of frost mounds. Confusion in the literature between palsas and other frost mound phenomena has arisen from the descriptive approach to landform classification. The current application of the term involves the use of descriptive modifiers within a genetic context (e.g. peat palsa) to better define mound character. Reviews of the palsa literature are provided by Washburn (1983) and Seppälä (1988).

### 2.4.3. STUDY AREA

Schefferville is located at 54°50'N, 66°40'W, approximately 525 km north of Sept-Iles (Figure 2.4.1). It is situated in the Labrador Trough, which is characterized by a strong ridge and valley topography aligned in a northwest-southeast direction. Peatlands occupy many topographic depressions of the Labrador-Ungava region. In the Schefferville area, fens occupy approximately 10-15% of the land surface (Allington 1961) with many of these peatlands containing palsas. This area was overridden by a thick ice sheet during the maximum of the Wisconsinan glaciation about 18,000 years B.P. (Ives 1979). Most researchers (Bryson *et al.* 1969; Ives 1979) believe that the eastern centre of Laurentide ice was at the current location of Kivivic Lake, 40 km northwest of Schefferville. Radiocarbon dating suggests initiation of peatlands occurred approximately 6000 years B.P. (Grayson 1957).

The mean annual air temperature for Schefferville is -4.9°C with a maximum mean annual temperature of -2.7°C and a minimum mean annual temperature of -7.9°C. It has approximately 90 frost-free days and mean annual precipitation of 785 mm, of which 378 mm is water equivalent of snow (personal communication, D. Barr, McGill Subarctic Research Station). In the Schefferville area, mining operations have

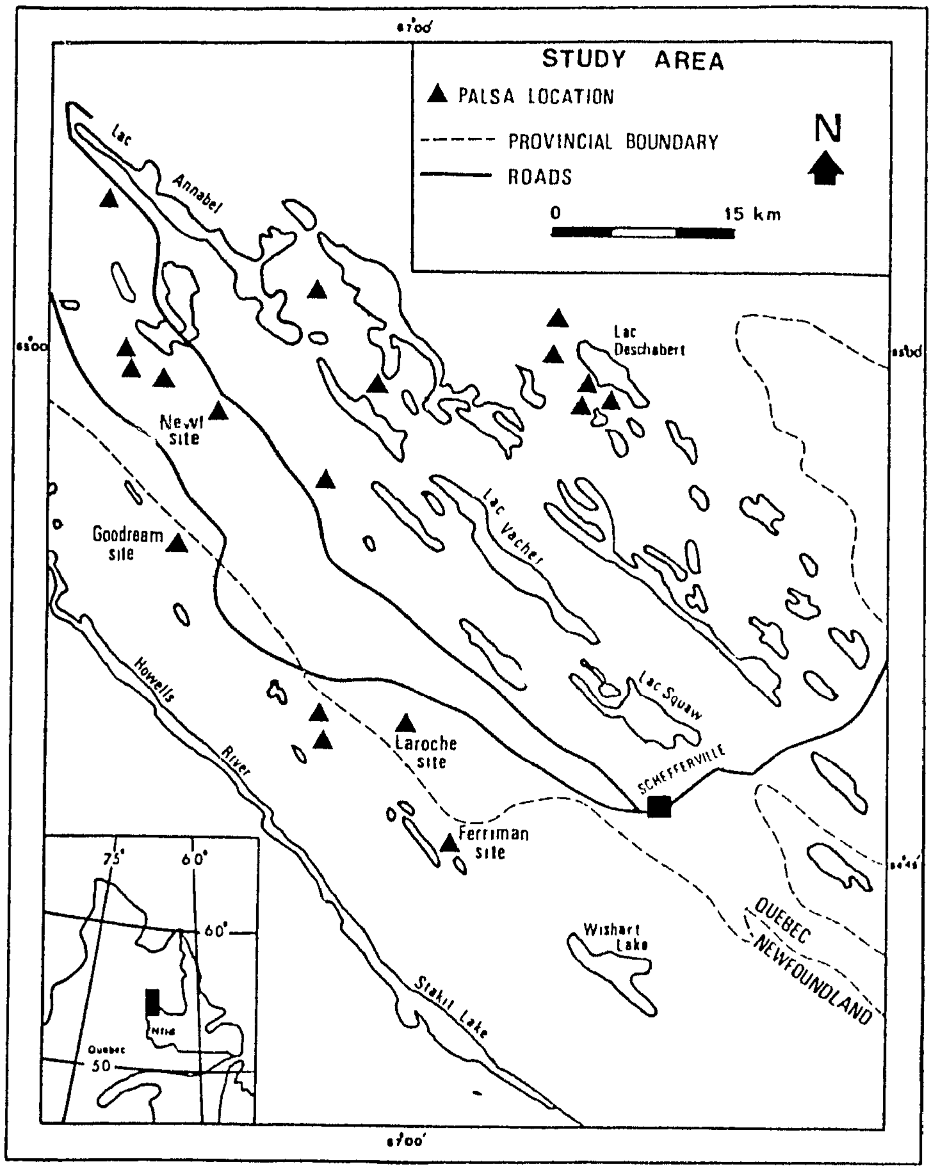



Figure 2.4.1. Location map of study sites.

encountered permafrost to depths of 60 m beneath exposed tundra ridges (Ives 1960)

The aims of this study are threefold: 1) to document permafrost landforms in the peatlands of the Schefferville area, 2) to describe surface and subsurface characteristics of these palsas, and 3) to evaluate this information with reference to cryogenetic classification.

## 2.4.4. METHODOLOGY

Field reconnaissance and aerial photograph interpretation led to the identification of 18 palsa sites within a 35 km radius of Schefferville (Figure 2.4.1). This paper focuses on four sites that are accessible using the existing network of mine roads. The results presented in this paper are based on field work in February, and from April to September, 1989. Peat cores, used for analysis of stratigraphic characteristics, were obtained using a CRREL permafrost coring kit. Vegetation cover on each palsa is based on the analysis of four, 1 $m^2$ selected quadrates. Unfrozen peat depths in the fens surrounding the palsas were obtained with a 3 m steel probe. Tree age was determined by tree-ring analysis of a cross-section of the tree taken just above the root crown. This was sanded and examined under 10x magnification. Snow depths were obtained using a Mount Rose snow sampler. A Yellow Springs Instruments needle probe was used to measure snow pit temperatures.

## 2.4.5. SITE DESCRIPTION AND SURFACE MORPHOLOGY

At the Goodream site, two palsas occur at 718 m asl in a small valley located between two till covered bedrock ridges. Both palsas are bound on three sides by standing water ranging from <0.5 to >2 m deep. The fourth side consists of a thin floating mat of peat with *Carex* and *Sphagnum* being co-dominant. The largest palsa is 28 m long, 15 m wide and 1.1 m high (all heights are measured relative to the water table). It is oval-shaped with its long axis trending northeast-southwest. It appears to be degrading by block failure along its perimeter (Figure 2.4.2a), similar to those described by Salmi (1968). As well, patches of bare peat are exposed on the surface (Table 2.4.1) and large cracks up to 15 cm wide and 30 cm deep traverse the entire palsa.

At the Ferriman site, one palsa occurs at 750 m asl in a topographic setting similar to the Goodream site . This palsa is surrounded by a deep (>2 m) 'moat'. It is circular in plan shape with a diameter of 12 m and a height of 0.7 m. This palsa also appears to be degrading as there are cracks, (up to 10 cm wide and 40 cm deep) traversing its entire surface (Figure 2.4.2b) along with thermokarst depressions.

The Laroche site contains two oval palsas located in a small valley (661 m asl) with a bedrock ridge to the east and till-covered bedrock to the west. The till surface is marked by non-sorted circles. The fen surrounding these palsas is dominated by *Carex* vegetation with the water table located 5 cm below the surface. A small pond (50 m in diameter) lies to the northwest of the palsas. The largest palsa is 58.7 m long (northwest-southeast axis) and 21.6 m wide, with a height of 1.0 m.

The Newf site contains nine palsas ranging from 5.6 to 21.0 m in length, 2.4 to 12.0 m in width and 0.5-0.8 m in height. The surface of the fen surrounding the palsas consists of a thin *Carex* and *Sphagnum* floating peat mat. This site is topographically different from the previous sites. There is no definite valley but rather gently sloping open lichen and feather moss forests surrounding the peatland. There are no large open water bodies, only small pools ($2m^2$). The palsa studied is 17.4 m long, 8.0 m wide and 0.8 m high.

The surface vegetation characteristics for the four palsa sites are shown in Table 2.4.1. At the Ferriman and Laroche sites, 70% of the palsa surfaces are free of vegetation. Bare peat, shrubs and lichen dominate the surface of Goodream palsa. The Newf site has the lowest percentage area of bare peat with lichen dominating the palsa surface. Trees were present at the Laroche site only. A larch tree 1.5 m high and 122 years old was found on the northwestern edge of the palsa. The very low percentages of sedges on all palsas and the absence of dead hydrophilic species indicate that their surfaces are relatively dry and have not been submerged recently.

Peat thickness overlying the mineral soil substrate, both on and surrounding the palsa, is summarized in Table 2.4.2. The surface peat at the Laroche site is

SURFACE PERCENT COVERAGE

| VEGETATION | GOODREAM | FERRIMAN | LAROCHE | NEWF |
|---|---|---|---|---|
| **BRYOPHYTES** | | | | |
| *Dicranum* spp. | 4 | 5 | 3 | 2 |
| *Polytrichum* spp. | 9 | 5 | 0 | 7 |
| *Sphagnum* spp | 5 | 0 | 0 | 1 |
| **TOTAL** | **18** | **10** | **3** | **10** |
| **SHRUBS** | | | | |
| *Betula glandulosa* | 17 | 4 | 4 | 5 |
| *Ledum groenlandicum* | 0 | 2 | 11 | 3 |
| *Vaccinium vitis-idaea* | 5 | 0 | 0 | 0 |
| *V uliginosum* | 3 | 5 | 2 | 0 |
| *Empetrum nigrum* | 2 | 3 | 3 | 0 |
| *Rubus chamaemorus* | 5 | 0 | 0 | 0 |
| **TOTAL** | **32** | **14** | **20** | **10** |
| **SEDGES** | | | | |
| *Carex* spp. | 0 | 0 | 0 | 0 |
| *Scirpus* spp | 0 | 2 | 2 | 0 |
| *Eriophorum chamissonis* | 0 | 2 | 2 | 2 |
| **TOTAL** | **0** | **4** | **4** | **4** |
| **LICHEN** | | | | |
| *Cladonia* spp. | 20 | 4 | 4 | 75 |
| **TREES** | | | | |
| *Larix laricina* | 0 | 0 | 1 | 0 |
| **BARE PEAT** | 30 | 70 | 70 | 3 |

**Table 2.4.1.** Surface vegetation cover of the four palsa sites.

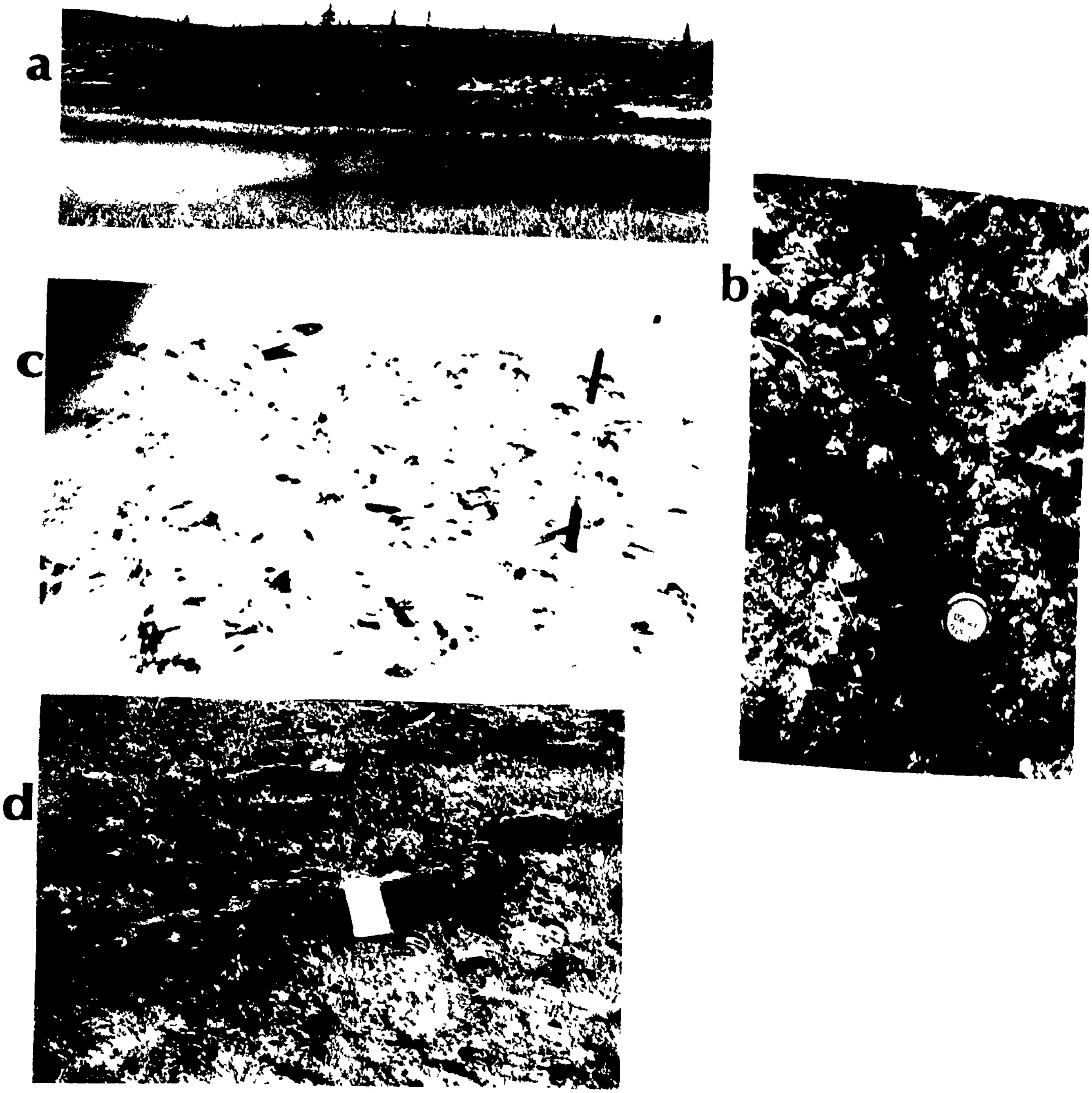


**Figure 2.4.2.** (a) Block failure on west face of Goodream palsa. Blocks range from 0.75-2 m long. (b) Cracks in surface peat at Ferriman Palsa. This seems to initiate block failure, (c) Ferriman palsa surface during winter of 1989. Much of the palsa surface (micro-hummocks) is free of snow. (d) Surface of Laroche palsa. Isolated blocks of peat resulting from winter wind erosion stand 18 cm above surrounding the unvegetated surface.

anomalously thin compared to the Goodream and Ferriman sites, while the thickness of the peat surrounding the palsa at the Laroche site, is similar to these two. At the Goodream and Ferriman sites the peat is thinnest at the edge of the fen and becomes thicker towards its centre.

## 2.4.6. INTERNAL CHARACTERISTICS

In the absence of long term process studies, the investigation of palsa structure provides one approach to the interpretation of mound genesis. In this study, stratigraphic observations are based on the analysis of cores up to 3.0 m long. Of particular interest to this study is the morphology and distribution of ground ice and the depth and nature of organic material and mineral soil.

The internal structure of 4 palsas is summarized in Figure 2.4.3. A variety of ice types are present, but segregated lens ice, in various geometric arrangements, is most common. The largest and greatest total thickness of lens ice is associated with the contact between the sedge-peat unit and underlying mineral soil. Approximately 32% of the total ice thickness were found at this location, 23% of total ice lenses is found within sedge peat and 17% within the mineral soil. An average of 73% of palsa height can be accounted for by accumulated ice lens thickness.

| PEAT THICKNESS (M) | GOODREAM | FERRIMAN | LAROCHE |
|---|---|---|---|
| On the palsa | 2.60 | 2.44 | 0.66 |
| Surrounding the palsa | 1.54-2.00 | 1.03-2.24 | 1.03-1.67 |

**Table 2.4.?.** Peat depths for three palsa sites. The peat depth on the surface of the Laroche is thinner than in the surrounding fen. At the Goodream and Ferriman sites the peat depth is thickest on the palsa.

The size of pore ice crystals varied considerably. Two size categories are proposed, (1) small ice crystals less than 1 mm in diameter, termed pore ice, and

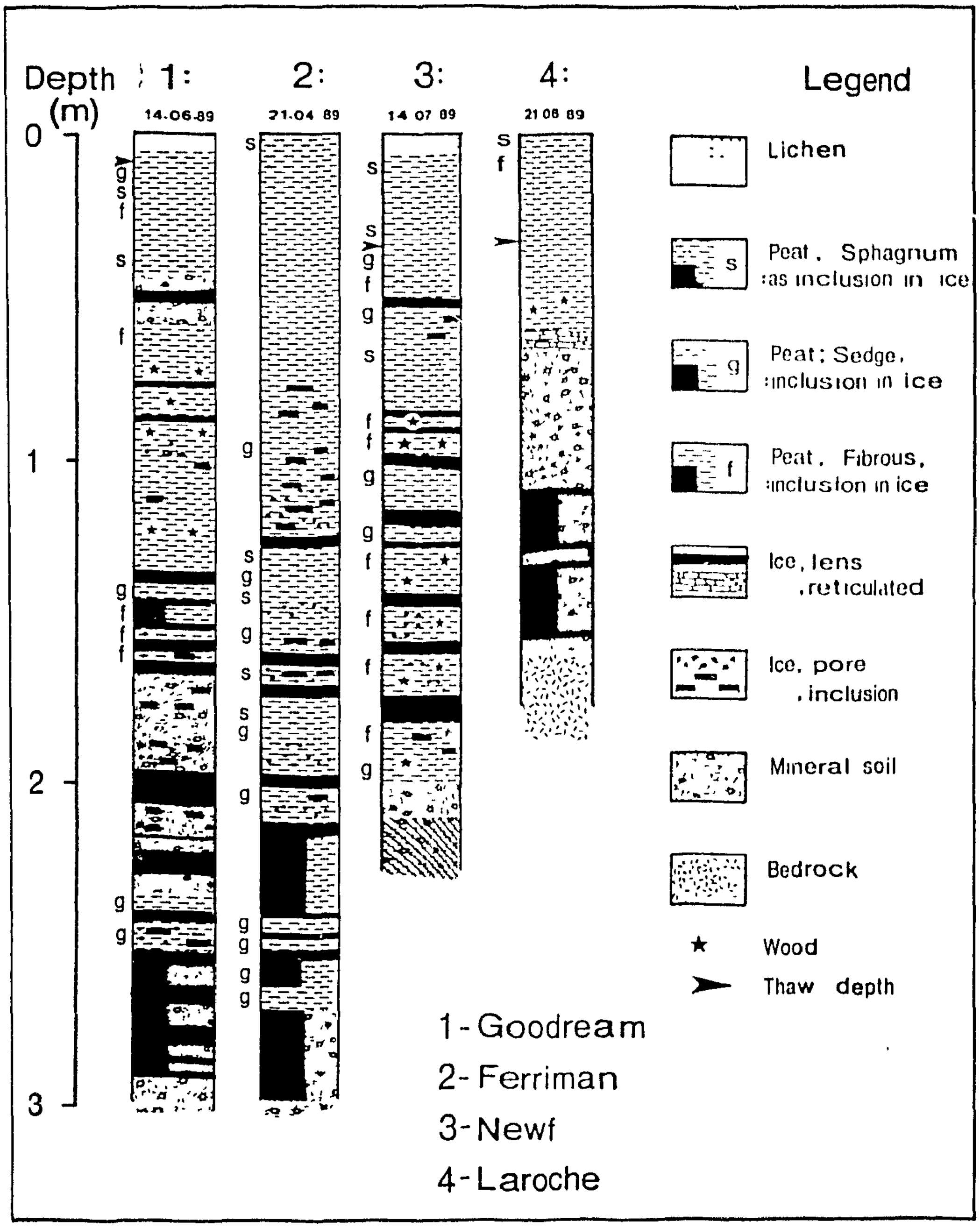



**Figure 2.4.3.** Detailed core logs from the four palsa sites.

(2) larger crystals 1-20 mm in diameter, termed inclusion ice. This distinction is entirely morphologic and does not imply a genetic difference. Both sizes of ice crystals occur in all types of peat but not in the mineral soil. In one case, reticulate ice veins occur within the mineral soil at the Laroche site. The origin of this cryotexture is not completely understood; however, it is known to be associated with ice segregation processes (Mackay, 1974).

Ice coatings occur on wood fragments in frozen fibrous peat. In all cases, the ice coatings were thickest on the upper wood surface. At the Goodream and Ferriman sites, brecciated inclusions of highly decomposed organic silt occur within large segregated ice layers. These inclusions range from 5-22 mm in length and were horizontally oriented.

### 2.4.7. WINTER CHARACTERISTICS

Snow conditions were investigated at the Goodream, Ferriman and Laroche sites during February 1989. Snow depths on the palsas were measured at 36 points, and ranged from 0 to 45 cm deep and averaged 10 cm. In the fen surrounding the palsa snow depths were measured at 48 points and ranged from 44 to 175 cm, with an average depth of 69 cm. The differences in snow depth produce marked differences in ground-snow interface temperatures. With an ambient air temperature of -31$^0$C (February 18, 1989) the ground-snow interface temperature beneath 11 and 78 cm of snow was -20$^0$C and -3.5$^0$C respectively.

A linear regression was developed to predict ground/snow interface temperatures from depth, density, water equivalents of snow and ambient air temperatures. A step-wise regression showed that the only significant variable at 85 % confidence interval was snow depth. The equation produced is:

$$\ln|T_{SI}| = 1.80-0.595(\ln d)$$

where: $\ln|T_{SI}|$ is the natural log* of the absolute value of the ground snow/interface temperature ($^0$C).

lnd is the natural log of snow depth (m).

* natural logs were used to linearize data.

An $R^2$ value of 0.89 is achieved, with a low mean square error (0.079). A two tailed t-test showed that the independent variable is significant at 98% confidence interval.

As much as 20% of the palsa surfaces at the Ferriman and Goodream sites were free of snow (Figure 2.4.2c). The exposed surfaces are susceptible to deflation by wind erosion. Small fragments of windblown peat, lichen and leaves were identified both on the snow surface and in snow pits in the lee of the palsas.

## 2.4.8 DISCUSSION AND CONCLUSIONS

### 2.4.8.1 Surface conditions

The vegetation species present at the four sites are very similar, although, their percent cover varies between sites. In earlier studies, the absence of surface vegetation was used to infer stage of development (e.g. Brown 1968; Salmi 1968). In this study, the type and percent of surface vegetation cover is used to develop a simple stage-process categorization which can be applied to either peat or mineral soil palsas. Using examples from Schefferville, we are attempting to demonstrate that palsa condition is simply a reflection of site specific permafrost processes. The three conditions proposed parallel the evolutionary stages of palsa development defined by Seppälä (1986), where he distinguished between embryonic, mature and old [collapsing] palsas. We recommend however, that terms having an evolutionary context do not clearly communicate the dynamic significance of the permafrost condition and may unintentionally suggest age, without the appropriate data. The terms aggrading, stable and degrading when used as a modifier of the term palsa imply the proper cryogenetic significance.

All the palsas studied have varying percentages of surface area covered by bare peat. The presence of other cover types, especially shrubs lichens and in one instance a mature larch tree, suggests that these palsas have been above the water table for a sufficient period of time to allow a succession of xerophilic species to colonize the palsa surface. Hence, one conclusion of this study is that these palsas are past the aggradational phase of development. Furthermore, the presence of a mature tree, thermokarst hollows, areas of bare peat and block failure suggest that the Goodream, Ferriman and Laroche palsas are all in various stages of degradation. The palsa at the Newf site did not display any degradational characteristics, had a low percentage of bare peat and maintained a high percentage cover of lichens and shrubs. This suggests a cryogeneticly stable palsa.

**2.4.8.2** Peat thickness and winter characteristics

The variable relationship between peat thickness on the palsa and in the surrounding fen was not anticipated. At the Goodream and Ferriman sites, peat thickness is thickest on the palsa. This seems appropriate because the fens appear to be formed in former small lakes, and lake infill is the dominant peat forming process, in addition the growth of ice lenses may expand the apparent thickness of peat. Lake infill also seems to be the dominant peat forming process at the Laroche site, but peat depths are thinner on the palsa. Zoltai and Tarnocai (1975) have suggested that palsa form is associated with ice lens growth in the mineral soil. This appears to apply at all the palsas, where the largest ice lenses are contained within the mineral soil.

It is hypothesized that in the past, the surface peat was much thicker on the Laroche palsa. Successive years of winter and summer wind erosion can remove a significant amount of surface material. During the winters of 1987-88 and 1988-89, approximately 18 cm of surface peat was eroded from the surface of Laroche palsa surface. This occurred on the most exposed portion of the palsa and is displayed in Figure 2.4.2d. The albedo of unvegetated surfaces is generally lower than surrounding areas of lichen (Railton and Sparling 1973). In theory, more solar radiation is absorbed and the surface peat layers become wetter (Wright 1981), thus increasing the thermal conductivity of the peat. This combination of factors could produce deeper active layers and possible surface thermokarst. From this we conclude that wind erosion is responsible for significant amounts of surface peat loss leading to degradation of the permafrost core.

There is a strong relationship between snow thickness and ground thermal regime (Nicholson, 1976). Clearly, where snow is absent, or thin, the ground surface is much colder than in the surrounding fen where the snow is much thicker. This permits maintenance and in some cases aggradation of the permafrost core within the palsa. However, summer conditions also have a strong influence on the ground thermal regime. From April to October the temperature 3 m below the surface at the Ferriman site rose from -1.6 to -0.6°C. With combinations of anomalously high or low snow fall, and warm or cold summers respectively, temperatures at depth may be significantly altered. Where snow is thin on the palsa surface, frost penetration is more intense and rapid, contributing to maintenance of colder temperatures throughout the summer.

This may seem to contradict the theory of winter wind erosion causing deeper active layers, as described above. However, the findings suggest that removal of surface peat by deflation does not occur at all sites, rather, it is selective and sporadic. The controlling factor appears to be the amount of unvegetated surface or bare peat. Areas of bare peat are more likely to be eroded than the vegetated areas. The result is a positive feedback system where unvegetated sections of the surface are more susceptible to erosion than the vegetated ones and wind erosion creates larger areas of bare peat, which are more readily eroded. This is the case with the degradational palsas at the Ferriman and Laroche sites. Hence, the amount of bare peat is significant to cryogenetic conditions of palsas.

The third conclusion also relates to the internal structure. Coring revealed that both mineral- and peat-cored palsas are found in relatively close association. In this study, neither mineral nor peat-cored palsas exhibit a greater tendency for degradation. However, we speculate that as erosion of the peat surface over a mineral-cored palsa continues, it is probable that a threshold will be reached at which the peat cover is no longer thick enough to preserve the permafrost core and a degradational palsa will result.

## CHAPTER 3: RESULTS-PALSA THERMAL REGIMES

### 3.1 BACKGROUND TO PAPER THREE

Very little research has been carried out on the thermal regime and maximum active layer depth of palsas on an annual basis. This is the subject of the third paper "Thermal regime and active layer development of palsas in the Schefferville area, northern Quebec".

Thermal conditions are of considerable importance when studying palsas since by definition they must contain permafrost. This paper documents both thermal regimes and development of active layers on two palsas in this region. In addition, ground thermal regimes are related to snow distribution on the palsas and climatic parameters recorded at the nearest meteorological station.

Least squares regression models were calculated using time and climatic parameters to predict maximum active layer depths. This is compared to values calculated using a popular analytical equation that includes both climatic and geotechnical parameters.

This paper does not include any detailed description of location, setting, morphology, surface or subsurface conditions of these palsas as they have been presented in detail in previous sections.

### 3.2 CUMMINGS, C.E. AND POLLARD, W.H. 1991. THERMAL REGIME AND ACTIVE LAYER DEVELOPMENT OF PALSAS IN THE SCHEFFERVILLE AREA, NORTHERN QUEBEC

#### 3.2.1 INTRODUCTION

A palsa is " a peaty permafrost mound possessing a core of alternating layers of segregated ice and peat or mineral soil material. ...Implicit in this definition are their constructional nature, their origin in wetlands (fens or bogs), and that ice segregation in mineral soil beneath peat is the process responsible for growth." (Permafrost Subcommittee 1988, p. 60). Palsas occur most widely in the discontinuous permafrost zone. Within the discontinuous permafrost zone, snow depth and distribution are important variables influencing the distribution of perennially frozen ground (Nicholson, 1976) and therefore, the distribution of palsas. Seppälä (1982), for example, demonstrated that palsas could be induced by systematic removal of snow from a fen surface in Finnish Lapland. In another study, Cummings and Pollard (1990) determined that snow-ground interface temperatures on palsas in the Schefferville area were related to air temperature as a log-linear function of snow depth. In the latter study, it was also demonstrated that removal of snow cover from the top of a palsa by wind redistribution, can lead to degradation of the permafrost by a combination of wind abrasion and deflation of surface peat. Snow depths of ≥ 80 cm along the edges of a palsa roughly 1 m high enhanced lateral thaw which contributed to block failure. Thus, it is apparent that snow and its seasonal pattern play a dynamic role influencing permafrost processes in the discontinuous zone and in the formation and degradation of palsas. Although this observation is not new, the dynamic nature of this relationship remains poorly understood because of limited field observations.

Many palsa studies have presented thermal profiles and observations on active layer depth (e.g. Kershaw and Gill, 1979) or thermal changes over short periods of time (e.g. Nelson *et al.*, 1985). Except for a few studies (e.g. Allard *et al.*, 1987; Lindqvist and Mattsson, 1965; Seppälä, 1983, 1990) there is little year-round or long-term data on palsa thermal conditions. Field observations from organic terrains in similar discontinuous permafrost settings or empirical studies may provide an alternative approach to the understanding of palsa thermal regimes. Seasonal thaw depth in mineral and organic soils has been shown to follow a linear relationship dependent on time (McRoberts, 1975). Similarly, Gray *et al.* (1988) developed log-linear regressions to predict maximum active layer depths in northern Quebec using climatic and terrain parameters.

This paper presents snow depth and ground thermal data for palsas in the Schefferville area of Nouveau Quebec and compares observed active layer temperatures with predicted values derived from (a) Stefan's equation and (b) equations derived by least squares regression of active layer development against regional climatic data.

### 3.2.2 STUDY AREA

Schefferville is located 525 km north of Sept-Iles at 54°50'N, 66°40'W. It lies within the Labrador Trough, an Archean fold belt characterized by a strong ridge and valley topography aligned in a northwest-southeast direction. The eastern centre of Laurentide ice is believed to have been located just north of Schefferville (Ives 1979; Bryson *et al.*, 1969) and radiocarbon dating suggest initiation of peatlands occurred approximately 6000 BP (Grayson 1957). Permafrost occurs beneath exposed ridges (Nicholson, 1979) and in isolated patches in wetlands at lower elevations. Palsas occur in fens and bogs throughout the Schefferville region (Cummings and Pollard 1989, 1990). They range from 3-30 m in diameter and from 70->200 cm in height. The mean annual air temperature for Schefferville is -4.9°C with maximum and minimum mean annual temperatures of -2.7 and -7.9°C, respectively (McGill Subarctic Research Station records 1955-1985, Figure 3.2.1c). The warmest and coldest months are July and January with means of 12.5 and -22.7°C, respectively (Figure 3.2.2). Extreme maximum temperatures can reach 30°C while extreme minimums may fall as low as -45°C. Schefferville averages 1300.9 thawing degree days with July having the highest average monthly contribution of 346.7. Freezing begins in September and the average total freezing degree days is 3297.9, with January contributing the highest number of freezing degree days, 768 on average. Annual snowfall is generally high, ranging from 200-600 cm year$^{-1}$ (Figure 3.2.1b). Snow cover exists from the end of September until mid to late May with the heaviest snowfalls occurring in November and December. Precipitation ranges from <300->600 mm year$^{-1}$ with approximately 50% of the total occurring as rainfall (Figure 3.2.1a). July experiences the highest rainfall and regularly exceeds 100 mm.

The two palsas discussed in this paper occur in fens that occupy topographical depressions in the area. Goodream palsa is 21.4 km from Schefferville airport and lies at 718 m asl. Ferriman palsa is 10.2 km from the Schefferville airport and lies at 750 m asl. The size, morphology, surface vegetation, peat thickness and internal structure of these palsas are described in detail by Cummings and Pollard (1990).

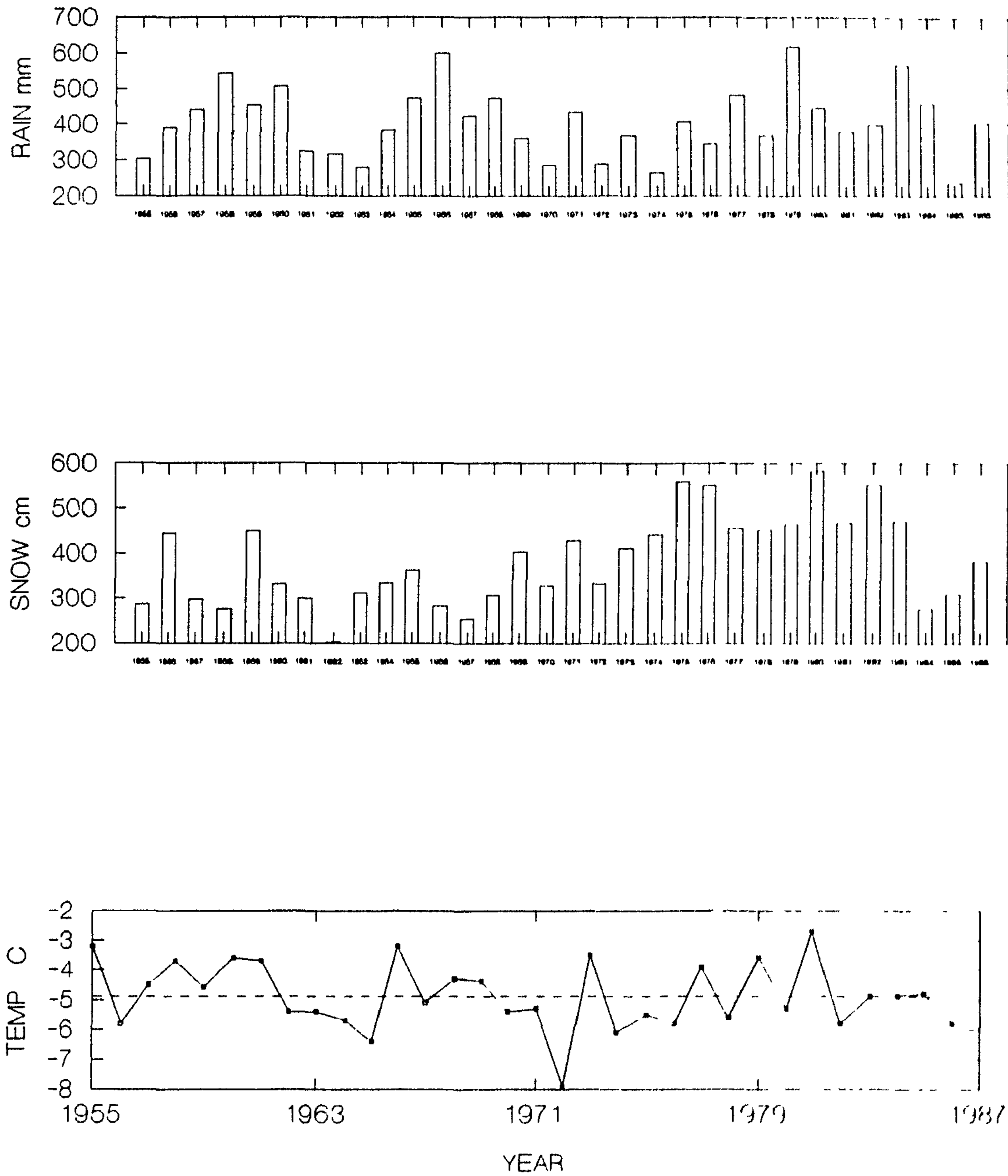



**Figure 3.2.1.** Climate of the Schefferville area between 1955-86. a) Annual rain fall in mm. b) Annual snow depth in cm. c) Annual average temperature in °C.

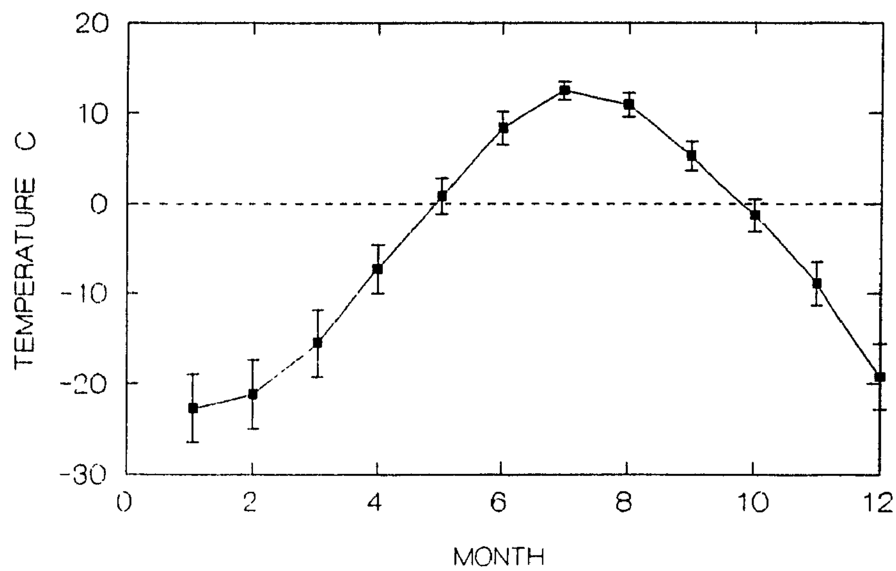



**Figure 3.2.2.** Average monthly temperature (°)C of the Schefferville area. Error bars are 1 standard deviation from the mean.

### 3.2.3 METHODS

Field studies were concerned with the measurement of vegetation on palsa surfaces, snow and temperature conditions and their variation in relation to palsa setting and morphology. Snow data were obtained with a Mount Rose snow sampler. Snow depth and density were recorded at 5 m intervals along transects oriented parallel and perpendicular to the long axis of each palsa. Active layer depths were monitored on a grid of 24 points on each palsa using a graduated steel probe and taking into account different vegetation associations. These depths were measured every three days between julian days 120 and 258. Ground temperature profiles were obtained using multi-thermistor cables equipped with YSI 44033 thermistors calibrated to 0.1°C and were recorded at three day intervals during the summer thaw and at two week intervals during the winter Meteorological data (e g. daily temperature, precipitation, bright sun-shine hours) were obtained from the Department of Transportation at the Schefferville Airport.

### 3.2.4 FIELD STUDIES

**3.2.4.1** Snow cover

Snow depth has been described as one of the major factors affecting the growth and decay of sporadic discontinuous permafrost. Average snowfall from 1955-1986 and 1988-1989 are shown in Figure 3.2.3. Snowfall is quite high in this region but varies considerably from year to year. During 1988-1989, total snowfall was 278.6 mm (water equivalents) with an average of 383.4 mm (water equivalents) In 1988-89, snowfall was close to average during the early winter (Oct -Dec.), however, January and March snowfall was far below average while April experienced the highest monthly snowfall of the year. Such dramatic variation in snowfall superimposed on the seasonal variation in air temperature can either enhance or retard frost penetration and permafrost.

Topography in the Schefferville area plays a major role in snow redistribution. The ridges (Tundra, Alpine Heath) rarely have any significant snow cover from wind redistribution it to the more protected areas. By comparison, the wooded valleys

(Open Lichen Woodland) often have snow drifts up to 2 m thick. Cummings and Pollard (1989) showed that vegetation density and micro and macro terrain factors strongly influence snow distribution in the area.

The snow depth and active layer development for Goodream and Ferriman palsas are shown in Figure 3.2.4. Snow depth on Goodream palsa varied considerably during the winter in 1988-89. In early winter, snow cover was absent except for a small patch in the centre of the palsa and along its edges. This was the period of thinnest snow depth at this site. By the end of February most of Goodream palsa had a 20-50 cm snow cover, reaching a depth of 1 m in one area. By the end of April snow cover was similar to that of early winter with only one snow patch on the palsa. This was the time of deepest snow accumulation in the surrounding fen, with depths of 1.75 m.

In comparison to Goodream palsa, Ferriman palsa had its deepest snow cover in early winter rather than April. The edges of Ferriman palsa maintained a deep snow cover, however, the snow on centre of the palsa rarely exceeded 25 cm and this only occurred in a depression in the palsa surface. Snow depth in the surrounding fen was deepest in late February, when it averaged 1.25 m.

**3.2.4.2** Ground thermal regimes

The annual ground thermal regime of Ferriman and Goodream palsas (Figure 3.2.5) shows two distinct features: (1) freeze-back begins around julian day 300, which does not necessarily mark the end of active layer development, but does mark the beginning of a transition period from thawing to freezing degree days, and (2) freeze-back takes place rapidly once temperatures of -14 and -10°C occur in the surface peat (Ferriman and Goodream palsas, respectively - on julian day 350). The surface of both palsas continues to cool until julian day 40, which corresponds with the coldest period of the winter (Figure 3.2.2). Following this, surface peat temperatures begin to rise slowly. A comparison of Figures 3.2.2 and 3.2.5 indicate that surface peat temperatures follow the average monthly air temperature, but are depressed by

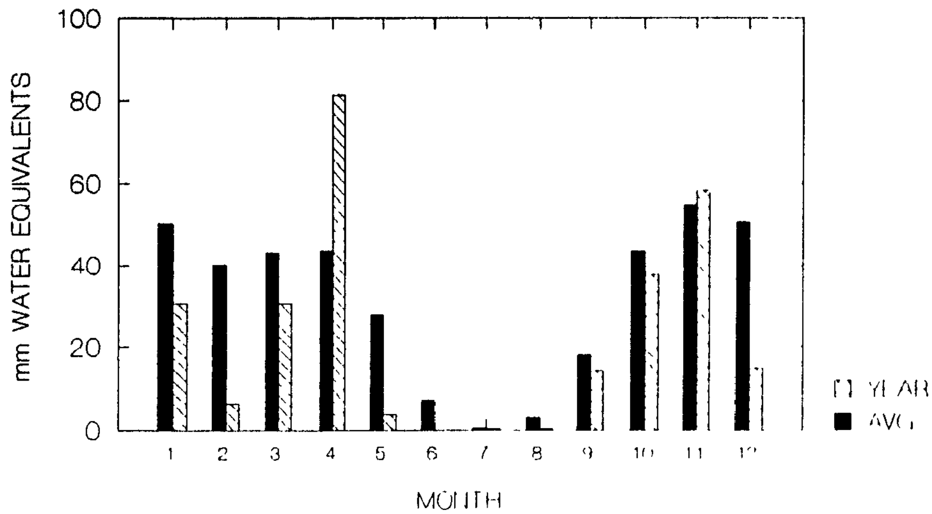



**Figure 3.2.3.** Average monthly snow fall for the Schefferville area between 1955-86 (AVG), and snowfall for the year 1988-1989 (YEAR).

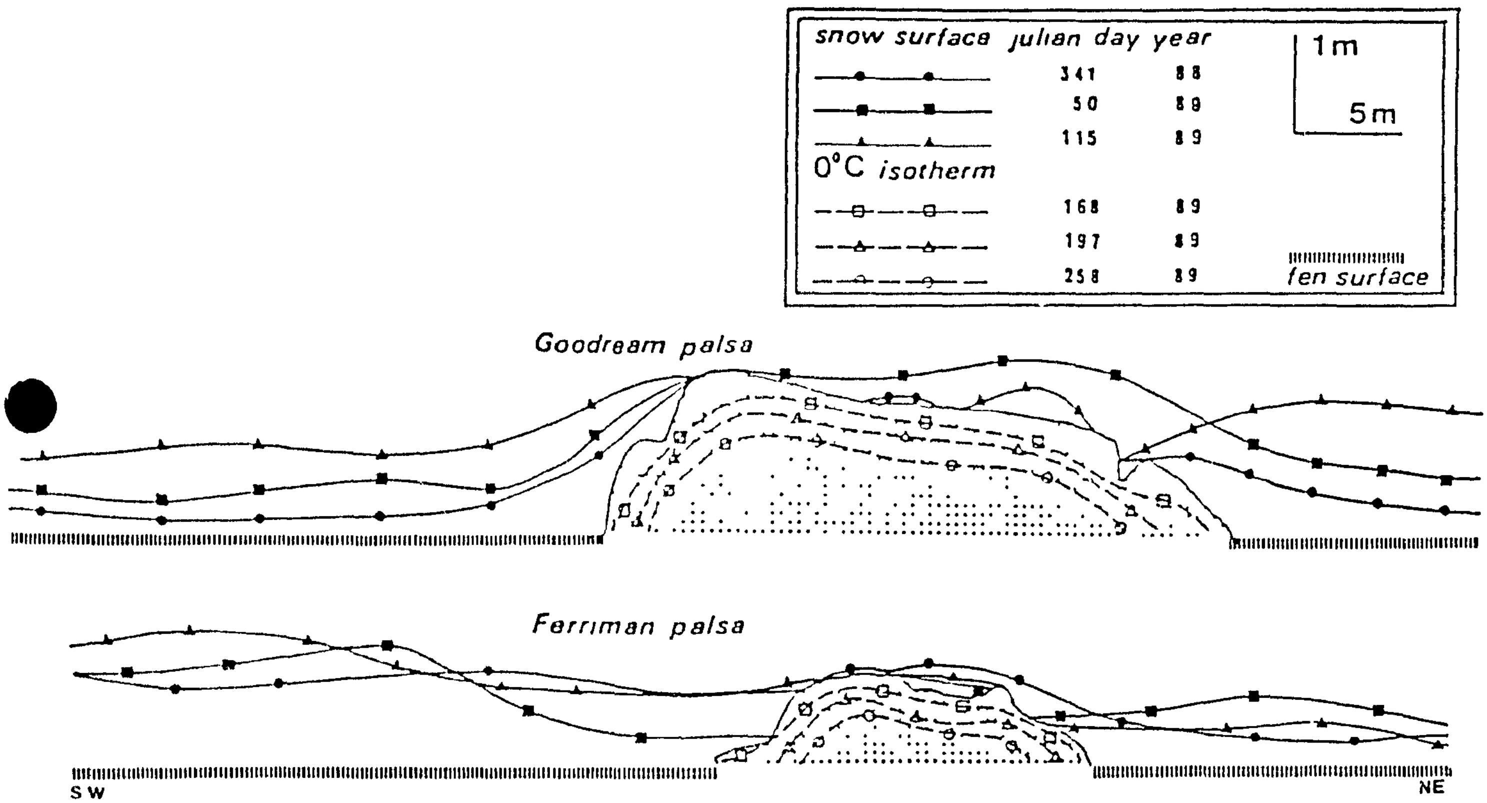
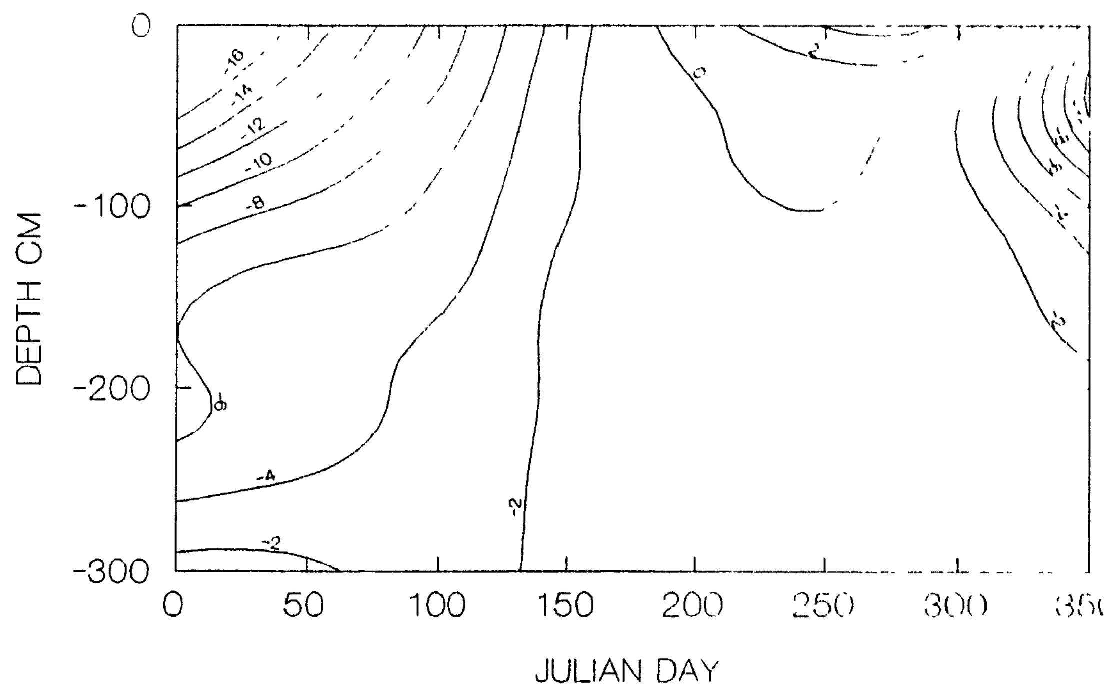



**Figure 3.2.4.** Snow depth and position of the 0°C isotherm at two palsa sites in 1988-89.

FERRIMAN PALSA




GOODREAM PALSA

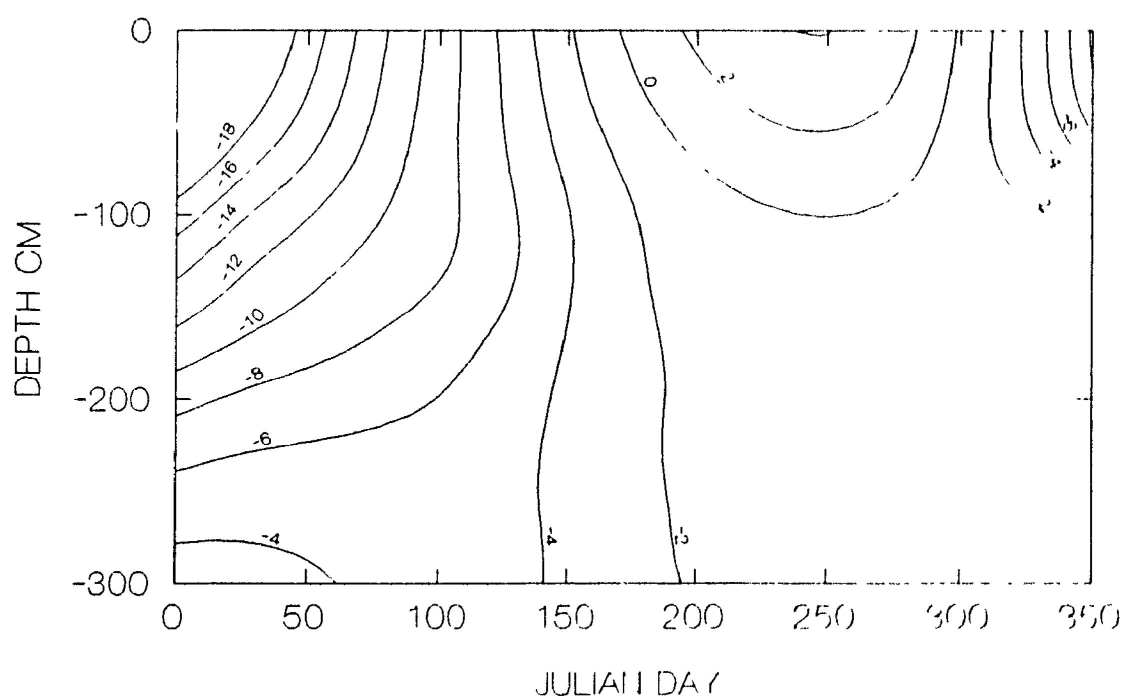



**Figure 3.2.5.** Isotherms (°C) for the two palsa sites in 1988-89.

approximately 4-6°C. The rate at which warming of the surface peat occurs is generally slower than the rate of winter cooling. Thaw begins around julian day 120. This differs from the data shown in Figure 3.2.7 because the shallowest thermistor is at a depth of 35 cm from the surface. When this is taken into account it does correspond to the data presented in Figure 3.2.7. At 35 cm from the surface peat temperatures reached a high of 4°C.

The pattern of temperatures at depth is quite different from the surface. It is well known that temperature fluctuations diminish with depth. Thus, an annual temperature amplitude of only 7°C at a depth of 2 m is not surprising. Immediately below the base of the active layer is a zone that remains relatively isothermal at a temperature close to 0°C (Figure 3.2.5). This is thought to reflect the zero curtain affect associated with the latent heat absorbed by the soil during spring thaw.

**3.2.4.3** Active layer

The surface vegetation on palsas in this area is quite variable (Cummings and Pollard, 1990) depending on cryogenic categorization and setting. Surface vegetation characteristics for the Goodream and Ferriman palsas are shown in Table 3.2.1. When the active layer sampling scheme was defined, various vegetation associations and percent covers were represented. Active layer development beneath shrubs was not included in this analysis as they are dominant along the edges of both palsas. Thawing of the seasonal frost along the edges of the palsas is discussed below. Theoretically, vegetation type and percent surface cover should affect active layer temperature and depth (Brown and Péwé 1973). Figure 3.2.6 shows how active layer development beneath bryophytes, bare peat, sedges and lichens follow a similar pattern, i.e. when active layer development is rapid beneath one vegetation type it is similarly rapid for other vegetation types. During the study period no significant differences between active layer depth and different vegetation associations were detected.

Active layer development at the Goodream and Ferriman palsa sites is diagrammatically shown in Figure 3.2.4. The average maximum active layer depth at both sites was 52 cm. By mid July permafrost or seasonal frost could not be detected along the edges of the palsas. The general shape of the active layer closely follows the palsa profiles. Perturbations associated with microtopographic structures such as surface cracks, are not reflected by the permatrost table. The larger depressions, such as those found in the central area of Ferriman palsa (Figure 3.2.4), do appear in the permafrost table.

The rate of active layer development differs between Goodream and Ferriman palsas. At both sites, the active layer began to develop approximately May 1. The first two weeks of active layer development progressed at a rate of 0.64 and 0.71 cm day$^{-1}$ for Goodream and Ferriman palsas, respectively. This rate remained relatively constant at Goodream until the end of July (julian day 211). At Ferriman palsa the active layer developed at a rate of 1 cm day$^{-1}$ for most of June, but dropped to 0.44 cm day$^{-1}$ until the end of July.

PALSA PERCENT COVER

| | BRYOPHYTES | BARE PEAT | SEDGES | LICHEN | SHRUBS |
|---|---|---|---|---|---|
| GOODREAM | 18 | 30 | 0 | 20 | 32 |
| FERRIMAN | 10 | 70 | 4 | 4 | 12 |

**Table 3.2.1.** Percent cover of surface vegetation on the Goodream and Ferriman palsa sites.

### 3.2.5 PREDICTION OF ACTIVE LAYER GROWTH

Since the two palsas discussed in this paper are situated in similar topographic positions, differences in their active layer development may be attributed to variations in microclimate and thermal properties of the soils rather than terrain effects. Accordingly, the two approaches used to predict maximum active layer development are: (1) cumulative climatic data and (2) Stefan's equation (Jumikis, 1977 p.208).

Cumulative data (e.g. thawing degree-days, bright sun-shine hours, rainfall, and time) are recorded from the beginning of the melt season and summed daily until its

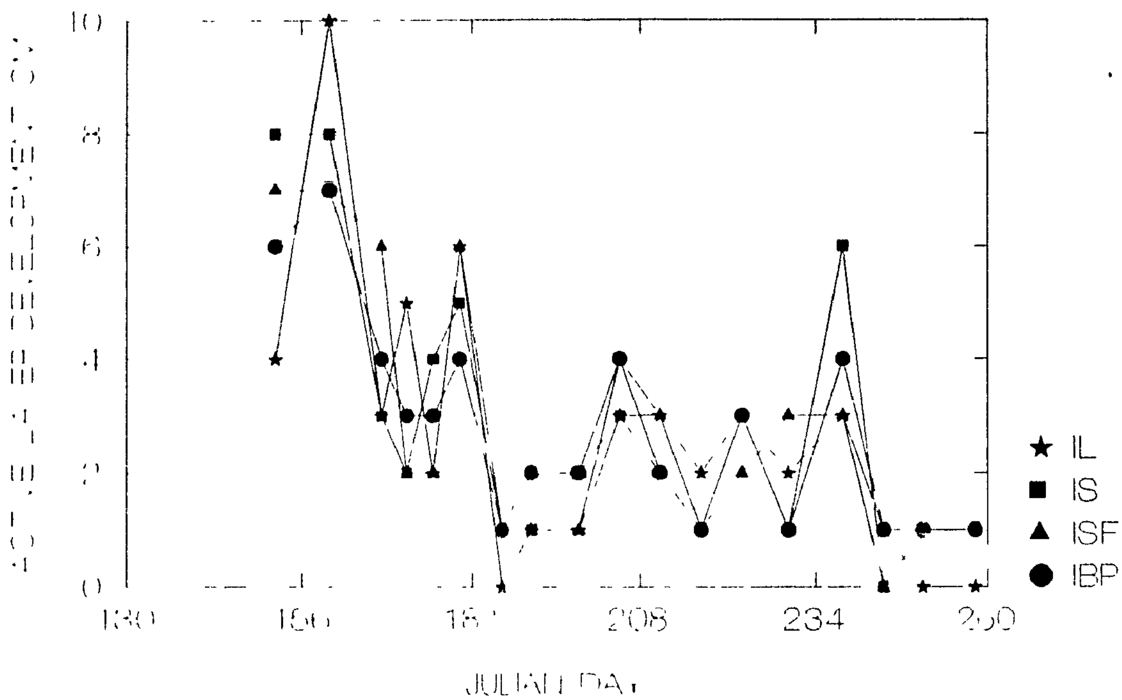



**Figure 3.2.6.** Active layer development beneath: bare peat (IBP), bryophytes (ISF), sedges (IS), and lichens (IL).

end. Several analytical and numerical models have been developed to predict active layer development based on a variety of variables, such as time, thermal conductivity, surface conditions and snow depth (e.g. Goodrich 1982; Gray *et al.*, 1988; and McRoberts 1975). However, the accuracy of these relationships is a direct function of the quality of site specific information such as thermal properties of the soil, soil moisture, etc. It would be useful for regional mapping purposes or for the prediction of past and future active layer fluctuations in response to climate change, if simple empirical models using readily attainable proxy data can be developed.

Using cumulative data, mean active layer depths for the summer period were plotted against environmental parameters. Least squares regression equations for all data were developed to correspond with maximum active layer depth. Since air temperature and its derivatives have been shown to be useful in permafrost prediction (Brown and Péwé 1973, Nelson 1986), thawing degree-days ($T_{sum}$) were used as the primary variable to predict maximum active layer depth. Brown (1963) states that solar radiation will raise ground surface temperature higher than the air temperature. Hence, bright sun-shine hours ($Q^{ss}$) were also included as a variable to predict maximum active layer depth. The soil moisture content strongly affects the thermal conductivity of the peat. Palsa origin has been related to the annual variation in thermal conductivity of peat (Seppala 1988). Because wet peat has a higher thermal conductivity (K) than dry (Farouki 1981), it seems logical that rain fall will increase the soils ability to transmit heat and increase active layer depth. Thus, rainfall (p) was also tested to predict maximum active layer depth. Finally, the Neumann solution has been used to estimate depth of thaw plane (Morgenstern and Nixon 1971). One of the main parameters in this equation is time. McRoberts (1975) has shown that the square root of time can be used to predict depth of thaw in a variety of soil types. Consequently, time (t, in julian days) will also be used in the prediction of maximum active layer depths.

Least squares regression lines for these cumulative environmental parameters are shown in Figure 3.2 7. The corresponding regression equations, $R^2$ values and estimation of maximum active layer depth are shown in Table 3.2.2

| RELATIONSHIP | EQUATION | $R^2$ | PREDICTED VALUE |
|---|---|---|---|
| x vs $T_{sur}$ | $\ln x = 16.42 - \ln T_{sur}$ | .98 | 54.65 |
| x vs Q" | $x = 1.235 + Q''0.059$ | .98 | 54.27 |
| x vs p | $x = -2.2 + (\ln p2.6)^{0.5}$ | .96 | 59.15 |
| x vs t | $x = 111.42 - 15067.7/t$ | .98 | 53.02 |

**Table 3.2.2.** Least squares regression equations and $R^2$ values and their estimates of active layer depth for accumulated environmental parameters from the Schefferville airport. ln identifies the natural logarithm. x - active layer depth in cm, $T_{sur}$ - thawing degree days, Q" - bright sunshine hrs., p - rainfall in mm., t - time in julian days. Maximum recorded active layer was 52 cm.

The cumulative data show a strong correlation with active layer development throughout most of the summer, with a departure from linearity at the onset of melt. This may be due to several factors, such as the timing of snowmelt and the fluctuation of air temperatures above and below 0°C. The best fit was achieved by regressing active layer depth against time resulting in a $R^2$ of 0.98 and a 1.96% error. Bright sun-shine hours, thawing degree-days and rain also produced good estimates of maximum active layers with $R^2$s of 0.98, 0.98, and 0.96. This produced errors of 4.36, 5.10, and 13.75% respectively.

Stefan's equation (Jumikis 1977, p.208) given in Equation 1 below, was also used to predict maximum active layer depth. Using this equation active layer depth is computed as a function of both environmental parameters (thawing degree-days) and thermal properties of the soil (moisture content and thermal conductivity). Maximum cumulative thawing degree-days as well as a range of moisture content of the peat and their corresponding thermal conductivities (from Farouki 1981, p.52) were used in these calculations. Gravimetric moisture content in the upper 10 cm of the palsa, measured at weekly intervals throughout the summer, ranged from a high of 90% to a low of 30%, with an averaged 70%. Using these values in Stefan's equation produced maximum active layer depths of 62.8, 55.1, and 53.3 cm which

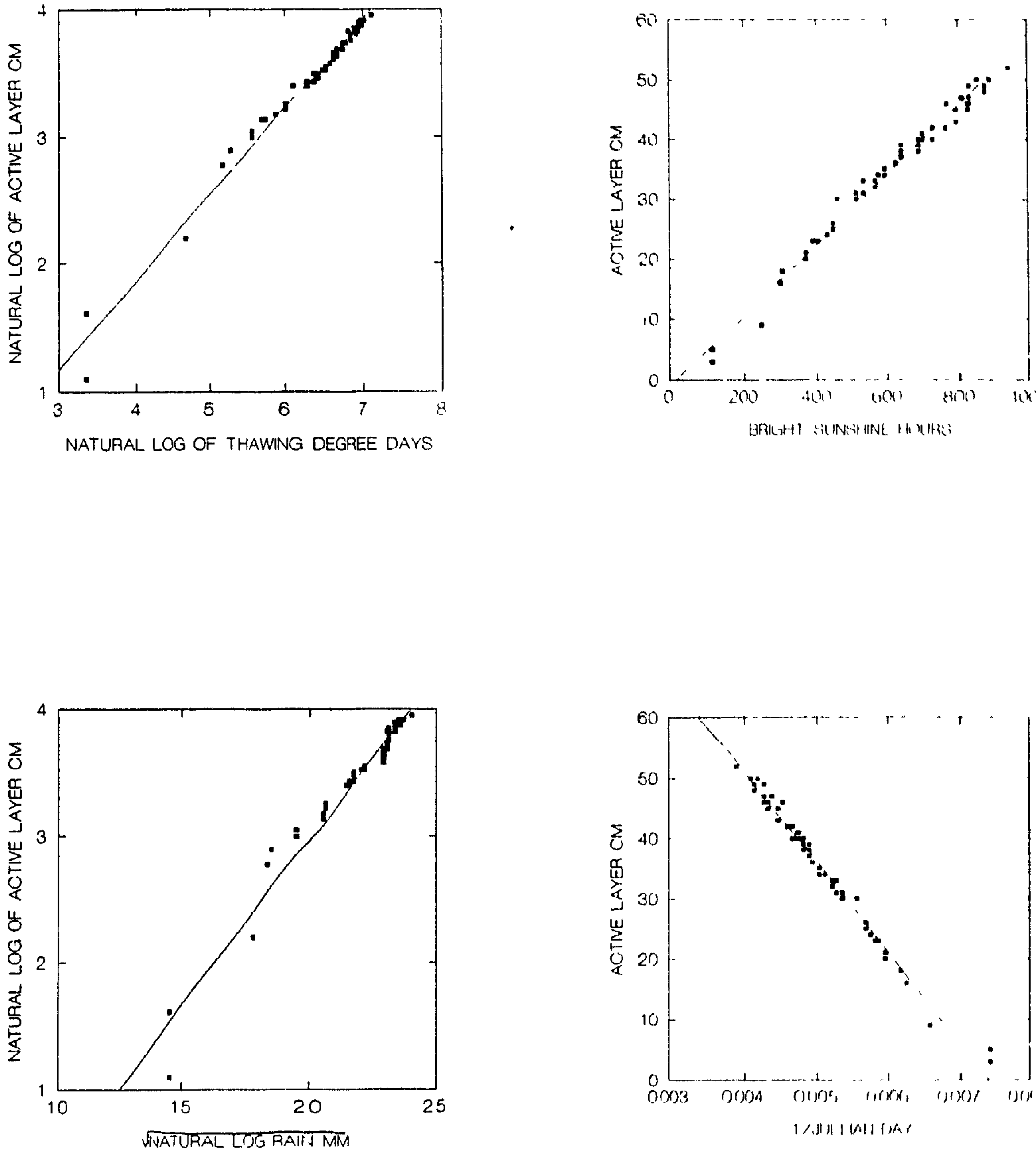



**Figure 3.2.7.** Least squares linear prediction of active layer depth (1988) using accumulated data.

resulted in percent errors of 12.08, 10.25, and 10.6% respectively.

$$x = \sqrt{\frac{48\ K\ T_{sur}}{Q_L}} \qquad (1)$$

where:

$x$ = active layer depth m.

$T_{sur}$ = thawing degree days °C

$K$ = coefficient of thermal conductivity Cal [m h °C]$^{-1}$

$Q_l$ = volumetric heat of fusion

= L w $y_d$

L = mass latent heat of fusion

w = moisture content (% of total weight)

$y_d$ = dry unit weight of soil kg m$^{-3}$

### 3.2.6 DISCUSSION

Since snow has a low thermal conductivity, it acts as an insulating layer inhibiting frost penetration in winter (Andersland and Anderson 1978). Because of this, snow cover affects summer thaw depths by reducing winter frost penetration. In a numerical model Goodrich (1982) demonstrated that active layers increased between 13 and 19% in areas with significant snow cover compared to no snow conditions. In this model, Goodrich assumed snow cover accumulated linearly to a maximum value and remained constant at that level until spring melt. However, snow depth on palsas varies both spatially and temporally, making a linear model of snow accumulation unapplicable. Furthermore, the seasonal pattern of snow distribution for different palsas is also highly variable. As shown in Figure 3.2.4, the maximum snow depth on one palsa corresponds to the same period of time as the minimum snow depth on another palsa. It seems likely that this pattern reflects a complex relationship between palsa morphology and setting and their effects on snow distribution. This assumption has not been investigated in this study.

Snow depth variations on palsa surfaces do not seem to affect the subsequent years active layer development. The active layer profile appears to closely follow the general palsa profile. Micro variations in palsa morphology (i.e. cracks) do not show up in the active layer profile. Larger variations in palsa morphology, such as elevated areas at the Goodream palsa and depressions at Ferriman palsa (Figure 3.2.4), are reflected in the shape of the active layer profile. This appears to be related to time and the thermal properties of the peat rather than winter snow conditions. The edges of the palsas were characterized by both thick snow cover and active layer depths much deeper than the palsa centres. Initially one may speculate that in this situation, snow acts as an insulating cover and limits the penetration of the winter cold. This would tend to limit the negative portion of the annual temperature wave, suggesting a warmer mean annual surface temperature and a deeper active layer. However, these effects are probably compensated for by lateral temperature fluxes. A more probable explanation is that deep active layer development is a function of the greater surface area over which temperatures can penetrate allowing both vertical and lateral penetration of the thaw front. With greater heat flux, the palsa edges would naturally display deeper and more rapid active layer development.

In general, various cumulative environmental parameters can be used to predict trends in active layer depth. Gray *et al.*, (1988) used cumulative thawing degree days to predict thaw depth of various soils on the west coast of Ungava Bay. Of particular interest are soils which are characterized by similar organic and vegetation characteristics as the palsas in the Schefferville area. Their maximum measured active layer was 30 cm while a log linear model estimated 40 cm resulting in an error of 33.3%. The models developed for the palsas in the Schefferville area are generally better than that of Gray *et al.*, (1988).

A comparison of wetland thermal regimes presented in Moore (1987, Figure 2) with data presented in Figure 3.2.5 shows a number of interesting trends. The most notable difference is the presence of permafrost in the palsas to a depth of at least 3 m (deepest thermistor). The lack of intense cold at depth in Moore's wetlands is another obvious difference. The coldest temperature recorded by Moore was -5° C at a depth of approximately 10 cm in December and January (julian days 325-31), while a palsa in the present study (Figure 3.2.5) maintained a temperature of -18°C to a depth of 90 cm from julian days 0-50. Moore's Figure 1 shows a snow pack of at least 50 cm, exceeding 150 cm by the end of February (julian day 58). The snow pack at the palsa sites (Figure 3.2 4) never exceeded 50 cm. Furthermore, for several extended periods significant portions of the palsa surface was snow free. It is these differences in snow depth that produced the different ground temperatures. These data generally agree with that of Nicholson (1976) who stated that above critical snow depth of >75-80 cm would inhibit permafrost formation in the Schefferville area

In the winter, near surface temperatures are quite dynamic and react relatively quickly to ambient air temperature fluctuations. This is not the case in summer, where temperature at a depth of 35 cm did not exceed 3°C. It is known that unfrozen peat has a lower thermal conductivity than frozen peat (Jumikis 1977), thereby causing slower reaction of peat temperatures to air temperature fluctuations. As well, melting of the frozen peat uses energy that is no longer available to raise its temperature During the winter, frozen peat, has a higher thermal conductivity, resulting in much more rapid air temperature fluctuations.

The temperatures below 2 m were relatively constant, varying only 6°C. In the upper peat layers, the temperature varied 20°C over the course of this study. Thus, as the annual thermal wave penetrates the peat surface to lower depths its amplitude decreases. This corresponds with the position of ice lenses in the palsas, as described by Cummings and Pollard (1990). The thickest and majority of ice lenses were found in the deeper portions of the palsas. The less steep thermal gradient at depth allows moisture to migrate to the freezing front, resulting in the development of segregated ice lenses.

### 3.2.7 CONCLUSIONS

Three main conclusions about the nature of palsa thermal regimes in the Schefferville area can be drawn from this study. First, snow depth on and around the palsas displays considerable variation throughout the winter. However, occasionally thick snow cover on top of the palsa appears to have little affect on active layer development and the thermal stability of permafrost in the palsa core. The size, shape and setting of palsas in the Schefferville area ensures that despite occasional burial by heavy snow or a snow drift that strong prevailing winds from the northwest will usually remove snow from the palsa surface. With the majority of snowfall occurring in early winter palsa surfaces are often snow free or covered by a thin snow layer during January and February when extremely cold ground surface temperatures propagate to depths of more than 2 m. Deep active layers and mechanical erosion of steep palsa edges seems to be more a function of a greater surface area over which heat penetrates the palsa rather than deep snow cover. This study only recorded one year of data and thus can not comment on the results of multiple years of high or low snow cover on these palsas and their subsequent active layer developments. A second conclusion is that differences in vegetation did not produce significant variation in either ground temperature or maximum active layer. This however, probably reflects the minor variation in the physical characteristics of the moss and lichen vegetation communities dominating palsa surfaces. The absence of wooded palsas in the area precluded consideration of the effects of more significant differences. Finally, in the absence of detailed site specific information on ground temperatures and ground thermal properties the statistical analysis of various cumulative environmental parameters such as thawing degree days, bright sunshine hours, rain or time, may provide a better first approximation of active layer development than widely used empirical relationships like Stefan's equation.

## CHAPTER 4: CONCLUSIONS

### 4.1 SUMMARY

Even though each paper contains a separate set of conclusions, there are several additional conclusions that can be made when the entire study is considered. These range from changes in the physical characteristics of the palsas over time and palsa dynamics, to reformulating the definition of a palsas. In addition to specific conclusions developed in each of the manuscripts, four broad conclusions can be drawn from the study.

First, in the Schefferville region palsas are relatively common permafrost phenomena. This observation contradicts suggestions made by Lagarec (1990) that palsas do not occur in this area. They occur in various wetland types but tend to occur most readily in small fens situated at high elevations, that is, within or on the sides of northwest-southeast trending bedrock ridges. For example, palsas documented at Ferriman ridge, Goodream lake and the Laroche site all conform to this setting. Fens found at lower elevations tend to have thick snow cover which inhibits deep frost penetration, where as the fens at higher elevations tend to blow clear of snow. This partly due to the lower and less dense forest cover surrounding these fens.

Second, palsas in the Schefferville area are smaller than those described along the Hudson Bay coast and in the Yukon Territory. The palsas in this study range from 5.6 to 59.0 m in length and up to 101 cm in height above the water table. They are typically oval to elongated in shape and posses a relatively smooth flat-topped profile. The vegetation cover varied with size age and relative stability of permafrost. In aggrading and stable palsas the vegetation cover is dominated by shrubs and lichens. Many of the features studied were interpreted as unstable or degrading, in these cases bare peat often typified the surface condition.

Third, in all cases the Schefferville palsas displayed a relatively thick organic sequence containing pore ice and ice lenses or ice coatings. At depth a mixture of organic and mineral sediment contained thick ice lenses and layers. Clearly, palsa growth and preservation is directly related to permafrost aggradation into the mineral rich horizon. Biostratigraphic analysis indicated a gradual infilling of the host fen and transition from hydrophilic to relatively xerophilic plant communities. It is thought that this transition corresponded with the initiation of permafrost.

And fourth, the environmental conditions that are most important in palsa formation and preservation near Schefferville are typically those described in the literature (e.g. Seppala, 1982, 1988a). Specifically a thick organic layer saturated with water and extremely cold winter temperatures. These conditions are readily met in the Schefferville area. Much of the local land surface is covered by wetlands and the mean annual temperature is -4.7 °C, with winter temperatures often as cold as -35°C. The dominant control, however, appears to be snowfall and its distribution relitive to elevation. Schefferville receives between 200-600 cm of snow annually. Much of which occurs in early winter. This has the direct result of insulating the ground from cold mid winter temperatures and inhibits frost penetration, particularly in dense woods and lowland areas. However, where snow is removed by winds there is a greater probability of deep frost penetration and permafrost aggradation. This process tends to occur on the bedrock ridges and fens at higher elevations.

## 4.2 DISCUSSION

Several research projects have been concerned with the permafrost of the Schefferville area (e.g. Nicholson 1976, 1979). Only vague references have been made to permafrost in the organic terrain of the region (e.g. Jahn, 1986, Waterway *et al.* 1984). To that end, this research has shown that permafrost, occurring as palsas, are common in organic terrain in the Schefferville region. Previous to this study, permafrost was thought only to be important in exposed ridges of the area. These two settings containing permafrost represent extremes. Both are areas where snow is absent or negligible, as well, the geotechnical properties of peat permit a net heat loss compared to the mineral soils of the area. These factors contribute to the formation and maintenance of permafrost islands called palsas.

The description of palsa morphology includes height (above immediate surroundings). However, these features can be surrounded by a variety of conditions ranging from dry or wet bog and fens to open water. By their very nature, peat surfaces tend to fluctuate vertically depending on moisture content (personal communication with Nigel Roulet, Department of Geography, York University). Because of this, the height of a palsa may change from day to day, depending on the amount of rainfall or evapotranspiration that has taken place. For example, if following a heavy rainfall the surface peat surrounding a palsa rose 5 cm, then the palsa would be 5 cm lower relative to its surroundings. Table 4.2.1 shows the changes in height of the Goodream and Ferriman Palsas throughout the three years of this study. From this we see that the size of palsas relative to the water table can be quite dynamic and can react quickly to various environmental and intra-palsa conditions. It is not known if these changes are a result of aggradation or degradation or erosion of the palsa surface. Quite probably it is the result of a combination of factors.

| Goodream | Length m | Height m | Date |
|---|---|---|---|
| | 28 | 0.78 | Sept. 87 |
| | 28 | 1.1 | Feb. 88 |
| | 27 | 0.98 | Sept. 89 |
| | 27 | 0.92 | March 90 |
| Ferriman | 12 | 0.7 | Feb.89 |
| | 12 | 0.82 | Sept. 89 |
| | 12 | 0.78 | March 90 |

**Table 4.2.1.** Changes in palsa size from September 1987 to March 1990.

Palsas are not acted upon solely by external conditions such as climate or terrain characteristics, but also by factors that result from palsa dynamics. The aggradation and degradation of a palsa will, in effect, alter these dynamics. For example, when block failure (Figure 2.2.4) occurs, the space between the fallen peat block and the palsa itself, will collect deeper snow (Figure 3.2.4). This in turn may reduce frost penetration during winter and may induce additional block failure during subsequent summers. This process will lead to loss of surface area and contribute to further degradation of the permafrost core. Conversely, an aggradational palsa, that is being vertically displaced, will generally have thinner snow cover than lower palsas. The thinner snow cover will allow deeper frost penetration and possibly ice lens growth and further vertical displacement. As vertical displacement takes place the moisture content of the surface peat (in the active layer) is lowered. This can again affect aggradation or degradation of the palsa. When the moisture content of the surface peat reaches a threshold condition lichens will colonize the surface of the palsa. This increases the albedo, resulting in greater net heat loss. While growth of shrubs will increase snow accumulation which can reduce heat loss. If however, the snow is thin or absent, the winter winds may induce surface peat loss and lead to further degradation of the permafrost core.

The palsa is a very complex landform that is not only affected by climate and terrain conditions but also its own dynamics or "intra palsa" conditions. The affect of these chains of events have rarely been studied but undoubtable play an important role on palsa dynamics in relation to permafrost aggradation and degradation.

## 4.3 WHAT IS A PALSA?

Seppalä's (1972) definition of a palsa was the first presented in a scientific context. Seppälä describes a palsa as "a hummock rising out of a bog with a core of ice". This definition lacks any mention of process and thus is limited in geomorphic context and should only be used as a morphological description. As well, the use of the terms bog and ice in this definition have also caused considerable confusion. The term bog refers to a specific type of organic terrain and palsas are located in fens, tundra mires etc.. This term should be broader to encompasses all aspects of peatlands and organic terrain. The use of the term ice has also caused much confusion. The term permafrost should be used instead of ice, as a core of ice would indicate a frost blister rather than palsa.

In recent years the term palsa has been used to label for a variety of frost mounds. For example, Hinkel *et al* (1987) state that their use of the term palsa is irrespective of genesis. This is geomorphologically unsound because many forms that are morphologically similar can be very different genetically. In fact Hinkel *et al.* (1987) "plea" for adoption of Washburn's (1983) definition. Washburn states that palsas can result from 2 different processes resulting in one type of frost mound; (1) permafrost aggradation and (2) disintegration of surfical deposits resulting in an isolated mound. The latter mound forming process can occur outside the permafrost zone and it should not be used in this specific context. Washburn's discussion did attempt to apply a process or genetic modifiers to the term palsa, however, at no point does Washburn describe the internal cryotic structure of palsas.

The cryotic structure of palsas is directly related to their mechanism of formation. In a review of pingo and palsa literature Pissart, (1985) states that " All authors are in agreement that palsas are mounds which form following the formation of segregation ice in the ground.". The formation of segregated ice produces alternating layers of ice and peat or mineral soil. This is the primary definition of palsas as presented by the Permafrost Subcommittee, Associate Committee on Geotechnical Research, National Research Council of Canada (1988, p.60).

The palsa surface ranges from lush vegetation to bare peat. The vegetation can include mosses or lichens, shrubs or mature trees. The surface can also be dissected by large fissures. Several attempts have been made to determine the age of palsas however, a finite age has yet to be determined. Suggested ages range from 2450 years (Ashman, 1977) to newly forming palsas as described by Allard *et al.* (1987).

Accordingly, the following definition of a palsa, incorporating both genetic and descriptive criteria derived from this study and the literature, is:

A palsa is a permafrost mound found in wetlands and composed of peat and or mineral soil containing segregated ice lenses. The positive relief of the palsa is the result of the formation of ice lenses in the peat and mineral soil core rather than normal accumulation of peat There should be no delimiting age or size range given for palsas as these are controlled by natural aggradation and degradation processes that act on specific palsas.

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