**“DEVELOPMENT OF COMPRESSION WOOD IN TREES OF THE
“DRUNKEN FOREST”, CENTRAL YUKON TERRITORY”**

by

LISA M. HUISMAN, B.Sc.

A thesis submitted to
the Faculty of Graduate Studies
in partial fulfillment of
the requirements for the degree of

Master of Arts

Carleton University

Ottawa, Ontario

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Abstract

Ninety-two cross-sectional discs were extracted from tilted trees growing in hummocky and non-hummocky permafrost terrain near Mayo, Yukon Territory, in order to investigate the development of compression wood between 1900 and 2000. Chronologies were constructed by calculating the percentage of trees showing compression wood in each year of the record. Trees growing at the hummocky site showed increased compression wood for 1908-11 and 1964-70. Climate conditions during these periods may have increased soil moisture, leading to greater frost action and increased tilting. Trees at the non-hummocky site showed increased compression wood for 1924-31, 1936-46, and 1956-63. There is no consistent climate signal associated with these periods. Periodic flooding of Stewart River may have increased soil moisture at this site resulting in greater cryoturbation, and increased compression-wood formation.

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Table of Contents

Thesis Acceptance	ii
Abstract	iii
Acknowledgements	iv
Table of Contents	vi
List of Tables	viii
List of Figures	ix
 CHAPTER 1: INTRODUCTION	 1
1.1 Objectives	1
1.2 Drunken Forest Underlain by Permafrost	1
1.3 Research Questions	3
1.4 Relevance to Geocryology	3
1.5 Organisation	5
 CHAPTER 2: DRUNKEN FOREST UNDERLAIN BY PERMAFROST	 6
2.1 The Permafrost Environment	6
2.1.1 The Buffer Layer	6
2.1.2 Buffer Layer Conditions in the Boreal Forest	8
2.1.3 The Active Layer	11
2.2 Frost Action in Soils	14
2.2.1 Cryoturbation	18
2.2.2 Patterned Ground Features	19
2.3 The Growth Response of Tilted Trees	20
2.3.1 Dendrogeomorphology	22
2.4 Tilted Trees Growing in Permafrost Terrain	24
2.4.1 Vegetation Growth in Hummocky Permafrost Terrain	25
2.4.2 Tree-ring Records of Ground Surface Displacement	25
 CHAPTER 3: STUDY AREA AND METHODS	 27
3.1 Physical Characteristics of Study Area	27
3.1.1 Climate	29
3.1.2 Soils	29
3.1.3 Vegetation	30
3.2 Field Methods	31
3.2.1 Site Selection	31
3.2.2 Vegetation	34
3.3.3 Soil Investigations	36
3.3.4 Sampling of Trees	36
3.3 Tree-ring Methods	37
3.3.1 Tree-ring Analysis	37
3.3.2 Initiation and Stabilisation Periods	38
3.3.3 Measurement Error Analysis	39
3.4 Climate	40
3.4.1 Climate Record	40
3.4.2 Annual and Seasonal Climate Trends	42

3.4.3	Water Level Record of Stewart River at Mayo, 1949-1999	46
3.4.5	Initiation and Stabilisation Periods and the Climate Record	48
CHAPTER 4: RESULTS AND DISCUSSION		51
4.1	Field Results	51
4.1.1	Vegetation Analysis	51
4.1.2	Soil Properties	54
4.1.3	Sampled Trees	58
4.2	Annual Compression Wood Chronologies	59
4.2.1	Summary Statistics of Compression Wood Chronologies	59
4.2.2	Initiation Periods	61
4.2.3	Stabilisation Periods	63
4.3	Frost Action and Climate	67
4.3.1	The Mayo Climate Record, 1927-2000	69
4.3.2	Water Level Record of Stewart River at Mayo, 1949-1999	73
4.4	Initiation and Stabilisation Periods	75
4.4.1	Initiation Periods and Climate	75
4.4.2	Stabilisation Periods and Climate	86
4.5	River Flooding and Tree Tilting	91
4.6	Discussion of Results	94
4.7	Chapter Summary	96
CHAPTER 5: CONCLUSIONS		98
REFERENCES		101

List of Tables

3.1: Summary of measurement error analysis	41
3.3 Descriptive statistics for the seasonal and annual temperature, precipitation, rainfall, and snowfall conditions for the period of record	50
4.1: Vegetation inventory and cover estimation at Site 1	52
4.2: Vegetation inventory and cover estimation at Site 2	53
4.3: Soil particle-size analyses for Site 1 and Site 2	55
4.4: Difference in annual and seasonal mean air temperature during initiation periods from the corresponding data for the entire record, 1900-2000	76
4.5: Seasonal and annual air temperature values converted to z-scores for the years 1907 to 1910 in the first Site 1 initiation period	77
4.6: Difference in annual and seasonal total precipitation, snowfall, and rainfall during initiation periods from the corresponding values for the entire climate record (1927-2000)	80
4.7: Seasonal and annual air temperature averages and precipitation totals converted to z-scores for the years 1963 to 1966 in the second Site 1 initiation period	81
4.8 Seasonal and annual air temperature values converted to z-scores for the years 1923 to 1926 in the first Site 2 initiation period	83
4.9 Seasonal and annual air temperature averages and precipitation totals converted to z-scores for the years 1935 to 1938 in the second Site 2 initiation period	85
4.10 Seasonal and annual air temperature averages and precipitation totals converted to z-scores for the years 1955 and 1958 in the third Site 2 initiation period	87
4.11 Difference in annual and seasonal mean air temperature during stabilisation periods from the corresponding values of preceding initiation periods	89
4.12 Difference in annual and seasonal total precipitation, snowfall, and rainfall during stabilisation periods from the corresponding values of preceding initiation periods	90

List of Figures

2.1: Distribution of permafrost zones in Canada	7
2.2: Schematic diagram of the buffer layer model	9
2.3: Adventitious root system of white spruce tree growing in permafrost terrain	13
2.4: Unfrozen water content at temperatures below 0°C in different soil types	16
2.5: The equilibrium model of hummock growth and soil circulation	21
2.6: Basal cross section of a 101-year-old black spruce tree, showing six compression-wood sequences	23
3.1: Map of study area with Site 1 located in Mayo River Valley and Site 2 located in Stewart River Valley	28
3.2: Drunken forest terrain at Site 1	33
3.3: Drunken forest terrain at Site 2	35
3.4: Dawson and Mayo annual mean air temperature, 1925-1998	43
3.5: Estimated Mayo annual mean temperature, 1900-2000	44
3.6 Rating curve for Stewart River at Mayo	47
4.1: Photo of 25 cm cracking at the base of hummock at Site 1	57
4.2: Percentage of trees showing annual compression wood at Site 1 and Site 2, 1900-2000	60
4.3: Frequency distribution of percent annual compression wood observations for Site 1 and Site 2 for period of record (1900-2000)	62
4.4: Percentage of trees showing annual compression wood at Site 1 standardised as z-scores	64
4.5: Percentage of trees showing annual compression wood at Site 2 standardised as z-scores	65
4.6: Frequency distribution of the percentage of trees initiating compression-wood sequences in each year of record at Site 1 and Site 2	66

4.7: Annual mean air temperature at Mayo, YT	70
4.8: Total annual precipitation at Mayo, YT	71
4.9: Total effective precipitation in summer season at Mayo, YT	72
4.10: Maximum annual water level of Stewart River at Mayo, 1949-1999	74
4.11: Percentage of trees showing annual compression wood at Site 2	92

CHAPTER 1: INTRODUCTION

1.1 Objectives

The primary objective of this thesis is to construct tree-ring records of ground displacement in “drunken” forest terrain. In permafrost terrain, a collection of tilted trees is referred to as drunken forest (Zoltai 1975a,b; Crampton 1977). Data for this study were collected at two drunken forest sites near Mayo, central Yukon Territory. Both study sites contain mature black spruce woodland. One site was located in hummocky permafrost terrain of glaciolacustrine origin, and the other was in non-hummocky permafrost terrain of alluvial origin (Hughes 1983). Sample discs were collected from approximately 50 trees at both study sites in order to construct compression wood chronologies for the period 1900 to 2000. The secondary objective of this thesis is to investigate the association between periods of increased compression-wood formation and variations in seasonal climate and the hydrological regime of Stewart River. The long-term climate record for the Mayo region is continuous from 1927 to 2000 (Meteorological Service of Canada 2002), and historical water level data for Stewart River at Mayo are available from 1949 to 1999 (Water Survey of Canada 1991; Meteorological Service of Canada 2002).

1.2 Drunken Forest Underlain by Permafrost

Permafrost, defined as ground that remains at or below 0°C for two or more consecutive years (ACGR 1988), underlies a large portion of Canada’s land area (Heginbottom *et al.* 1995). In Canada, much of the discontinuous, and southern portions

of the continuous, permafrost zones are covered by boreal forest (French 1996). The boreal forest is a broad circumpolar zone, composed of several coniferous and deciduous tree species, that extends over approximately 17% of the world's land surface area (Bonan 1989). In forests underlain by permafrost, growing conditions are restricted by low soil temperatures, a thin, seasonally thawed layer of ground, the effects of a relatively impenetrable frost table on moisture migration and aeration, low nutrient availability, and slow decomposition of organic materials (Viereck *et al.* 1983; Van Cleve and Yarie 1986). A shallow, seasonally thawed layer and short growing season can also restrict root system development and plant stability (Gill 1970).

Soil displacements, resulting from repeated seasonal freezing and thawing are an important characteristic of permafrost environments. In forested areas underlain by permafrost, lateral and adventitious rooting may not prevent trees from tilting as a result of frost heave (Gill 1975; Zoltai and Pettapiece 1974). Accordingly, in permafrost terrain, the term "drunken forest" applies to haphazardly tilted trees which are subject to seasonal frost action (Crampton 1977; Zoltai 1975a). Previous research within Mackenzie Valley and northern Yukon specifically attributed the presence of tilted trees to episodic soil cryoturbation within active earth hummocks (Zoltai and Pettapiece 1974; Zoltai 1975a,b). From limited climate data, Zoltai (1975b) proposed that increased cryogenic activity is associated with higher than normal late-summer temperatures and rainfall, which lead to increased soil moisture conditions.

The purposes of this thesis are: (1) to investigate the compression-wood chronologies exhibited by tilted trees growing in hummocky and non-hummocky

permafrost terrain, (2) to investigate the association between variations in seasonal climate parameters and periods of increased compression-wood growth in tilted trees, and (3) to investigate the association between the flooding regime of Stewart River and periods of increased compression-wood growth in tilted trees.

1.3 Research Questions

This thesis will address specific research questions in order to meet the outlined objectives. These research questions include the following:

- (1) How are the annual compression-wood chronologies constructed from tilted trees growing in hummocky and non-hummocky terrain different or similar?
- (2) Do specific initiation periods occur within each chronology when numerous trees develop compression wood?
- (3) Are the climate conditions associated with initiation periods, different from the mean conditions of the climate record?
- (4) What seasonal climate parameters are associated with increased compression-wood formation in hummocky and non-hummocky terrain?
- (5) What effect does the hydrological regime of Stewart River have on the percentage of trees initiating compression wood?

1.4 Relevance to Geocryology

Trees carry a record of past climate and growing conditions in the sequence of their annual growth rings. Thus, trees growing at the same location in permafrost terrain

may record ground-surface stability in the pattern of compression wood in their annual growth rings. Compression wood appears as eccentric crescents of dark, dense, annual ring-widths, and develops in coniferous trees when the ground beneath becomes unstable, causing them to tilt (Scurfield 1973). Ground-surface displacement in areas underlain by permafrost is largely a consequence of frost action (Zoltai and Pettapiece 1974), which is the result of two processes: frost heave and thaw settlement (French 1996). The magnitude of frost heave at a particular location is controlled by soil moisture conditions, the ground thermal regime, and soil texture (Burt and Williams 1976; Williams and Smith 1989). Variations in the atmospheric climate, can significantly alter the interactions between microclimatic components leading to increased or decreased frost action in permafrost environments (Luthin and Guymon 1974; Williams and Smith 1989).

This thesis endeavors to explore the association between periods of increased ground displacements, as indicated within the constructed compression-wood chronologies, and variations within seasonal climate parameters. Ground stability in permafrost terrain is of great concern to residents in many of Canada's northern communities. Changing climate conditions may result in melting of near surface permafrost and an increase in ground surface displacements. This study may be of interest to individuals concerned with increased climate variability and its effect on ground stability in permafrost environments.

1.5 Organisation

This thesis is presented in five chapters. The next chapter reviews relevant background literature associated with processes that operate in forest environments underlain by permafrost. Chapter Three describes the study area and the methodology used in collecting the data. Chapter Four presents and discusses the results of field work, the constructed compression-wood chronologies, and the associations between the climate record and compression-wood chronologies. Chapter Five summarizes and concludes the thesis.

CHAPTER 2: DRUNKEN FOREST UNDERLAIN BY PERMAFROST

This chapter introduces the aspects of geocryology and dendrogeomorphology relevant to the study. The relation between tilted trees and permafrost-related processes affecting ground stability is discussed.

2.1 THE PERMAFROST ENVIRONMENT

As a phenomenon defined by temperature alone, permafrost encompasses all components of the ground including mineral and organic material, water and ice, and may occur where the annual mean ground temperature is below 0°C. Permafrost conditions are widespread throughout Canada, as classified permafrost regions underlie approximately half of the land area (Heginbottom *et al.* 1995). Climate is the dominant factor controlling the continental distribution of permafrost, resulting in greater occurrence and thickness of permafrost with an increase in latitude and elevation. The permafrost map of Canada (Heginbottom *et al.* 1995) outlines four permafrost zones of continuous, extensive discontinuous, sporadic discontinuous and isolated patches of permafrost, which are based on ground temperature and ground ice observations (Figure 2.1). The continuous permafrost zone extends over terrain where 90-100% of the land area is underlain by permafrost, while the extensive and sporadic discontinuous permafrost zones have, respectively, 50-90% and 10-50% of the land area underlain by permafrost.

2.1.1 The Buffer Layer

The ground thermal regime and hydrological conditions are broadly determined

Figure 2.1: Distribution of permafrost zones in Canada (after Heginbottom *et al.* 1995).

by the atmospheric climate. However, where permafrost is spatially discontinuous, the detailed distribution is controlled by a buffer layer composed of vegetation, surface organic material and snow cover which moderate the atmosphere's influence on soil conditions (Luthin and Guymon 1974; Smith 1975; Williams and Burn 1996) (Figure 2.2). The mean annual ground temperature at a location may differ by several degrees from the mean annual air temperature. In terrain where ground temperatures are close to 0°C, the presence or absence of permafrost is often determined by local conditions such as variations in snow depth, availability of water for evaporation, vegetation conditions, and surface and subsurface materials (Luthin and Guymon 1974; Smith 1975; Williams and Smith 1989; Smith and Riseborough 2002). At the southern margin of the discontinuous zone, permafrost is limited to certain terrain types, usually peat bogs (Brown 1969, Vitt *et al.* 1994a; Halsey *et al.* 1995).

2.1.2 Buffer Layer Conditions in the Boreal Forest

The boreal forest region is a circumpolar mixture of coniferous and deciduous tree species, and is widespread throughout the discontinuous permafrost zones and along the southern margin of the continuous permafrost zone (Bonan 1989, Halsey *et al.* 1995). The dominant tree species of the boreal forest are white spruce (*Picea glauca*) and black spruce (*Picea mariana*) (Briggs *et al.* 1993), both of which are tolerant of permafrost. Tree growth is restricted, due to low soil temperature and low nutrient availability in permafrost regions (Bonan 1989). Low soil temperatures, high soil moisture, and low nutrient availability are factors characteristic of boreal forest terrain (Van Cleve and Yarie 1986).

Figure 2.2: Schematic diagram of the buffer layer model (after Luthin and Guymon 1974).

Coniferous trees greatly impact permafrost conditions in the discontinuous permafrost zone, and to a lesser extent in the continuous permafrost zone. The forest canopy increases shading and shields the ground surface from maximum solar radiation during the summer thaw period, inhibiting ground surface warming, thereby protecting existing permafrost conditions (Brown and Péwé 1973). Reduced snow accumulation due to interception in the canopy also increases winter heat loss from the ground, in comparison to open areas where deep snow cover may insulate the ground surface (Goodrich 1982; Smith and Riseborough 2002).

An extensive moss layer may also grow on the ground surface in coniferous forest terrain, as the tree canopy shades the underlying soil surface leading to favourable moisture conditions. During summer months, the dry moss layer has a low thermal conductivity and insulates the near surface, thereby preserving existing frozen ground (Riseborough 1985). In fall, precipitation may saturate the moss layer which then freezes. Consequently, in the winter, the moss is an icy layer possessing a high thermal conductivity. This results in upward heat conduction and enhanced ground cooling. In peatlands, the depth of seasonal thawing is much less than in other terrain types (French 1996). Furthermore, at locations within the boreal forest, a positive feedback is established between coniferous trees, snow cover, and the peat-moss layer which may result in permafrost aggradation (Vitt *et al.* 1994a; Halsey *et al.* 1995; Camill and Clark 1998; Camill 1999)

Poor drainage has a large impact on the local distribution of permafrost (Viereck *et al.* 1983). Black spruce is the dominant tree species in lowland peatlands, on poorly-drained soils, and glacial tills in alpine valleys within Yukon (Viereck 1970; Cody 1996).

High moisture conditions favour the growth of a thick moss layer on the soil surface which contributes to cooler ground surface temperatures (Luthin and Guymon 1974). The interaction between trees, moss and poor drainage conditions results in a shallow, saturated active layer and very low ground temperatures (Viereck 1970).

2.1.3 The Active Layer

The surface layer of the ground which is subject to annual freezing and thawing in areas underlain by permafrost is defined as the active layer (ACGR 1988). The thickness of this layer can vary inter-annually and is influenced by a number of interacting microclimate factors including the annual mean air and ground temperatures, the amplitude of the annual temperature cycle at the ground surface, the nature of the surface cover, particularly snow cover, and the thermal properties of the soil material (Smith 1975; Williams and Smith 1989; Smith and Riseborough 2002). Processes that operate within the active layer greatly affect the ecological and hydrological systems at a site, as the frost table restricts water infiltration, plant growth, and development of root systems in permafrost areas (Gill 1975).

When the summer is warmer than the previous year, more heat enters the ground, resulting in a deepening of the active layer. This change in active layer depth can be reversed by a colder summer in the following year which results in a shallowing of the active layer. Over several years, permafrost aggradation or degradation occurs in accordance with the net flux of heat into or out of the ground (Williams and Smith 1989). Where the active layer is thin, plants may develop lateral root systems for greater stability (Gill 1971). In alluvial landscapes that are underlain by permafrost, sediment deposition may occur with a concurrent rise in the permafrost table. Plants growing in such terrain

develop lateral roots from the buried lower portion of their stem into the constantly elevating active layer (Figure 2.3). These adventitious root systems are essential to plant survival, as the rising permafrost table would engulf the roots and restrict their function (Gill 1975).

The topography of the frost table and variations in active layer depth are often related to the distribution of vegetation on the ground surface (Hopkins and Sigafos 1951; Benninghof 1952; Brown 1966; Gill 1971). Unevenly distributed vegetation at a local scale and the resultant accumulations of organic material cause variations in ground temperatures and soil moisture. In areas with accumulated vegetation, the active layer is usually thinner, when compared to areas with sparse vegetation (Brown 1966). In discontinuous permafrost, Viereck (1965) found that individual white spruce trees alter the soil moisture and thermal regime causing ice lenses to form beneath them. The formation of localized ice lenses was attributed to lower snow accumulation and the development of an extensive moss layer under the tree canopy causing ground temperatures to lower and the aggradation of ice lenses. However, in the alluvial environment of Mackenzie River delta, Gill (1975) found the permafrost table beneath white spruce trees to be depressed in a conical shape surrounding the tree stem. The localized depression of the frost table was attributed to a number of interacting environmental factors including the interception of precipitation resulting in reduced soil moisture beneath the spruce crown, and the accelerated sediment deposition around spruce trunks resulting in restricted growth of highly insulative mosses. With a less extensive moss layer the ground has a lower thermal conductivity, leading restricted heat loss and a thicker active layer around the tree trunk.

Figure 2.3: Adventitious root system of white spruce tree growing in permafrost terrain (After Gill 1971).

Active-layer thickness is also influenced by soil texture which affects drainage conditions. Field evidence shows that the active layer is usually thicker in well-drained, coarse-textured soils, i.e. sands and gravels, in comparison with poorly-drained, fine-textured soils, i.e. silts and clays (Brown 1974). Poorly-drained soils have lower soil temperatures, because a large amount of the incoming solar radiation may be used to evaporate soil water, while in well-drained soils incoming solar radiation may quickly warm the soil (French 1996). As a result, fine-textured soils with high soil moisture contents often have a thin active layer. The relation between poorly-drained soils and permafrost conditions is complex, as permafrost may be the result, or cause, of poor drainage conditions. In some areas, the permafrost table may restrict drainage leading to increased soil moisture, resulting in the development of a thick peat-moss layer and additional ground insulation to maintain the existing permafrost.

2.2 FROST ACTION IN SOILS

Frost action, leading to the destabilisation of soils, is the result of two processes: frost heave, which occurs during freeze-back when water in the active layer freezes; and thaw settlement, which occurs when frozen ground thaws (French 1996). As water freezes, an expansion of 9 % occurs; however this is not usually considered frost heave (Williams and Smith 1989). Frost heave relates to the redistribution of water and the subsequent development of ice lenses in soil, which can cause substantial ground displacements. The magnitude of heave exhibited by a freezing soil is controlled by the amount and availability of soil moisture, temperature induced hydraulic gradients in the

soil water, and the soil texture (Burt and Williams 1976; Smith 1985; Williams and Smith 1989).

Soils below 0°C contain unfrozen water. The amount of unfrozen water decreases as soil temperature decreases and varies according to soil texture (Figure 2.4). The unfrozen water occurs because soil water commonly contains dissolved salts, which depresses its freezing-point. In addition, the freezing-point is also influenced by adsorption and capillary forces within the soil particle matrix (Williams and Smith 1989). Mineral particle surfaces have distinct adsorption properties, resulting in a reduced freezing temperature for a thin film of water on the surface of a soil particle. The amount of adsorbed water within a soil is a function of the specific surface area of the soil (Brady and Weil 1996), and is held at high tension (low pressure) on the surface of soil particles. As the temperature decreases the remaining unfrozen soil water experiences higher adsorbed forces and is under greater tension, in proportion to the temperature depression below 0°C. During freezing, water flow is directed from warmer, higher pressure (low tension) regions towards the colder, low pressure (high tension) regions of the soil. As the temperature decreases, and the amount of unfrozen water declines, the hydraulic conductivity decreases causing unfrozen soil water to accumulate at the freezing front where segregated ice lenses form.

The frost-susceptibility of a soil is broadly determined by the amount of unfrozen water in a soil present below 0°C, and the soil's ability to transmit water at temperatures below 0°C, or its hydraulic conductivity (Burt and Williams 1976). Coarse-grained, sandy soils are not frost-susceptible. While these soils exhibit a high intrinsic permeability and hydraulic conductivity, they do not contain large amounts of unfrozen

Figure 2.4: Unfrozen water content at temperatures below 0°C in different soil types (Williams and Smith 1989, Figure 1.4).

water below 0°C. Soils with high clay contents also possess a low frost-susceptibility. These soils typically have high amounts of unfrozen water at freezing temperatures, but also exhibit a low intrinsic permeability. As a result, unfrozen soil water is not easily transmitted at temperatures below 0°C. In comparison, fine-grained soils with high silt contents are highly frost-susceptible. These soils have moderate amounts of unfrozen water at freezing temperatures, but also have a moderate intrinsic permeability and, hence, hydraulic conductivity. Soil water in moderate amounts can then migrate towards a freezing front resulting in ice lens growth, frost heave and ground-surface displacement.

Local differential frost heaving occurs when the magnitude of heaving is greater in one area than in surrounding areas. Van Vliet-Lanoe (1991) proposed that differential frost heaving is the main mechanism leading to cryoturbation or mass displacement of soils in cold environments, which can be enhanced by the effects of the vegetation cover on the ground thermal regime. In areas where there is reduced insulation leading to greater thaw penetration during the summer, or where highly frost-susceptible soils are present, the growth of ice lenses may be enhanced (Mackay 1980; Washburn 1979; 1989). Hopkins and Sigafoos (1950), attributed the formation of microrelief features in soil, such as hummocks, to localized areas of frost action in perennially frozen ground.

The process of consolidation occurs during summer thaw when there is a reduction in soil volume and settlement (Morgenstern and Nixon 1971). Thaw consolidation occurs in fine-grained, frost-susceptible soils which exhibit frost heave and ice segregation (Williams and Smith 1989). Pore-water pressures may be elevated from rapid thawing of the soil and ice lenses. Unless the generated melt water drains quickly,

pore-water pressures remain elevated and the liberated water bears the weight of the overlying soil (Williams and Smith 1989).

Ground instability during thaw may be attributed to increased pore-water pressure reducing the effective stress (soil strength) of the soil, coupled with the loss of soil cohesion. When drainage of water is unimpeded during thaw, settlement with time is controlled by the location of the thawing front (Morgenstern and Nixon 1971). The generated water will flow laterally and vertically upward from the soil as it is produced, and the ground will remain relatively stable. The flow of water is effectively controlled by the unfrozen hydraulic conductivity and permeability of the soil. In frost-susceptible, fine-grained soils, the soil permeability is usually low, resulting in poor drainage of water generated during the thaw season

2.2.1 Cryoturbation

Cryoturbation is the general term which refers to the process of churning in soil caused by repeated frost heaving and thaw settlement within the active layer (Sigafos and Hopkins 1950; Washburn 1956). More specifically, cryoturbation results in the lateral and vertical displacements of soil and has been attributed to frost heave, thaw settlement, and differential soil movements including expansion and contraction as a result of soil temperature changes and ice segregation (French 1996). Within frost-susceptible soils, involution structures of water-saturated sediments may be the result from intense frost action within the active layer.

During freeze-back, the middle section of the active layer becomes desiccated by downward and upward water loss (Mackay and MacKay 1976; Mackay 1980), so that in winter, soils are ice-rich at both the top and bottom of the active layer (Mackay 1983).

Cryoturbations, or involutions, may result as a consequence of moisture-controlled density differences in sediments of different grain size within the thawing active layer (French 1986; Van Vliet-Lanoe 1991). These involutions appear as discoloured lobes rising from the top of permafrost (Agriculture Canada 1998; Swanson *et al.* 1999). In late-summer, the active layer becomes saturated as a result of high rainfall or the thaw ice-rich sediments at the permafrost table. Saturated sediments that exhibit high pore-water pressures in comparison to surrounding sediments may deform as involution structures within the thawing active layer (French 1986; Swanson *et al.* 1999). Regularly spaced involutions formed within the active layer provide evidence of soil displacements and intense cryoturbation.

2.2.2 Patterned Ground Features

In permafrost terrain, processes associated with cryoturbation can significantly alter the microtopography of the ground surface. Soil displacements resulting from cryoturbation have been linked to various patterned ground phenomena in areas underlain by permafrost. Most patterned-ground features occur within the active layer and have been classified in the past in terms of geometric form, and the extent of sorting (Washburn 1956). These features include circles, polygons, stripes, nets, plugs and steps, all which can either be sorted or non-sorted. Earth hummocks are a form of patterned ground widespread throughout the arctic tundra region, and subarctic woodlands, which are closely associated with permafrost (Zoltai and Pettapiece 1974; Zoltai and Tarnocai 1981; Washburn 1985). Several factors may determine the formation of most patterned-ground features, such as the duration of the cyclic freezing and thawing, soil moisture

content, and environmental characteristics including vegetation cover, snow cover, exposure, water drainage, slope, and soil texture (Krantz 1990).

Earth hummocks located in permafrost regions are vegetated mounds, and occur mainly on fine-grained, frost-susceptible soils with imperfect to poor drainage. Earth hummock formation has been attributed to a wide variety of cryoturbation processes which result in soil circulation. Radiocarbon dating of buried organic material within various earth hummocks has led some researchers to believe that earth hummocks are relatively stable features that develop quickly, and subsequently become stable or maintain their form through internal soil circulation (Tarnocai and Zoltai 1978; Mackay 1980). Initiation of the hummock feature has been attributed to differential frost heaving and diapiric motion of saturated sediments (Mackay 1980; Washburn 1989; Van Vliet-Lanoe 1991; Swanson *et al.*, 1999). Once initiated, it appears that the hummock form is sustained by repeated freeze-thaw cycles along inclined freezing fronts, as suggested in the equilibrium theory by Mackay (1980), in combination with the diapiric displacement of low-density saturated material which collects at the base of the active layer during the thaw season (Swanson *et al.* 1999) (Figure 2.5).

2.3 THE GROWTH RESPONSE OF TILTED TREES

Tilted trees often result from unidirectional, gravitational stresses which may be induced by such factors as wind, snow accumulation, or mass-movement (Scurfield 1973). A stress may also displace the soil directly beneath a tree causing that tree to tilt. Once tilted, the natural growth response of a tree is to regain the vertical habit. There are several ways in which trees strive to recover from processes which induce tilting

Figure 2.5: The equilibrium model of hummock growth and soil circulation (after Mackay 1980).

(Shroder 1978): when tilting is extreme, a lateral bud may grow vertically upward and eventually replace the displaced tree trunk; realignment may also allow the main stem to regain the vertical position, which is observable in trees that exhibit main stem curvatures. These curvatures indicate that at some time a stress resulted in tilting. Physiologically, the growth response of a tilted tree is the formation of reaction wood (Scurfield 1973).

Reaction wood is asymmetric radial growth and varies according to tree species. Reaction wood forms on the underside of conifer trees as compression wood, and in the direction of tilt (Schweingruber 1996). Multiple tilting events may be distinguished by observing the radial direction of different compression-wood sequences (Figure 2.6). Once a tree recovers from a tilting event, the compression wood gradually diminishes, over a decade or so, until only normal wood is produced (Zoltai 1975b). A subsequent soil displacement may create a new sequence of compression wood. By identifying the transition from normal annual growth rings to compression growth rings, it is possible to date initiation of compression wood development. Standard dendrochronological methods are employed when using annual tree-rings to date geomorphic events; hence this type of research has been described as dendrogeomorphology (Shroder 1978).

2.3.1 Dendrogeomorphology

Dendrogeomorphology concentrates on local, site-specific geomorphic processes that are reflected in tree growth. As a result, the spatial and temporal aspects of many mass movement processes have been studied and dated through tree-ring analysis (Wu 1984; Schweingruber 1996; Denneker and Schweingruber 1993; Fantucci and Sorriso-Valvo 1999). Shroder (1978) analysed compression-wood formation in tilted trees on a

Figure 2.6: Basal cross section of a 101-year-old black spruce tree, showing six compression-wood sequences.

boulder deposit at Table Cliffs Plateau, Utah, and was subsequently able to estimate the frequency of slope movements. Landslide activity was studied by Clague and Souther (1982) in the southern Coast Mountains of British Columbia, using tree-ring analysis from trees damaged by slide activity. Additional mass movement events such as debris flows, rock slides and falls, creeping and sliding slopes, and slush flows have also been studied using a variety of dendrogeomorphological techniques (Schweingruber 1996).

In addition to mass movements, a wide variety of geomorphological processes have been investigated through the growth response of trees affected by local, site-specific processes. These include glacial activity, such as rock glacier movements (Carter *et al.* 1999) and ice advances (Luckman and Osborn 1979; Luckman 1993; Luckman *et al.* 1993; Osborn and Gerloff 1997). Additional geomorphological processes which can significantly affect tree growth include: wind throw, tectonic activity (LaMarche and Wallace 1972), coastal erosion (Begin and Filion 1985), and soil cryoturbation (Zoltai 1975).

2.4 TILTED TREES GROWING IN PERMAFROST TERRAIN

In frost-affected regions, seasonal frost heave and thaw settlement can result in soil displacements and cryoturbation. In many parts of the boreal forest, destabilisation of the ground surface by these processes may lead to tilted trees (Zoltai and Pettapiece 1974). The resulting drunken forest, often serves as an ecological indicator for the presence of permafrost (Zoltai 1975a,b; Crampton 1977).

2.4.1 Vegetation Growth in Hummocky Permafrost Terrain

In hummocky permafrost terrain, the distribution of vegetation is affected by the surface microtopography. Hummock tops are usually vegetated with plants that have no roots, such as lichens and mosses, or by short-lived plants. In forested hummocky areas of Mackenzie River valley and northern Yukon, Zoltai and Pettapiece (1974) found few trees on hummock tops, but many on hummock sides and in inter-hummock troughs. Zoltai and Pettapiece (1974) initially proposed that improved drainage conditions on hummock tops may have influenced the distribution of trees growing in hummocky terrain, but, additional field investigations in poorly-drained hummocky areas revealed that few trees were found on hummock tops there as well, indicating that moisture constraints might not be the limiting growth factor. Consequently, Zoltai and Pettapiece (1974) hypothesized that the scarcity of trees growing on hummock tops may be related to the effects of cryoturbation. The influence of soil movement on tree distribution was also supported by the observation that the majority of trees lean away from hummocks. Curvatures within the main stems of tilted trees were also observed. As a result, hummocks were described as episodically, if not constantly, active features. Zoltai and Pettapiece (1974) associated cryogenic activity with climate, suggesting that a series of extremely wet and cold years may lead to greater frost heave and sufficient moisture in the active layer for increased cryoturbation and tree tilting.

2.4.2 Tree-ring Records of Ground Surface Displacement

Trees growing on severely cryoturbated soils in permafrost terrain produce compression wood in response to ground displacements caused by frost action. At several study sites in Mackenzie River valley, Zoltai (1975a,b) extracted cross-sections

from tilted trees growing on hummocky permafrost terrain and found that all trees exhibited at least one period of compression-wood growth. Many trees showed multiple initiations of compression wood in different directions. Periods of compression-wood formation were used to develop a chronology of hummock activity from the sampled trees. The chronology of ground heave movements showed periods of high activity and periods of quiescence. With a limited climate record for the study region, Zoltai (1975b) suggested that periods of increased ground displacements reflected above average summer temperature and rainfall.

The purpose of this thesis is to investigate the tree-ring records of ground displacements in both hummocky and non-hummocky forested permafrost terrain in order to examine the hypothesis that increased frost action results in tree tilting, and compression wood formation in both hummocky and non-hummocky drunken forest terrain. Previous studies have related tilted trees in drunken forest terrain to episodes of increased hummock activity (Zoltai and Pettapiece 1974; Zoltai 1975a,b). However, this study draws on tilted trees from within frost-affected regions where hummocks are not yet fully formed. By examining the tree-ring records of tilted trees growing in both hummocky and non-hummocky terrain, processes resulting in the drunken forest phenomena will be further investigated. Frost action, resulting in ground displacements, is recorded by tilted trees as compression-wood growth. By relating compression-wood chronologies constructed from trees at both hummocky and non-hummocky terrain to the climate record, periods of increased frost action may be attributed to specific climate conditions.

CHAPTER 3.0 STUDY AREA AND METHODS

This chapter introduces the physical characteristics of the study area near the village of Mayo (135°35' W, 63°35' N, 470 m a.s.l.), central Yukon Territory. Two study sites near Mayo, situated in drunken forest terrain are described in detail. Methods used throughout the course of study are also described.

3.1 PHYSICAL CHARACTERISTICS OF STUDY AREA

The study area is located in central Yukon, in the quadrangle defined by 63°35'N, 63°45'N, 136°00'W, and 136°45'W (Figure 3.1). This area lies approximately 20 km east of the Late-Wisconsinan, McConnell glacial limit. Site 1 is located within Mayo River valley, which is approximately 3 km wide with adjacent hills that rise up to 1300 m. Site 2 is located within Stewart River valley, which is approximately 5 km wide, and bounded by hills that rise up to 1200 m from the valley floor. The study area is located within the Widespread Discontinuous Permafrost zone (Heginbottom *et al.* 1995). Recently-deposited alluvial sediments are generally permafrost-free, while patches of older glaciolacustrine sediments found in the lowlands usually contain ice-rich permafrost (Burn 1986). In alluvial sediments near Mayo where permafrost has aggraded, permafrost thickness ranges from 20 to 30 m, while in glaciolacustrine sediments it ranges from 30 to 40 m (Burn 1992).

The local topography of the study region comprises tablelands, dissected by broad, U-shaped valleys (Bostock 1966). Drainage in the Mayo area is directed westward towards Yukon River by Stewart River and its tributaries. Stewart River, a major component of the central Yukon landscape, is a meandering river with characteristic cut bank and slip-off slopes. There are numerous former channels in the floodplain.

Figure 3.1: Map of study area with Site 1 located in Mayo River Valley and Site 2 located in Stewart River Valley.

3.1.1 Climate

In broad terms, the climate of the study region is high-latitude, continental (Kendrew and Kerr 1955). The mean annual air temperature at Mayo is -3.6°C , while the normal precipitation is approximately 300 mm with an average of 130 mm (water equivalent) falling as snow (Atmospheric Environment Service 1993). From October until April, the area is strongly influenced by dry, cold, continental arctic air masses. The St. Elias and Coast mountain ranges block most Pacific maritime air masses from entering central Yukon, and consequently the annual precipitation is relatively low (300 to 400 mm) in the interior valleys and lowland areas. The continental climate results in large annual, day-to-day, and daily ranges in temperature, and moderate to low precipitation (Wahl *et al.* 1987). The local climate of the study area is further influenced by its valley location. Due to temperature inversions in winter, the air temperature at Mayo is often lower than nearby Elsa which is located at a higher elevation.

3.1.2 Soils

Soil development is limited in cold climates as a result of low soil temperatures, restricted chemical weathering and organic matter decomposition (Van Cleve and Yarie 1986). In northern terrain, soil development is most advanced in forested areas with moderate to high drainage. In lowlands where drainage is restricted, and on mountain slopes, soil development is hampered (Van Cleve and Yarie 1986). In depression areas where drainage is poor, thick organic soils underlain by permafrost commonly develop (Smith 1975).

Eutric Brunisol and Turbic Cryosol are the primary soil types in the study area (White *et al.* 1994). Brunisols occur in a variety of climatic and vegetative environments including the boreal forest, subarctic tundra, and mixed forest of southern Canada. Eutric Brunisols lack a fully developed mineral-organic surface horizon and occur mainly on basic

parent material and under forested conditions (Agriculture Canada 1998). In the study area, these soils are found in Stewart River valley, in the hills west of Wareham Lake, and in the hills south of Stewart River (White *et al.* 1994).

Cryosols are prevalent in subarctic forest terrain where fine-textured, frost-susceptible soils are present. These soils form in either mineral or organic materials that have permafrost within 2 metres of the surface. They may also exhibit signs of frost action associated with cryoturbation within the active layer, resulting in disrupted, mixed or broken soil horizons (Agriculture Canada 1998). Turbic Cryosols are soils with developed mineral horizons that exhibit distinct signs of cryoturbation. Cryoturbation may lead to formation of patterned ground features, such as earth hummocks and sorted circles (Zoltai and Tarnocai 1974). Turbic Cryosols are found at both study sites, in the hills east of Wareham Lake at Site 1 and in Stewart River valley east of Mayo at Site 2 (White *et al.* 1994).

3.1.3 Vegetation

The study area lies within the Yukon Plateau-North ecoregion of central Yukon (Ecological Stratification Working Group 1995). The local distribution of vegetation is affected by microclimate components including slope, aspect, drainage, soil temperature, fire history, and river channel migration (e.g. Smith 1975). The dominant tree species in stable terrain throughout the area is white spruce, which favours warmer, drier locations than black spruce. Willow (*Salix* spp.) and alder (*Alnus* spp.) shrubs are predominant in well-drained areas. In lowland areas with poor drainage, usually underlain by permafrost, black spruce bogs occur with stunted trees and a thick moss cover. In these areas, the ground surface is usually blanketed by feather mosses (*Hypnum* spp. and *Hylocomium* spp.) and lichen (*Cladonia* spp. and *Cetraria* spp.).

Moisture conditions also influence the distribution of shrubs and herbs found within the forest. In moist forests, the shrub and herb layer is dominated by labrador tea (*Ledum groenlandicum*), bog cranberry (*Vaccinium-vitis idaea*), and red bearberry (*Arctostaphylos rubra*) (Cody 1996). In drier forests, the shrub and herb layer is dominated by kinnikinnick (*Arctostaphylos uva-ursi*), wild rose (*Rosa acicularis*), and lupin (*Lupinus arcticus*) (Cody 1996).

Vegetation succession as a result of forest fire and river channel migration can alter the environmental conditions at a particular location. In older stable areas, such as the outside edges of river meanders, mature white and black spruce forests are prevalent. Cooler soil temperatures, a thick moss layer, and reduced snow cover often lead to permafrost aggradation in these forested areas (e.g. Smith 1975). In recently flooded alluvial areas, willow and alder are the first shrubs to colonize. As time progresses, a moss layer develops in alluvial areas reducing soil temperatures, resulting in re-vegetation of disturbed areas by coniferous trees. In coniferous forest terrain underlain by permafrost, tilted trees may occur. Drunken forest is common throughout the study region.

3.2 FIELD METHODS

In summer 2001, two sites in drunken forest close to Mayo were investigated. Several trees were cut down and a collection of sample discs was obtained from both sites. The sample discs were subsequently polished and analysed in the laboratory in order to construct a compression-wood chronology for each site.

3.2.1 Site Selection

Both sites were located within mature black spruce forest underlain by permafrost, complete with a thick ground surface covering of feather mosses. Tilted trees were ubiquitous at both study sites. The primary soil type at both sites was Turbic Cryosol.

Patterned ground features, such as earth hummocks, are often a consequence of the intense frost action associated with Cryosols (French 1996). At the first study site the microrelief of the ground surface was hummocky in appearance, while at the second study site the ground surface did not comprise well-defined hummocks, but was, nevertheless, undulating.

Site 1

Site 1 was located approximately 10 km north of Mayo, in a poorly-drained lowland area at the base of Glacier Hill and east of Wareham Lake (Figure 3.1). Hughes (1983) classified the material at this site as a glaciolacustrine and colluvial complex deposit. The glacial sediments were deposited at the end of the McConnell glaciation, about 14,000 years B.P. (Tarnocai *et al.* 1985). The average slope along a 100 m transect at Site 1 was 2 degrees. The study site was situated within an open black spruce woodland, and mature trees were predominantly tilted (Figure 3.2). The hummocky ground surface was covered by a thick moss (*Hylocomium splendens*) and lichen (*Cladina stellaris*) organic layer. The local dominant trees, shrubs, and herbs were black spruce, labrador tea, and bog cranberry, respectively. The shrub and tree species found at the study site all favour moist and cool soil conditions (Cody 1996). Drainage at this study site was poor and, as the thaw season progressed, pools of water occurred in depressions.

Hummocks were widespread but not ubiquitous at this site. They were 30 to 50 cm high with a diameter of 1 to 2 m. In trough areas covered by *Hylocomium splendens* and *Sphagnum* spp., thaw depths ranged between 30 and 50 cm at the end of August. Hummock tops were covered primarily by lichen and labrador tea. Thaw depths in the centre of the hummocks were greater than those in trough areas, and ranged from 50 to 90 cm in late August. The hummocky micro-relief observed at Site 1 is associated with the presence of fine-grained frost-susceptible soil, imperfect drainage, a thin active layer, and the presence of permafrost with an undulating frost table.

Figure 3.2: Drunken forest terrain at Site 1 (Photo: Catherine Kennedy).

Site 2

Site 2 was located approximately 25 km east of Mayo, near Stewart River (Figure 3.1). The underlying surficial material at Site 2 is of alluvial origin (Hughes 1983), and comprises well-graded, coarse sand beneath fine flood sediment. The slope of this site was approximately 1 degree along a 100 m transect. Similar to Site 1, this site was situated within an open black spruce forest woodland where tilted trees were predominant (Figure 3.3). The vegetation characteristics at Site 2 indicate that alluvial sediments deposited by Stewart River are as old as the oldest trees growing at the site. The material on this site is relatively young, perhaps only several centuries old compared to Site 1, which has received little sedimentation since deposition. The ground surface at Site 2 was covered with a thick organic layer, consisting of feather moss and lichen. The local dominant trees, shrubs, and herbs were black spruce, labrador tea, and bog cranberry, respectively. Overall, Site 2 was drier than Site 1, although drainage conditions varied from moderate to poor. Near the river bank drainage was moderate, but wetter conditions were found away from the river.

In association with the improved drainage conditions, the microrelief at Site 2 did not possess clearly defined hummocks like those found at Site 1. Rather the ground surface was undulating, with drier raised areas covered by lichen, and low-lying depressions covered by a thick moss cover. At the end of the thaw season, in low-lying depression areas where the moss cover was approximately 30 cm thick, thaw depths ranged from 30 to 50 cm. In raised areas covered extensively by lichen, thaw depths were greater, ranging from 40 to 60 cm.

3.2.2 Vegetation

Catherine Kennedy (Yukon Territorial Government) identified vegetation species at the sites, and these were subsequently verified with Cody (1996). An inventory of vegetation species was taken in a sample area of approximately 10 m² at each study site.

Figure 3.3: Drunken forest terrain at Site 2.

The percent cover of each plant species was estimated visually at different strata levels within each area. The strata levels were defined by specified heights of the tree and shrub canopies, as well as individual herb, moss, and lichen layers.

3.2.3 Soil Investigations

In late August 2001, soil pits 1 m in depth were dug at each site. Samples were taken from the centre of each visible soil horizon. Simple tools such as a shovel, trowel, and moisture-proof soil bags were used to collect the soil samples. A tape measure was used to measure the depth of samples, and the thickness of the soil horizons, moss and organic layers. Depths were measured from the top of the living moss cover at the ground surface. The organic layer was measured as the combined thickness of the living moss layer, peat and humus.

Following ASTM (1998) guidelines, moisture content was determined for mineral soil horizons. The dried soil samples were then ground with mortar and pestle and sub-sampled with a soil splitter for particle-size analyses. The coarse grain-size distribution (>0.05 mm) was determined using ASTM (1998) guidelines for wet sieving. The fine grain-size distribution (<0.05 mm) was determined through Laser Particle-Size Analysis at the Geological Survey of Canada.

At Site 1, several hummock top and trough areas were excavated in order to observe involution of buried organic materials, as a result of cryoturbation and soil mixing in the hummock features.

3.2.4 Sampling of Trees

At each study site, a 100 m long transect was established and adjacent tilted trees were selected at random if their measured circumference was greater than 15 cm. Trees were cut 10-30 cm above the ground surface and a sample disc was obtained from each tree selected. At Site 1, approximately 90 trees were selected and cut down, while at Site 2

approximately 50 trees were taken. At Site 1, it was noted if the sampled trees were growing either on the top, side, or trough of a hummock.

3.3 TREE-RING METHODS

Compression-wood chronologies at both Site 1 and Site 2 were constructed from sampled trees in order to investigate the differences and similarities between compression-wood chronologies of tilted trees growing on hummocky and non-hummocky permafrost terrain. The compression-wood chronologies were constructed for the period 1900 to 2000.

3.3.1 Tree-ring Analysis

Discs obtained from sampled trees were polished with increasingly fine sand paper so that annual growth rings were clearly distinguishable. The polished discs were examined under 50x magnification with a microscope that was mounted on a Velmex-type stage measurement system. The age of each sample was recorded by counting the entire sequence of annual growth rings from pith to bark.

Rings of compression wood were found on all prepared sample discs and years of initiation and termination of each series of compression wood were recorded. A compression-wood series was recorded when 3 or more years of compression wood occurred in sequence along a single radial line. A new series of compression wood was recorded after a series of normal annual growth rings was observed following a previous period of compression wood or when the radial path within a compression-wood series changed direction. The age and compression-wood record of each tree sample were recorded initially and then verified a second time in order to reduce measurement error. If the age and compression-wood record was unreplicated, the sample was analysed a third time. Following the correct determination of sample age, compression-wood series were constructed on Excel spreadsheets by designating “1” for years with compression wood, “2”

for years when a compression-wood sequence was initiated, and “0” in normal growth years without compression wood. The compression-wood chronology for each site was constructed by determining the annual percentage of trees exhibiting compression wood (rings designated “1” and “2”) in each year of the record. An initiation chronology for each site was constructed by determining the annual percentage of trees initiating compression-wood sequences (rings designated “2”) in each year of the record.

3.3.2 Initiation and Stabilisation Periods

In order to determine periods when the annual percentage of trees exhibiting compression wood was higher than the average percentage of annual compression wood, the chronologies were divided into initiation periods and stabilisation periods. Statistical measures of dispersion take into account the amount of variation within values of a particular data set. Some measures account for every value in the data set based on the deviations of the values from the mean. The variance (σ^2) of a data set is determined by calculating the sum of the square of each value's deviation from the mean. A common descriptive measure of dispersion is the standard deviation (σ), or the square root of the variance. Initiation periods were determined by converting the annual percentage of compression wood values comprising each chronology to standardised z-scores. A z-score is the difference between an individual value and the sample mean divided by the standard deviation of the sample [$\text{z-score} = (\text{value} - \text{mean})/\text{standard deviation}$] (Ebdon 1985). Z-scores express a particular value as a percentage of the standard deviation exhibited by the data set, so that if a value exhibits a high z-score value, there is a greater difference between the individual value and the mean of that data set (Ebdon 1985). In both compression-wood chronologies, there are sequences of years in which z-scores are greater than +1.0 and less than -1.0.

In the years following initiation, the percentage of trees exhibiting annual compression wood progressively rises. Thus, an initiation period was defined as a sequence of years with increasingly higher percentages of annual compression wood, reaching a maximum z-score greater than +1.0.

The percentage of annual compression wood rises during an initiation period because ground instability causes trees to tilt, resulting in increased compression-wood growth. Compression wood is formed in trees until stabilisation occurs, leading to the formation of normal annual growth rings. Once normal annual growth rings are produced, the percentage of trees exhibiting compression wood growth rapidly declines. A stabilisation period was defined as a sequence of years following an initiation period, when the z-score of trees with compression wood progressively declines to a minimum lower than -1.0.

3.3.3 Measurement Error Analysis

Dendrochronologists use cross-dating techniques to synchronize variations in annual ring-width patterns exhibited by a collection of tree cores (Fritts 1976). When cross-dating, the ring-width pattern of an individual sample is compared to the ring-width pattern established by a collection of samples. Thus, the accuracy of individual ring-widths and the annual signal of the entire chronology are verified. Errors within individual samples can be attributed to mechanical measurement error of the annual tree-rings, but can also result from missing annual rings, or false rings within a sample. The cross-dating technique ensures that annual ring-widths are matched up with common marker years and ring-width patterns are identified.

Trees that are subject to various tilting events in multiple directions grow asymmetric annual growth rings, or compression wood. It is difficult to cross-date samples with multiple compression-wood sequences because a radial path of normal annual ring-

widths from the pith to bark may not exist. These difficulties were encountered when analysing the sample discs collected from both study sites. To assess the level of measurement error within the constructed compression-wood chronologies, 15 prepared tree discs were chosen at random from the samples collected at Site 1 and re-analysed. The first measurement of the samples was then compared to the second measurement and the percentage of error was determined. The error was then expressed in terms of the different growth possibilities: years when compression wood was initiated, years when compression wood was in sequence, and years with normal growth.

Results from the measurement error analysis are presented in Table 3.1. From the collection of re-measured samples, it was found that 13.0% of the annual rings did not match the growth sequence designation recorded previously. A total of 62.8% of the annual rings counted were normal growth rings, of which 57.8% were correctly measured a second time. A total of 34.2% of the annual rings counted exhibited compression wood in sequence, of which 28.1% were correctly measured a second time. Only 3.1% of the annual rings counted were rings initiating a compression wood sequence, of which 1.1% were correctly measured a second time.

3.4 CLIMATE

One of the objectives of this thesis was to investigate the association between periods of increased and decreased compression wood formation and variations in seasonal climate.

3.4.1 Climate Record

Monthly mean values of air temperature, total precipitation, snowfall, and rainfall recorded at the Mayo climate station were gathered from the Historical Canadian Climate Database (Meteorological Service of Canada 2002). The database is a long-term

TABLE 3.1. Summary of measurement error analysis.

Annual growth possibilities	Correct	Error	Total	
Normal growth ring (0)	57.8%(0,0)	3.7%(0,1)	1.2%(0,2)	62.8%
Compression wood in sequence (1)	28.1%(1,1)	5.1%(1,0)	1.0%(1,2)	34.2%
Compression wood initiated (2)	1.1%(2,2)	0.7%(2,0)	1.3%(2,1)	3.1%
	87.0%	13.0%		100%

temperature time series which has been homogenized and designed specifically for climate change analyses over Canada (Vincent and Gullett 1999). Climate data have been recorded at the Mayo climate station since 1925, and provide the second longest record of climate in Yukon Territory, after Dawson City. The daily minimum and maximum values are taken from hourly measurements, and from these the daily mean value is calculated. Monthly mean values are derived from the daily mean values.

Dawson City has the longest climate record in Yukon Territory, from 1897 to present. The annual mean temperature at Dawson City is approximately 2°C cooler than at Mayo (McCoy and Burn 2001). Data from both stations are available for 1925 to 1998, and the two annual mean temperatures are significantly correlated at the 95% confidence interval (McCoy and Burn 2001). The coefficient of determination (r^2) for the annual mean temperature at Mayo and Dawson City is 0.96 (Figure 3.4). Thus, annual mean air temperatures from Dawson prior to 1927 may be used to estimate conditions at Mayo (Figure 3.5). A composite Mayo record for annual mean air temperatures was constructed for the period of 1900 to 1924 based on the regression equation derived from correlating the annual mean air temperatures for Mayo and Dawson City from 1925 to 1998. The coefficient of determination (r^2) for the annual total precipitation at Mayo and Dawson City is 0.34, and not significant at the 95% confidence interval. Thus, total precipitation, snowfall, and rainfall were gathered solely from the Mayo climate record from the period of 1927 to 2000.

3.4.2 Annual and Seasonal Climate Trends

To investigate the annual trends and to smooth inter-annual variation within the climate record, five-year running means were calculated for temperature, precipitation, rainfall, and snowfall climate variables. To investigate seasonal trends within the climate record, the monthly mean air temperature and total monthly precipitation records were

Figure 3.4: Dawson and Mayo annual mean air temperature, 1925-1998
(Line: $y=1.065x+2.09$, where y = Mayo air temperature and x = Dawson
air temperature)
(McCoy and Burn 2001, Figure 7).

Figure 3.5: Estimated Mayo annual mean air temperature, 1900-2000 (After McCoy and Burn 2001).

aggregated into the following seasons: Thaw (April and May), Summer (June to August), Active (May to September), Fall (September to November), and Winter (previous December to March). The active season was defined to include the months of the year when the active layer progressively thaws as the soil warms, and the ground heat flux reverses from positive (upward heat flow) to negative (downward heat flow). The fall season was defined to incorporate the months of the year when fall freeze-back and the formation of ice lenses occur within the active layer, leading to frost heave and ground surface displacement.

Seasonal air temperature was calculated by averaging the monthly mean air temperature of each defined season for each year of the record (1900-2000). Total seasonal precipitation, rainfall, and snowfall were calculated by totalling the monthly precipitation values of each defined season for each year of the record (1927-2000). From the total monthly rainfall record, Summer (June to August) rainfall was calculated. From the total monthly snowfall record, Fall (September to November) snowfall and Winter (previous December to March) snowfall were calculated.

The effective precipitation was calculated each summer 1927 to 2000, to assess the relative amount of soil moisture retained by the soil at the start of fall freeze-back. Effective precipitation was calculated by determining the potential evapotranspiration (E_o) using a heat index (H) developed by Thornthwaite (1948):

$$E_o = 16(10T/H)^a \text{ mm mo}^{-1}$$

where

$$a = (0.675H^3 - 77.1H^2 + 17920H + 492,390) \times 10^{-6}$$

and

$$H = \sum_{i=1}^{12} (T/5)^{1.514}.$$

The heat index uses mean monthly air temperature (T) as a surrogate measure of the radiation used in evapotranspiration. Potential evapotranspiration can only be determined

when the mean monthly air temperature is above 0°C, so that the potential evapotranspiration rate is positive (Sellers 1965). Total effective precipitation on an annual basis was calculated by subtracting the summer (June to August) potential evapotranspiration from the total summer precipitation.

3.4.3 Water Level Record of Stewart River at Mayo, 1949-1999

With the close proximity of Stewart River to Site 2, water level and discharge data were gathered for Stewart River at Mayo. There are records of annual maximum discharge (m^3/s) of Stewart River at Mayo for 1949 to 1979 (Water Survey Canada 1991, 1992). From 1980 to 1999, there are records of annual maximum water level for Stewart River above a datum at Mayo (473 m a.s.l.) (Meteorological Service of Canada 2002). Prior to 1979, water level and discharge measurements were recorded at the Mayo gauging station; however, after 1979, the gauging station was moved to Fraser Falls, which is approximately 30 km upriver from Mayo. The station was moved because the riverbed near Mayo is composed of sedimentary materials which are susceptible to erosion, whereas the riverbed at Fraser Falls is composed of bedrock which is less susceptible to erosion. The hydrological regime of Stewart River should not differ significantly between these locations, as there are no additional tributaries flowing into Stewart River between Fraser Falls and Mayo. Thus, discharge measurements taken at Fraser Falls can be used as surrogate values for daily discharge measurements in the construction of a rating curve for Stewart River at Mayo.

As a result of the discontinuous streamflow record for Stewart River at Mayo, a rating curve was constructed to convert the annual maximum discharge values to water levels for 1949 to 1979 (Figure 3.6). Daily discharge values for Stewart River at Fraser Falls were correlated with daily water levels at Mayo for the period 1980 to 1999 (Meteorological Service of Canada 2002). A rating curve was obtained from the regression

Figure 3.6: Rating curve constructed for Stewart River at Mayo.

(Line: $y = -3E-07x^2 + 0.0027x + 3.3247$, where y = Stewart River water level measured above 473 a.s.l. datum, and x = Stewart River discharge measured above Fraser Falls)

(Water Survey of Canada 1992, Meteorological Service of Canada 2002).

line, which was then used to derive the annual maximum water levels for Stewart River at Mayo for 1949 to 1979. The polynomial fit line had a coefficient of determination (r^2) of 0.94.

The association between the water level record and initiation periods outlined in the Site 2 compression wood chronology was also examined. The annual maximum water levels on record were ranked in order to determine the probability of occurrence [$P = m/(n+1)$], where P is probability, m is the ranking, and n is the number of years in the record. The probability values were then plotted on Gumbel extreme-value probability paper. A best-fit line was estimated by eye through the plotted values. The return period (RP) of each annual maximum water level was determined by taking the reciprocal of its probability for any year ($RP = 1/P$). The association between annual maximum water levels that showed a low probability of occurrence and the incidence of initiation periods in the Site 2 chronology was investigated. The percentage of trees initiating compression-wood sequences was calculated following a year that corresponded with a high water level on record.

With a limited record of Stewart River water level data prior to 1949, historical evidence of high water events was also investigated. The Mayo Historical Society (1990) has documented an extreme flood event during the summer of 1936. The Site 2 initiation period corresponding with this year was examined to see whether a larger percentage of trees initiated compression wood sequences following this flood event.

3.4.4 Initiation and Stabilisation Periods and the Climate Record

To investigate the association between initiation and stabilisation periods identified in the compression-wood chronologies and variables from the Mayo climate record, average air temperature and total precipitation values were calculated for the years corresponding to initiation and stabilisation periods. The difference between the climate conditions

associated with initiation and stabilisation periods and the corresponding annual and seasonal averages for the period of the entire record (1900-2000) was then determined.

To further investigate how the climate conditions differed during specific years at the onset of initiation periods, the annual and seasonal air temperature and precipitation totals corresponding with the first three years of an initiation period, and one year prior to an initiation period, were standardised as z-scores. Higher z-scores reflect extreme values that lie at the tails of the standard Normal distribution (Ebdon 1985). As a result, years that are associated with climate conditions that correspond with high z-scores differ greatly from the mean of the record.

When a data set approximates a Normal distribution, it is possible to calculate the probability that a datum in the set will be less than a particular reference, given the reference value's departure from the mean of the distribution (Ebdon 1985). A data set which is Normally distributed exhibits a skewness of 0.0, and kurtosis of 3.0. Skewness measures the symmetry, or the degree to which the mode coincides with the mean of a distribution, while kurtosis measures the 'peakedness' of a distribution (Ebdon 1985). A 'flat' distribution is said to be platykurtic, with a kurtosis value less than 3.0, while a 'peaky' distribution is said to be leptokurtic, with a kurtosis value greater than 3.0. The descriptive statistics for variables comprising the Mayo climate record are presented in Table 3.2. The skewness values range between -0.22 and 0.83, while kurtosis values range between 0.05 and 1.23. Thus, most variables exhibit symmetrical, platykurtic distributions. The seasonal and annual climate variables comprising the Mayo climate all record approximate Normal distributions. Thus, standardised z-scores based on climate conditions during specific initiation years were used to calculate percentiles on the cumulative probability scale for the standard Normal curve.

TABLE 3.2: Descriptive statistics for the seasonal and annual temperature, precipitation, rainfall, and snowfall conditions for the period of record.

Temperature (1900-2000) (°C)	Mean	Standard Deviation	Kurtosis	Skewness
Annual (Jan – Dec)	-3.6	1.5	0.68	0.00
Thaw (Apr – May)	4.2	1.8	0.33	0.10
Summer (Jun – Aug)	14.4	1.2	0.16	0.44
Active (May – Sept)	11.6	1.1	0.46	0.32
Fall (Sept – Nov)	-3.9	2.3	0.38	0.03
Winter (prev. Dec – Mar)	-20.7	3.9	0.70	0.21
Precipitation (1927 – 2000) (mm)				
Annual (Jan – Dec)	343.1	70.7	0.69	0.03
Thaw (Apr – May)	35.1	13.9	0.57	0.83
Summer (Jun – Aug)	139.2	38.7	0.92	0.66
Active (May – Sept)	199.7	44.7	0.24	0.29
Fall (Sept – Nov)	92.7	28.3	0.05	0.29
Winter (prev. Dec – Mar)	76.9	32.5	0.24	0.24
Summer Effective Precipitation (Jun – Aug)	-105.1	40.6	1.23	0.68
Rainfall (mm)				
Annual (Jan – Dec)	209.7	45.2	0.25	0.21
Summer (Jun – Aug)	138.6	38.8	0.97	0.69
Snowfall (mm snow water equiv.)				
Annual (Jan – Dec)	133.9	43.1	0.71	-0.22
Fall (Sept – Nov)	49.3	22.9	0.61	0.08
Winter (prev. Dec – Mar)	134.5	45.7	0.44	-0.02

CHAPTER 4.0 RESULTS AND DISCUSSION

This chapter has four parts. The first part outlines the results from field work carried out at both study sites including vegetation analysis, soil properties, and characteristics of sampled trees. The second presents summary statistics for compression-wood chronologies constructed from tree samples collected at both study sites. One aim of this project was to compare compression-wood chronologies for tilted trees growing on hummocky and non-hummocky permafrost terrain. Separate initiation and stabilisation periods identified within the compression-wood chronologies are presented in detail. The third describes the associations between initiation and stabilisation periods within the compression-wood chronologies and variables from the Mayo climate record, including temperature, precipitation, snowfall, and rainfall. The fourth describes the association between initiation periods at Site 2 and the hydrological regime of Stewart River.

4.1 FIELD RESULTS

4.1.1 Vegetation Analysis

An inventory of plant species was taken at each study site and the percent cover of each species was estimated at specified strata levels (Table 4.1 and Table 4.2). The vegetation characteristics of both study sites were similar with respect to plant species composition and percent cover. At both study sites, black spruce was the dominant tree species with comparable amounts in both the tall and low tree canopies, and in the tall and medium shrub canopies. The herb layers were also similar at both sites, consisting of dwarf scouring rush and cloudberry in equivalent percent cover. While the percent cover of mosses at each site was similar, *Sphagnum* spp. mosses were present at Site 1, but absent at

TABLE 4.1: Vegetation inventory and cover estimation at Site 1.

Cover type	Common plant name	Percentage cover
Tall tree canopy (>5 m)		
<i>Picea mariana</i>	Black spruce	1
Low tree canopy (<5 m)		
<i>Picea mariana</i>	Black spruce	10
Tall shrub (>1.5 m)		
<i>Picea mariana</i>	Black spruce	15
<i>Salix glauca</i>	Grey-leaved willow	1
<i>Salix arbusculoides</i>	Little-tree willow	p
Medium shrub (1.5 – 0.5 m)		
<i>Picea mariana</i>	Black spruce	10
<i>Salix glauca</i>	Grey-leaved willow	5
<i>Salix arbusculoides</i>	Little-tree willow	p
<i>Betula glandulosa</i>	Bog birch	p
<i>Ledum groenlandicum</i>	Labrador tea	p
Low shrub (<0.5 m)		
<i>Ledum groenlandicum</i>	Labrador tea	15
<i>Picea mariana</i>	Black spruce	5
<i>Betula glandulosa</i>	Bog birch	1
<i>Potentilla fruticosa</i>	Shrubby cinquefoil	1
<i>Vaccinium uliginosum</i>	Bog blueberry	1
Ground shrub		
<i>Vaccinium-vitis idaea</i>	Bog cranberry	10
<i>Arctostaphylos rubra</i>	Red bearberry	5
<i>Empetrum nigrum</i>	Crowberry	1
<i>Oxycoccus microcarpus</i>	Small bog cranberry	1
Herb		
<i>Equisetum scirpoides</i>	Dwarf scouring rush	5
<i>Rubus chamaemorus</i>	Cloudberry	1
<i>Pyrola asarifolia</i>	Pink wintergreen	p
<i>Habenaria dilatata</i>	Tall-white bog orchid	p
<i>Equisetum arvense</i>	Common horsetail	p
Moss		
<i>Hylocomium splendens</i>		50
<i>Sphagnum</i> spp.		15
<i>Tomenthypnum nitens</i>		10
Lichens		
<i>Cladina stellaris</i>		25
<i>Cladina rangiferina</i>		15
<i>Cetraria cucullata</i>		5
<i>Cladina mitis</i>		5
<i>Peltigera aphthosa</i>		1
<i>Cetraria islandica</i>		1

p indicates present but with less than 1% plant cover

Plant species verified with Cody (1996).

TABLE 4.2: Vegetation inventory and cover estimation at Site 2.

Cover type	Common plant name	Percentage cover
Tall tree canopy (>5 m)		
<i>Picea mariana</i>	Black spruce	1
Low tree canopy (<5 m)		
<i>Picea mariana</i>	Black spruce	5
Tall shrub (>1.5 m)		
<i>Picea mariana</i>	Black spruce	10
<i>Salix glauca</i>	Grey-leaved willow	1
Medium shrub (1.5 – 0.5 m)		
<i>Picea mariana</i>	Black spruce	10
<i>Salix glauca</i>	Grey-leaved willow	5
<i>Salix arbusculoides</i>	Little-tree willow	1
<i>Potentilla fruticosa</i>	Shrubby cinquefoil	p
Low shrub (<0.5 m)		
<i>Ledum groenlandicum</i>	Labrador tea	25
<i>Vaccinium uliginosum</i>	Bog blueberry	10
<i>Picea mariana</i>	Black spruce	5
<i>Salix glauca</i>	Grey-leaved willow	1
<i>Potentilla fruticosa</i>	Shrubby cinquefoil	1
Ground shrub		
<i>Vaccinium-vitis idaea</i>	Bog cranberry	15
<i>Arctostaphylos rubra</i>	Red bearberry	10
<i>Empetrum nigrum</i>	Crowberry	10
Herb		
<i>Equisetum scirpoides</i>	Dwarf scouring rush	5
<i>Rubus chamaemorus</i>	Cloudberry	1
Moss		
<i>Hylocomium splendens</i>		65
<i>Tomenthypnum nitens</i>		15
Lichens		
<i>Cladina stellaris</i>		25
<i>Cladina rangiferina</i>		25
<i>Cladina mitis</i>		15

p indicates present but with less than 1% plant cover

Plant species verified with Cody (1996).

Site 2. A greater number of lichen species was also present at Site 1; however, the percent cover of lichen was greater at Site 2.

4.1.2 Soil Properties

Organic-Layer Thickness

The total organic layer was measured from the top of the Of horizon at the ground surface to the base of the Oh horizon. At Site 1, the thickness of this layer ranged from 20 to 30 cm on the top of hummocks. The total organic layer was thickest in trough areas, ranging from 25 to 50 cm. In raised areas at Site 2, the total organic layer was 20 cm thick, while in low-lying depressed areas it was 35 cm thick.

Active-Layer Thickness

In late August, the frost table was within one metre of the ground surface (measured from the top of the living moss layer) at both sites. A 25 metre long transect was established at both study sites, and the active layer was probed at one metre intervals. The variability in active-layer thickness was greater at Site 1. In hummock-top areas at Site 1, the depth to frost ranged from 42 to 86 cm, while in trough areas, it ranged from 35 to 56 cm. In raised areas at Site 2, the depth to frost ranged from 30 to 55 cm; in lower-lying areas, it ranged from 25 to 45 cm.

Soil Texture

Particle-size analyses revealed that soils collected from both study sites exhibited the same textural characteristics, being classified as silt (Table 4.3). Soil from Site 1 showed a slightly higher silt content with 91%, compared to 87% at Site 2 soil. The percentages of sand and gravel particles in both soils were similar, while the percentage of clay particles was higher for Site 2 with 4% compared to 1% at Site 1. Based on the high silt contents, Site 1 and Site 2 soils are highly frost-susceptible (Williams and Smith 1989).

Table 4.3: Soil particle-size analyses for Site 1 and Site 2 (B-horizon).

	Percentage of Analysed Soil		
	Sand (>0.05 mm)	Silt (0.05 mm – 0.005 mm)	Clay (<0.005 mm)
Site 1	8%	91%	1%
Site 2	9%	87%	4%

Consequently, moderate amounts of soil water may migrate towards a freezing front resulting in the growth of ice lenses, frost heave and ground surface displacement (Burt and Williams 1976).

While the soil texture analyses revealed that both study sites exhibit similar soil texture characteristics, the origin of these soils are different. Surficial material at Site 1 is classified as a glaciolacustrine and colluvial complex deposit (Hughes 1983). However, Site 2 surficial material is classified as alluvial in origin, and the dominance of silt implies the near surface material is an overbank flood deposit (Hughes 1983). Thus, the soil characteristics of Site 2 remain largely influenced by the hydrological regime of Stewart River.

Soil Classification

The soils at both study sites were classified as Histic Eutric Turbic Cryosol by Scott Smith (Agriculture and Agri-food Canada). This soil is characterised by a relatively high degree of base saturation, and thick (>15 cm) organic horizon in the upper one metre (Agriculture Canada 1998). Hummock excavations in late-August at Site 1 showed mineral horizons that were strongly distorted by cryoturbation. Within the mineral horizon, small lobes of intruding mineral and organic materials were present. A gleyed horizon was also present immediately above the permafrost table. Some hummocks located in wetter parts of Site 1 were found ruptured at the apex, indicating internal pressure development (Crampton 1977; Tarnocai and Zoltai 1978). The organic mat was found split at the base and apex of some hummock features as well (Figure 4.1).

Soil pits dug in late-August at Site 2 revealed similar soil characteristics as at Site 1. The mineral horizons were distorted by cryoturbation, as lobes of mineral and organic materials were found mottled throughout the mineral horizon. A gleyed horizon above the permafrost table was also found.

Figure 4.1: Photo of 25 cm cracking at base of hummock at Site 1.

Soil Moisture Content

Gravimetric soil moisture content at Site 1 varied from 30% to 50% in mineral soil horizons. Soils at Site 2 exhibited lower soil moisture content than those found at Site 1. The soil moisture content was approximately 30% in mineral soil horizons on level ground near Stewart River.

4.1.3 Sampled Trees

Sample discs from 51 tilted trees were used to construct the compression-wood chronology for Site 1. Ages of the sampled trees ranged from 101 to 184 years, while the median age was 151 years. The trees exhibited a mean diameter of 7.7 cm. The heights of sampled trees varied, but in general, mature trees were approximately 10 m tall. Nearly all trees from which sample discs were extracted were tilted.

It was also noted where sampled trees were growing, with respect to hummock features. Trees were predominantly growing in hummock trough areas and on the sides of hummocks. A total of 49% of the sampled trees were found growing on the sides of hummocks, while 41% were found growing in inter-hummock troughs. Only 10% of the sampled trees were growing on the tops of hummocks. The median ages of trees did not vary significantly with location. The median age of trees growing on the sides of hummocks was 154 years. Similarly, in trough areas the median age was 149 years, while the median age of trees growing on hummock top areas was 163 years.

Sample discs from 41 tilted trees were used to construct the compression wood chronology for Site 2. Ages of the sampled trees ranged from 107 to 248 years, with median age 156 years. The trees exhibited a mean diameter of 9.0 cm. Trees at Site 2 were slightly taller than the trees found at Site 1, as mature trees were approximately 12 to 15 m tall.

4.2 ANNUAL COMPRESSION WOOD CHRONOLOGIES

4.2.1. Summary Statistics of Compression Wood Chronologies

Annual compression-wood chronologies were constructed from trees sampled at Site 1 and Site 2 for the period 1900 to 2000. The compression-wood chronology for each site was constructed by determining the annual number of trees showing compression wood as a percentage of the total population (Figure 4.2). All tree samples at Site 1 exhibited at least one compression-wood sequence, and the mean number of distinct compression-wood sequences for Site 1 tree samples was 6. The average duration of each compression-wood sequence was 13 years. Over the record (1900-2000), the percentage of annual compression wood exhibited by Site 1 trees ranged from a maximum of 71%, in 1970, to a minimum of 29%, in 1996. The median percentage of annual compression wood exhibited by the sampled trees was 43%.

The mean number of distinct compression-wood sequences for Site 2 samples was 5, and the average duration of each compression-wood sequence was 9 years. The percentage of annual compression wood exhibited by Site 2 trees ranged from a maximum of 49%, in 1969, to a minimum of 10%, in 1924. The median percentage of annual compression wood exhibited by the sampled trees was 27%.

The Site 1 chronology shows the highest percentage of trees showing compression wood in the late 1960s and early 1970s. Following the 1970s, the percentage of compression wood decreases. The lowest percentage of trees showing compression wood at Site 1 occurs in the 1990s. In contrast, the Site 2 chronology shows the highest percentage of compression wood in the late 1920s and early 1930s. The lowest percentage of trees showing compression wood at Site 2 occurs in the early 1920s. While Site 1 trees exhibit a progressive reduction in the percentage of annual compression wood during the 1980s and

Figure 4.2: Percentage of trees showing annual compression wood at Site 1 and Site 2, 1900-2000.

1990s, Site 2 trees show an increase in the 1980s and 1990s following a progressive decline during the 1970s.

The frequency distributions of annual percentage of trees showing compression wood at Site 1 and Site for the period 1900 to 2000 are presented in Figure 4.3. Both chronologies show relatively symmetrical frequency distributions, as skewness measured for the Site 1 distribution was 0.9, while for Site 2 it was 0.3. The Site 1 frequency distribution exhibited a kurtosis value of 1.1, while the Site 2 frequency distribution had a value of 0.3. Consequently, the frequency distributions for the percent annual compression wood at Sites 1 and 2 both approximate Normal distributions.

4.2.2 Initiation Periods

The compression-wood chronologies at the two sites produce a correlation coefficient of 0.35, significant at the 95% confidence interval. However, there are periods within each chronology when the percentage of compression wood is significantly higher and lower than the median percentage of annual compression wood over the entire record. To define these periods within the chronologies, the percentages of trees showing annual compression wood during the period of record were standardised as z-scores. In both compression-wood chronologies there are several years in which the percentage of annual compression wood has z-scores greater than +1.0.

An initiation period was defined as a sequence of years showing progressively higher percentages of annual compression wood, and thus higher z-scores, leading up to a maximum z-score greater than +1.0. During initiation periods, a large proportion of trees initiate compression-wood sequences. Thus, the percentage of trees showing annual compression wood rises during an initiating period. The compression-wood chronologies constructed from trees sampled at Site 1 and Site 2 both show more than one initiation period. The Site 1 chronology exhibits two such periods. The first occurred from 1908 to

Figure 4.3: Frequency distribution of percent annual compression wood observations for Site 1 and Site 2 for 1900-2000.

1911, and the second occurred from 1964 to 1970 (Figure 4.4). In comparison, the Site 2 chronology exhibits three initiation periods. The first occurred from 1924 to 1931, the second from 1936 to 1946, and the third from 1956 to 1963 (Figure 4.5).

Initiation compression-wood chronologies were constructed from the trees sampled at Site 1 and Site 2. The percentage of trees initiating a compression wood sequence in ratio to the total number of trees sampled in a given year was calculated for the period of record (1900-2000). The frequency distributions of the percentage of sampled trees initiating compression wood sequences in each year of the record are presented in Figure 4.6. At Site 1, the percentage of trees initiating compression wood sequences in a given year ranged from a low of 0% to a maximum of 14%, with a median of 2%. At Site 2, the percentage of trees initiating compression wood sequences in a given year ranged from a low of 0% to a maximum of 12%, also with a median of 2%.

4.2.3 Stabilisation Periods

In both compression-wood chronologies there are several years in which the percentage of annual compression wood corresponds with z-scores below -1.0 (Figure 4.4 and Figure 4.5). A stabilisation period was defined as a sequence of years following an initiation period with progressively lower percentages of annual compression wood, and thus lower z-scores. During stabilisation periods, a large proportion of the trees do not initiate compression wood growth. Thus, the percentage of annual compression wood decreases during a stabilisation period until environmental conditions initiate a new sequence of compression wood growth.

The compression wood chronologies constructed for Site 1 and Site 2 both show more than one stabilisation period. The Site 1 chronology exhibits two such periods. The first period occurred from 1921 to 1926, and the second from 1971 to 1996 (Figure 4.4). In comparison, the Site 2 chronology exhibits three stabilisation periods. The first occurred

Figure 4.4: Percentage of trees showing annual compression wood at Site 1 standardised as z-scores. Initiation (I) and stabilisation (S) periods are noted on the graph, where $I_1 = 1908-11$, $I_2 = 1964-70$, $S_1 = 1921-26$, and $S_2 = 1971-96$.

Figure 4.5: Percentage of trees showing annual compression wood at Site 2 standardised as z-scores. Initiation (I) and stabilisation (S) periods are noted on the graph, where $I_1 = 1924-31$, $I_2 = 1936-46$, $I_3 = 1956-63$, $S_1 = 1932-1935$, $S_2 = 1947-55$, and $S_3 = 1970-80$.

Figure 4.6: Frequency distribution of the percentage of trees initiating compression wood sequences in each year of record at Site 1 and Site 2.

from 1932 to 1935, the second from 1947 to 1955, and the third from 1970 to 1980 (Figure 4.5). The only overlap in stabilisation periods between both study sites occurred from 1970 to 1980.

4.3 FROST ACTION AND CLIMATE

Frost action is the result of two processes: frost heave, which occurs during fall freeze-back when water in the active layer freezes, resulting in the formation of ice lenses, and thaw settlement, which occurs during the thaw season when ice lenses in the active layer progressively thaw leading to a reduction in soil volume (French 1996). As a result of repeated frost heave and thaw settlement, soil churning, or cryoturbation, may occur in the active layer. In years when frost heave or differential thaw settlement is enhanced, cryoturbation of saturated sediments in the active layer may increase, leading to a reduction in ground stability. Zoltai (1975a) attributed the initiation of compression wood within tilted trees growing on hummocky permafrost terrain to episodes of increased frost action and hummock cryoturbation. An increase in frost action is largely the result of increased soil moisture within the active layer. Three factors which may lead to greater soil moisture within the active layer are increased effective precipitation, a deepening of the active layer leading to the melt of ice-rich sediments at the top of permafrost, and flooding in areas adjacent to water bodies.

Frost heave is broadly controlled by the amount and availability of soil moisture, the rate of freezing, and the frost-susceptibility of a soil (Williams and Smith 1989). Thus, during fall freeze-back, greater amounts of soil moisture present in a frost-susceptible soil should result in an increase in the formation of ice lenses. In years when the rate of freezing is slow, unfrozen soil water can migrate towards the freezing fronts over a longer period of time, resulting in greater amounts of ice lens formation at the top and bottom of the active

layer (Williams and Smith 1989). In years when freeze-back progresses rapidly, the ground temperature gradient is steep and heat loss from the ground is enhanced. Thus, moisture migration towards rapidly descending and ascending freezing fronts is decreased and ice lens formation in the active layer is restricted, resulting in less frost heave and ground surface displacement. Fall and winter air temperatures, as well as the timing and depth of snow accumulation can influence the rate of ground cooling during freeze-back (Williams and Smith 1989).

During fall freeze-back, ice lenses form at the top of the active layer, and at the base of the active layer, producing an ice-rich zone at both levels. Mackay (1983) found that in summer, water migrates downwards through frozen ground in response to both thermodynamic and gravitational potentials. In summer, soil water is replenished by summer rainfall, snowmelt runoff, and groundwater flow. With an abundance of moisture available near the base of the active layer at the start of freeze-back, some ice lenses form subparallel to the ground surface by downward freezing, and also subparallel to the frost table by upward freezing.

Whereas near-surface ice lenses thaw seasonally, ice lenses formed in the ice-rich zone at the top of permafrost may not thaw annually. If a summer thaw season is warmer than average, thawing of the active layer and top of permafrost may be enhanced. These conditions can lead to the melt of the ice-rich zone at the top of permafrost, increasing soil moisture and leading to greater cryoturbation within the active layer. With an increase in cryoturbation, ground stability may be reduced causing a larger percentage of tilted trees to initiate compression wood growth.

The “cyclical” nature of the annual percentage of compression wood exhibited by the trees at both sites may be attributed to the nature of compression-wood formation in tilted trees. Initiation of compression wood in drunken forest terrain underlain by

permafrost may be the result of seasonal climate conditions interacting to produce increased frost action (Zoltai 1975b). Once a tree is tilted as a result of a ground-displacing event and compression wood is initiated, the tree exhibits compression wood growth until it has stabilised (Scurfield 1973). Following stabilisation, the tree exhibits normal annual growth rings devoid of compression wood. Thus, the variation exhibited by a collection of trees showing compression wood over a long-term record is not continuous, but episodic as a result of external factors which trigger compression-wood formation (Scurfield 1973).

Although the compression-wood chronologies constructed from trees at Site 1 and Site 2 are significantly correlated at the 95% confidence interval, the distinct periods of increased compression-wood formation do not overlap, in general. Both study sites are situated in the same climatic region, in highly frost-susceptible soils and beneath similar vegetation covers. Increases in cryoturbation leading to tree tilting and compression-wood formation may therefore be attributed to increases in soil moisture.

4.3.1. The Mayo Climate Record, 1900-2000

The annual mean air temperature record at Mayo reveals that the 1990s, 1980s, and 1940s were the warmest decades on record (Figure 4.7). The lowest annual mean air temperatures occurred in the 1930s, 1960s, and 1970s. Over the entire record, from 1900 to 2000, there is a gradual rise in the annual mean air temperature, of approximately 1.5°C (McCoy and Burn 2001). The total annual precipitation record (1927-2000) shows a different pattern than the annual mean air temperature record (Figure 4.8). The highest annual precipitation totals on record occurred in the 1960s and 1970s, while the lowest totals on record occurred in the 1930s, 1940s, and 1950s.

Effective precipitation was calculated over the summer (June to August) for the period that corresponds with the Mayo precipitation record (Figure 4.9). The average summer effective precipitation for the period of record was determined to be -105 mm. The

Figure 4.7: Annual mean air temperature at Mayo, YT (data from Meteorological Service of Canada 2002).

Figure 4.8: Total annual precipitation at Mayo, YT (data from Meteorological Service of Canada 2002).

Figure 4.9: Total effective precipitation in summer season at Mayo, YT.

highest values of summer effective precipitation occurred in the mid-1960s and 1970s, while the lowest values occurred in the late-1950s and 1990s.

The mean annual air temperature at Mayo for 1900 to 2000 is -3.4°C , while the mean total annual precipitation at Mayo for 1927 to 2000 is 344 mm. For the period 1980 to 2000, the mean annual air temperature was higher than the overall mean, as it was -2.8°C during the 1980s, and -2.1°C during the 1990s. Higher air temperatures may have contributed to higher potential evapotranspiration during this period, as summer effective precipitation values were lower during the 1990s than the overall average effective precipitation. The 1940s and 1950s also experienced warm and dry climate conditions, with lower precipitation totals and warmer annual mean air temperatures compared to the entire record. Warmer air temperatures and low precipitation totals during this period contributed to the lowest summer effective precipitation on record. In contrast, the 1960s and 1970s were decades associated with cool and wet climate conditions. Soil moisture conditions at the onset of freeze-back may have been increased during the 1960s and 1970s, leading to a possible increase in the magnitude of frost heave in the Mayo area. During this period the annual mean air temperature was lower than the mean for the entire record, while total precipitation, snowfall, and rainfall were the highest on record. As a result of lower mean air temperature and high precipitation, this period was associated with the highest summer effective precipitation.

4.3.2. Water Level Record of Stewart River at Mayo, 1949-1999

For the period 1949 to 1999, the annual maximum water level of Stewart River at Mayo varied from 5.5 to 9.7 m above the Mayo datum of 473 m a.s.l. (Figure 4.10). The median annual maximum water level was 7.5 m. The highest annual maximum water level occurred in 1992, with 9.7 m. This water level has a return period of 50 years, and a probability of 0.02. The second highest annual maximum water levels on record occurred

Figure 4.10: Maximum annual water level of Stewart River at Mayo (1949-1999). Highest five maximum water levels on record denoted by (*). (Water Survey of Canada 1992, Environment Canada unpublished data).

in 1964 and 1983, with 9.4 m. This water level has a return period of 25 years, and a probability of 0.04. The third highest annual maximum water levels on record occurred in 1957 and 1961, with 9.2 m. This water level has a return period of 14 years, and a probability of 0.07.

4.4 INITIATION AND STABILISATION PERIODS

4.4.1 Initiation Periods and Climate

To investigate the association between initiation periods identified within the compression-wood chronologies and the Mayo climate record, the climate characteristics associated with the two initiation periods (1908-1911, 1964-1970) in the Site 1 chronology were compared with the corresponding values for the climate record, as were the three initiation periods (1924-1931, 1936-1946, 1956-1963) in the Site 2 chronology. In calculating the difference between mean annual and seasonal climate conditions for the entire record and for initiation periods, it was determined whether the annual and seasonal climate characteristics of years coinciding with initiation periods differed from, or were similar to, the climate conditions for the entire record (Table 4.4).

In addition, seasonal and annual air temperature averages and precipitation totals for the first three years of an initiation period, and one year prior to an initiation period were converted to z-scores. At the onset of an initiation period, climate conditions may have led to an increase in the amount of frost action within the active layer, resulting in a larger number of sampled trees initiating and exhibiting compression-wood growth. By referring to the cumulative probability scale for the standard Normal curve, climate conditions for each year were described as a percentile, based on the value's position on the Normal curve (Table 4.5). Very high and low percentiles, 90% and 10% respectively, indicate that climate conditions lie at the tails of a Normal distribution, and may be described as

TABLE 4.4: Difference in annual and seasonal mean air temperature during initiation periods from corresponding data for the entire record, 1900-2000.

Temperature	Mean Air Temperature (°C) Record (1900 – 2000)	Site 1 Initiation Periods			Site 2 Initiation Periods		
		1908 – 1911 ^a (Δ)	1964 – 1970 (Δ)	1924 – 1931 (Δ)	1936 – 1946 (Δ)	1956 – 1963 (Δ)	
Annual (Jan – Dec)	-3.6	-0.8	-0.8	-0.1	-0.7	-0.4	
Summer (Jun – Aug)	14.3	+1.0	-0.8	+0.2	-0.7	-0.7	
Thaw (Apr – May)	4.2	+1.6	-1.6	-1.3	+0.2	-0.5	
Active (May – Sept)	11.6	+1.5	-0.9	0.0	-0.4	-0.4	
Fall (Sept – Nov)	-3.9	-0.9	-0.5	+0.5	+1.0	+0.3	
Winter (prev. Dec – Mar)	-20.7	-3.5	-0.9	-0.1	+1.5	+0.1	

^aNote: Air temperature values for 1908 to 1911 initiation period estimated from Dawson City air temperature record.

TABLE 4.5: Seasonal and annual air temperature values converted to z-scores for the years 1907 to 1910 in the first Site 1 initiation period.

Temperature	1907	1908	1909	1910
Annual (Jan – Dec)	0.73	-0.40	-2.00	-0.93
Thaw (Apr – May)	1.49	0.72	-0.79	-0.29
Summer (Jun – Aug)	1.16	1.19	1.19	0.86
Active (May – Sept)	1.81	1.01	0.94	1.15
Fall (Sept – Nov)	-0.13	-1.26	-1.38	0.07
Winter (prev. Dec – Mar)	-0.10	-1.50	-1.03	-1.11

Note. Red z-scores lie beyond the 90th percentile, while Blue z-scores lie below the 10th percentile, on the cumulative probability scale for the standard normal curve.

‘extreme’ values within the data set (Ebdon 1985). The total annual precipitation, rainfall, and snowfall records for Mayo only exist from 1927 to present. Thus, initiation periods observed in both chronologies prior to 1927 were not compared with precipitation factors.

Site 1

The Site 1 initiation periods (1908-1911, 1964-1970) were both associated with lower than average annual and fall mean air temperature when compared with the entire record (Table 4.4). However, summer, thaw, and active seasons were warmer during the 1908 to 1911 initiation period compared with the entire record. Warmer summer, thaw, and active seasons during this period may have led to a deepening of the active layer resulting in melting of ice-rich sediments at the top of the permafrost. Increased soil moisture conditions could have resulted in greater cryoturbation and ground surface displacement during this period, leading to an increase in tree tilting and compression-wood initiation in affected trees.

Prior to the 1908 to 1911 initiation period, the climate conditions associated with the year 1907, indicate that thaw and active air temperature values were higher than average, as both values lay beyond the 90th percentile on the standard normal curve (Table 4.5). Preceding thaw conditions may have led to increased soil moisture and greater cryoturbation within the active layer, leading to the initiation of compression-wood growth in the tilted trees. Summer air temperatures in 1907, 1908, and 1909 were also above one unit of standard deviation (82nd percentile). With higher air temperatures during the summer season, the ice-rich zone at the top of permafrost may have melted, thereby increasing the amount of soil moisture within the active layer. Increased soil moisture over a sequence of years may have resulted in enhanced cryoturbation and thaw settlement leading to greater instability within the active layer, and the incidence of this initiation period.

In contrast, the 1964 to 1970 initiation period was associated with colder annual and seasonal air temperatures when compared to the entire record (Table 4.4). In addition, this period also exhibited higher total precipitation, rainfall, and snowfall (Table 4.6). However, the average summer effective precipitation during this period was -103.8 mm, which is comparable to the average summer effective precipitation over the entire record. Increased snowfall over the fall and winter season during this period may have insulated the ground, thus slowing the rate of freezing. As a result of a prolonged fall freeze-back period, unfrozen soil water could migrate towards the downward and upward freezing fronts, thereby increasing the likelihood of appreciable ice lens formation at the top and bottom of the active layer, causing significant ground surface displacement and tree tilting.

The climate conditions recorded for the year prior to the start of the 1964 to 1970 Site 1 initiation period, and the first three years of the period, all appear to contribute to the thinning of the active layer and thickening of the ice-rich zone at the top of permafrost, resulting in a greater magnitude of frost heave during the fall freeze-back (Table 4.6). In the 1963-64, the snowfall exhibits a z-score of 2.15, at the 98th percentile of the cumulative probability scale for the standard Normal curve (Table 4.7). Lower than average air temperature and higher than average annual and seasonal precipitation conditions throughout 1964, also resulted in a higher than average summer effective precipitation for this year. Coupled with a large snowfall in the previous winter, and a summer effective precipitation value higher than average, soil moisture conditions were greatly enhanced at the onset of fall freeze-back in 1964. The 1964 annual snowfall value was also higher than average, with a z-score of 1.80, which lies beyond the 90th percentile on the cumulative probability scale. With increased snow accumulation in 1964, the rate of heat loss during fall freeze-back would be reduced, resulting in a slow rate of freeze-back and increased formation of ice lenses in the active layer. Increased ice lens formation at the base of the

TABLE 4.6: Difference in annual and seasonal total precipitation, snowfall, and rainfall during initiation periods from the corresponding values for the entire climate record (1927-2000).

Precipitation (mm)	Mean Total for Record (1927 - 2000)	Site 1 Initiation Period		Site 2 Initiation Periods	
		1964 - 1970 (Δ)	1936 - 1946 (Δ)	1956 - 1963 (Δ)	
Annual (Jan - Dec)	345.6	+33.5	-32.5	-44.4	
Summer (Jun - Aug)	140.1	+12.0	+2.9	-17.3	
Thaw (Apr - May)	34.7	+2.8	+2.4	-3.8	
Active (May - Sept)	200.1	+8.4	+8.0	-28.4	
Fall (Sept - Nov)	66.3	-1.4	-1.2	-12.4	
Winter (prev. Dec - Mar)	104.3	+22.4	-36.4	-8.9	
Summer Effective Precipitation (Jun - Aug)	-105.1	+1.3	+2.4	-9.9	
Rainfall (mm)					
Annual (Jan - Dec)	210.8	+5.3	+10.8	-30.2	
Summer (Jun - Aug)	139.9	+12.2	+3.1	-17.1	
Snowfall					
(snow water equiv. in mm)					
Annual (Jan - Dec)	134.9	+28.1	-43.4	-14.3	
Fall (Sept - Nov)	26.1	+5.6	-6.0	-7.3	
Winter (prev. Dec - Mar)	134.1	+30.2	-42.3	-15.8	

TABLE 4.7: Seasonal and annual air temperature averages and precipitation totals converted to z-scores for the years 1963 to 1966 in the second Site 1 initiation period.

Temperature	1963	1964	1965	1966
Annual (Jan – Dec)	0.33	-1.27	-1.20	-1.93
Thaw (Apr – May)	-0.47	-2.47	-0.78	-1.17
Summer (Jun – Aug)	-0.92	-0.69	-1.17	-0.81
Active (May – Sept)	-0.33	-1.51	-1.13	-0.85
Fall (Sept – Nov)	-0.42	0.45	-0.94	-1.46
Winter (prev. Dec – Mar)	0.56	-1.15	-0.83	-0.64
Precipitation				
Annual (Jan – Dec)	0.95	1.50	1.14	-0.50
Thaw (Apr – May)	-0.30	3.26	-0.97	-0.01
Summer (Jun – Aug)	0.12	1.38	1.12	-1.06
Active (May – Sept)	0.04	1.09	0.64	-1.37
Fall (Sept – Nov)	0.81	-0.61	0.92	0.23
Winter (prev. Dec to Mar)	0.95	0.53	0.69	0.71
Summer Effective Precipitation (Jun – Aug)	0.31	1.25	1.24	-0.93
Rainfall				
Annual (Jan – Dec)	0.19	0.54	0.66	-1.17
Summer (Jun – Aug)	0.14	1.39	1.13	-1.04
Snowfall				
Annual (Jan – Dec)	1.29	1.80	1.12	0.37
Fall (Sept – Nov)	0.80	0.21	0.85	0.77
Winter (prev. Dec – Mar)	0.11	2.15	0.63	0.91

Note. Red z-scores lie beyond the 90th percentile, while Blue z-scores lie below the 10th percentile, on the cumulative probability scale for the standard normal curve.

active layer, would thicken the ice-rich zone, leading to increased frost heave and ground instability. This ground instability may have sufficiently tilted a number of the trees at Site 1, causing a large proportion of them to initiate compression wood. Clearly, the interacting climate conditions associated with this particular year may have resulted in greater frost heave, causing tree tilting and compression-wood formation in subsequent years.

Site 2

Even though Site 1 and Site 2 are located in the same climatic region of central Yukon, there was not a consistent association between climate conditions and initiation periods in the Site 2 chronology. In contrast, initiation periods in the Site 1 chronology were associated with climate conditions which may lead to increased soil moisture within the active layer, resulting in greater cryoturbation and frost heave.

The 1924 to 1931 initiation period in the Site 2 chronology was associated with lower mean air temperatures during the thaw season compared with the corresponding value for the entire record (Table 4.4). This period was also associated with a higher fall air temperature compared to the entire record. A higher fall air temperature over this period may have prolonged freeze-back allowing for greater ice lens formation to occur in the active layer, and greater instability leading to tree tilting. For all other seasons, this period exhibited air temperature characteristics that did not differ from corresponding values for the entire record.

The climate conditions associated with 1923, may also account for the incidence of the 1924 to 1931 initiation period. The average air temperature during thaw, summer, and active seasons in 1923 were all associated with z-scores greater than 1.63, which lie beyond the 94th percentile on the cumulative probability scale (Table 4.8). With higher air temperatures throughout the 1923 thaw season, melting of the ice-rich zone at the top of permafrost may have occurred, increasing the amount of soil moisture within the active

TABLE 4.8: Seasonal and annual air temperature values converted to z-scores for the years 1923 to 1926 in the first Site 2 initiation period.

Temperature	1923	1924	1925	1926
Annual (Jan – Dec)	0.40	-0.53	-0.73	1.60
Thaw (Apr – May)	0.54	-1.32	-0.61	0.64
Summer (Jun – Aug)	2.79	0.48	-0.72	-0.67
Active (May – Sept)	2.45	0.67	-0.36	-0.45
Fall (Sept – Nov)	1.63	-0.45	1.13	0.43
Winter (prev. Dec – Mar)	0.12	-1.80	2.24	0.43

Note. Red z-scores lie beyond the 90th percentile, while Blue z-scores lie below the 10th percentile, on the cumulative probability scale for the standard normal curve.

layer. Increased soil moisture conditions may have resulted in greater cryoturbation and instability within the active layer, leading to the formation of compression wood in subsequent years.

The 1936 to 1946 initiation period was associated with lower mean annual, summer and active air temperatures than the entire record (Table 4.4). In contrast, this period was also associated with higher fall and winter air temperatures than the record. This period was also associated with higher total precipitation during the active season (Table 4.6).

However, lower fall and winter snowfall during this period would have increased the rate of heat loss during freeze-back, thereby reducing the duration of water migration towards the freezing fronts and frost heave.

Climate conditions associated with 1935, and the following three years do not reveal additional evidence for an increase in compression wood formation at the onset of the 1936 to 1946 initiation period (Table 4.9). While 1935 is associated with lower than average annual and seasonal air temperatures, precipitation totals and summer effective precipitation were also low, indicating that effective soil moisture may not have been significantly increased. However, 1937 and 1938 were both associated with higher than average fall air temperature, and thus fall freeze-back may have been prolonged during those years, leading to increased frost heave and ice lens formation.

The 1956 to 1963 initiation period was associated with lower mean annual, summer, thaw, and active air temperature compared with the corresponding mean air temperatures for the entire record (Table 4.4). This period was associated with lower thaw and fall total precipitation, and higher total annual snowfall, compared with corresponding values for the entire record (Table 4.6). This period was also associated with lower precipitation and rainfall totals, and average summer effective precipitation indicating that soil moisture may have been in limited supply at the onset of freeze-back.

TABLE 4.9: Seasonal and annual air temperature averages and precipitation totals converted to z-scores for the years 1935 to 1938 in the second Site 2 initiation period.

Temperature	1935	1936	1937	1938
Annual (Jan – Dec)	-1.13	-0.93	0.60	0.67
Thaw (Apr – May)	-1.11	-0.75	0.08	0.36
Summer (Jun – Aug)	-1.83	0.75	-1.17	-0.78
Active (May – Sept)	-1.85	0.20	-0.55	0.07
Fall (Sept – Nov)	-1.41	0.93	1.55	1.81
Winter (prev. Dec – Mar)	-0.83	0.13	0.02	-0.03
Precipitation				
Annual (Jan – Dec)	0.25	0.16	-0.56	-1.91
Thaw (Apr – May)	0.79	-0.47	-0.11	0.66
Summer (Jun – Aug)	-0.27	0.97	0.60	-1.42
Active (May – Sept)	-0.13	1.33	0.79	-1.56
Fall (Sept – Nov)	1.02	1.38	-0.52	-1.89
Winter (prev. Dec – Mar)	-0.99	-1.40	-1.86	0.41
Summer Effective Precipitation (Jun – Aug)	0.05	0.56	0.83	-1.15
Rainfall				
Annual (Jan – Dec)	-0.30	1.48	1.21	-1.56
Summer (Jun – Aug)	-0.25	0.98	0.62	-1.40
Snowfall				
Annual (Jan – Dec)	0.68	-1.25	-2.09	-1.45
Fall (Sept – Nov)	1.76	0.28	-1.72	-1.00
Winter (prev. Dec – Mar)	0.09	-1.03	-2.32	-0.43

Note. Red z-scores that lie beyond the 90th percentile, while Blue z-scores lie below the 10th percentile, on the cumulative probability scale for the standard normal curve.

Climate conditions associated with the year prior to the start of the 1956 to 1963 initiation period, and the first years of the period were all associated with lower than average annual and seasonal air temperature, and lower than average precipitation totals (Table 4.10). These years were associated with cool and dry climate conditions, leading to reduced soil moisture conditions, and presumably less cryoturbation within the active layer, potentially leading to greater ground stability.

The Site 2 initiation periods (1924-1931, 1936-1946, 1956-1963) were each associated with different climatic conditions. Consequently there is no apparent consistent pattern or climate signal associated with the initiation periods. An alternate explanation for the periods of increased compression wood is the effect of Stewart River flooding. High water events could significantly increase the soil moisture content at Site 2 leading to increased cryoturbation and instability within the active layer, leading to increased tree tilting and compression wood growth. This association is investigated later in Section 4.5.

4.4.2 Stabilisation Periods and Climate

Climate conditions associated with stabilisation periods were compared with conditions in preceding initiation periods to determine differences between initiation and stabilisation periods. The percentage of trees showing compression wood progressively rises during initiation periods, while it progressively declines during stabilisation periods. Thus, climate conditions associated with initiation periods may increase frost action and cryoturbation leading to increased tilting and compression wood formation, but not in stabilisation periods. The climates of two stabilisation periods (1921-1926, 1971-1996) in the Site 1 chronology were compared with the climates of the two prior initiation periods (1908-1911, 1964-1970). The climates of three stabilisation periods (1932-1935, 1947-1955, 1970-1980) in the Site 2 chronology were compared with the climates of the three prior initiation periods (1924-1931, 1936-1947, 1956-1963). Stabilisation periods in both

TABLE 4.10: Seasonal and annual air temperature averages and precipitation totals converted to z-scores for the years 1955 to 1958 in the third Site 2 initiation period.

Temperature	1955	1956	1957	1958
Annual (Jan – Dec)	-0.87	-1.13	0.27	0.47
Thaw (Apr – May)	-0.75	-0.42	-0.50	0.69
Summer (Jun – Aug)	-0.72	-0.42	0.31	-0.06
Active (May – Sept)	-0.98	-0.49	0.31	-0.36
Fall (Sept – Nov)	-1.29	-0.03	0.91	-0.46
Winter (prev. Dec – Mar)	-0.82	-0.37	0.54	-0.62
Precipitation				
Annual (Jan – Dec)	-1.53	-0.28	-1.40	-0.42
Thaw (Apr – May)	-1.47	-1.07	-0.01	-0.78
Summer (Jun – Aug)	-1.41	0.58	-1.73	-0.35
Active (May – Sept)	-1.76	-0.17	-1.47	-1.12
Fall (Sept – Nov)	-1.57	0.22	-0.44	-0.01
Winter (prev. Dec to Mar)	-1.21	-0.69	-0.53	0.13
Summer Effective Precipitation (Jun – Aug)	-1.30	0.53	-1.84	-0.46
Rainfall				
Annual (Jan – Dec)	-1.99	-0.05	-1.60	-1.06
Summer (Jun – Aug)	-1.39	0.59	-1.71	-0.33
Snowfall				
Annual (Jan – Dec)	-0.42	-0.40	-0.60	0.39
Fall (Sept – Nov)	-1.16	0.89	-0.21	1.35
Winter (prev. Dec – Mar)	-1.54	-0.11	-0.64	0.79

Note. Red z-scores lie beyond the 90th percentile, while Blue z-scores lie below the 10th percentile, on the cumulative probability scale for the standard normal curve.

chronologies before 1927 were not tested with precipitation factors due to the absence of precipitation data for this period (Table 4.11 and Table 4.12).

Site 1

There are few similarities between the annual and seasonal air temperature conditions associated with both stabilisation periods in comparison with the preceding initiation periods in the Site 1 chronology. The 1921 to 1926 stabilisation period was associated with lower thaw, summer and active mean air temperatures than corresponding values for the preceding initiation period, 1908-1911. With lower thaw, summer, and active air temperature during this period, thawing of the active layer may not have led to melting of the ice-rich zone at the top of permafrost, reducing the amount of soil moisture within the active layer. A reduction in soil moisture during this period may have decreased the amount of thaw settlement or cryoturbation in the active layer, resulting in less tree tilting and stabilisation.

The 1971 to 1996 stabilisation period was associated with higher annual mean and seasonal air temperatures when compared with corresponding values for the preceding initiation period (1964-1970). Higher summer air temperature and reduced summer precipitation totals during this period resulted in a lower effective precipitation total compared to the preceding initiation period. With a reduced effective precipitation, soil moisture would be lower at the onset of freeze-back, leading to a decrease in the formation of ice lenses and frost heave. Fall and winter snowfall values were lower during this period compared to the preceding initiation period, indicating that heat loss during fall freeze-back may have been increased, leading to rapid freeze-back and reduced ice lens formation. The differences in climate during this stabilisation period in comparison with the preceding initiation period, may account for the reduction in the percentage of trees initiating and exhibiting compression-wood growth.

TABLE 4.1.1: Difference in annual and seasonal mean air temperature during stabilisation periods from the corresponding values of preceding initiation periods.

	Site 1 Stabilisation Periods			Site 2 Stabilisation Periods		
	1921 – 1926 (Δ)	1971 – 1996 (Δ)	1932 – 1935 (Δ)	1947 – 1955 (Δ)	1970 – 1980 (Δ)	
Temperature						
Annual (Jan – Dec)	+0.1	+0.8	-0.9	+0.7	0.0	
Summer (Jun – Aug)	-0.3	+0.7	-1.7	-3.0	+0.2	
Thaw (Apr – May)	-2.0	+2.1	+0.3	-0.9	+0.3	
Active (May – Sept)	-0.6	+1.0	-0.6	0.0	-0.1	
Fall (Sept – Nov)	+0.7	+0.4	-1.0	-0.2	-0.3	
Winter (prev. Dec – Mar)	+0.4	+2.2	-0.6	-1.2	-0.6	

TABLE 4.12: Difference in annual and seasonal total precipitation, snowfall, and rainfall during stabilisation periods from the corresponding values of preceding initiation periods.

Precipitation (mm)	Site 1 Stabilisation Period	Site 2 Stabilisation Periods		
	1971 – 1996 (Δ)	1947 – 1955 (Δ)	1970 – 1980 (Δ)	
Annual (Jan – Dec)	+0.8	-17.9	+32.2	
Summer (Jun – Aug)	-4.3	-21.5	+7.3	
Thaw (Apr – May)	+0.2	-7.9	+7.7	
Active (May – Sept)	+5.2	-33.5	+27.8	
Fall (Sept – Nov)	+11.9	-17.5	+19.3	
Winter (prev. Dec – Mar)	-9.0	+23.9	-7.1	
Summer Effective	-8.0	-22.7	+13.5	
Precipitation (Jun – Aug)				
Rainfall (mm)				
Annual (Jan – Dec)	+8.0	-32.5	+32.4	
Summer (Jun – Aug)	-4.9	-21.5	+19.4	
Snowfall				
(snow water equiv. in mm)				
Annual (Jan – Dec)	+2.8	+18.2	-0.2	
Fall (Sept – Nov)	-3.1	-0.2	-5.9	
Winter (prev. Dec – Mar)	-11.1	+18.5	-0.7	

Site 2

Initiation periods in the Site 2 chronology were not associated with a consistent climate signal that could account for the increase in frost heave or cryoturbation, leading to increased tilting and compression-wood formation. In addition, the stabilisation periods defined within the Site 2 chronology also differed from the climate conditions associated with preceding initiation periods (Table 4.11 and Table 4.12). These results indicate that climate conditions may not account for either the increase or decrease in compression-wood growth exhibited by the sampled trees at Site 2.

4.5 RIVER FLOODING AND TREE TILTING

With the proximity of Stewart River to Site 2, and contrasting climate conditions associated with initiation periods, the timing of peak water levels may account for the incidence of initiation periods in the Site 2 compression-wood chronology. With no historical data on Stewart River maximum water levels prior to 1936, the association of the first Site 2 initiation period of 1924 to 1931 with flooding is unknown.

Information gathered by the Mayo Historical Society (1990) describes an extreme flood event that occurred at Mayo in the summer of 1936. This flood corresponds with the onset of the second initiation period in the Site 2 chronology (Figure 4.11). In 1936, 20% of sampled trees exhibited compression-wood growth, which progressively increased to 42% by 1946, at the end of the initiation period. In the five years following 1936, approximately 27% of all trees sampled initiated compression-wood sequences. The total effective precipitation of the 1936 summer was -82.2 mm, which is higher than the average total effective precipitation (-105.1 mm) of the record. In relative terms, the soil moisture content at the end of the 1936 summer should have been high, due to both flooding and high effective precipitation. Increased soil moisture would increase cryoturbation within the

Figure 4.11: Percentage of trees showing annual compression wood at Site 2. Stewart River high water years denoted by (*).

active layer leading to reduced ground stability. These ground surface displacements may have caused trees to tilt following the flood, resulting in an increase in the initiation of compression-wood growth.

The third initiation period within the Site 2 chronology occurred from 1956 to 1963, which coincides with two years when Stewart River showed high peak water levels compared to the average annual maximum water level for 1949 to 1999. These peak water levels occurred in 1957 and 1961, when Stewart River rose 9.2 m above the Mayo datum, to reach its third highest level on record. Following the occurrence of these high water levels, flooding may have occurred in land areas adjacent to the river. The percentage of trees showing annual compression wood rose from 24.4% in 1956 to 39% in 1963. In 1964, the annual maximum water level of Stewart River at Mayo was 9.4 m, the second highest annual maximum water level on record with a 25-year return period. Although in 1964 40% of the trees already showed compression wood, as a result of flooding following the 1957 and 1961 high water events, the percentage continued to increase after 1964. By 1969, the percentage was 49%. The total summer effective precipitation corresponding with the 1957, 1961, and 1964 high water years were -179.6 mm, -81.0 mm, and -54.2 mm, respectively. Both 1961 and 1964 exhibited higher than average total effective precipitation, while 1957 exhibited a lower than average total effective precipitation. With increased soil moisture available as a result of possible flooding and reduced potential evapotranspiration, cryoturbation in the active layer may have been enhanced, leading to greater tree tilting and an increase in the percentage of trees showing annual compression wood.

While the percentage of trees exhibiting compression wood declined steadily at Site 1 since the last initiation period (1964-1970), at Site 2 the sampled trees exhibited two increases in the percentage of annual compression wood during the 1980s and 1990s. The

highest annual maximum water level on record occurred in 1992, when Stewart River rose to 9.7 m, which has a return period of 50 years. There was a 10% increase in the percentage of trees exhibiting compression wood in the years following 1992. In 1983, the annual maximum water level rose to 9.4 m, which is also the second highest annual maximum water level on record. Following 1983, there was a 10% increase in the percentage of trees exhibiting compression wood. While 1983 and 1992 are two of the highest water levels on record, the total summer effective precipitation for 1982 and 1993 were -121.1 mm and -127.5 mm, respectively. These values are lower than the average effective precipitation for the entire record (-105.1 mm). With an increase in potential evapotranspiration during these years, soil moisture derived from flooding may have been evaporated. Soil moisture conditions may not have enhanced cryoturbation within the active layer, resulting in less ground surface displacement and compression-wood formation at Site 2.

4.6 DISCUSSION OF RESULTS

In comparing the climate characteristics associated with initiation and stabilisation periods in the compression-wood chronologies to the climate of the entire record, a single climate signal associated with periods of increased and decreased compression-wood formation was not apparent. The initiation and stabilisation periods identified in each chronology were associated with different climate conditions. While the initiation periods of Site 1 showed some similarities between associated climate conditions, in particular significantly lower than average annual and fall mean air temperature, the initiation periods of Site 2 were associated with different climate conditions, which also did not resemble the climate of Site 1 initiation periods.

At Site 1, climate conditions leading to increased soil moisture at the end of summer and a prolonged fall freeze-back may account for increased frost heave and cryoturbation

within the active layer, leading to ground surface displacement and compression-wood formation. Due to the absence of precipitation data during the first Site 1 initiation period, soil moisture conditions are unknown. However, higher than average thaw, summer, and active air temperature during the 1908 to 1911 period, may have resulted in a deeper thaw of the active layer, resulting in the melt of ice-rich sediments at the top of permafrost. With an increase in soil moisture conditions, cryoturbation of saturated sediments may have reduced ground stability, causing tree tilting and the initiation of compression-wood growth. The 1964 to 1970 initiation period was associated with lower than average seasonal and annual air temperature, higher than average seasonal precipitation totals, and higher than average fall and winter snowfall. These climate conditions may have resulted in greater ice lens formation within the active layer, and a thickening of the ice-rich zone at the top of permafrost. With a shallowing of the active layer, and increased frost heave, a greater percentage of trees may have initiated compression-wood sequences during this period.

Analysis of the Site 2 initiation periods (1924-1931, 1936-1946, 1956-1963) did not reveal a consistent climate signal, nor did the climate conditions resemble the climate of Site 1 initiation periods. Upon examination of the water level record of Stewart River at Mayo from 1949 to 1999 and historical flood documentation (Mayo Historical Society 1990), high water levels causing possible flooding at Site 2 occurred prior to the 1936 to 1946 and 1956 to 1963 initiation periods. At the onset of these initiation periods, the percentage of trees initiating compression wood increased. The annual percentage of trees initiating compression wood also increased following high water levels in 1983 and 1992. In the years when Stewart River overflows its banks, the soil moisture of affected areas may increase. An increase in the soil moisture of an area underlain by permafrost, possessing frost-susceptible soils may result in greater frost action during the fall freeze-back (Zoltai 1975b). The Site 2 initiation periods were not associated with a consistent climate signal,

while the occurrence of high water levels did coincide with start of Site 2 initiation periods. Therefore, the flood behaviour of Stewart River may be associated with initiation periods in the Site 2 chronology.

The frequency distribution of the percentage of annual compression wood observations for both chronologies indicates that trees sampled at Site 1 exhibit a consistently higher percentage of compression-wood growth than trees sampled at Site 2. The maximum percentage of annual compression wood was 71% at Site 1, while at Site 2 it was 49%. Climate investigations during initiation periods for Site 1 and Site 2 indicated that trees at Site 1 did show a climate pattern associated with increased compression-wood initiation, while trees at Site 2 did not. The incidence of increased compression-wood initiation at Site 2 coincides with years in which Stewart River reaches higher than average annual maximum water levels. Thus, climate conditions associated with increased frost heave and cryoturbation at Site 1, which is located in hummocky permafrost terrain, may lead to greater tree tilting and compression-wood formation in comparison with the effects of increased soil moisture conditions and enhanced cryoturbation associated with possible Stewart River flooding at Site 2, which is located in non-hummocky permafrost terrain.

4.7 CHAPTER SUMMARY

Frost action resulting in ground displacements, indicated by periods of increased compression-wood formation in the Site 1 chronology, appears to be associated with higher than average air temperature leading to thaw of ice-rich sediments at the top of permafrost, and increased effective precipitation and a prolonged freeze-back leading to greater ice lens formation and frost heave. Site 1 and Site 2 initiation periods did not coincide, nor were they associated similar climate conditions. In contrast, initiation periods in the Site 2 chronology were not associated with climate conditions, which would result in increased

cryoturbation or frost heave. Periods of increased compression-wood formation may be associated with the flooding of Stewart River, as two of the three Site 2 initiation periods appear to follow high annual maximum water levels. Thus, Stewart River flooding, leading to increased soil moisture and frost heave, may account for the variations in compression-wood formation at Site 2, while climate conditions that increase the magnitude of cryoturbation and frost heave in the active layer may account for the variations in compression-wood formation at Site 1.

5.0 CONCLUSIONS

Several conclusions can be drawn from the compression-wood chronologies constructed from tilted trees sampled at Site 1 and Site 2. Periods of increased and decreased compression-wood formation occur in both chronologies, and were identified as initiation and stabilisation periods. In the Site 1 chronology, two initiation periods occurred from 1908 to 1911 and 1964 to 1970, and two stabilisation periods from 1921 to 1926 and 1970 to 1996. In the Site 2 chronology, three initiation periods occurred from 1924 to 1931, 1936 to 1946, and 1956 to 1963, and three stabilisation periods from 1932 to 1935, 1947 to 1955, and 1970 to 1980. Initiation periods in the Site 1 and Site 2 chronologies did not overlap, and the climate conditions associated with these periods did not reveal a consistent pattern between sites.

At Site 1, the first initiation period, 1908 to 1911, was associated with higher than average thaw, summer, and active air temperatures, which may have led to a deepening of the active layer and thaw of ice-rich sediments at the top of permafrost. With increased soil moisture, cryoturbation may have increased, leading to ground instability, tree tilting, and the initiation of compression-wood growth. The second initiation period, 1964 to 1970, was associated with lower than average annual and seasonal air temperature, and increased annual and seasonal precipitation totals. In the winter of 1963-64, snowfall was higher than average, resulting in increased soil moisture conditions at the onset of thawing in 1964. With cooler temperatures and increased soil moisture in the summer of 1964, the active layer may have thinned, leading to increased ice lens formation and a thickening of the ice-rich zone at the top of permafrost. Increased frost heave may have tilted the trees at Site 1, leading to increased compression-wood formation throughout this period. The climate conditions associated with both Site 1 initiation periods are linked to an increase in soil

moisture, as deeper thawing of the active layer can lead to increased cryoturbation, while cooler temperatures and increased precipitation and snowmelt runoff can lead to increased ice lens formation and frost heave. These conditions may have resulted in reduced ground stability and increase in compression wood formation in tilted trees.

The initiation periods in the Site 2 chronology were each associated with different climate conditions, which did not resemble conditions associated with Site 1 initiation periods. Thus, a climate signal was not apparent in the analysis of Site 2 initiation periods. However, the incidence of increased compression-wood formation at Site 2 was associated with high water in Stewart River. High water events causing possible flooding at Site 2 occurred prior to the 1936 to 1946 and 1956 to 1963 initiation periods. In the years when Stewart River overflows its banks, flooding occurs in adjacent land areas, thereby increasing the soil moisture conditions in these areas. With greater moisture availability at the onset of fall freeze-back, the magnitude of ice lens formation and frost heave may increase, leading to increased ground displacement and compression wood-formation. The highest Stewart River water levels on record occurred in 1983 and 1992. Following these years, the percentage of trees initiating compression wood also increased by approximately 10%. Thus, the flood behaviour of Stewart River may be associated with increased compression-wood formation in tilted trees at Site 2.

Further research opportunities exist in the sampling of tilted trees located in several drunken forest sites throughout central Yukon. A regional chronology of compression wood formation would provide greater evidence for the association between periods of increased compression wood formation and climate conditions which lead to increased frost action. Chronologies developed from tilted trees located in areas adjacent to river systems

would also provide further evidence concerning the relation between compression wood formation and hydrological regimes.

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