

**FOLIAR NUTRIENTS IN BLACK COTTONWOOD AND SITKA ALDER
ALONG A SOIL CHRONOSEQUENCE AT EXIT GLACIER, KENAI FJORDS
NATIONAL PARK, ALASKA**

by

Joel A. Cusick

THESIS

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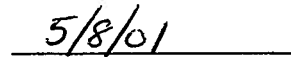
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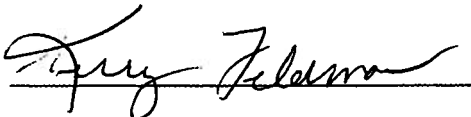


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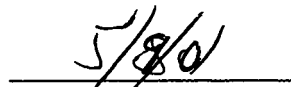


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DEDICATION PAGE

I dedicate this thesis to my mother, Velma Irene Cusick (1920-1998) who was always there with my early school work and told me I could do this. Thank goodness for spell checkers now.

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ABSTRACT

This study compared foliar mineral nutrition in *Alnus sinuata* (Sitka alder) and *Populus balsamifera* ssp. *trichocarpa* (black cottonwood) across a successional sequence in the forelands of Exit Glacier near Seward, Alaska. Expectations were that Nitrogen (N) concentrations in leaves were likely to be consistently high within alder due to association with *Frankia*, a nitrogen fixing endosymbiont, while those of black cottonwood would likely increase across a consequence of successional soil development. Other foliar minerals were also compared between species and across the chronosequence. Anticipated patterns in foliar N between species were found, however, these patterns differed only with respect to the early part of the chronosequence. Foliar concentrations of Phosphorus (P) and Potassium (K) increased in cottonwood leaves across the chronosequence, while Potassium (K), Magnesium (Mg), and Manganese (Mn) increased in alder. Patterns of foliar nutrients associated with distance from the glacier were revealed only after site selection was restricted to areas free of detectable fluvial disturbance.

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1 INTRODUCTION

“Nowhere can succession be studied more profitably than in the valley below the front of a large glacier. (Ellenberg, 1988:440)

A classic approach to the study of plant succession, soil development and nutrient dynamics is to examine their changes along a chronosequence developed on a glacier foreland. The existence of terrain of increasing age with distance from a retreating glacier enables researchers to identify changes which took place over decades and centuries. Glacier forelands present an ideal laboratory for ecologists, due to their spatially compact areas, short history of modification by changing environmental processes and relatively simple ecosystems due to severe climate (Matthews, 1992).

1.1 Objectives

The intent of this research is to investigate foliar nutrient variability across the chronosequence at Exit Glacier forelands. Due to the small size of the Exit Glacier forelands, and dominance by black cottonwood and Sitka alder across most sites, this area provides a consistent background for evaluating the relationships of foliar mineral concentrations across the chronosequence. **The objectives are to evaluate predictions that: 1) black cottonwood foliar nitrogen will more likely to vary across the successional landscape than Sitka alder, due to alder's symbiosis with N-fixing organisms, and 2) other nutrients will show similar patterns of variation between species across the landscape.** In order to accomplish this, I also expand on the description of the Exit Glacier forelands through an explicitly spatial analysis of foliar nutrients, soil nutrients, and soil development and further clarify the timing and landform dynamics associated with glacial retreat at Exit Glacier forelands.

The ecological significance of recently deglaciated terrain depends on the existence of a timescale. Few landscapes exist where the relative age of the land surface exhibits a simple pattern or can be established with any certainty (Matthews, 1992). Jenny (1941, 1980) identified the major “state factors”

controlling soils and ecosystems as climate, relief (or topography), organisms, parent material, and time.

This framework provides a widely used conceptual model for examining the ultimate controls on ecosystem structure and function (Vitousek et al., 1992).

The most influential research on the ecology of recently-deglaciated terrain has been from Glacier Bay Alaska, where initial studies on plant succession was first introduced by Cooper (1931, 1939).

Vegetation successions around different glaciers in coastal Alaska are similar, but each chronosequence is unique due to different environments, seed sources, and site histories (Helm and Allen, 1995). A vegetation chronosequence, developed on an outwash plain at Exit Glacier (Kenai Fjords National Park, Alaska), was described by Helm and Allen (1995). This sequence, along a series of de-glaciated moraines spanning nearly 200 years supports relatively few species and is dominated by *Populus balsamifera* and an understory of *Alnus sinuata*. This community provides a relatively consistent background for evaluating the relationships of foliar nutrient concentrations across the chronosequence.

Alnus is well known for its capacity to fix atmospheric nitrogen in symbiosis with the arbuscular mycorrhizae (AM) *Frankia* (Domenach et al., 1989). The long-term cumulative effect of nitrogen and carbon accretion on outwash gravel has been shown by Crocker and Major (1955), which provides insight as to rates of fixation that can be expected in nature for a shrub species of alder growing on an infertile site. They found that soil nitrogen under the influence of *Alnus sinuata* (Reg) Rydb. increased until the age of 50 years, after which alder was largely replaced by conifer forest type. Domenach et al., (1989), Radwan and DeBell, (1988) report alders can significantly increase the growth rate of associated poplars, but the exact mechanism involved in this phenomenon is still unclear. Several theories have been put forward to explain why poplars grow better when associated with alders. One suggestion is that increased poplar growth can be attributed to an increase in total N due to litter fall and from root and nodule turnover (Dawson et al., 1983). Other possibilities include alder possibly being less competitive in soil N uptake, or increased poplar growth from alder association leads to cottonwood exploiting greater soil volumes and hence greater availability of nutrients (Côté and Camieré, 1984).

The effect of alder facilitation of cottonwood is well studied in controlled treatment plots set up by Lawrence (1953); Lawrence et al., (1967). It was determined that the application of fresh alder leaves proved effective in continually stimulating the growth of *Populus balsamifera ssp. trichocarpa* over a 6-year period. *Alnus crispa* appears also to have a markedly stimulating effect on young cottonwoods growing nearby. Lawrence and Hulbert, (1950) found *P. balsamifera* surrounded by alders to grow approximately three times as fast as those growing separately.

1.2 Foliar Nutrients – A Review

Plants require large numbers of elements which are either derived from minerals or from the biological breakdown of organic matter. Because of their relative concentration in plant tissues, nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg) and sulfur (S) are known as macronutrients and all are required in considerable amounts. The trace elements, or micronutrients, iron (Fe), manganese (Mn), zinc (Zn), copper (Cu), molybdenum (Mo), boron (B) and chlorine (Cl) are vitally essential to the plant and irreplaceable (Larcher, 1995). Most macronutrients are constituents of organic compounds, such as proteins and nucleic acids, and may act as osmotica, while most micronutrients are constituents of enzyme molecules and thus essential only in small amounts. The functions of several essential nutrients will be summarized below (based on Larcher, 1995).

1.2.1 Macronutrients

Nitrogen is usually taken up into the plant in two ionic forms: NO_3^- or NH_4^+ . Its main function is to serve as an essential component of protoplasm, chlorophyll and enzymes, and it is accumulated in the young shoots, leaves, buds, seeds and storage organs. Phosphorus, incorporated into the plant as phosphate ions, is essential for basal metabolism and synthesis (phosphorylation) and is primarily stored in reproductive organs of the plant. Potassium, primarily incorporated into the plant in dissolved form (mainly in cell sap), serves as a regulator of hydration, electrochemical effects and enzyme activation, and it is accumulated in the meristem, young tissue and at sites of intense metabolism. Sulfur taken up as sulfate

from the soil and as sulfur dioxide from the air, is a component of protoplasm and enzymes. Sulfur accumulates in leaves and seeds. Magnesium regulates hydration and basal metabolism (photosynthesis, phosphate transfer) and is primarily found in the leaves. Calcium is known to regulate hydration, enzyme activation, and growth and is found in greatest concentration in the middle lamella of cell walls of leaves and tree bark.

1.2.2 Micronutrients

Iron serves in basal metabolism, nitrogen metabolism and chlorophyll synthesis and accumulates primarily in leaves. Manganese is essential for photosynthesis and phosphate transfer, as well as nucleic acid synthesis and chloroplast structure. Manganese accumulates in both roots and shoots. Zinc is a component of enzymes (carbonic anhydrase, alcohol dehydrogenase) and functions in the plant in enzyme activation, chlorophyll formation, basal metabolism, protein breakdown, biosynthesis of growth regulators (IAA); it accumulates in roots and shoots. Copper functions in basal and nitrogen metabolism and accumulates primarily in woody shoots.

1.3 Foliar Nutrient Analysis

Foliar nutrient analysis has been used extensively in horticulture and forestry to determine the level of mineral nutrients on the assumption that a low concentration of an element in leaves indicates a deficiency (Kozlowski and Pallardy, 1997). Concentrations of foliar nutrients are also used widely as a measure of plant nutrient status, productive potential and even the probability of limitations by particular nutrients (van den Driessche, 1974; Grubb, 1977; Vitousek et al., 1995), because, in general, the nutritional status of a plant is better reflected in the mineral concentration of leaves than in that of other plant organs (Marschner, 1995). Leaves all serve the same basic function as that of the principle photosynthetic organ, which influences growth of the plant, and all leaves utilize the same suite of nutrients in the process of fixing energy into organic forms. Data on the extent to which plants on different sites accumulate nutrients

in leaves can thus be useful in comparing nutrient status in different species and sites (van den Driessche, 1974; Vitousek and Sanford, 1986).

The use of foliar nutrient analysis for determining forest stand nutrient status is complicated not only by spatial variations in the mineral composition of samples in the stand, but also by variations with position on the tree, with season, and with age (McLennan, 1990; Leyton, 1948; van den Driessche, 1974; Chapin et al., 1986), in addition to soil nutrient availability (Vitousek and Stanford, 1986; Vitousek et al., 1995).

Spatial variability within the canopy of individual black cottonwood trees has been investigated by several authors. Compared with samples from the lower canopies, Heilman (1985) found significantly higher concentrations of foliar N in the upper canopies of 6-year-old trees. Blackmon and White (1972) found similar differences between foliage from the upper and lower crowns for foliar N in *Populus deltoides*, although foliar P values did not vary appreciably. McLennan (1990) found significantly higher concentrations of N, P, K, S, Cu in the upper canopy of black cottonwoods sampled from seven sites in British Columbia, while Mn, Zn, Ca and possibly Fe were significantly higher in the lower canopy. His study suggested that upper canopy foliage would provide the most useful interpretations of black cottonwood stand status.

Different species vary in their requirements for nutrients in the period at which these nutrients are absorbed. These seasonal differences have been shown to affect N, P, K, Ca concentration in foliage of hardwoods including spruce and birch (Mitchell, 1936; Hoyle, 1985) and a number of micronutrients including Fe, B, Zn and Na (Guha and Mitchell, 1965). Indicators for the best time to sample for nutrient status should be those periods of maximum "nutrient stress", probably, for example, when extension of foliar growth is complete (van den Driessche, 1974).

Nutrient concentrations in foliage also vary as a function of foliar age. When more than one year's foliage is retained on the tree, differences in composition may also occur according to the age of the foliage (Leyton, 1948). Leaching of nutrients from foliage occurs most readily during periods of rapid spring leaf

growth or autumn senescence or in plants of high nutrient stress (Chapin, 1980). Half or more of the maximum nitrogen and phosphorus content of a deciduous leaf is translocated to other plant parts before leaf abscission. Potassium is removed from leaves by leaching, and calcium, being immobile in the phloem, is not translocated at all (Chapin, 1980).

Adequate interpretation of foliar nutrient data is also confounded by spatial variability for foliar nutrients within a stand. It is apparent that differences in foliar nutrient concentrations exist between bred lines and clones of many forest tree species growing under closely comparable conditions (van den Driessche, 1974).

In addition to the variability in foliar concentrations of minerals due to canopy, season and leaf age, external factors, such as nutrient availability to the plant from the soil, govern much of what the plant absorbs in its lifetime. Nutrient concentrations in individual trees are more likely to reflect the influence of soil fertility. Soils vary in their ability to supply nutrients, and the factors which give rise to this variation are those which determine the development of soils. Nevertheless, where nutrient concentrations within a species vary substantially among sites, this variation generally can be interpreted in terms of the supply of nutrients to plant or nutrient balances within plants (Medina and Cuevas, 1989; Vitousek et al., 1995).

Often other external factors, such as moisture stress, year to year variation and competition effects, are largely ignored with foliar analysis studies, but controlling for the factors shown in this review may lead to interpretation of significant differences in foliar nutrients as a measure of nutrient status.

2 STUDY AREA OVERVIEW

This chapter presents an overview of the Exit Glacier foreland along with a review of dendrochronological and topographic data on the timing of Little Ice Age (LIA) events at Exit Glacier. This establishes a temporal stage upon which to discuss the foliar nutrients of black cottonwood and Sitka alder across the recently-deglaciated landscape.

2.1 Exit Glacier Setting

2.1.1 Harding Icefield

Exit Glacier is an outlet glacier of the Harding Icefield on the southern Kenai Peninsula in southcentral Alaska (Fig 2.1). This icefield is approximately 80 km long (NE-SW) and 50 km across and covers an area of approximately 1800 km². It is the largest icefield completely within the borders of the United States (Rice, 1987). Slightly more than half of the icefield lies within Kenai Fjords National Park; the remainder lies within the Kenai National Wildlife Refuge (Fig. 2.1). It has a variety of glacier types, including outlet, land terminating and tidewater glaciers. Contrasting climate regimes affect the glacier systems. The western flank is dominated by maritime climate and tidewater glaciers, while the eastern flank is dominated by terrestrial climate and land-terminating glaciers. At least 38 glaciers of various sizes and types emanate from the Harding Icefield. Late Holocene glacier chronologies for the Harding Icefield have been produced by Post (1980), Rice (1987), Wiles and Calkin (1990; 1994), Wiles (1992), and Adalgeirsdottir and others (1997, 1998).

2.1.2 Exit Glacier Forelands

Exit Glacier (60° 11'N, 149° 39'W) is a small, land-terminating, relatively steep glacier (10° surface slope) that drains from 1200 m a. s. l. along the northern side of the Harding Icefield. It has a northeastern aspect (Figure 2.1; Figure 2.2) with an overall length of 7 km and an area of 43 km² (Adalgeirsdottir, 1997; Adalgeirsdottir et al., 1998). The terminus lies at 140 m a. s. l. and is located 13 km northwest of Seward, Alaska.

Studies of the surface and elevation changes since the 1950's for the Harding Icefield and Exit Glacier have been made possible by region-wide aerial photography developed by the U.S. Geological Survey (USGS) for topographic map production. Rice's (1987) study compared Alaska High Altitude Photography (AHAP) to USGS topographic maps and showed the areal extent of the icefield decreased approximately 5% over a 34-year period. Using a GPS airborne surface elevation profiling system, Adalgeirsdottir (1997; 1998) recorded changes to Exit Glacier from the 1950's to the 1990's documenting a decrease of 0.25 km² in area and a 490m recession of the terminus. The surface appears to have changed shape since the U.S. Geological Survey maps (1:63,360 scale) were made (Seward Quadrangle A7, A8; production date 1951), but contrast in the mapping photographs is poor, and contours may have been poorly drawn (Adalgeirsdottir, 1997; Adalgeirsdottir et al., 1998).

Exit Glacier movement has been recorded by several studies. Rice (1987) recorded surface velocities of the glacier in the summer of 1985 between 150 and 180 m yr⁻¹. A tripod erected on the glacier in the spring of 1983 to record ice velocities was rediscovered at the terminus of the glacier in November 2000, recording an ice flow of over 1200m in a span of 17 years for a rate of motion at 71m⁻¹. Mike Tetreau (National Park Service, Kenai Fjords National Park) recorded a rate of advance on the ice edge at 0.3 m day⁻¹ in November 1989 and a 7 m advance of the terminus in the winter months of 1989-1990 (Tetreau, M., personal communication, March 2000). Since on-site investigations were begun at measuring the glacial snout, the glacier terminus has advanced several times over previously deglaciated terrain. In the spring of 1993 the ice advanced more than 30 meters beyond the 1988 position of the terminus, ploughing up large amounts of sediments in front of the terminus. The resultant proglacial features called push moraines are evident today on the glacial forelands and have been described by Hart (1995). Recession of the terminus from these seasonal advances can be seen in photos from 1996 recording an estimated 10 meter recession from a 1995 spring position (Figures 2.6a and b).

The Exit Glacier forelands is approximately 7.4 km² in size, extending to the western boundary of Chugach National Forest and the Resurrection River to the east, and bordered by mountains to the north and

south (Fig. 2.1). The largely barren outwash plain adjacent to the present terminus is relatively flat (gradient: 4.1 m km^{-1}) and is subjected to standing or moving water during the wet season and wind erosion during dry periods (Fig. 2.2; 2.3). Multiple channels merge into one main channel 500 meters down valley from the present glacier terminus and flow northeastward with an average gradient of 9.3 m km^{-1} before joining the Resurrection River 2.6 km downstream. Exit Glacier Creek is turbid and transports large sediment loads during spring and fall high water events.

2.1.3 Vegetation Chronosequence

The Exit Glacier foreland consists of 1) an active floodplain deglaciated since 1950 and currently being colonized by vegetation, 2) slightly higher terraces above most flooding events that have been colonized since the most current retreat, which started after 1950, and 3) mature forests established prior to 1950 (Helm and Allen, 1995; Figs. 2.2, 2.3). Old drainage patterns are visible in overviews of the valley floor (Fig. 2.3). A large part of the forested valley floor is covered by *Populus balsamifera* ssp. *trichocarpa* and *Alnus sinuata*, and the hillsides are forested by the *Picea sitchensis* (Sitka spruce) and *Tsuga mertensiana* (mountain hemlock). Viereck and Foote (1970) found extensive hybridization of *P. balsamifera* ssp. and *P. balsamifera* ssp. *trichocarpa* on the Kenai Peninsula.

The following vegetation stages have been developed for the Exit Glacier outwash plain by Helm and Allen (1995).

- 1) Barren: The youngest vegetative stage found on recently developed moraines and on the outwash plain at the glacial forefront of Exit Glacier. Portions of these areas are flooded annually and are interlaced with small drainages of various textured surfaces and exposed to wind action. Elevated sites are devoid of plants, with the majority of seedlings established near drainages. Majority of seedlings are *Populus balsamifera* with scattered *Epilobium latifolium* and isolated fragments of moss (*Rhacomitrium* ssp.).
- 2) Isolated Plant: This stage probably occurs about 10 – 20 years after flooding has stopped and occupies the raised gravel terraces and sparsely vegetated areas adjacent to the barren area.

Cover of vascular plant species is about 1%, with *P. balsamifera* dominating and fewer *Salix sitchensis* and *S. alaxensis*. Moss cover (mostly *Rhacomitrium* spp.) averages 17% of total surface.

- 3) Patchy: The patchy stage occupies areas adjacent to the barren stage and is characterized by clumps of vegetation. Moss covers over 50% of the surface, whereas vascular plants cover approximately 10%. *P. balsamifera* provides over half of the vascular plant cover in this stage, while lichens (*Stereocaulon* spp.) provide 5% cover.
- 4) Alder: The youngest vegetative stage providing significant cover is the alder stage, found in areas of disturbance such as avalanche chutes and on recent moraines. The dominant plant species, *A. sinuata*, provides 81% cover, while *P. balsamifera* contributes at least as many stems (6% cover). These stands have an estimated 93% total living plant cover and are the youngest stand described by Helm and Allen (1995) as providing significant ground cover in the form of litter.
- 5) Cottonwood: The cottonwood stage is the most common stage at Exit Glacier. Large *P. balsamifera* dominate the recently-deglaciated moraines, with *A. sinuata* and *Salix alaxensis* providing diminishing cover as one proceeds down valley. *Picea sitchensis* provides on average 2% cover across sites (Helm and Allen, 1995). Ground cover of *Pyrola secunda* is greater in earlier stages, but *P. asarifolia* is also present in small quantities. Mosses, *Epilobium angustifolium*, *Calamagrostis canadensis*, and ferns are more prominent in later stages.
- 6) Spruce-Cottonwood: This stage occupies areas where plant growth started over 200 years ago, with *Picea sitchensis* providing almost twice as much cover as *Populus balsamifera*. Many of the original *P. balsamifera* are dead or decadent. Cover of *T. mertensiana* is still low, although seedlings occur on decaying logs.

- 7) Spruce Hemlock: The oldest stage sampled by Helm and Allen (1995) occupies the areas above the trimline on the hillslopes above the outwash plain at Exit Glacier. Vegetation is dominated by *Picea sitchensis* and *Tsuga mertensiana* with substantial cover by ferns and some *Oploplanax horridum*.

The mycorrhizal chronosequence at Exit Glacier described by Helm et al., (1996) documents changes in mycorrhizae on existing woody plants, including black cottonwood, a dominant species in earlier stages. Sitka alder and Sitka spruce have few ectomycorrhizal (EM) fungal associates (which typify later successional stages). Black cottonwood may be ectomycorrhizae (EM) or arbuscular mycorrhizae (AM), both or neither (Helm and Allen, 1995), but was found to be predominately infected with EM fungi, even on the floodplain with mostly mineral soil. AM fungi were negligible in the Exit Glacier chronosequence and were not found on any woody plants (Helm et al., 1996).

2.1.4 Climate

The Harding Icefield exhibits a subarctic maritime margin along the southeastern side of the Kenai Mountains, with a subarctic continental margin on the northwest. The climate is dominated by the Aleutian low pressure center, which causes a counter-clockwise circulation over the Gulf of Alaska, bringing copious amounts of precipitation, especially snow, to the east flank of the Harding Icefield (Benson, 1980). The weather station at Seward, 13 km southeast of Exit Glacier, (Figure 2.4 a; 2.4b) has recorded weather data for a nearly continuous 92-year period. Total precipitation averages 1665 mm yr⁻¹ (range 848-2448 mm yr⁻¹), and mean annual temperature is 4.2° C. The coastal town of Homer to the west, receives only 600 mm yr⁻¹ with an average annual temperature of 3.0° (NCDC, 2000). Precipitation also varies substantially with increases in elevation and distance from coastal influences. For example, during one storm almost three times as much precipitation fell at 1275 m a. s. l. on the Harding Icefield as in Seward (Rice, 1987). Snow depths measured in May 1996 (Adalgeirsdottir, 1997) on the glacier recorded a depth of 3.3 m.

Localized monthly temperature and precipitation records have been recorded at the ranger residence at Exit Glacier since 1984 (Figs. 2.4c; 2.4d). Total precipitation averaged slightly more than

Seward at 1695 mm yr^{-1} (range $918\text{-}2330 \text{ mm yr}^{-1}$) while mean annual temperatures were significantly colder than Seward (2.3°C). Mean range of annual temperatures are nearly four times colder at Exit Glacier than at Seward, likely due to the inland location and cooler temperatures from katabatic winds. Thus, Exit Glacier receives almost twice the snowfall depths as Seward for the same time period (Figure 2.5). In the year of this study, total precipitation averaged about 172 cm yr^{-1} , which is slightly more than the 16-year average for the weather history at Exit Glacier from 1984-2000. The early growing season at Exit Glacier begins in May and continues through July. This time is relatively dry with late-summer rain starting in late July or early August (Figs. 2.4c; 2.4d).

2.1.5 *Geologic Setting*

The southern Kenai Peninsula is part of the Chugach Terrane with local bedrock types including the Upper Cretaceous Valdez Group, a largely marine sedimentary rock formation widely distributed throughout southcentral Alaska (Kelly, 1985). These sandstones, siltstones, mudstone flysch, and pebble conglomerates formed on the edge of the Pacific plate as it drifted northward and subducted under the North American Plate (Pfeiffenberger, 1995). Within the Harding Icefield are exposed bodies of intrusive granite. These rocks intrude slate and sandstone of the Cretaceous Valdez Group and, near the Resurrection Peninsula, probably intrude mafic igneous rocks of the Valdez Group as well (Tysdal and Case, 1979).

The Resurrection River and Kenai River drainage systems on the north side of the Harding Icefield are underlain by unconsolidated surficial deposits of glaciofluvial origin, left during recession of the Naptowne ice about 10,000 to 14,000 years ago (Tysdal and Case, 1979). Geologic units in the Exit Glacier area were described by Sloan (1985). These units include:

1. Bedrock: Ice-scoured exposures north of the present terminus comprised mostly of slate.
2. Glacial Till: Unsorted mixture of rock fragments occurring in curvilinear ridges marking previous positions of the Exit Glacier terminus. Till is also found in lateral moraines along valley sides and may occur in a layer overlying bedrock but beneath fluvial sands and gravels

in the valley. Large boulders and stones litter most moraine surfaces and occur in the subsurface till deposits.

3. Fluvial Sand and Gravel: The majority of the Exit Glacier valley floor is covered with glacial outwash deposits of sand and gravel. Thickness may be as much as several hundred feet in places and may occur as lenses or layers in the outwash alluvium.

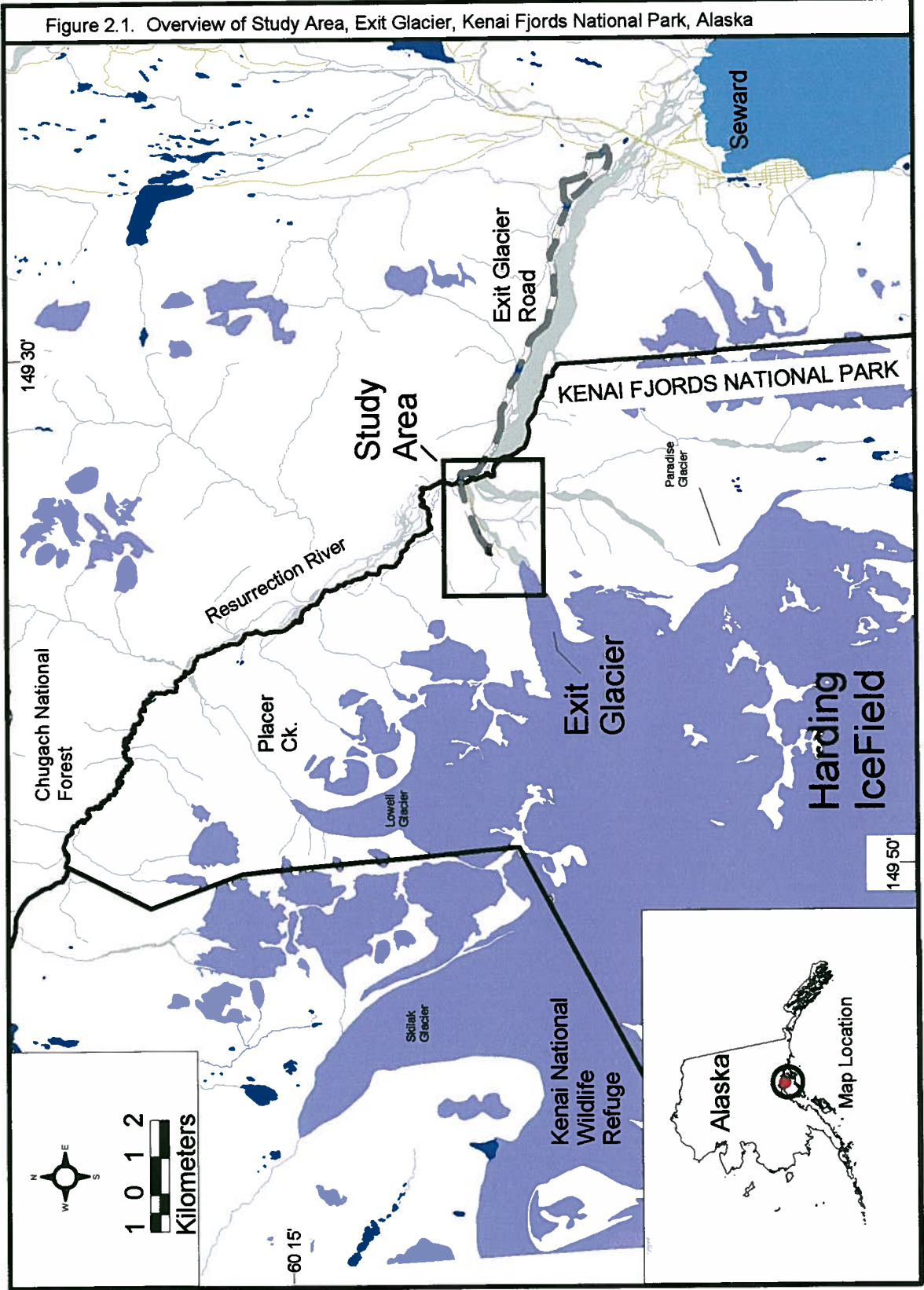
2.2 Complexity in the Forelands and Challenges to this Study

Few landscapes exist where the age of the land surface exhibits a simple pattern or can be established with any certainty. Because glacier retreat rates are rarely constant, the relationship between distance from a retreating glacier and time is non-linear, and more information is needed to obtain numerical (absolute) age estimates (Matthews, 1992). Biological dating techniques such as tree-ring dating are crude estimates and can establish minimum ages of terrain if correction factors such as ecesis (colonization time) are calculated.

There was ample evidence prior to this study that Exit Glacier had retreated from a Little Ice Age maxima sometime at the turn of the 19th century and was within 1.5 km of its outer moraine between the 17th and early 18th centuries (Wiles, 1992). However, the precise timing of moraine deposition after the LIA maxima was vague because: 1) dendrochronological studies were based on small sample sizes, 2) there was a lack of adequate mapping of tree coring locations and documentation of archived core samples, and 3) tree-ring dating efforts were concentrated along the road corridor (Fig. 2.3) and subject to possible anthropogenic disturbances such as trampling and road-building affects. In addition, tree-ring dating efforts at Exit Glacier also relied on colonization times of black cottonwood and Sitka spruce estimated from glacial forelands with dissimilar climatological patterns.

This study improves the recent recessional history of Exit Glacier using the techniques of dendrochronology along a transect down the centerline of Exit Glacier retreat and away from road affects. In addition, historical sources such as photography and maps were compiled to serve as calibration of

biological dating techniques. Integration of photography, especially more recently acquired aerial photography, as well as enhanced depiction of ground features using geographic information systems (GIS), serve to extend the temporal scale of glacial recession and therefore enhance the studies of foliar nutrient concentrations.



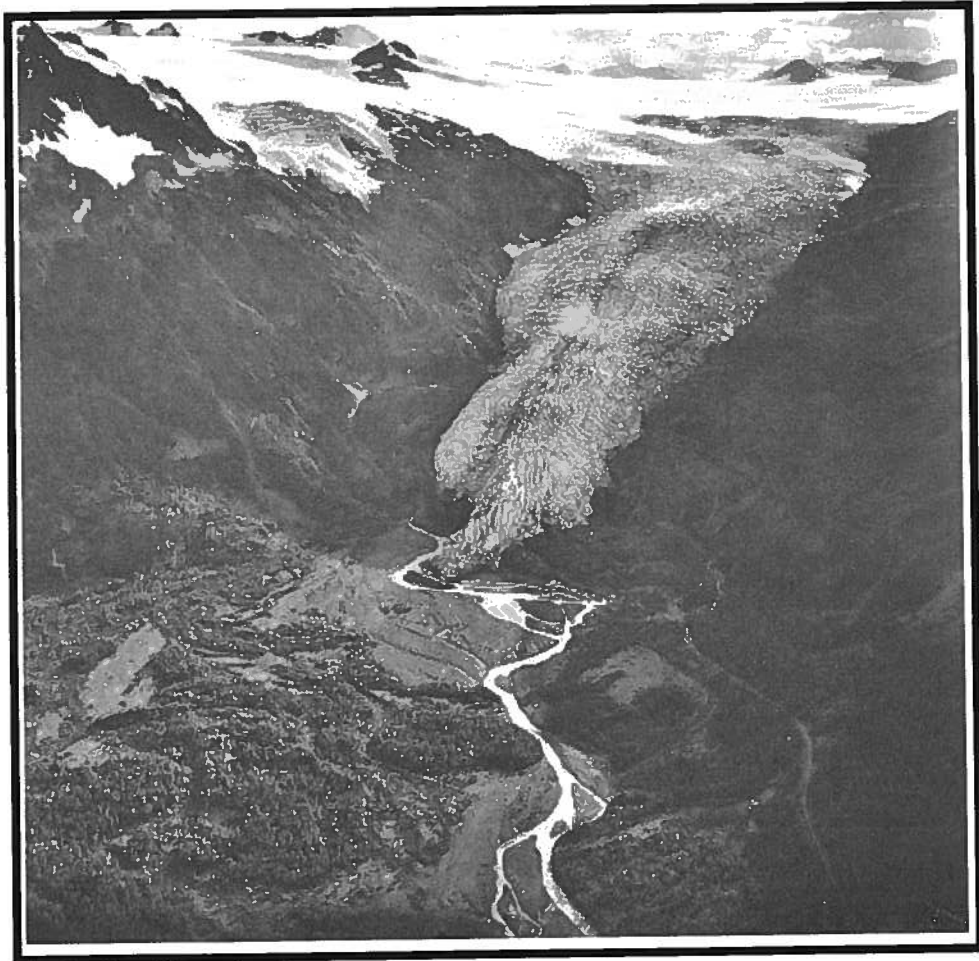
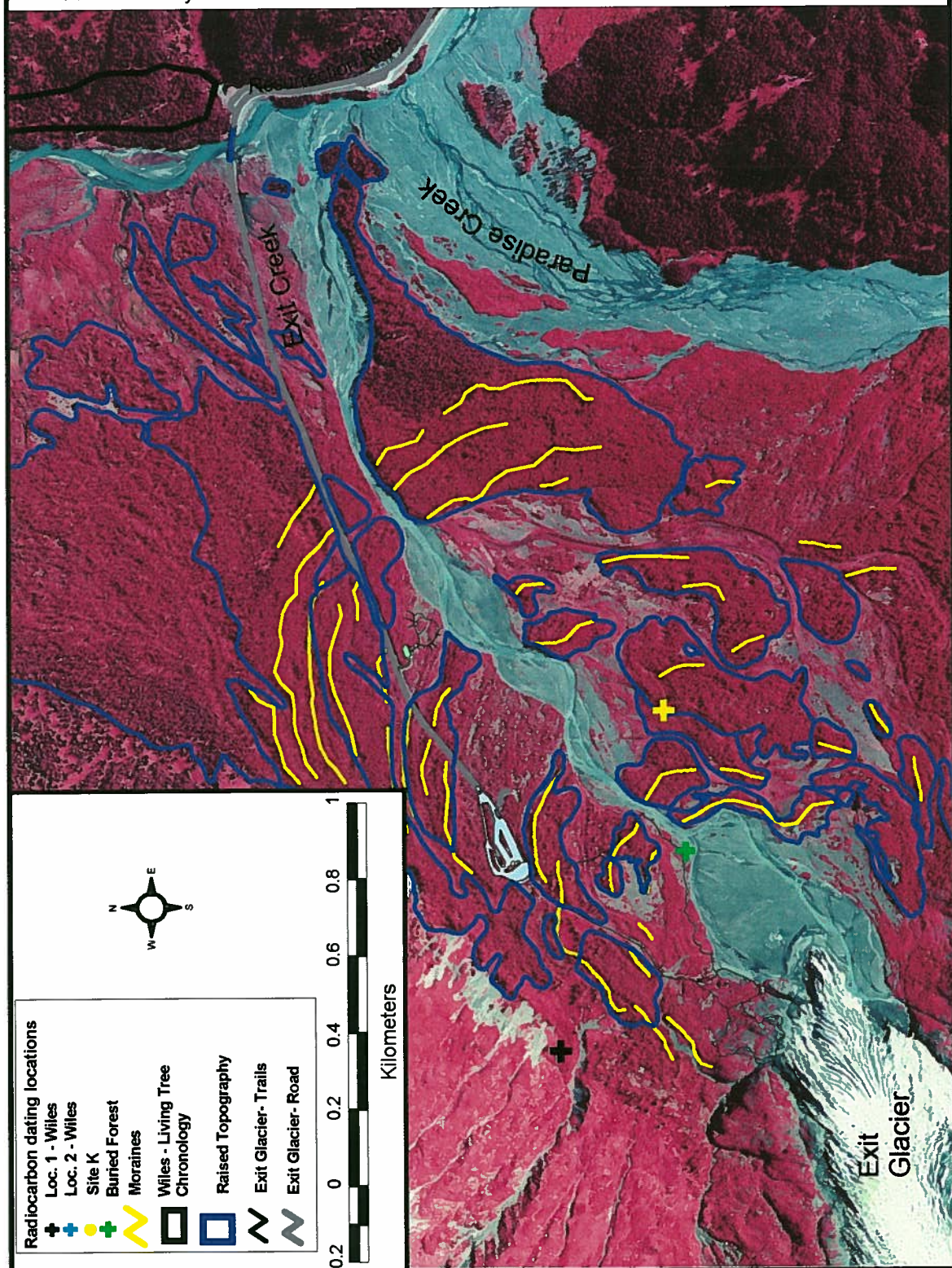
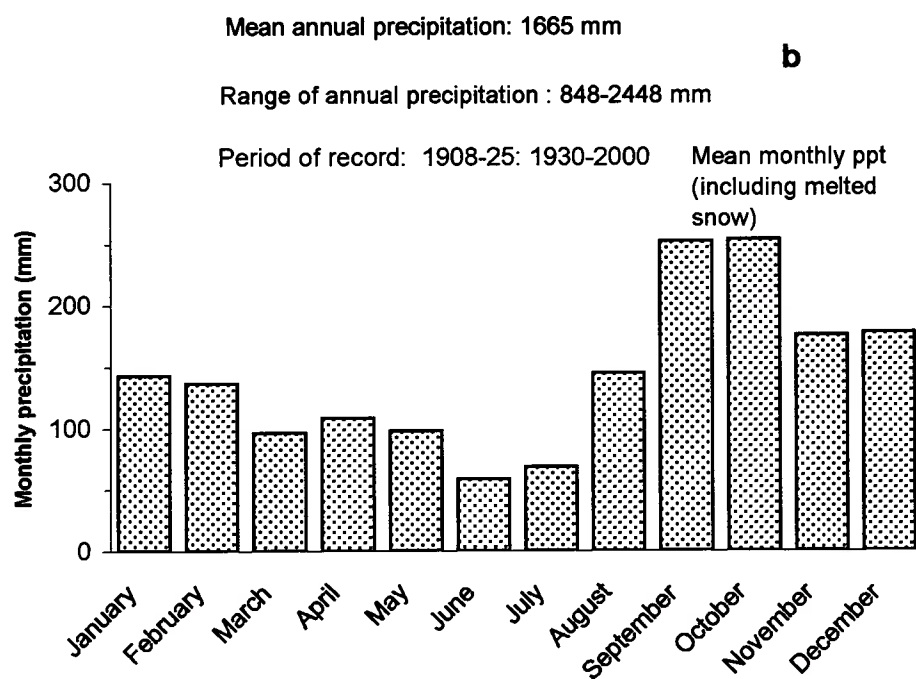
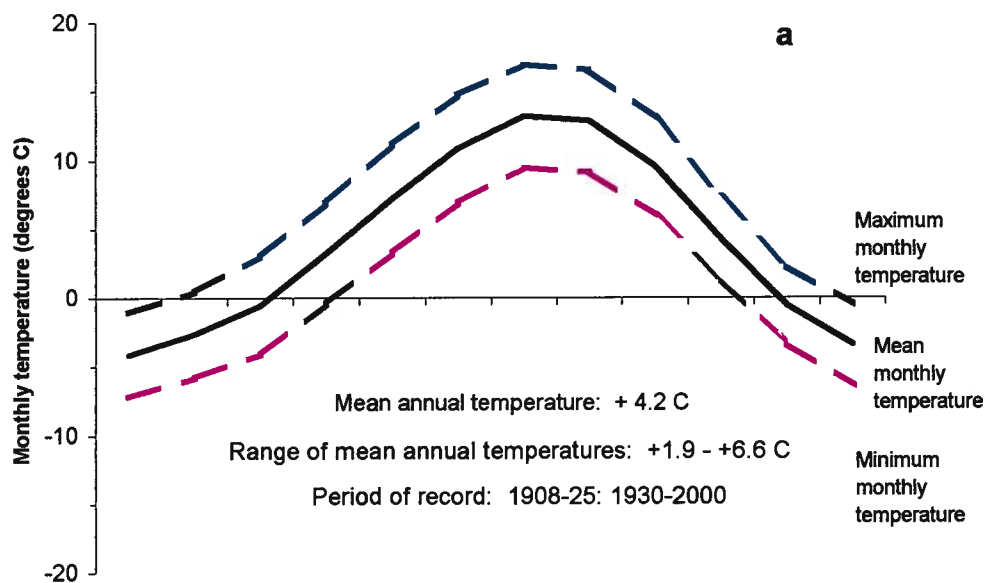


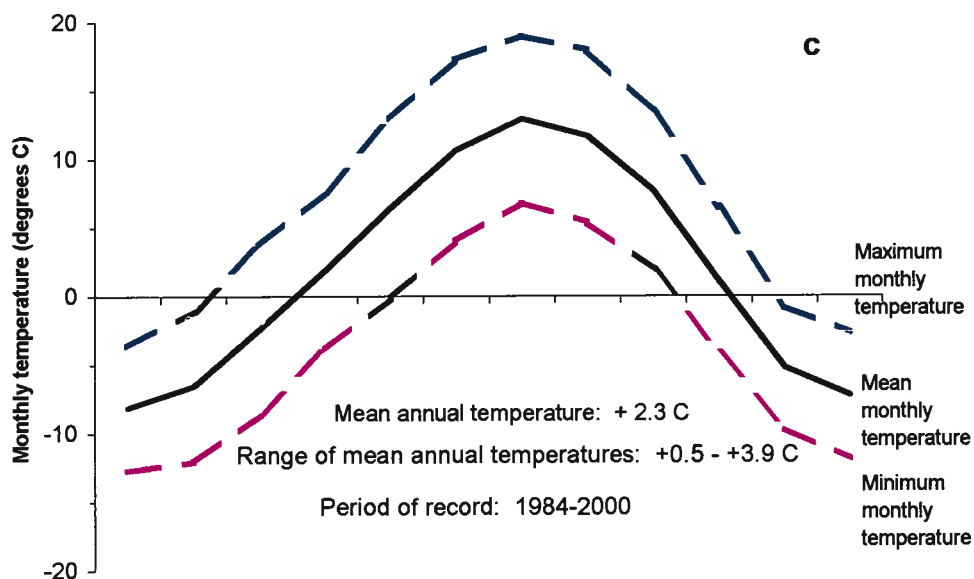
Figure 2.2. Exit Glacier, in 1984, looking southwest. Photo courtesy of University of Alaska Fairbanks, Geophysical Institute, GeoData Center, Fairbanks, Alaska. A. Post, photographer.

Figure 2.3. Aerial view of the Exit Glacier outwash plain, August 1998. Photo is a color infrared (CIR), Locations of radiocarbon sample sites, living tree chronology (Wiles, 1992) and moraines. Photo courtesy of U.S. Forest Service.





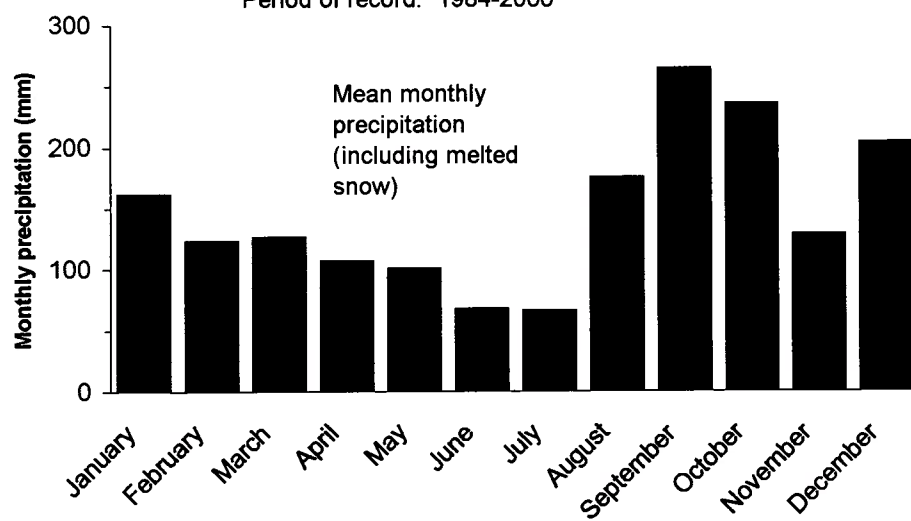
Figures 2.4 a and b. Summary statistics of meteorological data from Seward, Alaska (508371). Compiled from NCDC (2000).



Mean annual precipitation: 1695 mm

Range of annual precipitation : 918-2330 mm

Period of record: 1984-2000



Figures 2.4 c and d. Summary statistics of meteorological data from Exit Glacier (Seward 9 NW;508375), Alaska. Compiled from NCDC (2000).

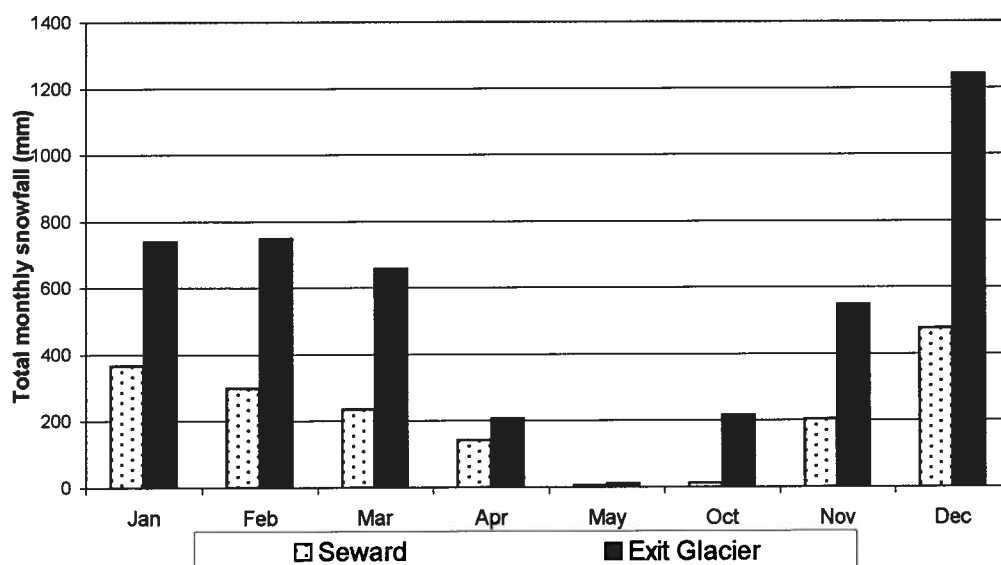


Figure 2.5 Comparison of total monthly snowfall for Seward (508371) and Exit Glacier (Seward 9NW; 508375), Alaska for the time period of 1984-2000. Compiled from NCDC (2000).



Figure 2.6 a. Margin of Exit Glacier and push moraine formation, 1996. 1995 moraine can be seen on left. Described by Hart (1995). Note people lower left for scale.



Figure 2.6 b. Close-up of margin of Exit Glacier and inter-moraine water flow channel, 1996. Described by Hart (1995). Photos courtesy of Thomas Lowell, Department of Geology, Univ. of Cincinnati, Ohio.

3 METHODS

In order to evaluate the hypothesis that black cottonwood and alder would differ with respect to foliar nitrogen concentrations (and exhibit similar foliar concentrations with respect to other mineral nutrients) across a successional sequence in a glacial foreland, leaves of both species were collected from known locations within the glacial foreland, analyzed for mineral nutrients, and compared with respect to values and trends using graphical and statistical methods. Initial attempts in 1998 used a haphazard sampling strategy with locations recorded using high precision GPS. Interpretation of these results resulted in a modified sampling strategy in 1999 aimed at better representing the temporal dimension of the glacial forelands. The methods used to establish sampling sites are detailed in the section entitled 'Dating and Description of the Exit Glacier Forelands' below. Leaf samples collected from the 1999 sites better reflected a chronosequence and were analyzed for mineral nutrients and compared using graphical and statistical techniques. Details of sample collection during the two years, as well as techniques used in processing and analysis directly follow and precede the section on methods used to establish a reliable chronosequence.

3.1 Method I: Foliar Nutrients

3.1.1 1998 Survey Field Methods

A pilot study was initiated in August 1998 to investigate foliar nutritional dynamics of *Populus balsamifera* ssp *trichocarpa* and *Alnus sinuata* across a time scale of ca. 200 years. Two hundred ninety-three unique alder and cottonwood trees were sampled for leaves between August 29 and August 31. All sample locations were located along a vector beginning near the northwest corner of the Exit Glacier terminus and proceeding down valley along the Exit Glacier road for a distance of 2500 meters (Fig. 3.1). Sample locations often paralleled existing visitor use trails. Six percent of the sites were located on the open outwash plain, while 19% of the sample sites were located within 20 meters of the Exit Glacier road or service parking area (Fig. 3.1). Since these positions were sampled haphazardly, no effort was made to

control for location of plants on raised surfaces. As a result, 26% of the sampled trees and shrubs were located on some raised surface (moraine features), while the other 74% were located on lower areas and in some cases abandoned stream channels (Fig. 3.1). In addition, as relative distance from the glacier increased, and the forests matured, black cottonwood trees were soon too tall to sample from ground level, limiting the amount of those species for analysis. As a result, only 25% of the samples were obtained from cottonwood.

Leaf sampling techniques were developed to minimize subjectiveness of the sample and allow for standardization of samples across all species. The top whorl of leaves (normally 2-3 leaves) was obtained and placed in a pre-numbered paper envelope. The sample number was unique to each tree or shrub and was subsequently associated with all field descriptive information and laboratory analyses. A series of leaf and tree measures was collected including: tree/shrub estimated height classes (0-50cm, 50cm-1m, 1m-2m, 2m-4m, 4m or greater), plant exposure or lack of shade (very low, low, moderately low, moderate, or high), diameter at breast height (DBH) if available, and presence of other species. In addition, other physical characteristics of the area were noted, including duff thickness (estimated by a kick sample), surface composition (greater than 50% organic or mineral), and surface soil composition (boulder, cobble, pebble, sand/silt). These data were recorded on-site using a Trimble© Pro XR GPS receiver following methods described in Chapter 3.2.

Samples were kept cool in the field and transported to University of Alaska Anchorage laboratory within a maximum of 3 days from collection. Leaves were removed from envelopes, photocopied and dried to 60 ° C for two days.

3.1.2 1999 Survey Field Methods

Following the 1998 season, it became apparent that site selection to detect patterns of foliar nutrients required restriction to areas free of detectable fluvial disturbance. A transect method was therefore established to effectively sample only raised topographic features assumed to be terminal push

moraines (Figs. 2.6a; 2.6b) and thereby conforming to a known date of establishment. Tying in terrain age mapping of similar features could then establish dates of moraines and allow for proper comparisons.

3.1.2.1 Leaf Transects

Eleven transects were established using a stratified random sampling design along raised topographic features south of Exit Creek (Table 3.1; Fig. 3.2). A meter tape was laid out along the length of a moraine keeping to the top of the feature as much as possible. A number between 0 and 10 was then drawn randomly from a set of cards to establish the "Zero" end of transect. From the distance between the randomly chosen zero end and 10 meters along the tape, 10 additional meters were counted off and the nearest black cottonwood and alder were sampled from that place. As a simplifying measure, the place where the closest ramet of alder emerged from the soil was used to identify the branch for sampling. The closest cottonwood was defined as the nearest side of tree facing the transect. This was repeated every 10 meters until 5 stations were sampled for a total of 5 alder and 5 cottonwood trees each for every transect. This pattern was followed for all transects except A1 and A2 where, due to the small size of area, two transects were established, one 40 meters long, the other 60 meters long. This site was sampled only for alders. In addition, transect A3 was the complementary cottonwood-only sampling transect, where 10 cottonwood seedlings were sampled along the 50 meter transect (Table 3.1; Fig. 3.2).

Foliage samples were collected between August 3 and August 10, 1999. Black cottonwood is characterized by heterophyllous foliage so that two types of leaves, preformed, early leaves and late leaves, are found within the same branch (McLennan, 1990). In the present study, for comparisons among the sites and between species, only the late leaves, those formed three leaves behind the apical meristem for both species, were sampled. Using these sample criteria, 10 foliage samples (about 30 grams fresh weight) were collected from lateral branches. Entire leaf and petioles were sampled and were deposited in pre-numbered paper envelopes. Dead stems and those leaves that were discolored or exhibited signs of aphid infestation were excluded from the sample.

All alder leaves were obtained from ground level. To facilitate sampling of tall black cottonwood trees, foliage was obtained from lateral branches throughout the canopy using a pole-mounted slingshot (Big Shot, W.T. Sherrill, Inc). Thick brush often prevented capture of branches from a consistent portion of the canopy retrieval so controlling for height of canopy for black cottonwood was not possible.

In order to test for within tree variation, leaf samples were obtained from various levels of the canopy at a site located 9.1 kilometers along the Exit Glacier road from the Seward Highway. Three trees were climbed on August 11, 1999, by Kenai Fjords National Park Resource Specialist, Mike Tetreau, using climbing equipment to ascend to the upper canopy of all 3 trees. A representative branch from the upper, middle and lower third of each tree was obtained, and leaves were sampled as outlined in methods above.

In order to facilitate comparisons of foliar nutrient concentrations between sampling years, a subsample of 1998 sample locations was recovered in 1999 using sub-2-meter accurate differential GPS (See Chapter 3.2). Ten trees (5 alder; 5 cottonwood) were re-sampled on August 6, 1999, in an open inter-moraine area along the 1917 moraine (Fig. 3.1), corresponding to the 1999 sampling times for leaf transects south of Exit Creek. Another group of samples was recovered on August 26 (10 alder; 10 cottonwood) from the north side of Exit Creek. These samples were collected to test variation between two sample dates separated by 20 calendar days.

Dates of 1999 leaf collection were as follows:

Sites	Sample Size	Date
• Leaf Transects A1, A2, A3, B, C, D, E, F, G, H and I	100	Aug. 3-6 1999
• Re-sampled 1998 trees around SCA camp	10	Aug. 6 1999
• Leaf Transect J and Canopy Test Trees	10+9	Aug. 10-11 1999
• Re-sampled 1998 trees – test for inter year	<u>20</u>	Aug. 26 1999
Total	149	

Ages of the trees or shrubs sampled along the transects were determined by tree-ring dating techniques outlined in Chapter 3.2. Alders were cored as close to ground as possible. Height of core was recorded for both alder and cottonwoods, as well as diameter at core height. Other data collected during foliar sampling included tree and shrub characteristics such as DBH for black cottonwood and diameter at ground height (DGH) for alders. Tree heights for black cottonwood were estimated using a standard Suunto model (PM-5) clinometer (Suunto, Inc., 1995) by measuring distance to the tree to the nearest 0.10 m and reading the percent scale. Height of tree was then calculated by:

$$\text{Height of tree} = \% \text{ reading on clinometer} * \text{distance } X$$

where

X= horizontal distance in meters from tree

3.1.3 *Laboratory Methods*

Concentrations of macro and micro nutrients for 1998 and 1999 foliage were determined using equipment and standards developed at the UAF Palmer Experimental Research Field Station, Palmer, Alaska. Methods between years were similar except that some micronutrients were not analyzed in both years. All foliage samples were stored in a cooler on dry ice and transported to the UAF Palmer Experimental Research Field Station within 48 hours of collection. Leaf morphometrics, including average width and length of leaf blade to the nearest 1 mm, were obtained for all foliage collected in 1999. Foliage collected in 1998 were photocopied along with the sample envelope.

Samples were oven dried at 60° C for 12 hours, ground to a fine powder in a Wiley mill, placed in 150 ml white propylene jars and capped tightly. Prior to all analyses, leaves were dried for 12 hours at 60° C. Concentrations of N and C were determined using a LECO® CHN 1000 infrared gas analyzer. P, K, Ca, Mg, Mn, B, Cu, Fe, Na, S and Zn were determined by digestion in nitric-perchloric acid

(Michaelson et al., 1993) followed by atomic absorption spectrophotometry using a Perkin-Elmer Optima 3000 Inductively Coupled Plasma Optical Emission Spectrometer (ICP-OES) and methods (Michaelson et al., 1993). Macronutrients (N, P, K, Ca and Mg) are expressed as percent concentration and micronutrients (Cu, Mn, Fe, and Zn) as parts per million of oven dry (OD) mass. Boron, sodium, sulfur and copper results were difficult to maintain with a high degree of confidence ($\pm 10\%$ from reference standard certified values) probably due to sample contamination and therefore rejected following quality control standards described above.

3.1.4 Statistical Tests

Data compilation, exploration, descriptive statistics and univariate graphics were produced in Microsoft Excel ©. The effects of terrain age on nutrient concentrations in both foliar and soil and their interaction were assessed using analysis of variance multiple range tests, and linear regression in the SPSS Ver 10.1 statistical computer package (SPSS, Inc., Chicago, IL). The one-sample Kolmogorov-Smirnov test was used to test variables meeting a normal distribution. Tests for equal variances for data from different moraines were conducted using the Levene test. Log transformations (natural log) were conducted on nutrient concentrations to assess reductions in variance across sites. Results of transformations were inconclusive since some nutrients were less variable after transforming, while other nutrients became more variable.

Paired-sample T tests were conducted on those alder and cottonwood trees sampled in both years (1998 and 1999) to test whether their means differed from zero. Regression analysis was conducted on mineral concentration data for both species across the chronosequence to test for relationship of foliar nutrients with time. General linear model (GLM) analyses were conducted on samples to test for relationships between selected co-variates with foliar concentrations. Duncan's multiple range tests were used to determine significance between sites. For all tests of significance between sites, values of $p < 0.05$ were considered to be statistically significant.

3.2 Method II: Dating and Description of the Exit Glacier Forelands

A variety of techniques and methods was used to date and describe the Exit Glacier forelands. Trees and shrubs on the moraines and on transect sites were dated by dendrochronology. Documentary and photographic evidence were used to determine the colonization time of spruce and cottonwood on the moraines and to determine the historic positions of the ice margin. Modern mapping techniques (GIS and GPS) were utilized to combine aerial vertical photography and on-ground surveys to accurately pinpoint sites for future studies, rectify imagery into a common geographic reference system, and produce topographic maps. Samples of buried soils and logs were collected for radiocarbon dating to document limiting ages on glacial advances or retreats. Field descriptions of soils and laboratory analysis were carried out using standard methods for determining soil chemical and physical characteristics.

3.2.1 Dendrochronology

Tree-ring dating has been extensively used to provide minimum ages for tree-covered surfaces following glacial retreat in the North American Cordillera (McCarthy, 1985; McCarthy et al., 1991; McCarthy and Luckman, 1993), on multiple glaciers emanating from icefields (Crossen, 1997; Wiles, 1992) and in the study area at Exit and Bear Glaciers (Viereck, 1967; Ahlstrand, 1983; Wiles, 1992). Dendrochronological studies must include the time required for trees to grow to the sampling height and a determination of elapsed time between glacial retreat and germination of the trees on the morainal deposits (ecesis) (See McCarthy et al, 1991; McCarthy and Luckman, 1993, for a full discussion on these corrections). This study established local correction factors at Exit Glacier, because tree growth and ecesis estimates are variable and dependent upon local and regional differences including distance from seed source, amount of precipitation and microclimate (McCarthy, 1985; McCarthy and Luckman, 1993; Wiles, 1992).

Tree-ring ages were obtained on the intermittent moraines located south of Exit Creek (Fig 2.3), because this was the focus area of the foliar research and because earlier research efforts (Ahlstrand, 1983; Wiles, 1992) concentrated their efforts along the road corridor north of Exit Creek. Moraines south of

Exit Creek were located down the valley center, thus minimizing effects of confusion with multiple lateral moraines (Fig 2.3). An effort was made to stay away from the public visitor facilities, so that anthropogenic effects such as soil compaction and trampling could be minimized.

Black cottonwood (*Populus balsamifera* ssp. *trichocarpa*) was the primary species used in dating, because most of the recently-deglaciated area is covered by this fast-growing species, and it has been shown to be the most abundant colonizer on the outwash plain dominating sites that are under 150 years old (Helm and Allen, 1995). This species, although easily cored, tends to have rotten centers and indistinct rings, making ring counting difficult. In addition, Sitka alder (*Alnus sinuata*) was cored on the youngest surfaces and Sitka spruce (*Picea sitchensis*) on the older surfaces. Trees sampled for foliar analysis were cored to determine ages, but these trees were randomly selected and not used to date the moraines.

Trees were chosen for age dating primarily by trunk size or by stunted effects due to early establishment on surfaces close to glacial fronts. Trees were cored on the top, distal, and proximal sides of the moraines. Trees in low-lying areas and in abandoned intermoraine outflow channels were cored to determine the age of channel abandonment. Shrubs and trees were cored as close as possible to their root crowns using 15, 30, 45 or 61 cm Haglof increment corers (5.15mm core diameter; 3 thread) depending on size of tree (Forestry Suppliers, Inc, Jackson, MS). A small pit was dug at the base of large trees to allow for swinging the corer handle, and in some cases, the bore handle was intermittently removed between turns to allow for minimal height above the mineral surface. All cores were collected perpendicular to the trunk with the aid of a carpenter's level in order to facilitate tree-ring width determinations for future studies. Since the corer was not slanted downwards toward the base of the tree, a sampling height-age correction factor for cores taken above the root crown was determined for black cottonwood and spruce.

Table 3.2 shows the heights and ages of five black cottonwood seedlings removed from leaf transect site A3, located on the outwash plain. These saplings were cut at their bases to determine ages

and measured for height. These results indicate an average growth rate of $4.4 \pm 0.5(\text{SE}) \text{ cm}^{-1}$ during the first 14 years of growth and an average increase in height of 0.2 yr cm^{-1}

A coring height correction factor for spruce was not determined at Exit Glacier, due to the lack of available samples on dated surfaces from aerial photography; however, available literature from various studies were researched to determine the best possible correction for this study. Correction factors for spruce ranged from 0.1 yr cm^{-1} to 1.0 yr cm^{-1} (Heusser, 1956; McCarthy, 1985; McCarthy et al, 1991) in the Canadian Cordillera while studies in Alaska near Exit Glacier used sampling height-age correction factors for spruce ranging from 0.3 yr cm^{-1} to 0.5 yr cm^{-1} on the Blackstone-Spencer Ice Complex and Harding Icefield, respectively (Crossen, 1997; Wiles, 1992). Wiles (1992) had applied the 0.5 yr cm^{-1} coring height correction factor for spruce collected at Exit Glacier, but these results were from the Western side of the Harding Icefield where temperatures are warmer and precipitation is less than those found at Exit Glacier (Wiles, 1992). In comparison, Crossen (1997) applied a correction factor for spruce of 0.3 yr cm^{-1} from a region with more similar temperature and precipitation ranges to Exit Glacier.

Therefore, sampling height-age correction factors of 0.3 yr cm^{-1} and 0.2 yr cm^{-1} were applied to spruce and cottonwood trees, respectively, based on the height they were cored above the mineral surface. This correction factor was not applied for tree-ring dates from previous authors, since sampling heights were unknown.

A total of 263 unique cores from 207 trees were collected, and 5 cottonwood seedlings were cut for this project, following techniques outlined in Stokes and Smiley (1968) and Agee and Huff (1986). See Appendix A for a complete list of all cores obtained in this study. The sampling occurred between July and October 1999. Every effort was made to core the pith of the tree, but in some cases the pith could not be reached after multiple corings. In other cases, the center of the tree was found to be rotten. Estimates of missing rings were not conducted in this study, since ring widths may vary tenfold at different stages of a tree's growth, making estimations unreliable (Campbell, 1981). In-field ocular estimates of proximity of core to pith were made and recorded.

Once cores were extracted from a tree, they were placed in wooden grooved core holders of white pine, glued and taped into place so that tracheids or vessel elements were mounted upright to the mounting block surface (Agee and Huff, 1986). Coring bore shafts were lubricated with beeswax before insertion into the tree to alleviate the risk of bit locking, while the bore shaft was lubricated with WD-40® for ease of extraction. Mounting cores in the field using blocks instead of the more traditional straws allowed for better control over core orientation and provided for stable transport from the field and during the drying process (Juday, J., personal communication, April 1999). Care was taken to obtain the pith of the tree, sometimes necessitating multiple cores per tree. However, on larger cottonwood trees greater than 50 cm DBH, this was often difficult to achieve. One hundred and seventeen core blocks were labeled in the field and allowed to air dry. Each tree position was also recorded using differentially corrected CA code GPS to enable long-term analysis of stands and expedite navigation through the thick canopy (see Chapter 3.2.4).

3.2.1.1 Tree Core Preparation

Cores for spruce and alder were prepared for analysis using standard tree-ring dating techniques (Stokes and Smiley, 1968). The diffuse-porous wood of cottonwood can make age determination difficult, so some modifications were made to help discern the rings of this species. Unique preparation of the cores included the following:

- Sanding cores using a range of sandpaper and polishing cloth up to 3000 grit (3M Co., Columbus, OH)
- Staining of increment cores in solutions of 1% phloroglucinol / 95% ethanol and 50% solution of HCL, then rinsing in tap water after a 30-second soak time (Patterson, 1959; Forestry Suppliers, Inc, 2000). This procedure allowed for readily discernible rings by staining the lignin of the wood a red color and leaving the cellulose unstained (Patterson, 1959).

- Cutting core block lengthwise to expose more of the core.

3.2.1.2 Tree Core Interpretation and Archiving

Tree rings were counted by two different observers (Kate Brainard, Palmer Field Station assistant and this researcher) using a dissecting scope under varying magnification levels (10X – 100X). Cores were viewed under wet and dry conditions to maximize visibility of rings. Year of first growth was counted as zero. Tree cores were subjectively graded on a scale of difficulty: 1) = Excellent (pith clearly seen); 2) = Moderately difficult to read (pith seen or estimated within 5 years); 3) = Poor quality (pith not seen – minimum of tree age given).

Judging by these criteria, 61% of the cores were excellent, 31% were moderately difficult, and 8% were of poor quality, sometimes requiring additional cutting and preparation. Thirty-eight percent of the cores required only one count; 51% required 2 counts; 31% required 3 counts; 2% required 4 counts; and 2% required 5 counts. If there was a 5% difference between first and second count, a third count and sometimes a fourth count was done. It was up to the observer to pick the best and most reliable estimate of age. Thirty-two of the 268 sampled trees (12%) were recut through the long axis of the core and recounted. Sixty-eight percent of all the mounted cores had a visible pith. Of those cores where a pith was not seen, 61% of those cores were judged close to the pith (< 5 rings).

Missing piths were not estimated in this study. Few people conduct such analyses probably due to tilting of the corer down toward the root crown. Refer to Norton et al. (1987) for a description of techniques for conducting such analyses.

Since multiple cores from different trees could be found on the same core block, each core block was labeled with the unique tree identification code, sampling date, observer, diameter at breast height (DBH) in cm, tree type ((Tree-age (TA), Tree Leaf trees (TL), Canopy Test trees (CT) or those trees sampled for Ecesis intervals (E)), allowing for cross-reference to GPS coordinates.

3.2.1.3 Ecesis

Ecesis estimates or colonization times for conifers have been determined by various authors. A 25-year ecesis period for spruce in North America was used by Sigafos and Hendricks (1969) and Crossen (1997) for spruce at Portage Glacier. Wiles (1992) estimated a 15-year ecesis period for Portlock Glacier located on the western side of the Grewingk Glacier complex and applied that estimate to spruce sampled at Exit Glacier (Wiles, 1992). Heusser and Marcus (1964) used 10 years as an ecesis estimate for the moraines at Lemon Creek Glacier in southeast Alaska, while other available tree ecesis data from the Canadian Cordillera suggest a range from 5 to 60 years (McCarthy and Luckman, 1993). Limited information can be found in the literature to document ecesis intervals for cottonwood or alder, both fast-growing species. Both Crossen (1997) and Wiles (1992) used a 0-year interval for cottonwood and alder. Ecesis estimates for this study were determined for both spruce and black cottonwood trees, the most common colonizer on the Exit Glacier forelands.

On a clearly defined moraine, 500 meters from the present terminus (Fig. 3.3), an August 1950 U.S. Geological Survey mapping vertical aerial photograph shows moraines being formed at the terminus. Five of the apparently largest cottonwood trees growing on the distal slope of a push moraine were sampled at their root crown (Fig. 3.3). The oldest cottonwood was dated to 1956, implying a 6-year lag for colonization.

Along a series of moraines extending out from the terminus, the relative time interval between the tree age of the oldest cottonwood and spruce growing on the same moraine was calculated to determine the ecesis interval for spruce. This method used the difference between the ring count of spruce and cottonwood, then added the 5-year interval for cottonwood to arrive at an estimate for ecesis interval for spruce. Utilizing 23 pairs of spruce/cottonwood trees (Ahlstrand, 1983; Wiles, 1992, and this study), an average relative age difference of 26 years $\pm$ 2.6 (1SE) was determined. Crossen (1997) also determined ca. 25-year ecesis interval for spruce near Portage, Alaska.

Based on these data, the ecesis interval used for cottonwood in this research is ca. 5 years, while the ecesis interval for spruce is ca. 25 years. Alder may colonize simultaneously and soon after deglaciation (Crossen, 1997), and its ecesis interval is estimated to be 0 years. These estimates should be considered a minimum, since periods of the colonization of trees may be biased due to the current period of warmer summers (McCarthy and Luckman, 1993). Since ecesis intervals in earlier studies at Exit Glacier assumed 15 years for spruce (Ahlstrand, 1983; Wiles, 1992), tree-ring counts from those studies will be recalibrated by adding an additional 10 years when used here.

3.2.2 *Radiocarbon Dating*

Radiocarbon samples collected from this and previous studies along the Exit Glacier forelands are presented in Appendix D. A wood sample from an exposed fluvial deposit adjacent to the Exit Glacier outwash plain was collected to test Neoglacial advances, while two ash samples from an exposed till were collected from outside the LIA maximum extent (Fig 2.3).

For this study, air-dried samples were dated at Beta Analytic, Inc., Miami, Florida. Each sample was pretreated with acid washes to remove organic sediment. Then, depending on the amount of remaining sample available, either standard radiometric analysis or accelerator mass spectrometry (AMS) technique was applied (Appendix D). Dates are reported in both conventional radiocarbon years (BP) and calibrated years (AD) using the INTCAL98 calibration database (Stuiver et al., 1998).

3.2.3 *Historical and Photographic Records*

The historical and photographic record for the Seward area spans a time of at least 100 years. Mining and trapping efforts in the Resurrection River drainage near Exit Glacier have been documented since 1907 (Cook and Norris, 1998); however, the lack of major commerce, in the form of either mining or transportation corridors along the Resurrection River, west of the Alaska railroad, has resulted in few photographs of the area (Norris, F. personal communication, 2000). An intended component of this study was to research and compile photography of the terminus region and Exit Glacier forelands to enhance and support earlier efforts to map the recession using tree-ring dating techniques.

Many archival resources from around the state were used to complete this research. The Alaska Resource Library, Anchorage, Alaska, provided access to geologic reconnaissance maps of the Kenai Peninsula (Martin et al., 1915). The Seward Library Archives provided a ground oblique taken of Exit Glacier ca. 1920. The National Park Service office in Seward provided unpublished photographs from various private and park collections, including a ca. 1935 oblique of Exit Glacier. The U.S. Forest Service Forestry Science Lab and Chugach National Forest Supervisor's Office, Anchorage, Alaska, supplied access to aerial photos from 1961, 1974, 1991, 1993 and 1998. The archives of the Anchorage Museum of History and Art provided unpublished aerial and ground oblique photographs from the Steve McCutcheon collection (1948 and 1968). The U.S. Geological Survey, Earth Science Information Center (ESIC), Anchorage, Alaska, provided access to indices from 1950 and 1973 aerial photography. The GeoData Center, University of Alaska Fairbanks, Geophysical Institute, provided aerial obliques from the Post collection (1984) and N.A.S.A. Alaska High Altitude Photography Project (AHAP) series (1978; 1984). The U.S.D.A., Forest Service, Engineering and Aviation Management, Juneau, Alaska, provided digital imagery from 1997. Aeromap US Inc., Anchorage, supplied color aerial photography from 1996; Bureau of Land Management, Cadastral Survey provided aerial photography from the summer of 1999; City of Seward, fall 1995; U.S.G.S., Water Resources Division, Anchorage, (Spring 1983 obliques) and Alaska Department of Transportation, Department of Highways (1985, 1995). National Resources Conservation Service, Palmer, Alaska, provided digital orthophoto quarter quads from 1996 and 1997. All photographs used in this research are listed in Appendix B.

3.2.4 *Mapping Efforts Using GPS and GIS*

Even though Exit Glacier is one of the most popular tourist destinations in Alaska, no detailed topographic map has been constructed of the glacial forelands. Previous studies used hand-drawn maps and small scale photography (1:40,000 scale and higher) to map moraines but often produced confusing and inaccurate terrain ages when compared to glacial landforms on the ground. Dendrochronological studies at Exit Glacier (Ahlstrand, 1983) relied on collecting cores primarily from along the Exit Glacier

road which provided researchers a fixed reference, but led to concentrated tree-coring efforts along a transect slicing through more of the Exit Glacier lateral moraine features than terminal ones, and produced confusing ages. In addition, sampling done away from the road was prone to errors in mapping locations and landforms, especially in dense alder canopy cover. In this study, therefore, preference was given to the use of Global Positioning Systems (GPS) for navigation and precise locations of study sites, as well as the use of Geographic Information Systems (GIS) to produce high resolution maps using available aerial photography to accurately map moraines and provide detailed images of the glacial forelands.

3.2.4.1 GPS Collection

A C/A code L1 frequency Trimble Pro XR GPS mapping receiver (Trimble, Inc., San Jose, CA) and a TDC-2 handheld datalogger were used to record all sample site locations, tree coring sites, tree leaf transects, moraine features and ground photo-control point features for scanned photo georeferencing.

All point features were collected for a minimum of 10 positions (1 position/second), while line features such as moraines were collected at a rate of three or five seconds. Optimized times for data collections were made possible by use of QuickPlan, a utility within Pathfinder Office© (Trimble, 1999), that allows for planning satellite availability from satellite almanac data. Files were transferred each evening from the datalogger to a laptop computer and checked for completeness using Pathfinder Office software (ver 2.51; Trimble, 1999). All features were then differentially corrected against a base station data provider located in Anchorage (Accupoint, Inc., Anchorage, AK) – a baseline difference of 115 km. Data was then combined into feature files and exported as Arc/Info (ESRI, Inc., Redlands, CA) coverage's for display in a GIS.

3.2.4.2 Aerial Photo-Control Points

All known aerial photographs taken of Exit Glacier were analyzed for quality and appropriate scale to depict the entire glacial forelands. A natural color, 1:14,000 scale contact vertical aerial print shot in June 1996 by Aeromap U.S., Inc., was selected for its overall quality, scanned at 1000dpi and enlarged to 3X photo scale for optimum photo quality for recording of visible ground landmarks,

including large boulders, stream intersections, shrubs, and various infrastructures in the tourist areas.

Objects less than 3 meters across were possible to identify clearly on the image.

Once a landmark was identified on the photo, a coordinate was collected over that point using a Pathfinder Pro XR GPS receiver. Point features were collected for a minimum of 10 positions at a logging rate of 1 position sec^{-1} . One hundred three control points were collected with an average horizontal precision of 1 meter (STD.: 0.68; variance 0.461) and a Position Dilution of Precision (PDOP) range of 2-5.4. PDOP is an assessment of satellite geometry overhead and is correlated with precision of data. A PDOP value below 6 is considered adequate for sub-2 meter positioning with these types of receivers. Earlier tests with this equipment over 2nd order survey control in Seward provided sub meter positioning accuracy with less than 1 minute occupation times (Cusick, unpublished tests – Seward). Differentially corrected positions were then exported as ARC/Info ver. 7x (ESRI, Inc., Redlands, CA) decimal degree coverage's to provide photo control.

A selected set of 55 photo control points was then used to georeference the 1996 scanned true color aerial photo to real-world coordinates using Image Warp extension (McVay, 1998) and ArcView© 3.1 (ESRI, Inc., Redlands, CA) on a Microsoft Windows © NT PC. A second-order polynomial model was applied for a root mean squared (RMS) error of 1.3m across all points. Image was then warped to an Alaska Albers projection (NAD27 Datum). Care was taken to ensure that selected reference points were placed in areas of even terrain and areas of high slope were ignored.

3.2.4.3 Map Construction in GIS

Once a high resolution photo basemap was constructed, it then served as a base for georeferencing all other images processed during this study. Selected vertical aerial photographs (Appendix B) were scanned at 600-1000 dots per inch (dpi), 256 or true color, depending on format, and stored as Tagged Image File Format (TIFF) uncompressed images for a resultant file size ranging from 45MB to 95 MB.

Georeferencing of additional imagery was conducted using Image Warp extension (McVay, 1998) and ArcView© 3.1 (ESRI, Inc., Redlands, CA) on a Microsoft Windows © NT PC by identifying the same features available on each image and warping the secondary image to Alaska Albers projection. Photo-control points were selected for each photo to ideally represent the best “fit” dependent on the scale and quality of photography. For example, the 1973 1:64,480 scale photograph (Appendix B) was ideally suited to provide a small scale map of the forelands due to lack of contrast and was georeferenced using photo-control scattered around the forelands and along Resurrection River. In contrast, the 1985, the 1:8,000 scale photograph flown by ADOT (Appendix B) was ideally suited for large scale analysis of terminus position and vegetation analysis, and therefore photo-control was centered within a 200 m radius from the visible and often objects smaller than a meter in size could be determined.

Maps were constructed in three ways: 1) digital photography and heads-up digitizing ice-margin positions using ArcView© 3.1 (ESRI, Redlands, CA), 2) transferring landmarks on oblique aerial and ground photography in relation to the glacier terminus, and 3) in-field collection of GPS positions while traversing moraine features. Digital maps produced from georeferenced photos could then be overlaid with graticules (measured latitude and longitude grids) and used in the field in conjunction with hand-held military Y-code Precision Lightweight Global Positioning receivers (PLGR's) to enable highly precise navigation to study sites, even in areas of thick alder forests.

In 1999, with funding support from Kenai Fjords National Park, a multi-agency mapping project was initiated by the NPS Alaska Support Office to construct a 0.5 meter digital elevation model (DEM), digital orthophotos and 0.5 meter contour topographic map of the Exit Glacier forelands. Appendix C presents a complete description of the map development process and 0.5 m contour map.

3.2.5 Soil Sampling and Analysis Methods

Detailed morphological descriptions and chemical analysis of glacial moraine soils were conducted as part of this study to assess soil nutrient availability for plants collected for foliar analysis, map soil development and relate patterns of plant nutrient concentrations to soil nutrients.

3.2.5.1 Site Selection and Field Sample Collection

Accurate and precise descriptions of soil profiles can be achieved only with a thorough understanding of pedological concepts and field experience with local soils and landscapes. Because there is an element of subjectivity in describing soil profiles, consistency is vital (Robertson et al., 1999), to achieve calibration with laboratory data. The needed experience and consistency were achieved through the field assistance of Dr. Chien-Lu Ping and Gary Michaelson (Plant, Animal and Soil Science Dept., UAF Palmer Field Station) and by use of standard methods of soils description and sampling according to Soil Survey Manual (Soil Survey Division Staff, 1993). These procedures assured consistent results across all moraines and provided a long-term monitoring framework upon which further studies may build.

The soil profile description and soil samples from each horizon were obtained on October 18 and 19, 1999, from 12 pits at 11 sites along the series of recessional moraines described in Chapter 4 and can be seen in Table 3.1. The main focus of site selection was to keep variability of minor relief factors and parent material to a minimum, while maintaining the desired uniform relationships between the soil site position and the leaf transect site. The latter was especially difficult, and the conditions were only partly met. For example, the mean distance to transects was 0.9 m, but for site G, the distance between leaf transect and soil pit was 40 m. Sampling locations were identified by the leaf transect site ID and corresponded to dated landforms determined by others and this study (Table 3.1). Locations correspond to minimum landform age (year AD) and include site A3 (1980), B (1951), C (1926), D (1914), E (1899), F (1894), G (1891), 1889 (1889), H (<1869) and I (<1748) and site K (ca. 4000 BP). Nine of these sites corresponded to a leaf transect location, while two of the sites (1889 and K) were sampled exclusively for soil characteristics (Table 3.1). See Chapter 4 for details on the basis for landform ages.

Site selection, profile description and field data collection were carried out by Dr. Chien-Lu Ping and Gary Michaelson from the Plant, Animal and Soil Science Department, UAF Palmer Field Station. Soil morphology, and properties including horizon and thickness, color, texture, structure, consistence, roots and degree of organic matter decomposition, were described to a depth of 1 meter after excavation

using shovels. Soil pits D and G were cut into the north-facing banks of Exit Creek, removing an outer portion of each face (0.5m) to access unaltered soil material.

Landscape characteristics such as landform, slope and aspect, drainage class, vegetation, ground features, and parent material were described for each location and recorded in field notebooks. Major soil horizons were then visually delineated and recorded by depth. Terminology and methodology for delineating horizons within a soil profile and for describing the morphological characteristics (depth range, color, structure, consistency, texture, reaction, and horizon boundary characteristics) followed those described in Soil Survey Division Staff, Soil (1993). See Appendix E for complete soil profile descriptions including photographs at each sampling location.

A representative soil sample was obtained from each horizon at the sampling locations seen in Table 3.1; Fig. 4.1. Soils were extracted using a knife, with organic surface soils being separated from underlying mineral soils where both were present. In situ bulk density was determined for 20 horizons with an Ely Volumeter by extracting a core (45 or 60 cc) of soil. Sampling frequency depended on type of soil – some soils contained large stones and cobbles which prevented an adequate sample. Bulk densities of organic horizons were obtained by excavation of a section of the organic layer using a knife and measuring length, width and height of sample. All samples were placed in plastic bags, labeled and stored in a cooler. Average temperatures for both days was 6.5° C (min: 4° C; max: 9° C) ensuring adequately cool conditions for sample storage (Ping, C. L., personal communication, 2000). Samples were transported to Palmer Field Station and refrigerated until analysis.

Photographs of all sites were obtained with 35mm cameras in analog and digital form. Accurate coordinates (<2.0 meters horizontal) of all soil pits were recorded using C/A code GPS equipment and differentially corrected following methods described in Section 3.2.4. Color was determined on moist samples within 1 day of collection using the Munsell Color Notation (Munsell Color Co., Baltimore, MD).

3.2.5.2 Laboratory Methods – Soils

All laboratory analyses were carried out at the University of Alaska Fairbanks, Soil and Plant Analysis Laboratory at the Agricultural Experiment Farm near Palmer, Alaska. Soil mineral and organic horizons were assigned unique sample numbers and stored in a cooler until being processed within 3 days of collection. Field-moist samples were weighed, then air dried (at ambient laboratory temperature and humidity) on plastic trays to determine soil water content. Mineral soil samples were passed through a 2 mm sieve to obtain representative subsamples and to exclude gravel and larger particles. After air-drying, mineral and organic samples were again weighed to the nearest 0.1 g, then sieved through a #10 (2mm) sieve by 2-10 minutes of hand crushing and grinding. Large woody organic fractions not passing through the sieve were weighed separately.

3.2.5.2.1 Physical Characteristics

Soil structure influences ecosystem processes by controlling the storage and flow of water and gases. Soil physical characteristics, such as gravel size distribution and particle size distribution, affect soil structure stability and water storage. Bulk density is correlated with many soil processes and affects water infiltration and movement, as well as aeration and root penetrability (Robertson et. al., 1999).

Coarse fragments obtained from soil horizons larger than 2mm were partitioned into USDA standard gravel classes using a mechanical shaker (methods in; Michaelson et al., 1993), with sieves numbering from #1 (63.5mm) to #10 (2mm) and shaken for 10 minutes. Gravel classes were then weighed to the nearest 0.1 g and summed to provide total % gravel by weight for each horizon sample. Weight percent of gravel was converted to volume percent gravel for determining coarse fragment totals for each mineral horizon. Volumes of gravel and < 2mm sieve soil were calculated by dividing the weights by the bulk densities, then percent volume gravel was calculated using this formula:

$$((\text{wt. gravel} / \text{BDR}) / ((\text{wt. gravel} / \text{BDR}) + (\text{wt. <2mm soil} / \text{BDS}))) * 100$$

where

Weight is expressed in grams

BDR = Bulk density of rock = (2.65 g / cm³)

BDS = Bulk density of soil = (1.3 g / cm³)

Particle size distribution analysis, which determines percentage of sand, silt and clay for each mineral horizon, was determined using the Bouyoucos-Hydrometer Method (Day, 1965). This procedure used approximately 50 grams of 2mm sieved soil (oven dried to 105⁰ C for 3 hours). The dispersed soil samples were allowed to settle in water and the various particle sizes that remained in suspension were determined with a soil hydrometer at various times as they settled according to Stokes Law. Textural classes of the soils were then determined from a USDA textural triangle (Brady, 1974).

Several methods were used to determine bulk density for mineral and organic horizons depending on soil structure in the field. Most mineral horizons were sampled in the field using the intact-core method (Soil Survey Division Staff, Soil, 1993), while organic layers were excavated using a knife and recording volume (height width; length). Each bulk density sample was oven-dried at 105⁰ C overnight and weighed to the nearest 0.01g. Results presented are in g cm⁻³ and calculated by this equation:

$$\text{Bulk density (g cm}^{-3}\text{)} = W / V$$

where

W = oven-dried soil weight in grams

V = volume of core or excavated surface in cm³

Mineral soils not estimated by the intact-core method in the field due to large stone or cobble fractions were estimated from a 2nd order polynomial regression of bulk density vs. % carbon for samples of comparable texture, since amount of carbon in samples relates to density of samples (Michaelson, G., personal communication, 2000). The formula used for estimating bulk density in sites A3-I was:

$$y = 0.942x^2 - 1.6735x + 2.0664 \quad (r^2 = 0.427)$$

where

y = oven-dry bulk density (cm³) of similar mineral horizons

x = % carbon in similar mineral horizons

Regression estimates of missing bulk density horizon data for the K site were treated separately due to the much older substrate. Values for determining the equation were taken from neighboring horizons and determined using the following formula:

$$y = 0.0006x^2 - 0.0334x + 0.939 \quad (r^2 = 0.470)$$

where

y = oven-dry bulk density (cm³) of similar mineral horizons

x = % carbon in similar mineral horizons

For cross-site comparative purposes, Exit Glacier mineral soil nutrient data were converted to an areal basis (g m⁻²) for particular sampling depths. Although soils were sampled and described by genetic horizons for utility in describing pedogenesis, this method limits comparisons of soil development through time. Horizons were converted to two separate mineral depth increments (0 – 10 cm below surface and 10 – 100 cm below surface) using appropriate proportions of soil horizon thicknesses. Field ocular estimates of areal percentages of coarse fragments (including cobble, stone and erratics) and gravel included in the

sample were then used to correct for soils (<2mm). Proportions of soil nutrients by horizon were then converted to areal basis by multiplying by bulk densities and adding these proportions through the entire pedon. Note that areal basis calculations become increasingly sensitive to rock content as rock content increases, and correspondingly less sensitive to bulk density. Since some locations at Exit Glacier recorded rock content nearing 70% in a soil profile (Table 5.1; App. E), this is certainly an impediment to providing accurate nutrient storage data. Nevertheless, by accepting to provide some nutrients on an areal basis provides cross-site comparisons and better ensures the comparability of long-term data sets (Robertson et. al., 1999).

3.2.5.2.2 Analytical Control Methods

All chemical properties determined for soils were compensated for analytical bias and accuracy by the use of blanks, reference materials and laboratory replicates placed throughout each "run." A run is defined as a set of 15-30 samples prepared and analyzed together. These determinates for quality control were used depending on the types of analyses and provided a means for assessing and documenting accuracy of results.

Laboratory blanks or reagent blanks were incorporated at the beginning of the laboratory analyses. These monitor reagent purity, sample handling and overall laboratory procedure (Robertson et. al., 1999). Blanks represented 2% - 6% of the samples during any particular run.

In addition to reagent blanks, various reference materials or external standards were used to calibrate instrumentation, determine analytical precision and accuracy of the instrumentation, as well as analytical bias caused by the analyst or measurement protocols. These quality control standards were matched with the appropriate matrix and analyte concentration of the samples found in a run; however, extremely low concentrations of elements in glacier soils and plant tissues were at times below the certified reference values. In-run reference standards analyzed as "unknowns" were monitored during analyses for variability from the certified values. ICP analyses of elements were considered sufficiently precise if values were within 5% of the 95% certified values. Other in-lab standards include those

developed by the UAF Palmer lab, as well as those provided by National Institute of Standards and Technology (NIST). Reference soil Buffalo River Sediment (SRM2704) was used for available nutrients; NANCY standard as an in-lab standard for all Mehlich extractions; Peach (SRM1514) and Apple (SRM1515) reference standards were used for plant tissue digests analyzed on the ICP; Pine (SRM1575) and Apple (SRM1515) were used as unknowns for total C and N analysis using the LECO® analyzer, as well as EDTA and CHNS for LECO® calibrations during soil organic and soil mineral analyses for total carbon and nitrogen.

Laboratory replicates, using field samples, were used to monitor the precision of the overall procedure and analysis scheme. At the beginning of each analysis, 10% of all samples were randomly chosen, prepared and analyzed along with other samples. Precision of these replicates was assessed by calculating a CV or coefficient of variation. The formula for CV is as follows:

$$CV = (s/x) \times 100$$

where

s = standard deviation

x = mean

In cases where CV exceeded 10% for replicates, the analyses were deemed too imprecise and sample runs were duplicated. Additionally, samples recognized as outliers were duplicated by processing as normal samples, placed at the end of each run and tested again for field quality and analysis methods.

3.2.5.2.3 Chemical Analyses

Various chemical properties were determined for both organic and mineral horizon samples collected from the Exit Glacier chronosequence. Soil organic matter (SOM) total and extractable nitrogen, soil pH, cation exchange capacity, as well as available nutrients (P, K, Mg, Ca, B, Cu, Fe, Mn

and Zn) and determination of soluble Fe, Al, Si and Mn were all determined using standard methods at the UAF Palmer Experimental Station near Palmer, Alaska (Michaelson et al., 1993).

Prior to all chemical analyses, a subsample of the <2mm soil fraction from each horizon (organic and mineral) was ground for approximately 2 minutes to a fine powder (40-60 mesh) size using a ball mill. Subsamples were then placed in 150 ml propylene jars. These subsamples were used for total carbon and nitrogen and loss-on-ignition tests (estimation of total organic matter) and Fe/Al (Dithionite-Citrate extraction) tests.

Soil organic matter (SOM) is important as a major pool of most nutrients, especially nitrogen, and it has a relatively large cation exchange capacity, as well as contributing to good soil structure, aeration, root penetration and control of soil pH (Robertson et. al., 1999). Soil nitrogen availability limits plant growth in many terrestrial ecosystems. Organic matter was determined using the loss-on-ignition method, while both C and N were determined using the dry (Dumas) combustion method.

Organic matter contents of ball milled soil subsamples (minerals and organics) were estimated with the loss-on-ignition method (LOI) by calculating mass loss following high-temperature combustion (400⁰ C) in a muffle furnace (Michaelson et al, 1993). The calculation of LOI is:

$$\% \text{ Loss-on-Ignition} = \frac{[(\text{OD soil} + \text{Twt}) - \text{Twt}] - [(\text{I soil} + \text{Twt}) - \text{Twt}]}{[(\text{OD soil} + \text{Twt}) - \text{Twt}]} \times 100$$

where

Twt = Tare weight of crucible (g)

OD = Oven dried soil weight – 105⁰ C overnight (g)

I = Ignition weight of soil - (400⁰ C) overnight (g)

The LOI method estimates carbon content by measuring mass loss following high-temperature combustion. The analysis is easily performed, but there are serious shortcomings. LOI measures volatilization of all material including water retained in clay complexes, and organic matter in various stages of decomposition can be erroneously interpreted. In such cases, LOI can be checked against a dry-combustion method to determine soil C content independently of OM.

Concentrations of total carbon and nitrogen (% dry wt.) were determined using a LECOTM CHN 1000 infrared gas analyzer. To ensure accuracy and precision, the instrument was calibrated using EDTA and CHN (LECO standards with known fractions of C, H, and N). Ball milled, air dried samples were placed in small crucibles and ignited at 1000⁰ C, while emitted CO₂ and N gases were measured. Results were read out directly in weight % and expressed on an oven-dry basis. Ten percent of all field samples were run as laboratory replicates and assessed for precision. Nitrogen concentrations were often below the CHN values; however, no other standard was available for the extremely low values encountered in these young soils.

Soil pH is a measure of hydrogen ion activity of the soil solution. Soil pH was measured for organic and mineral soils in a 1:1 soil-water ratio mixture using a pH electrode (Michaelson et al., 1993). Approximately 10 g of air-dried soil 2mm sieved soil was placed in a small cup with 10 ml of de-ionized water, stirred thoroughly and restirred after 30 minutes, then measured with an OrionTM pH meter. Electrodes were standardized using commercial buffer standards (pH 4.0 and pH 7.0) and rinsed with distilled water between each measure. Values were reported to the nearest 0.1 pH units.

Cation exchange capacity (CEC) is the sum total milliequivalents (meq) per gram soil (OD) of exchangeable cations that a soil can adsorb. Generally, this involves flooding the exchange sites primarily on clay and organic matter surfaces of a soil with ions (NH₄⁺) from an extractant (ammonium acetate; pH 7). The cations forced off of the soil exchange sites can then be measured in solution as exchangeable cations, and the amount of ammonium retained by the soil is equal to the CEC. Total CEC's were

determined on air-dried 2 mm sieved soil (mineral and organic) samples using an ammonium acetate (NH_4OAc) pH 7.0 automatic extraction method and steam distillation-titration of the ammonium (Michaelson et al., 1993). A mechanical extractor (Centurion Instruments, Lincoln, NE), was used to extract samples. Each run of samples included 22 soil samples, one reagent blank (5% of run) and one laboratory standard (NANCY silt loam) (Michaelson et al., 1993). A subsample of extraction solution was then analyzed for extractable cations (K, Ca, Mg and Na) using Inductively Coupled Plasma Optical Emission Spectrometer (ICP-OES Optima 3000, Perkin-Elmer Co.). Stock standards and reagents were developed by Palmer lab personnel, and ICP-OES methods were used according to Analytical Methods for Atomic Absorption Spectrophotometry (Perkin Elmer, 1982).

All CEC and extractable cation concentrations (K, Ca, and Mg) are expressed on a gravimetric basis as element moles of charge ($\text{cmol}_c \text{ element} / \text{kg (OD)}$) and on an areal basis (g element m^{-2}). Cation concentrations of Na were not reliable across all 60 samples due to saturation of the instrument and/or contamination of reagents or field samples and, therefore, will not be presented in this report. Areal calculations are as follows:

$$\text{g element} / \text{m}^2 = C_g \times \text{BD} \times \text{SD}$$

where

C_g = element mass on gravimetric basis as ppm element / soil

BD = bulk density as g soil / cm^3 soil

SD = sample depth in meters

Measurement of extractable nitrogen is perhaps the most common and best means available to assess nitrogen fertility, related as it is to both the size of the labile soil organic matter (SOM) pool and the activity of the organisms responsible for the oxidation (Robertson et. al., 1999). Extractable N in its available forms (ammonium (NH_4^+), nitrate (NO_3^-)) was determined for organic and mineral soils by 2-N

KCl extraction (Bremner, 1982), followed by colorimetric determination on an autoanalyzer (Orion Scientific Instruments). Results were recorded on a gravimetric basis as NH_4^+ -N (ppm) and NO_3^- -N (ppm), and totaled to provide extractable N (ppm). Total extractable N was also converted to an areal basis and results are expressed in (g N m^{-3}).

Total phosphorus (P) was determined for all soil horizons (including organic layers). Phosphorus is a major element in SOM and is derived from the weathering of minerals in parent rock material. It is usually the second most limiting nutrient for terrestrial primary production (after nitrogen) (Robertson et al., 1999). Total P was determined using a nitric-perchloric acid digestion (Michaelson et al. 1993) and the digest analyzed using Inductively Coupled Plasma Optical Emission Spectrometer (ICP-OES Optima 3000, Perkin-Elmer Co). Results of total P in soils are expressed on a gravimetric basis only (OD wt % P). Since much of the phosphorus is tied up in minerals and is inaccessible to the plants (Michaelson, G., personal communication, 2001), soil plant-available P was extracted using Mehlich 3 extraction (discussed below).

In order to compare foliar tissue mineral nutrients across the chronosequence at Exit Glacier with soil data, several of the same minerals were determined for all the organic and soil horizon data. Extractable or labile boron (B), calcium(Ca), copper(Cu), iron (Fe), potassium (K), magnesium (Mg), manganese (Mn), sodium (Na), phosphorus (P), sulfur (S) and zinc (Zn) were determined for all soils (including the organic horizon) using a Mehlich 3 extraction (pH 2.5) method (Mehlich, 1982) and analyzed using Inductively Coupled Plasma Optical Emission Spectrometer (ICP-OES Optima 3000, Perkin-Elmer Co.). Boron, sodium and sulfur results were difficult to maintain with a high degree of confidence ($\pm 10\%$ from reference standard certified values) probably due to sample contamination and, therefore, rejected following quality control standards described above. Only calcium(Ca), copper(Cu), iron (Fe), potassium (K), magnesium (Mg), manganese (Mn), phosphorus (P) and zinc (Zn) results will be presented. All concentrations will be expressed in ppm on an oven dried (OD) basis.

The elements Fe, Al, and Mn are released in various forms by soil forming processes (Blume and Schwertmann, 1969). Iron and manganese are plant nutrients, and their accumulation in vegetation must be considered. This is especially true for Mn, since a high proportion of the total Mn participates in the biocycle (Blume, Schwertmann, 1969). Relative degree of soil weathering can be implied from the amounts and forms of these elements present in the soil profile. Various pedogenic forms of Fe, Al, Si and Mn can be determined by extraction with Na pyrophosphate (humus bound forms), acid oxalate (allophanic + humus bound + amorphous) and dithionite-citrate (allophanic + humus bound + amorphous + crystalline). Soluble Fe, Al and Mn were extracted by dithionite-citrate ($Fe_d; Al_d; Mn_d$; (Mehra and Jackson, 1960)). Soluble Fe and Al were extracted by Na pyrophosphate ($Fe_p; Al_p$; (McKeague and Day, 1966)). Soluble Fe, Al and Si were also extracted by an ammonium oxalate solution ($Fe_o; Al_o; Si_o$; (Schwertmann, 1964)). Units are expressed in percentage (OD weight).

Figure 3.1 . Leaf sampling locations for Sitka alder and black cottonwood, 1998.

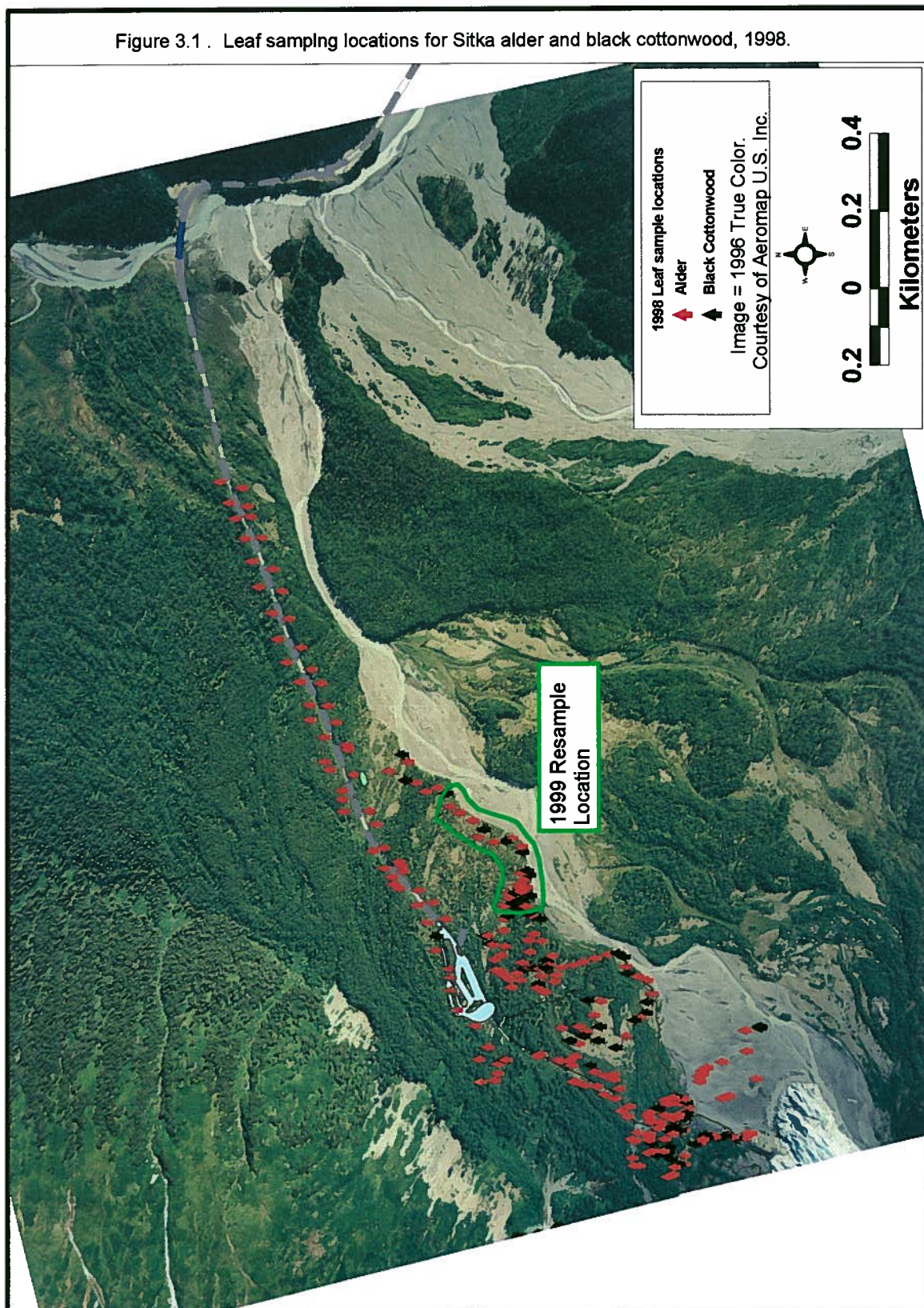


Figure 3.2. Leaf sampling transects and soil sampling locations, 1999.

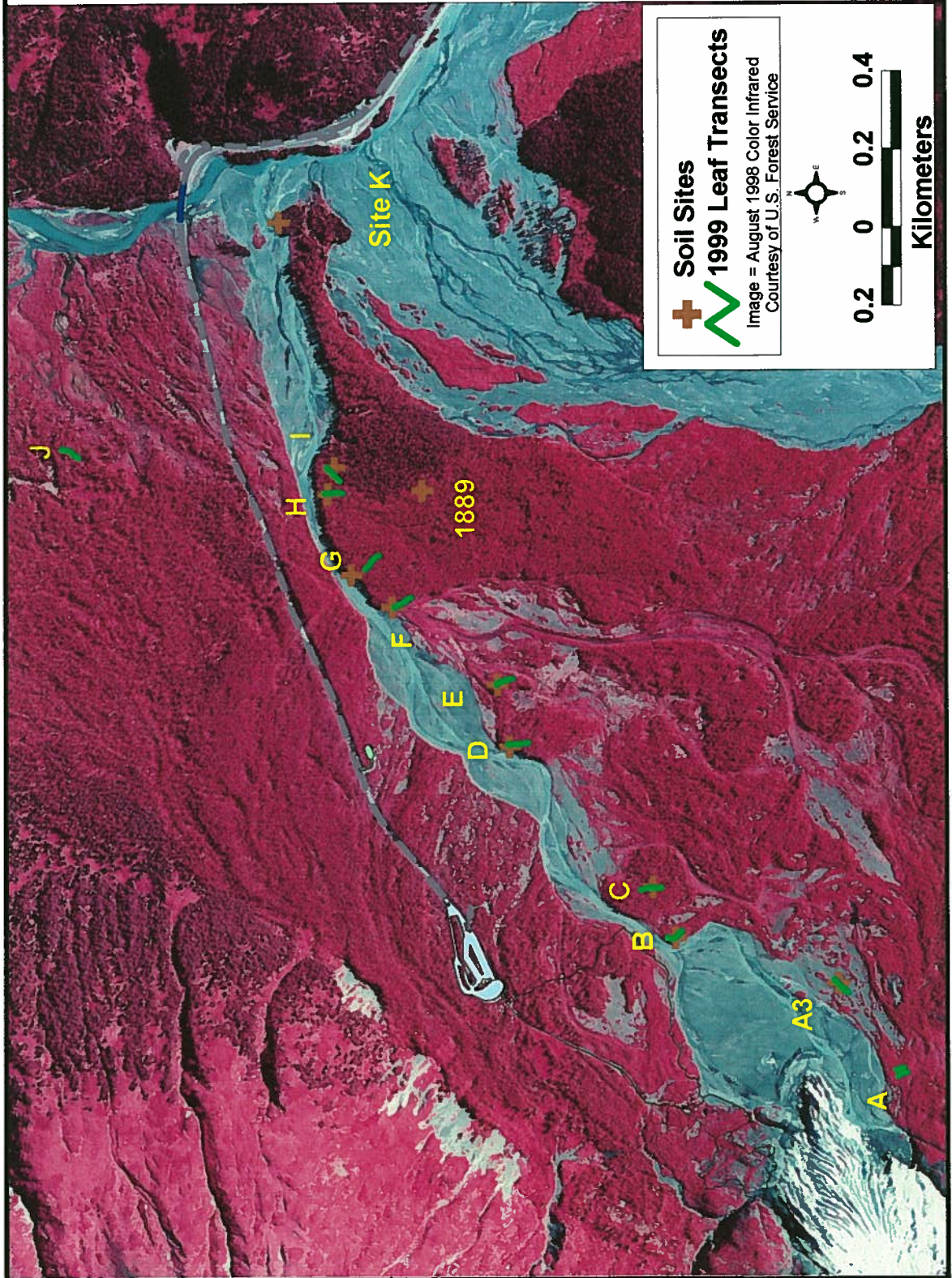


Table 3.1. Exit Glacier sample site locations for soil pits and leaf transects. Date of deglaciation and age from various sources.
All ice-free dates estimated using tree rings have an estimated error of ± 5 years.

Site	Study		Date ice-free (Years BP)	Evidence	Basis of Landform Age
	S=Soil	L = Leaf			
A3	S/L		ice-free ca. 1961 - 1969 outwash stabilized by 1980 (19)	tree ring/photography	ca. 1980 (cottonwood) - this study; the 1980 seedlings indicate stabilization of substrate; 1961 photograph indicates deglaciation
A*	L		1969 (30)	tree ring/photography	ca. 1969 (cottonwood) - this study; 1968 photography supports deglaciation
B	S/L		1951 (48)	tree ring/photography	1951 (cottonwood) - this study. Possibly ice-free along some portions of moraine ca. 1948
C	S/L		1926 (73)	tree ring/photography	1926 (spruce) - this study. ca 1935 photograph shows glacier upvalley from this position
D	S/L		1914 (85)	tree ring	1914 (spruce) - Wiles (1992)
E	S/L		1899 (100)	tree ring	1899 (spruce) - Wiles (1992)
F	S/L		1894 (105)	tree ring	calculated as ice-free ca. 1894. Oldest tree suggests deglaciation prior to 1912
G	S/L		1891 (108)	tree ring	calculated as ice-free ca. 1891. Oldest tree suggests deglaciation prior to 1903
1889	S		1889	tree ring	ca. 1889 (spruce) - Wiles (1992) and Ahlstrand (1983); deglaciation by 1889
H	S/L		<1869 (130)	tree ring	ca. 1869 (spruce) - this study and Ahlstrand (1983); moraine eroded by past flooding
I	S/L		<1748 (251)	tree ring	ca. 1748 (spruce) - this study and Ahlstrand (1983); moraine eroded by past flooding
J	L		<1904	tree ring	ca. 1905 (cottonwood) - this study. Abandoned LIA outwash plain; oldest tree suggests deglaciation prior to 1904
Site K	S		ca. 4000 BP	radiocarbon	Oldest tree (1631-Ahlstrand (1983)) and radiocarbon results suggest deglaciation prior to 4000BP

* Transects A1 and A2 were combined as Transect A.

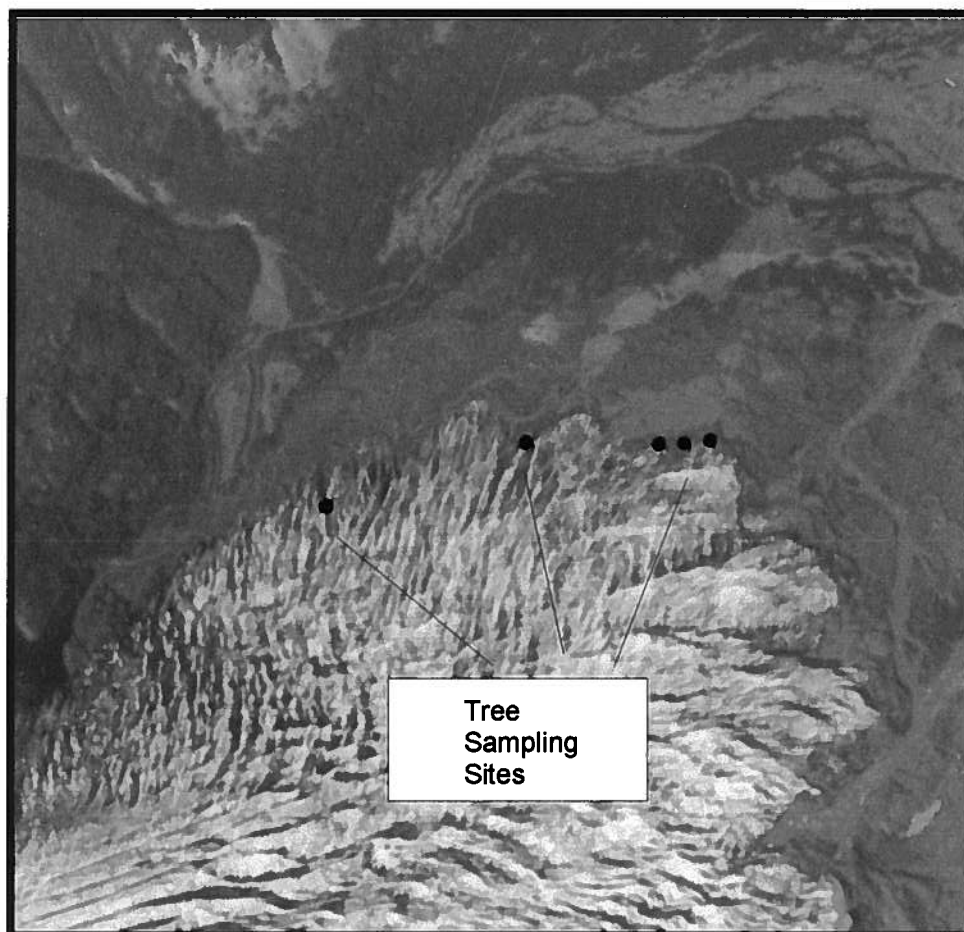


Figure 3.3. Location of five black cottonwood trees sampled on the distal slope of the 1950 moraine for determination of ecesis interval. Photo taken August 8, 1950. Courtesy of U.S. Geological Survey.

Table 3.2. Correction factor for coring height based on increasing height of black cottonwood (*Populus balsamifera*) seedlings over time.

Location	Height (cm)	Age (yr)	Growth Rate (cm/yr)	Correction Factor (yr/cm)
Site A3	24	5	4.8	0.2
Site A3	55	14	3.9	0.3
Site A3	40	9	4.4	0.2
Site A3	60	10	6.0	0.2
Site A3	30	10	3.0	0.3
n = 5				
Average increase in height and standard error = 4.4 ± 0.5 cm yr ⁻¹				
Average correction factor = 0.2 yr cm ⁻¹ height increase				

4 CHRONOLOGY OF THE FORELANDS AND SELECTION OF SITES

In order to implement leaf sampling of black cottonwood and Sitka alder along a chronosequence, it was necessary to establish a valid timescale, drawing upon various studies and this research. Tree-ring dating and radiocarbon analyses were used in this study to integrate previous studies of glacial advances on the Exit Glacier forelands and to provide new data on the timing of such events. Correlations between ice retreats and historical photography were facilitated by the use of GPS and GIS. This chapter will present an integrated review of available material on the timing of Exit Glacier retreat, thereby dating the moraines upon which leaf and soil site research was conducted.

4.1 Recent History 1950-2000 – Sites A1-A2 and A3

The barren, open gravel outwash at the present-day glacial forefront is one of the most conspicuous portions of the Exit Glacier area today (Figs. 2.2; 3.1; 4.2). This area is frequently flooded by small, intermittent drainages (Helm and Allen, 1995). This zone extends from the present terminus of the glacier to the glacier position in 1950, as captured from the U.S Geological Survey photo (August 18, 1950) (Fig. 2.2; 3.3).

Aerial photography documenting the time period from 1950 to present was sporadic but good. Exit Glacier receded 211 meters from 1950 to 1961 and then another 240 meters from 1961 to 1968. Considerable wasting of ice along the edges probably contributed to the extensive reworking of sediments in front of the glacier. Extensive hummocky ridges, estimated from the 1968 oblique to be over 5 meters tall, were gone by 1974. However, the point of the glacier snout has been in approximately the same area since 1968. Extent of the glacier on the north side of Exit Creek, where the present-day lower and upper loop trails begin, support Ahlstrand's evidence of alder growing on the newly exposed rock outcrop in 1971 (Sites K-N; Ahlstrand, 1983). The glacier probably continued a gradual thinning of ice along the north side of the channel, affected by the large outcrop apparent on the right side of Figure 4.3.

Areas along the south side of the glacier's present terminus, containing patches of alders, have been the focus of dating of glacial retreat (Ahlstrand, 1983) and chronosequence work (Helm and Allen, 1995). An alder patch at the base of an avalanche chute on the south side of the glacier terminus (Fig. 4.3) was the location of the "Alder stage" defined by Helm and Allen (1995) and served as the location for this study's A1 and A2 transects. This area is located on a raised river terrace that appears to have been vegetated as early as 1974, as observed in aerial photography. This site was $40 \text{ m} \pm 5 \text{ m}$ inside the 1961 glacier terminus and estimated to have been ice-free by 1968 (Fig. 4.3). A cottonwood sapling sampled for terrain age (13 cm DBH) was 24 years old in 1999. Assuming a 5-year ecesis interval, the abandonment of this channel area dates to ca. 1969 (Table 4.1, Appendix A), while the oldest alder sampled from the leaf transect of the area dates to 1978. The 1973 high altitude photography shows this area on the fringe of an avalanche chute. Evidence of previous landslides and woody debris is found throughout the area. The avalanche may have introduced soil and living material to the site subsequent to deglaciation. This research shows that this area stabilized as early as 1969 (based on 24-year-old cottonwood and a 5-year colonization period). The area may have been ice-free for some interval of time between 1961 and 1968 (based on aerial photography) but possibly would have been subjected to flooding or disturbance from avalanches subsequent to ice removal.

The other transect located within the 1951 margin on a raised abandoned river terrace, A3, follows roughly the same pattern of deglaciation. Located ca. 25 meters inside the 1961 margin, this site was subject to subsequent flooding as evidenced by the soil in this area (Table 3.1; See Chapter 5). Although no attempt was made in this area to seek out the largest and oldest specimens, five of the ten cottonwood samples were randomly selected from this transect, extracted from the soil and cut at the root crown for age determination. Assuming a 5-year ecesis interval, the oldest sample from this site dates to 1980. Close inspection of the large-scale 1985 black/white photo indicates the presence of isolated vegetation on the site of the transect, supporting evidence of establishment of cottonwood in this area by at least 1980. Aerial

photography from 1973, 1974 and 1978 do not reveal vegetation in this area. However, this may be the result of low resolution due to smaller scale photography.

Aerial photography and tree-ring evidence therefore suggests that the outwash plain up valley from the 1951 moraine and to the present terminus became largely ice-free by 1968. During the 17-year interval from 1951 to 1968, the glacier snout receded 505 meters, roughly half of which occurred between 1951 and 1961 as observed in aerial photography. The periphery of the glacier, however, receded at a slower rate, exposing portions along the north and south side of the glacier in 1971 and 1969 respectively. Large mounds of till, over 5 meters high in front of the 1968 margin, may be evidence of one or two years of a stationary position with time to build up a push moraine. A combination of rapid retreat sometime after 1951 and before 1968 may have produced flooding on a relatively flat outwash plain, resulting in the present-day appearance of this exposed area. In summary, both leaf transect sites A and A3 were ice-free by 1961 or shortly thereafter. However, aggradation of substrate and disturbance from fluvial processes prevented establishment of plants until 1969 and 1980 respectively.

4.2 1951 Moraine – First Down Valley Terminal Moraine – Leaf Transect B

The 1951 moraine is one of the most visible features of the Exit Glacier forelands, forming a clearly pronounced ridge around the edge of the modern outwash plain (Fig. 2.3). This study's leaf and soil sites "B" were located on this moraine. It was dated by Ahlstrand (1983) and Wiles (1992) as having formed in 1950.

The August 8, 1950, U.S. Geological Survey photo (1:40,000 scale) captured the snout of Exit Glacier and was used in the construction of the Seward A7 and Seward A8 1:63,360 quadrangles of the area. Upon close inspection, a meandering edge of the glacier can be seen with several fingers of ice extending into the terrain and plowing up massive hummocky ridges, while in other places large outflow streams can be seen exiting from under the ice, south of the present-day Exit Creek (Fig. 3.3) at the site of a

GPS control survey monument 13A (Appendix C; Figure 1). North of Exit Creek, the glacier can be seen forming a moraine as well.

Trees were cored as part of the leaf transect B for ecesis tests (See Chapter 3.2) and for terrain age along portions of the moraine (App. A), and the results were consistent with previous studies (Table 4.1; Ahlstrand, 1983; Wiles, 1992). Ahlstrand (personal communication, 1999) sampled several cottonwood trees growing at the distal base of the moraine, north of Exit Creek, and one tree was 25 years old in 1983 (Table 4.1; App. A). Assuming a 5-year ecesis interval, the moraine dates to ca. 1953. Wiles (personal communication, 2000) sampled a 37-year-old cottonwood tree in 1989 south of Exit Creek which dates this feature to 1952 (assuming no age-height correction factors and a 5-year ecesis interval). This study in 1999 cored a cottonwood tree growing near the distal base of the moraine north of Exit Creek as part of ecesis tests described in Chapter 3.2. The 39-year-old tree, assuming a 5-year ecesis time and an age-height correction factor of 4 years, dates the moraine to 1951 (Table 4.1, App. A).

An aerial oblique dating from July 1948 (App. A) shows evidence of moraine building forces along the present-day 1950 moraine. Analysis of the photograph reveals the large hummocky blocky terrain to the south of Exit Creek to be forming, the site of the GPS survey control monuments 13A and 14 (App. C). The glacier apparently remained in this position until 1951, based on tree-ring data from this study.

This research shows that the moraine began forming as early as 1948 (based on July 1948 aerial oblique), and ice remained along portions of the moraine north of Exit Creek until 1951 (based on tree-ring evidence; Table 4.1; App. A). Using a minimum age of 1951 for the moraine along the southern portion of Exit Creek seems appropriate here.

4.3 1926 Moraine – Parallel to Nature Trail – Leaf Transect C

This intermittent moraine, unofficially known as the “Nature Trail” moraine (this study), is a multi-ridged end moraine that extends from an open area east of the midpoint on the main visitor trail, 220 meters south of the main tourist billboard, and is encountered 225 meters down the nature trail that begins near the

main parking lot (Fig. 4.1). A series of low (1-2.5 meter), rounded moraine features within a cottonwood grove can be observed for about 150 meters to the north side of Exit Creek. At the river near the park bench, a view southeast across the creek reveals the 4.5-meter tall bank on the opposite shore.

This moraine was the site of leaf transect C (Figs. 3.2; 4.1). Previous workers (Ahlstrand, 1983; Wiles, 1992) did not identify this moraine. Fifteen trees were cored along this moraine, including 10 alder and cottonwood sampled for leaf nutrients. The largest spruce tree here (located 20 meters south of Exit Creek) was 38-years-old in 1999 (Table 4.1; App A). Assuming an age/ht. correction factor of 10 years and an ecesis interval of 25, the moraine dates to 1926.

Historical evidence of Exit Glacier's position around this time consists of a relatively poor quality, small-scale historical photograph ca. 1935 (App. B) taken from a ridge southeast of Exit Glacier across the Resurrection River. This photograph depicts the terminus of Exit Glacier in an approximate location up valley from the 1926 moraine. Although this photo is of poor quality and questionable date (Tetreau, M., personal communication, 2000), it does confirm that Exit Glacier still maintained the piedmont-like shape seen in the 1950 photo with an extensive network of braided channels emanating from its terminus.

4.4 1917 Moraine – Moraine S. of Ranger Station

The third major moraine down valley from the present Exit Glacier terminus is most visible to visitors at the start of the Nature Trail which begins south of the Ranger Station (Figs. 2.2; 4.1). Two parallel ridges trend southwestward from here, with heights 2 – 4.5 meters above the local terrain. The Exit Glacier Nature Trail begins at the location of the northernmost moraine. This was the location of site G in Ahlstrand's study (1983) which he defined as being 1.5 road miles (RM) from the western edge of the Resurrection River bridge crossing. He sampled a black cottonwood in 1983 dating to 41 years of age, which translates to a calendar age of 1937, assuming a 5-year ecesis interval (App. A). Wiles (1992) also appears to have sampled the same set of moraines in 1989 during his study and calculated a minimum calendar age of 1927 using his ecesis interval of 15 years for spruce.

In this study, 15 trees were sampled along discrete moraine hummock ridges south of the creek, with the oldest tree dating to 1929 (Mark Q04S; Table 4.1; App. A). The lack of a well defined ridge near Exit Creek made this moraine difficult to map south of the creek. Since this research did not date any trees older than those cored by Wiles (1992), this moraine will be dated to 1917, 10 years younger than 1927 calculated by Wiles.

4.5 1914 Moraine – Leaf Transect D

The next group of moraines encountered 350 meters down valley from the 1917 moraine is dominated by an open growth of cottonwood with a dense, sometimes decadent alder understory (Figs. 4.1; 4.2). Intermittent 3.5-meter-high lateral moraines, located 100 meters due north of the parking lot toll booth, loop through the forest before terminating in a 1-meter-high mound located 23 meters north of the road. These lateral moraines north of the road were dated to 1934 by Ahlstrand (Site F) using an ecesis interval of 5 years (Table 4.1, App. A). Wiles (personal communication, 1999) also cored a spruce tree along these lateral moraines close to the road dating to 1939 in his 1989 survey (Table 4.1, App. A). This moraine was termed the “1924” moraine, assuming a 15-year ecesis interval (Wiles, 1992).

South of Exit Creek, the stream cuts into a 5-meter-high till face (Figs. 2.3; 4.2) where it crosses this moraine. This small, raised feature, approximately 2.6 hectares in size, is comprised of a hummocky glacial till with open cottonwood forest and occasional spruce. It is the location for a leaf transect and soil pit site D in this study (Fig. 4.1).

Twelve trees were sampled on a remnant of this moraine, 10 of which were randomly chosen for leaf nutrients. A 51-year-old cottonwood specifically targeted for terrain age determination was found along the leaf transect and, assuming a 25-year age/ht correction factor and a 5-year ecesis interval, this moraine was dated to ca.1918 (Table 4.1). However, the pith was never reached, but apparent wide rings near the center indicate that the 1918 date is close.

Scattered and ill-defined moraines to the south of the leaf transect site date from 1936 to 1924 (Mark Y and Mark W series; App. A). These were likely terminal end moraines, but fluvial disturbance south of Exit Creek has made resolving glacial maxima by tree coring in this area quite difficult.

Historical documentation from the Grant and Higgins geologic reconnaissance map of the area (Martin et al., 1915; Fig. 4.4) from a survey in the Exit Glacier area in 1911 (Cook and Norris, 1998) depicts a lobate appearance of the glacier and is in fairly good agreement with these dates. Although the scale of this map is quite coarse (1:250,000), these minimum dates are somewhat in agreement.

In summary, this research did not date any trees older than those cored by Wiles (1992). Recalculation of his "1924" moraine to 1914 appears to correspond well with tree-ring data collected in this study and with historical documentation from Grant and Higgins' 1911 survey.

4.6 1899 Moraine – Leaf Transect E

Located 185 meters down valley along Exit Creek and 110 meters west of the previous moraine is the moraine termed "1909" by Wiles (1992). Several parallel ridges can be seen north of the road. Heights range from 2 meters above mean terrain to 3.5-meter-tall moraines southwest of the campground. This feature was examined several times by Ahlstrand (1983) and at least once by Wiles (1992). Coring in this study was exclusively done south of the creek on the location of leaf transect E (Fig. 4.1).

The leaf transect site E was located in the middle of this small (1.0 hectare) moraine feature. This feature, in the shape of a "V", rises approximately 8 meters above mean terrain. A spruce dating to 61 years was cored near the beginning of the transect in 1999. Using an age/ht correction factor of 8 years and an ecesis interval of 25 years, this moraine dates to 1905 (Table 4.1; App. A). In his 1992 dissertation, Wiles revealed that he also sampled the lateral moraine along the road, coring a tree to 65 rings in 1989. This resulted in his determination of 1909 with an ecesis interval of 15 years. Ahlstrand found a cottonwood dating to 1939, placing his landform age at 1934, assuming an ecesis interval of 5 years.

Using an ecesis interval of 25 years, instead of the 15 previously used by Wiles (1992), the minimum date of this moraine can be determined to be 1899. There appears to be good agreement between this study's 1905 date and Wiles' 1899 date (Table 4.1; App. A). Coring efforts to the south of the leaf transect E yielded results ranging from 1911 to 1934 (1909 series; App. A). Limited numbers of remaining raised morainal features prevent adequate determination of the more lateral moraines north of the road and south of the leaf transect area.

4.7 Inter-Moraine Area - 1899 & 1889 Moraines. Leaf Transects F(1894) and G(1891)

Continuing down valley nearly 512 meters from the 1899 moraine is a series of moraine features seen clearly from the road (Site D; Ahlstrand, (1983)). This area was subjected to historic flooding events. Two leaf transect sites (F and G) were established on two of these raised moraines south of Exit Creek within a closed overstory of cottonwood and thick understory of alder (Fig. 4.1).

Aerial photography clearly shows an arcuate sweeping moraine that begins near the northern hillside and crosses the road, then continues as a clearly defined sharp ridge that defines a heavily forested region to the Resurrection River (Figs. 2.3; 4.1). A large, 3-meter wide erratic sits atop the broad moraine just south of the road. The moraine ranges from 5 meters above the Exit Creek on the south side of the creek to over 4 meters above mean terrain north of the road. This broad, flat moraine, described by Ahlstrand as a distinct moraine located 0.90 miles from the Resurrection Bridge, is dominated by black cottonwood with scattered Sitka spruce. Ahlstrand's oldest black cottonwood tree recorded in 1983 (sampled along Exit Glacier road) dated to 1919, assuming a 5-year ecesis interval (Table 4.1; App. A). A spruce tree sampled sometime after 1983 and recorded in Ahlstrand's unpublished 1999 manuscript indicates a landform date of 1916, assuming a 25-year ecesis interval (Ahlstrand, G., personal communication, 2000).

This study cored 18 trees along a moraine south of the road, 10 of which were part of leaf transect F (Table 4.1; App. A). The oldest tree, a cottonwood located 121 meters south of the creek and 6.5 meters

northeast of the moraine crest, had 75 rings in 1999. This dates the landform to 1912, assuming a 5-year ecesis interval and a 7-year age-height correction factor. Several other trees along this front yielded landform dates of 1914 to 1916. Few Sitka spruce could be found in this area.

Located 136 meters down valley from Site F was the location of leaf transect site G (Fig. 4.1). Twelve trees were cored along the leaf transect located on a raised moraine, two of which were specifically targeted for terrain age. The oldest tree was 87-years-old in 1999 (G20C), which dates the landform to 1903 (assuming a 5-year ecesis time and an age-height correction factor of 4 years). Continuing 45 meters to the south of the transect on an 8 m high moraine was a cottonwood dating to 1915, while others in the area dated to 1912.

Although the landforms sampled for leaves were on raised surfaces, they must have been disturbed following deglaciation. Causes include: 1) flooding/re-working of terminal ice margins or 2) the landforms are remnants of riverbanks. This study suggests that due to this area's height above mean terrain, only extreme flooding events like those following rapid glacial retreat, could have affected this area. Disturbance to substrate may, therefore, explain the younger tree ages found along transects F and G, as well as the apparent outwash fan seen in Figure 4.2 located just down valley from the 1891 moraine. It is possible that the oldest tree in this area was not cored, however similar dates were obtained from the Exit Glacier road (Ahlstrand, 1983; App. E). Without additional study, these dates on these moraines can only be estimated using relative distance between more precisely dated moraines up and down valley. Thus, moraines F and G were assigned dates of 1894 and 1891, respectively, by calculating their relative distance from the 1889 moraine (91 m: Transect G; 227 m: Transect F), dividing these distances by 512 meters (total distance between 1889 and 1899) and multiplying the percentages by the time span of 10 years.

In summary, this area underwent periods of heavy flooding after the rapid retreat of the glacier from the 1889 position ($510 \text{ m} / 10 \text{ years} (51 \text{ m/yr})$). In some places, large sweeping floods may have delayed stabilization of substrate and therefore establishment of trees along the transects until sometime

after the turn of the century (1900). However, without further research, these areas will be assigned 1894 and 1891 dates.

4.8 1889 Moraine – Soil Pit site 1889

One of the most prominent moraines on the Exit Glacier forelands is the 1889 moraine. Visitors encounter this moraine 0.75 miles after crossing the Resurrection River, and it is the site of Ahlstrand's Site C (1983) and Wiles' 1899 Site (Table 4.1). This moraine is the most prominent along the western side of a forested area that appears dark in the color infrared photograph of the region (Figs. 2.3; 4.2). This moraine was the site of soil pit "1889," but was not sampled for foliar nutrients (Table 3.2).

This is an area of closed black cottonwood and Sitka spruce. Ahlstrand cored a spruce in 1983 with an age of 69 years, placing establishment of this moraine at 1889 using a 25-year ecesis interval. Wiles also sampled this feature in 1989 with a spruce dating to 75 years. His original date for this moraine was 1899, using a 15-year ecesis interval.

South of Exit Creek, this feature is a prominent moraine ranging from 8 meters high at 70 meters south of the creek, to 11 meters high between 270 meters and 600 meters south of the creek. Seven trees (6 cottonwood and 1 spruce) were cored along the crest and distal mid-slope of this moraine. The oldest tree, a cottonwood obtained from the distal mid-slope region of this moraine, dates the moraine to 1891 (Table 4.1, App. A).

The size of this moraine may indicate several seasons of push moraine formations, allowing for continual disturbance and lack of tree establishment until the glacier pulled away from this position by ca. 1889.

In summary, tree-ring data from this research and Wiles (Table 4.1) indicate that this moraine has been deglaciated since at least 1889. The large size of this feature and steep distal side indicate that this moraine may have formed from repeated advances prior to 1889.

4.9 Region K – 1869 – Leaf Transect H

Leaf transect H was located on the eastern or distal side of the steep 1889 moraine. The oldest tree sampled on the transect dates the area to 1897 (Table 4.1; App. A), while a large spruce tree located 200 meters south of the transect and on the distal side of the 1889 moraine dates the area to 1869. Ahlstrand cored an 89-year-old spruce on the distal side of this moraine (Site C; Ahlstrand, personal communication, 1999) located north of Exit Glacier Road. Assuming a 25-year ecesis interval, this dates the moraine to 1869.

Topography in this area is best described as river terrace, nearly level to slightly undulating with dissecting channels that indicate previous fluvial processes. A soil pit dug on this site exhibited more than 90% sand (See Chapter 5; Appendix E), yet a significant A and AC horizon had developed, thus indicating that fluvial processes had not occurred in recent times. Gravels at the base of trees in this area indicate flood deposition after seedling establishment. Therefore, ages may be underestimated due to coring at greater heights above root crowns.

Few features mark the retreat of the glacier in this area, while evidence from soils and tree-rings strongly suggest flooding occurred following deglaciation, but before the ice had retreated from the 1889 moraine. Cored trees in this area imply a minimum stabilization of substrate in this area of at least by 1869 (Table 4.1; Appendix A).

4.10 1815 Moraine – LIA Maxima

The first moraine encountered driving towards Exit Glacier is the site of Ahlstrand's B Site (1983). A remnant of this outer moraine exists 51 meters north of the road and is 4.8 meters above mean terrain. A spruce core with 143 rings dates this moraine to 1835. Another cottonwood dates the moraine to 1839 in the same area. Wiles (1992) cored a tree with 149 rings in 1989. This dates the landform to 1815, using a 25-year ecesis interval.

Tree-ring dates from previous studies suggest this moraine is the LIA maxima, however no data were collected in this area for this research. The 1815 date of the LIA maxima suggests that the glacier remained near this outermost position for ca. 60 years until it retreated up valley to the 1869 moraine.

4.11 Area beyond LIA Maxima

Just east of the Little Ice Age (LIA) maximum, several areas were sampled for leaf and terrain age and soil properties. Age determination of these areas was from tree-ring dates and radiocarbon analyses. Results from each of the sites will be discussed.

4.11.1 NE on the Outwash Plain – Leaf Transect J

Initial photo analysis of the area down valley from the most apparent moraines revealed several cottonwood stands north of the road. Dense understory prevented detection of moraine features on aerial photos, so several ground surveys were conducted to detect older moraines. Leaf transect J was established in this area as the northeasternmost leaf transect, and was located 440 meters north of the road (Fig. 4.1). Ages of the cottonwoods on this site ranged from 54 to 89-years-old. Establishment of vegetation, using an ecesis estimate of 5 years, is estimated to occur between 1940 and 1905, but is likely older, because the oldest trees were not targeted, and the cored trees were difficult to read (Table 4.1, App. A; Fig. 4.1). There were no apparent moraines between Site J and Site A along the north side of Exit Glacier road (this study; Ahlstrand, G., personal communication, 1999). This area is a closed, mixed forest of mature Sitka spruce and black cottonwood. This is likely a former floodplain of the Resurrection River floodplain during the LIA, but flooding decreased as the glacier receded westward and the channel of Exit Creek deepened. The abandonment of this area by 1905 is supported by the 1911 map (Martin et al., 1915) which depicts only one drainage pattern leading from the terminus (Fig. 4.4). The large open area north of the present road exhibits no drainage patterns. The ground oblique photograph from 1920 also supports the abandonment of this area, because the stream in the middle of the photo is likely Exit Creek.

4.11.2 *Distal Sites to 1815 Moraine - Leaf Transect I*

On the south side of Exit Creek, leaf transect I is located in a transitional forest cover composed of large cottonwood, spruce and occasional hemlock, described by Helm and Allen (1995) as the “Spruce-Cottonwood stage” (See Chapter 2). Two spruce dating to 1748 and 1761 were cored on the north side of Exit Creek corresponding to this same area (Ahlstrand, 1983; Site A; Ahlstrand, G., personal communication, 1999). The largest cottonwood in this study dates to 1790. Many cored trees contained rotten wood, and piths in other cores were difficult to locate (Table 4.1; App. A).

Evidence of flooding is prevalent in this area south of Exit Creek. Surface water was observed (20-50 cm deep) several times in this area, while a soil pit dug on site I had a water table at 90cm depth. Surface gravels and sand deposited at the base of trees are possibly contributing to the darkened forest floor clearly evident on the USGS oblique photo from 1983 (Fig. 4.2) and most likely limit the precision of dating trees in this area.

4.12 Area beyond LIA Limit

Only small remnants of a pre-LIA forest can be found within the Exit Glacier forelands. Wiles’ 415-year chronology (from 1574 to 1988) was based on living trees from northwest of the Resurrection bridge (Fig. 2.3). This chronology was used to date subfossil logs from the forefield and to infer the climatic history of the area (Wiles, 1992). A small spruce-hemlock community near the confluence of Exit Creek and the Resurrection River (Fig. 4.1) was the location of soil site K, as well as a tree cored by Ahlstrand (personal communication, 1999), dating to 1631 (Table 4.1; Appendix A). Several features, including the old forest and thick layers of moss-covered, downed woody debris, attest to a mature forest indicating considerable time since deglaciation.

Two soil samples from an exposed pit, 30 meters west of Resurrection River and 5 meters above creek level (Figs. 2.3; 4.1; 4.2; App. E), produced dates of 3790 ± 60 yr. BP (calibrated age of 2445 – 2030 BC) and 3590 ± 40 yr. BP (calibrated age of 2030 – 1875 BC; App. D). The two sigma dates overlap at

4000 BP. These samples were obtained from a silt cap containing tephra above a well defined reticular 2C horizon. The strong reticular structure of the 2C horizon suggests these soils were developed slowly in a cold climate during continuous freeze-thaw cycles permitting layering of ice and soil. This cryogenic process could possibly have spanned several hundred years and suggests this feature was formed during a much colder environment than today (Ping, C. L., personal communication, 2001). The date of ca. 4000 years from a tephra layer dates only the deposition of volcanic ash and only suggests that this feature was left undisturbed for at least 4000 years. Deposition of the glacial till and subsequent formation of the 2C horizon can, therefore, be inferred to have occurred at some time **before** 4000 years ago. This date also confirms that this area near the confluence of Resurrection River and Exit Creek was beyond the LIA advance.

4.13 Discussion and Conclusions

4.13.1 Exit Glacier Chronology

Evidence of an early advancement of Exit Glacier comes from the site of a buried forest located inside the current 1951 margin (Fig. 2.3; Appendix D) and discovered by NPS personnel in the fall of 2000. Plant material from this deposit, found approximately 2.5 meters below the surface, appears to have contained *Equisetum*. A log recovered from here dates to 1170 and gives evidence of a forest floor at this location sometime before 1170 AD. This area may have been overrun by an advancing ice front, buried by outwash emanating from the glacier, or affected by a catastrophic event (jökulhlaup, landslide or large amounts of outflow) which could have led to the preservation of this section.

This was a time (1100-1200 AD) when numerous glaciers, both tidewater and terrestrial, expanded throughout Prince William Sound (Barclay et al., 1996) and has been interpreted as a cooling period. Three tidewater glaciers advanced during this period: Ailak Glacier overran trees by ca. 1125 AD (Wiles, 1992), and Blackstone and Beloit glaciers may have begun advancing ca. 1120 AD (Crossen, 1997). Two glaciers

in the northern Kenai Mountains also advanced: Billings Glacier by ca. 1210 AD (Barclay et al., 1996; Crossen, 1997) and Tebenkov Glacier by ca. 1240 AD (Crossen, 1997).

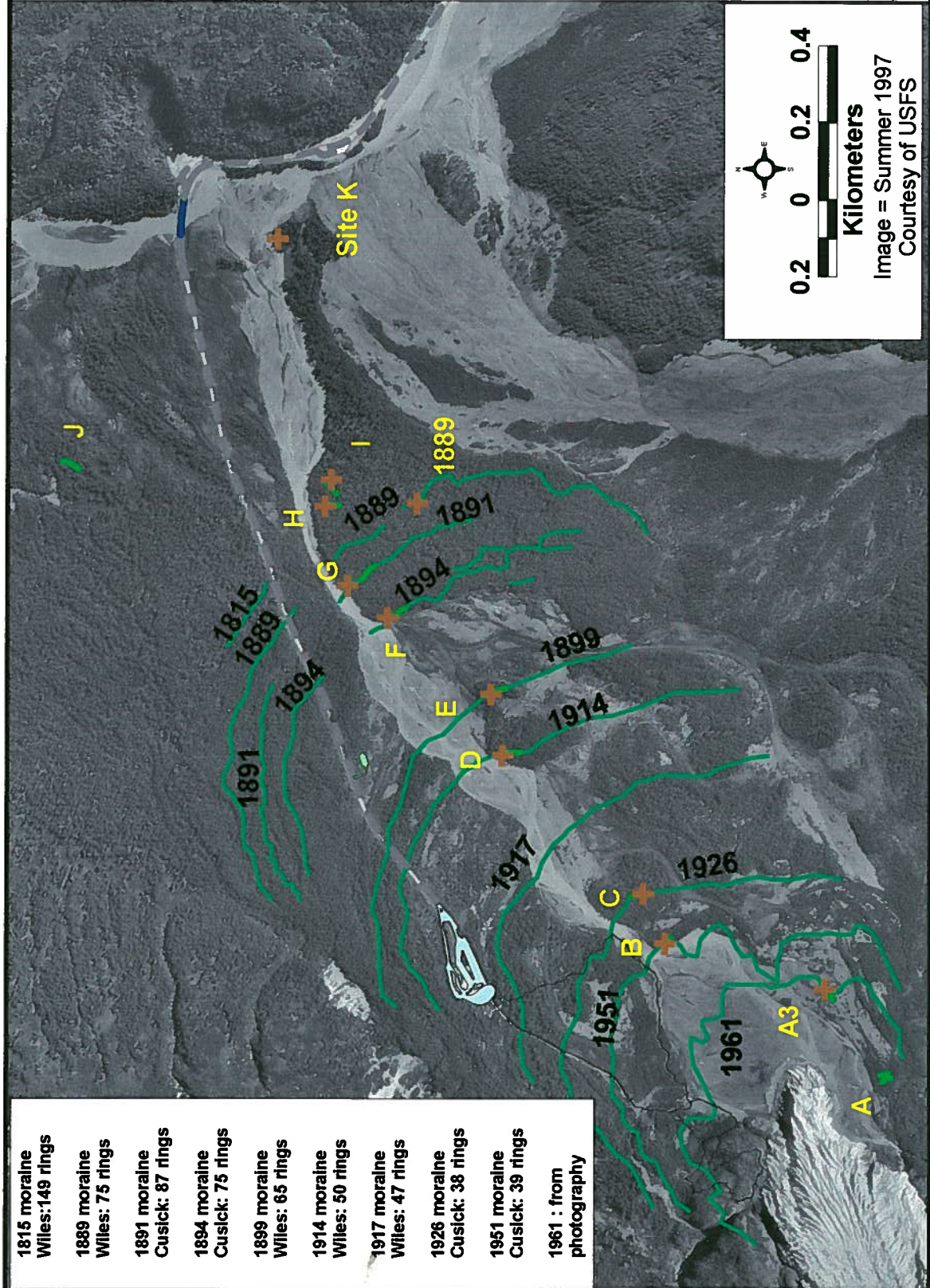
Evidence from a mature spruce-hemlock community found at the confluence of Exit Creek and Resurrection River indicate that Exit Glacier had not advanced out to this position for at least 300 years (as indicated from tree rings; Table 4.1; Appendix A) and possibly not since 4000 BP. Other glacial advances from this time period include those in McCarty Fjord (southern Kenai Mountains) ca. 3500 BP (Wiles, 1992). Exit Glacier may have been advancing during this time as well. If the maximum advance reached beyond the current LIA maximum and advanced to the Resurrection River, then this event must have occurred before ca. 4000 years BP.

The earliest evidence from subfossil log locations Wiles (1992) and Wiles and Calkin (1994) suggests that Exit Glacier was expanding in the early LIA ca. 1580 AD (Appendix D), burying cottonwood logs (Loc. 1; Fig. 2.3) along the trimline on the northwest side of the valley. Outwash aggradation reached its maximum (Loc. 2, Fig. 2.3) at approximately 1714 AD, indicating that Exit Glacier was within 1.2 km of its outermost LIA moraine between the 17th and early 18th centuries (Wiles, 1992; Wiles and Calkin, 1994).

4.13.2 *Dating of LIA retreat*

The time-distance diagram (Fig. 4.5) and Table 4.2 indicates the terminus retreat of Exit Glacier since the LIA maximum. Tree ring data from Ahlstrand (1983), Wiles (1992) and this study provide minimum dates for the moraines at 1815, 1889, 1891, 1894, 1899, 1914, 1917, 1926 and 1951 (Figs 4.1; 4.2). These ice-marginal landforms may have formed much like the seasonal and annual push moraines evident today in front of the ice margin (Figs. 2.6a; b). More sustained re-advances, termed composite push moraines, may be responsible for the outermost moraines found on the Exit Glacier forelands, as well as the 1951 moraine complex. Without additional geomorphological and stratigraphic information, however, interpretation of these features remains unclear. Fluvial processes appear to dominate over moraine building processes at the terminus of this relatively small glacier (Figs. 2.6a, 2.6b). The combination of a relatively flat floodplain and a supply of meltwater enable the stream to constantly reshape this foreland.

Figure 4.1. Map of Exit Glacier valley showing moraines. Ages assigned to moraines are based on dendrochronology and photography from several studies. Photo from 1997, Kenai DOQ project.



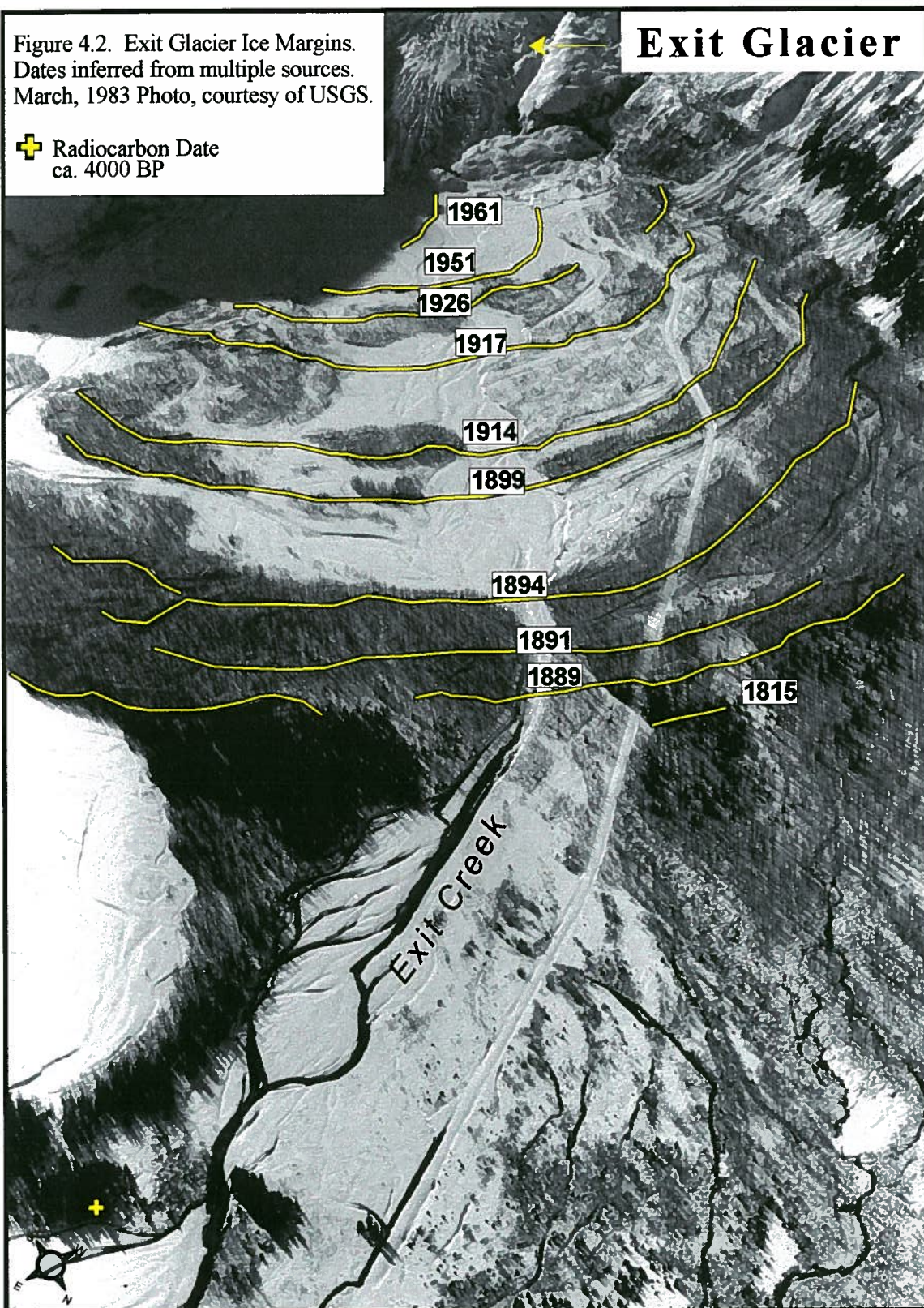


Table 4.1. Exit Glacier tree core samples.

Tree ID	Site	Coll. *	Genus **	# of Cores ***	Type	Year of Sampling	Ring Count	PiTh cored (cm)	Age/Ht. Factor (yrs)	Eccesis	Oldest Possible Year AD	
Closest to Glacier - Leaf Transects Alder - A1, A2												
A2_01C	A2	CU	POBA		TA	1999	21	good	20	4	5	1969
Southeast of Present Terminus - Leaf Transect Cottonwood A3												
A3_50C#1	A3	CU	POBA		TL	1999	10	good	0	0	5	1984
A3_20C#2	A3	CU	POBA		TL	1999	14	good	0	0	5	1980
1951 Moraine - First downvalley terminal Moraine - Leaf Transect B												
1950_03C	1950	CU	POBA		E	1999	39	good	20	4	5	1951
1926 Moraine - Parrallel to Nature Trail - Leaf Transect C												
C01S	C	CU	PISI		TA	1999	33	near	9	3	25	1938
C04S	C	CU	PISI		TA	1999	38	good	33	10	25	1926
1917 Moraine - Moraine S. of Ranger Station												
MARK_Q04S	MARK_Q	CU	PISI		TA	1999	39	good	19	6	25	1929
G_WI	G	WI	PISI			1989	47	na	0	0	25	1917
1914 Moraine - Leaf Transect D												
D01C	D	CU	POBA		TA	1999	51	wide	125	25	5	1918
MARK_W04C	MARK_W	CU	POBA		TA	1999	64	good	64	13	5	1917
F_WI	F	WI	PISI			1989	50	na	0	0	25	1914
1899 Moraine - Leaf Transect E												
E01S	E	CU	PISI	2	TA	1999	61	wide	28	8	25	1905
E_WI	E	WI	PISI			1989	65	na	0	0	25	1899
1894 Moraine - Leaf Transect F												
1899_06C	1899	CU	POBA	2	TA	1999	74	good	32	6	5	1914
1899_03C	1899	CU	POBA		TA	1999	75	near	34	7	5	1912
1891 Moraine - Leaf Transect G												
1899_11C	1899	CU	POBA		TA	1999	76	good	48	10	5	1908
G20C	G	CU	POBA	2	TL	1999	87	wide	20	4	5	1903

Table 4.1. (continued) Exit Glacier tree core samples.

Tree ID	Site	Coll. *	Genus **	# of Cores	Type ***	Year of Sampling	Ring Count	PiTh Seen	Height cored (cm)	Age/Ht. Factor (yrs)	Eccesis	Oldest Possible Year AD
1889 Moraine - Soil Pit 1889												
C_AH	C	AH	PISI			1983	69	na	0	0	25	1889
C_WI	C	WI	PISI			1989	75	na	0	0	25	1889
Region K (ca. 1869) Distal Side of 1889 Moraine - Leaf Transect H												
AH		AH	PISI			1983	89	na	0	0	25	1869
REGION_K01S	REGION_K	CU	PISI	2	TA	1999	96	near	29	9	25	1869
1815 Moraine												
B_WI	B	WI	PISI			1989	149	na	0	0	25	1815
Distal sites to 1815 moraine - Leaf Transect I												
I30C	I	CU	POBA	2	TL	1999	215	good	84	17	5	1762
A_AH	A	AH	PISI			1983	197	na	0	0	25	1761
I02S	I	CU	PISI		TA	1999	208	good	61	18	25	1748
NE on the Outwash Plain - Leaf Transect J												
J50C	J	CU	POBA	2	TL	1999	79	good	50	10	5	1905
Beyond LJA MAX - Wiles Living Tree Chronology - near Res. River												
K_AH	K	AH	PISI			1983	327	na	0	0	25	1631
EXG_WI	EXG	WI	PISI			1989	400	na	0	0	15	1574

* Coll.: Collector: CU=Cusick (this study); AH = Ahlstrand (1983); WI = Wiles (1992)

** Genus: ALS1 = Sitka Alder; POBA = black cottonwood; PISI = Sitka spruce

*** Type of tree core sample: E = Eccesis test; TA: tree sampled for terrain age;

TL: Tree sampled as part of leaf transect

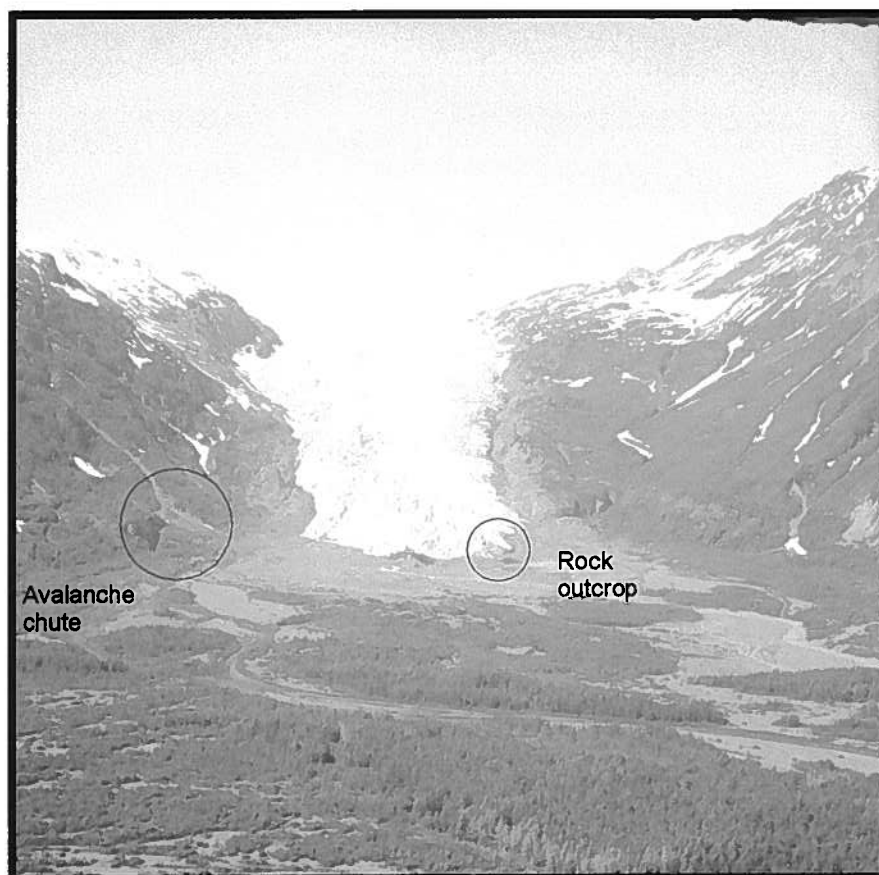
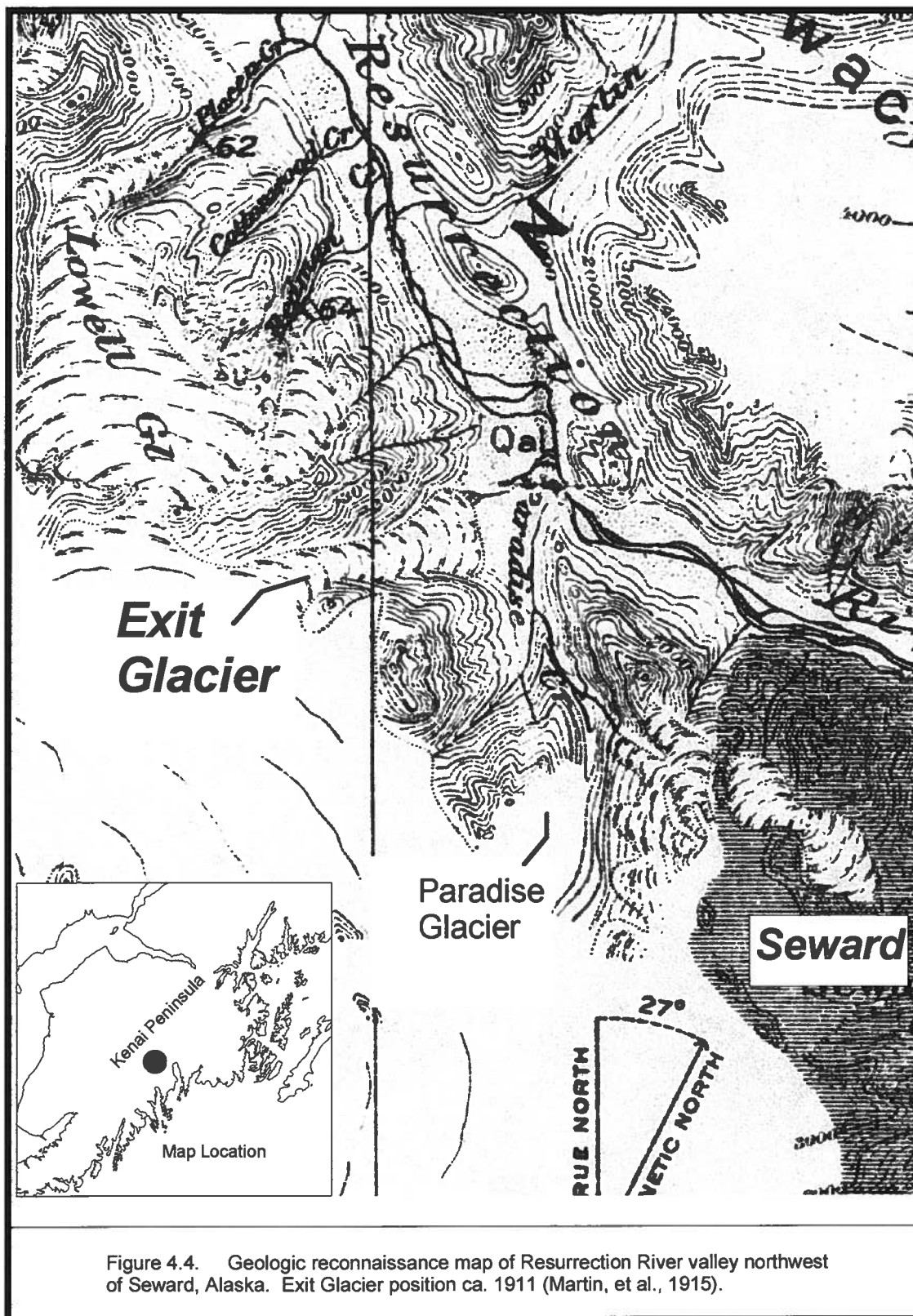


Figure 4.3. Exit Glacier in July 1968, looking southwest. Photo courtesy of Anchorage Museum. Steve McCutcheon, photographer. Avalanche chute on left and rock outcrop on right.



Exit Glacier Time-Distance Diagram

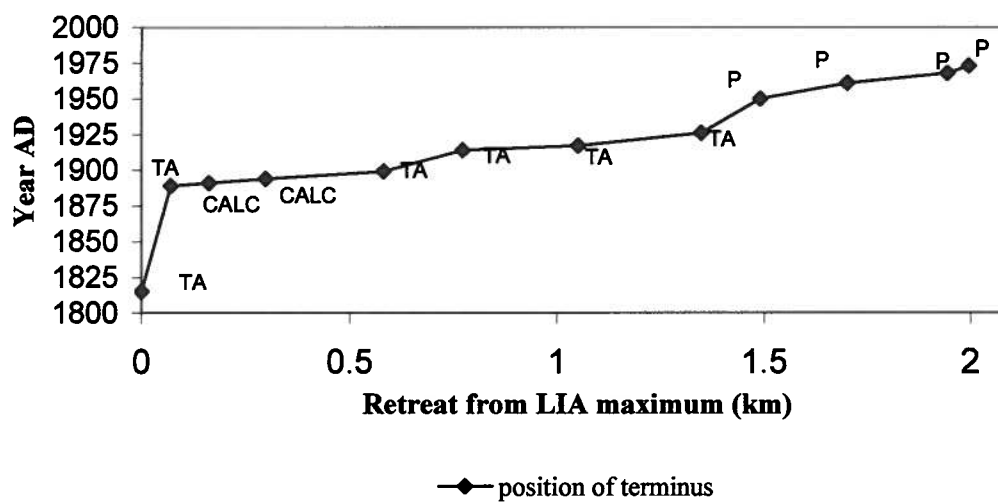


Figure 4.5. Time distance diagram showing the LIA retreat of Exit Glacier based on evidence from moraines dated by tree rings (TA), calculated rates of retreat (CALC) and photographs (P).

Table 4.2 Morainal and photographic evidence of the retreat of Exit Glacier.

DATE Year A.D.	DISTANCE of RETREAT (m)	RETREAT RATE (m yr ⁻¹)
1815-1889	70	1
1889-1891	91	46
1891-1894	136	45
1894-1899	285	57
1899-1914	192	13
1914-1917	277	92
1917-1926	297	33
1926-1950	143	7
1950-1961	211	19
1961-1968	242	35
1968-1973	52	10
TOTAL RETREAT		
1815-1999	1996 m	13 m yr⁻¹

5 SOIL ANALYSIS RESULTS

An analysis of soils for both characteristics and nutrients helps establish the rationale for site selection relative to leaf nutrient studies on the Exit Glacier forelands. The objectives of this soil study are: 1) to provide a detailed morphological description of the soils on dated, proglacial moraine features near foliar nutrient study sites, and 2) to assess soil nutrient concentrations.

Physical environment of soil study sites, and the physical and chemical characteristics of the soils sampled at Exit Glacier will be presented here. Nine of the eleven sites (A3, B, C, D, E, F, G, H, and I) corresponded to leaf transect site locations, while sites 1889 and K were sampled opportunistically (Fig.3.2; Table 3.1). Appendix E provides detailed description of soil profiles along the recessional transects including site photographs.

The analytical data presented in this study can be calculated on two different bases: percentage weight or by volume. The absolute values obtained by the two methods are dissimilar, and although the trend within the profile is not always consistent, the trend along the recessional sequence is not affected. In the following discussion, the data used for interpreting the results were obtained on the basis of the weight percentage. The data obtained on a volume basis have been used to prepare Figures 5.6 a and b.

The presence of large amounts of coarse fragments (>2mm in diameter) in glacial till makes it a very difficult parent material upon which to base pedological investigations of this type (Crocker and Major, 1955). Coarse fragment content in profiles at Exit Glacier were exceptionally high ranging from 20% to over 80% by volume in mineral soils (Appendix E.). Too much emphasis should not be given, therefore, to the finer detail of nutrient storage estimates. However, these inherent difficulties do not mask the general trends and the main characteristics of soils along the chronosequence developed on the Exit Glacier foreland.

5.1 Physical Environment

The physical environment of the soil sampling sites at Exit Glacier can be seen in Table 5.1. Site elevation (a. m. s. l.) ranged from 88 m at site K near Resurrection River, to 120 m at site A3 located 50 m southwest of the Exit Glacier terminus (Figs. 4.1; 4.2). Landforms ranged from an outwash plain (Site A3) to moraine ridges for sites B, C, D, E, F, G, 1889 and site K, to river outwash terraces on sites H and I. Three of the sites (D, G and K) were positioned on moraine ridge tops and were excavated from exposed river banks, while others were excavated using open pits. Soil pits were located on slopes ranging from 0 – 15% for sites A3, B, C, D, E, G, H, I and K, while two pits (F and 1889) were dug into exposed flanks of steep moraines (40% and 30% slope respectively; Table 5.1). Most sites were well drained. The exceptions were site C located in a slightly concave depression on a moraine ridge and site I, located on a raised abandoned river terrace, which had an apparent water table 90 cm below surface (Table 5.1; Appendix E). Rock fragments, including large cobble and stone, were common on the surface for most sites, ranging from 5% at sites C and 1889 to 80% at the youngest site (A3). Large erratics (exceeding 2 m) were found on the surface at site B (Table 5.1).

5.2 Physical Properties of the Soils

5.2.1 Soil Depth and Horizonation

Upon deposition and stabilization of stranded glacial till, climate and vegetation begin to modify the soils and to impart soil development with depth. Soil development characteristics and physical properties of the soil profiles for all sites are presented in Table 5.2., while Fig. 5.1 graphically depicts the soil development along the chronosequence at Exit Glacier. Site D (85-years-old) is the first site to develop a second organic horizon (Oa), yet still lacks an A horizon. Not until the 100-year-old site E is there evidence of soil development and incorporation of organic material in mineral layers as indicated by a 3-cm thick A horizon. Although site F (105-years-old) had a 5 cm thick Oi/Oa horizon, both A and AC horizons were well developed and extending down to 32 cm below the soil surface (Table 5.2; Fig. 5.1). Sites G and

1889 continue to show a general trend of progressive soil development including color changes and spotty iron stains in the A and AC horizons, suggesting increased oxidation (Fig. 5.1; App. E). The upper subsoils of the older sites 1889, H and I are well developed but depth to bottom of AC horizon rises from 40 cm to 30 cm below the soil surface at site I. Site K (ca. 4000 BP; Chapter 4) had the most developed and complex soils with well developed B horizons including Bh_s and Bs (Appendix E).

5.2.2 *Texture*

Coarse substrates characterize the sample sites from site A3 to site I (Table 5.2). Sandy textures predominate throughout all sites except for the ca. 4000 BP soils at site K. The percentages of sand, silt, and clay in the upper 10-cm of soil have been plotted as a function of depth and of time for the series of sample sites (Fig. 5.2). Surface mineral horizons exceed 90% sand for the youngest site (A3) and the two sites located on river terraces (sites H and I). The next prominent size class is less well defined, with clay slightly predominating in sites B, C, D, E and F. There may be a general tendency for clay and silt fractions to increase slightly through time at the expense of the sand fraction for at least the first four sites (A3, B, C and D). However, this trend is reversed at site E through the older sites, where both clay and silt decrease in concentration relative to sand. In all study sites, soil textures are modified by the presence of rock fragments. Thus most of the soil textures are either extremely stony or cobbly, and a few are bouldery.

5.2.3 *Bulk Density*

Bulk densities of soils is governed by many factors including particle size distribution (higher sand concentration, greater BD) and amounts of incorporated soil organic matter (higher SOM = lower BD). Bulk densities for soils at sites A3 - I are in the range of sandy loams and sand ($1.2 - 1.8 \text{ g m}^{-3}$), but are highest in the mineral horizons that are dominated by sandy textural mineral layers (Table 5.2). A plot of bulk density of the surface horizons and time can be seen in Figure 5.3. If the two sandy sites H and I are excluded, because they both formed in river outwash and the fine particles were washed away, then a general decreasing trend in bulk density ($r^2 = 0.683$) can be seen (Figure 5.3). There were no clear trends of bulk density with depth for any of the sites and along the chronosequence due to the minimal horizonation.

5.3 Chemical properties of the soils and forest floor

Along the chronosequence at Exit Glacier, changes in pH for both the organic and soil mineral horizons were observed. The pH values of organic horizons range from 5.0 to 3.8. The pH values in the uppermost soil mineral layers ranged from 7.4 near the glacier (site A3) to 5.1 at (site I) and then dropped nearly one-half unit at the oldest site sampled (site K; Table 5.3). The pH values fall most rapidly in the surface layers of the mineral soil, while trends for declining pH are also present in the organic and subsurface mineral horizons. This trend across the chronosequence at Exit Glacier, as well as the r^2 values (logarithmic), is depicted in Figure 5.4. This trend reflects the effect of increased leaching with time. Removing sites H and I had little effect on fitness of regression. The lowest pH values for organic and soil mineral horizons were found at Site K, beyond the estimated LIA maximum extent and estimated at ca. 4000 years BP (Table 5.2).

Depth functions to 50 cm below the soil surface of pH for the mineral soils along the Exit Glacier chronosequence can be seen in Figure 5.5. Changes in pH take place more slowly at greater depths for all sites, and there is no appreciable change in the 50-cm level in the successional sequence. The greatest change in pH takes place during the period between the youngest site located on the gravel outwash plain (site A3; Table 5.1) and the alder stage (site B). Following initial rapid lowering of the pH, the rates slow with little increase at depths greater than about 15 cm for the three youngest sites. pH with depth for the five youngest sites is lowest at site E, then pH increases with depth for sites F and G. High rates of pH change with depth, relative to all other sites, occur at site I (Fig. 5.5) which had greater concentrations of sand, subsurface water and buried organic debris as a result of apparent fluvial processes (Table 5.1; 5.2).

Cation exchange capacity (CEC) for both organic and mineral horizons are lowest at the youngest site (A3) and progressively higher with increasing terrain age out to Site G (Table 5.3). CEC's of the organic horizon range from 69 $\text{cmol}_c \text{ kg}^{-1}$ to 115 $\text{cmol}_c \text{ kg}^{-1}$ through sites A3-G, then decrease to 104 $\text{cmol}_c \text{ kg}^{-1}$ at site I. Surficial mineral horizons CEC's range from 0.2 $\text{cmol}_c \text{ kg}^{-1}$ at site A3 to 4.6 $\text{cmol}_c \text{ kg}^{-1}$ at site G, then decrease to 3.6 $\text{cmol}_c \text{ kg}^{-1}$ at site I. CEC's in the mineral horizons at the oldest site (Site K: ca.

4000 BP) are on an order of magnitude higher than the earlier sites (Table 5.3). Mean CEC's across entire profiles (organic + mineral horizons) are most highly correlated with soil organic matter ($r^2 = 0.892$) when sites affected by apparent flooding (H and I) were excluded. Percent clay distribution was the next parameter most likely to explain CEC through time ($r^2 = 0.625$).

Figure 5.6 (a and b) depicts the carbon and nitrogen stores (kg m^{-2}) for the organic and standardized mineral horizons (0-10cm and 10-100cm below the soil surface) for soil sites A3-G. Carbon and nitrogen in the organic horizons generally increased from site A3 to the 85-year-old site (D), then became more variable out to the oldest site I. Sites F and H had low C and N concentrations in the organic horizons relative to sites on either side of them (Fig. 2.3). Linear regressions depicted in Figure 5.6 a and b show an overall increasing trend through time for carbon ($r^2=0.573$) and nitrogen ($r^2=0.621$). There is also a trend of increasing storage of carbon at depth (top 10 cm of mineral horizon) through time ($r^2=0.687$), while nitrogen remains fairly constant ($r^2=0.371$) as a function of time. The greatest relative concentration for carbon and nitrogen resides in the 10-100cm mineral depth for the earlier sites, but then drops relative to the organic and upper mineral horizon after 85 years.

A strong inverse relationship between the concentration of carbon (kg m^{-2}) in the organic horizon and pH can be seen in Figure 5.7. Since carbon is directly correlated with organic content and, therefore, organic acid secretion from decomposition, this correlation is not unexpected. However, the greater acidity at sites E and I may be due in part to the wetter nature of the soils (site E located on a convex moraine shoulder; site I located on an abandoned river terrace).

Extractable-N concentrations were high in surface organic horizons and generally decreased with depth; however, many of the profile depths recorded less than 1ppm extractable N (Table 5.3). Concentrations of extractable N, P, K, Mg and Ca are depicted in Figure 5.8. The concentrations (ppm) were summed through organic and mineral horizons down to 100 cm depth. In order to depict all nutrients on the same graph, concentrations of K and Mg were divided by 10 while Ca was divided by 100. Concentrations across all sites were highest in Ca, followed by K, Mg, and P, then N. Except for site A3,

all nutrients showed only slightly downward trends for K, Mg and Ca. Values of extractable K were estimated to have exceeded 930 ppm for three organic horizons (B, C and E) since the ICP became saturated above 932 ppm.

5.4 Discussion

No single factor can account for the chemical and physical changes induced in soils on glacial forelands. The greatest changes with time were seen in the particle size distribution, horizon differentiation, and pH. Organic horizons reached a maximum observable depth of 12 cm, and an AC horizon appeared at site E, over 100 years after deglaciation. In comparison, the recessional sequence at Casement Glacier at Glacier Bay (Ugolini, 1996) had a 10cm deep A1 horizon by 35 years under a thick alder canopy. Although this study did not analyze any soils under totally barren conditions, the isolated plant stage (site A3) at 19 years was more equivalent to a 50-year-old site at Glacier Bay in terms of soil profile acidity. The lack of black crust (*Dryas drummondii*), a known N-fixer, may delay incorporation of N in the barren soils at Exit Glacier. Changes in pH with depth were also less prominent than at Glacier Bay (Ugolini, 1966).

Decreases in bulk density of the uppermost horizons over a chronosequence have been observed in Glacier Bay (Crocker and Major, 1955) and Mt. Shasta (Dickson and Crocker, 1954) due to incorporation of organic matter and root intrusion. There is also a general tendency for bulk density to rise with profile depth, due to lower content of organic matter and less aggregation and root penetration (Brady, 1974). Such trends with depth were not so clearly seen at Exit Glacier, most likely due to the difficult task in estimating bulk density with large amounts of skeletal material in horizons (Appendix E) and the coarse methods employed for estimating bulk density for horizons (Chapter 3.2). Despite these difficulties, trends in bulk density, were observed to be taking place along a soil chronosequence over 100 years.

The warmer and wetter climate at Glacier Bay (average annual temp: 5.8 C; average. annual precipitation; 2924mm) as compared to Exit Glacier (average. annual temp: 2.3 C; average. annual precipitation: 1700mm) allows for more rapid vegetative growth and colonization, and thus soil

development. This profusion of colonizing vegetation, therefore, likely increases the leaching potential in the soil and accelerates soil development relative to the soils at Exit Glacier. Biomass estimates were not made in this study, so direct comparisons with other chronosequences in terms of accumulation was not possible. However, this study has confirmed the general accumulation of organic carbon through time, with the greatest increase being shown at the 48-year-old site (B) where alder provides significant cover (Chapter 2).

A sequence of moraines developed at Exit Glacier as a result of the receding ice front of the glacier were sampled in this study to characterize the soils and relate soil development with leaf nutrient status of black cottonwood and alder. Development of the soil profiles (H and I) at Exit Glacier has been shown to be strongly influenced by fluvial processes even on raised moraine surfaces. Confounding effects of sampling only one soil pit per transect have most likely hindered an ability to make profound conclusions on trends across the chronosequence.

Table 5.1 Physical environment of the soil-study sites at Exit Glacier, Kenai Fjords National Park, Alaska. All sites shown.

Latitude N.								
Site No.	Longitude W.	Elev. *	Landform	Soil pit position	Drainage Class	Slope(%) Aspect	Parent Material	
	(Datum = NAD27) *	(m a.s.l.)						
A3	60° 10' 49.16"N 149° 37' 47.12"W	120	outwash plain, dissected by abandoned water channels, slightly undulating	terrace floor	excessive	0-2 N	gravelly outwash, 40% cobble, 40% stones	
B	60° 11' 03.60"N 149° 37' 36.68"W	116	moraine, hummocky	on saddle	well	0-2 NW	glacial moraine, 10% stone w/ erratics > 2m across	
C	60° 11' 05.31"N 149° 37' 27.13"W	115	moraine, hummocky	on moraine ridge, slightly concave position	moderately well	4 NW	glacial moraine, 5% erratics	
D	60° 11' 17.40"N 149° 36' 59.57"W	110	moraine, hummocky	on moraine ridge top, cut into bank	well	10 W	glacial moraine, 10% stones	
E	60° 11' 18.11"N 149° 36' 48.11"W	112	moraine, hummocky	on shoulder slope of moraine ridge, convex	well	15 S	glacial moraine, extremely cobbley and 1% surface stone	
F	60° 11' 27.15"N 149° 36' 32.52"W	105	moraine, hummocky	on shoulder slope of moraine ridge	well	40 NE	glacial moraine, 45% rock fragment containing 5% stone, 30% cobble	
G	60° 11' 30.63"N 149° 36' 26.06"W	107	moraine ridge	on moraine ridge top, cut into bank	well	0-3 N	glacial moraine, not compacted	
1889	60° 11' 23.75"N 149° 36' 11.52"W	110	moraine ridge (esker-like)	on shoulder slope	well	30 SW	glacial moraine, 5% surface stone	
H	60° 11' 32.22"N 149° 36' 10.94"W	97	river terrace, nearly level-slightly undulating w/ dissected channels	terrace floor	well	0-2 SW	river outwash	
I	60° 11' 31.52"N 149° 36' 06.14"W	99	river terrace, braided slightly undulating w/ relief 30-60 cm	terrace floor	water table - 90cm	0-2 SE	river outwash	
PITS K1&K2	60° 11' 35.05"N 149° 35' 20.42"W	88	glacial moraine, hummocky w/ windthrown mounds	on moraine ridge top, cut into bank	moderately well	5 NE	tephra over glacial moraine	
* Position and elevation determined using differential C/A code GPS. Elevations estimated +/- 3 meters								

Table 5.2. Physical properties of soils at Exit Glacier, Kenai Fjords National Park, AK. All sites shown. nd= Not determined

Site & Horizon	Age (Yrs)	Depth (cm)	Particle Size distribution				Texture
			Horizon Thickness (cm)	Water Content (%)	Bulk		
					Density (g m ⁻³)	Gravel (%)	
A3.	AC	0-2	2	47	1.5	50	Extremely gravelly sand
	C1	2-7	5	14	1.6	56	Extremely cobbly sand
	C2	7-30	23	10	1.6	69	Extremely cobbly sand
	C3	30-100	70	10	1.6	68	Extremely cobbly sand
	Sandy-skeletal, mixed Typic Cryorthents						
B.	Oi/Oe	0-3	3	374	0.1	2	Mucky peat
	C1	3-10	7	18	1.3	30	Very cobbly sandy loam
	C2	10-30	20	14	1.5	46	Extr. cobbly sandy loam
	C3	30-100	70	14	1.5	64	Extr. cobbly sandy loam
	Loamy-skeletal, mixed Typic Cryorthents						
C.	Oe	0-4	4	351	0.1	17	Peaty muck
	C1	4-12	8	20	1.3	37	V. cobbly sandy clay loam
	C2	12-32	20	17	1.4	38	Extr. cobbly sandy clay loam
	C3	32-100	68	16	1.4	34	Extr. cobbly sandy clay loam
	Loamy-skeletal, mixed Typic Cryorthents						
D.	Oi/Oa	0-1/1-5	5	310	0.1	18	Muck
	C1	5-10	5	20	1.4	35	V. cobbly sandy clay loam
	C2	10-35	25	17	1.4	44	V. cobbly sandy clay loam
	C3	35-70	35	16	1.5	37	V. cobbly sandy clay loam
	C4	70-100	30	14	1.5	37	V. cobbly sandy clay loam
E.	Oi/Oe/Oa	0-1/1-8/8-11	12	370	0.1	3	Peaty muck
	AC	12-15	3	33	1.2	44	Extr. cobbly loamy sand
	C1	15-35	20	17	1.4	46	Extr. sandy loam
	C2	35-60	25	17	1.4	74	Extr. loamy sand
	C3	60-100	40	14	1.5	64	Extremely cobbly sand

Table 5.2. Physical properties of soils at Exit Glacier, Kenai Fjords National Park, AK. All sites shown. nd= Not determined

Site & Horizon	Age (Yrs)	Depth (cm)	Horizon Thickness (cm)	Particle Size Distribution		Texture					
				Horizon	Bulk						
				Water Content (%)	Density (g m ⁻³)						
Gravel											
Loamy-skeletal, mixed Typic Cryorthents											
F.	Oi/Oa	105	0-1/1-5	5	377	0.1	3	nd	nd	nd	Peat
	A		5-17	12	19	1.4	47	63	17	20	Very cobbly sandy loam
	AC		17-32	15	14	1.5	48	69	17	14	Very cobbly sandy loam
	C		32-100	68	13	1.5	48	65	19	16	Very cobbly sandy loam
Loamy-skeletal, mixed Typic Cryorthents											
G.	Oi/Oe	108	0-2/2-8	8	351	0.1	13	nd	nd	nd	Peaty muck
	A		8-16	8	22	1.4	53	73	15	12	Very cobbly sand loam
	AC		16-30	14	16	1.5	57	71	15	14	Very cobbly sand loam
	C1		30-70	40	13	1.5	56	73	15	12	Very cobbly sand loam
1889.	C2		70-100	30	10	1.5	56	80	14	6	Very cobbly loamy sand
	Sandy-skeletal, mixed Typic Cryorthents										
	Oi/Oe	110	0-2/2-6	6	323	0.1	15	nd	nd	nd	Peat
	A		6-22	16	16	1.4	65	82	14	4	Very cobbly loamy sand
H.	AC		22-45	23	15	1.5	57	80	10	10	Very cobbly loamy sand
	C		45-100	55	13	1.6	54	85	8	8	Very cobbly loamy sand
	Sandy-skeletal, mixed Typic Cryorthents										
	Oi/Oa	130	0-1/1-6	6	328	0.1	4	nd	nd	nd	Peat
I.	A		6-16	10	22	1.4	60	94	4	2	Extremely cobbly sand
	AC		16-42	26	21	1.3	78	92	6	2	Extremely cobbly sand
	C		42-100	58	17	1.3	80	93	4	3	Extremely cobbly sand
	Sandy-skeletal, mixed Typic Cryofluvents										
Oe	251	0-9	9	365	0.1	0	nd	nd	nd	nd	Peaty muck
I.	A		9-18	9	20	1.4	56	96	2	2	Very gravelly sand
	AC		18-39	21	12	1.5	64	96	2	2	Very gravelly sand
	C1		39-61	22	10	1.6	30	96	2	2	Very cobbly coarse sand
	C2		61-100	39	21	1.6	19	97	1	2	Gravelly sand

Table 5.2. Physical properties of soils at Exit Glacier, Kenai Fjords National Park, AK. All sites shown. nd= Not determined

Site & Horizon	Age (Yrs)	Depth (cm)	Horizon Thickness (cm)	Water Content (%)	Particle Size distribution					
					Bulk Density (g m ⁻³)	Gravel (%)	Humicryods			
							Sand (%)	Silt (%)	Clay (%)	Texture
K2										
Oi/Oa	ca. 4000 (BP)	0-5/5-11	11	154	nd	6	nd	nd	nd	Peaty muck
E		11-16	5	69	0.8	18	38	44	18	Loam
Bhs		16-30	14	60	0.6	31	72	18	10	Sandy loam
Bs		30-50	20	48	0.7	32	84	0	16	Gravelly loamy sand
BC		50-67	17	22	0.9	28	68	20	12	Gravelly sandy loam
2C		67-200	133	12	1.5	33	68	17	16	Very gravelly sandy loam
K1.										
Oi	ca. 4155 (BP)	0-8	8	411		0	nd	nd	nd	Peat
Oa		8-11	3	215		0	nd	nd	nd	Muck
E		11-13	2	56	0.8	14	35	46	19	Loam
Bhs		13-20	7	64	0.6	30	76	14	10	Sandy loam
Bs1		20-60	40	71	0.8	37	52	32	16	Sandy loam
Bs2		60-73	13	91	0.7	41	53	34	14	Sandy loam
Eb		73-78	5	74	0.8	24	40	41	19	Loam
Bsb		78-100	22	48	0.8	35	62	24	14	Gravelly sandy loam
2C		100-200	100	12	1.6	36	66	18	17	Very gravelly sandy loam

Figure 5.1. Development of soil profiles along the chronosequence at Exit Glacier.

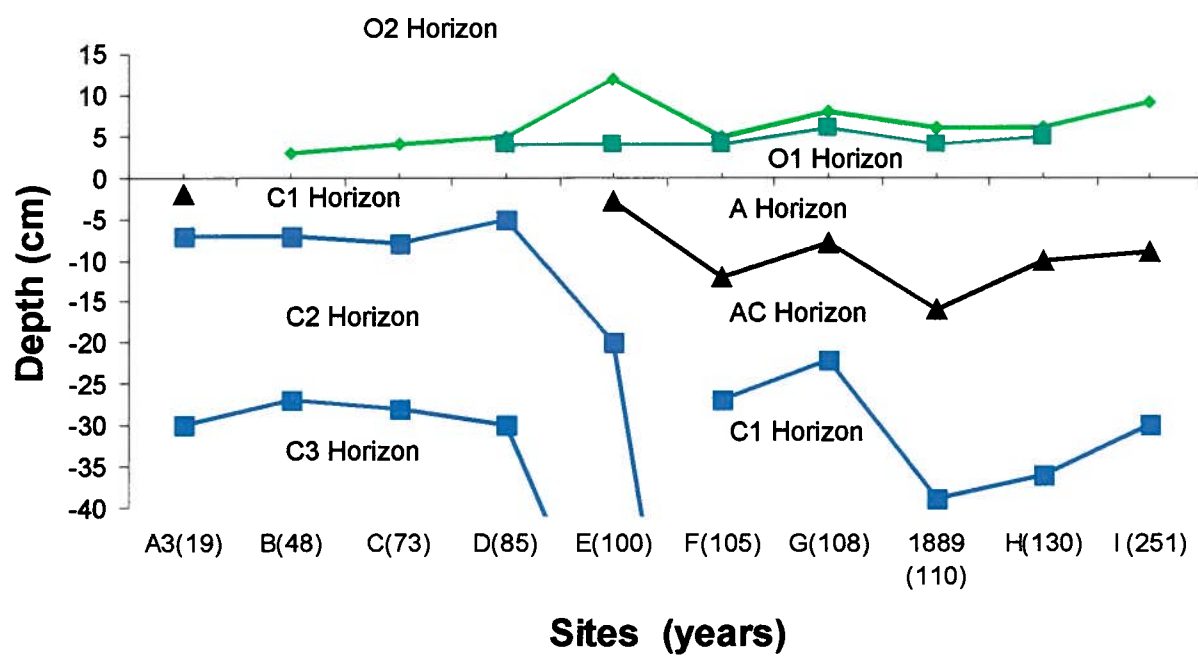


Figure 5.2. Percentages of sand, silt, and clay at the 10-cm depth in the soils along the chronosequence at Exit Glacier. N = 1. Sites 1889 and K excluded.

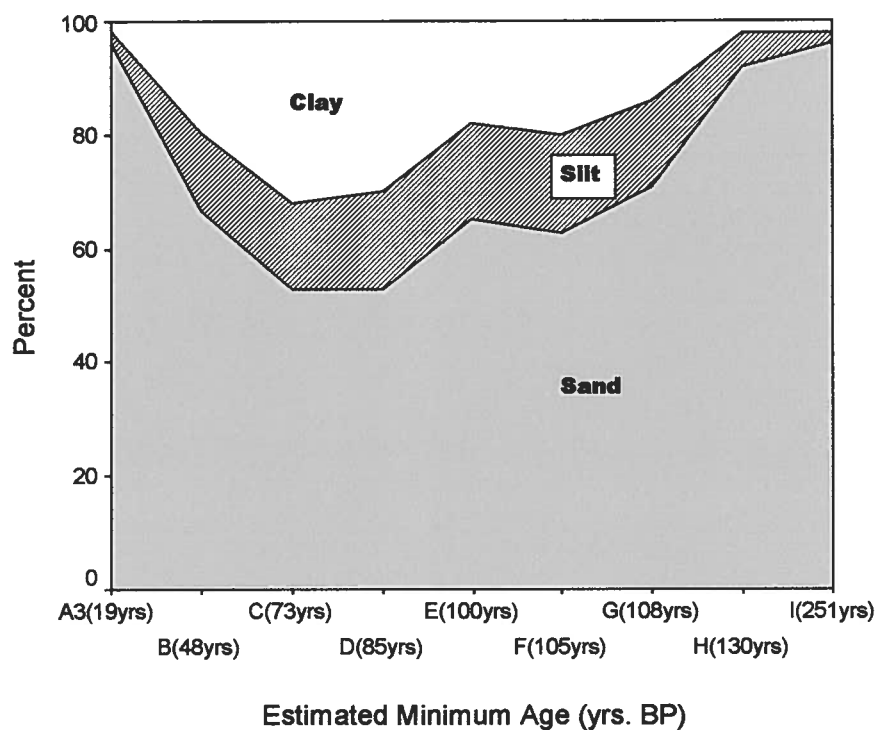


Figure 5.3. Bulk density of the surface soil horizons as a function of time since deglaciation or stabilization of substrate. Sites H and I were not used in regression due to flooding effects (Chapter 4).

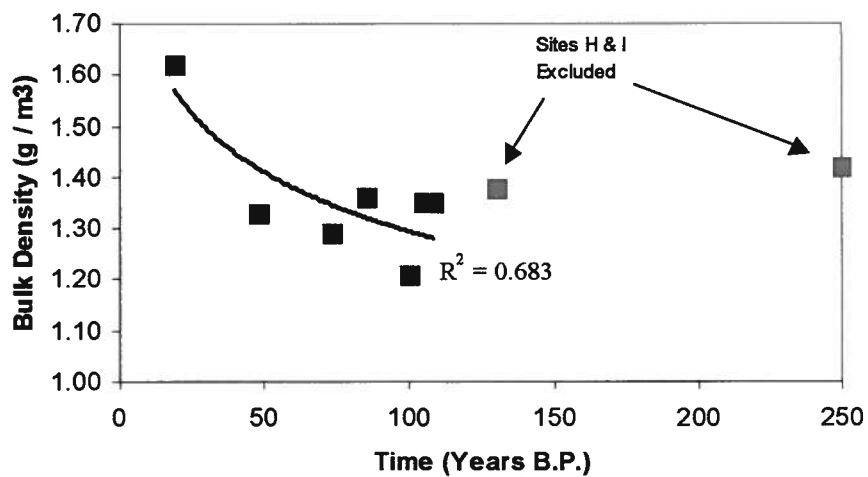


Table 5.3 Chemical properties of Exit Glacier soils.

Site (Age)	Horizon	Depth	pH	NH ₄	NO ₃	Extractable		Total			OM	CEC	Exchangeable Bases			Extractable							Extractable							
						N	P	N	P	C			K	Ca	Mg	Ca	Cu	Fe	K	Mg	Mn	Zn	Fe _o	Al _o	Si _o	Fe _d	Al _d	Mn _d	Fe _p	Al _p
				mg kg ⁻¹	mg kg ⁻¹	mg kg ⁻¹	mg kg ⁻¹	%	%	%	%	cmolc / kg ⁻¹	cmolc / kg ⁻¹			mg kg ⁻¹							%							
A3(19)	AC	0-2	6.0	2	1	3	7	0.07	0.09	0.7	1.3	0.2	.04	1.47	.13	216.5	11.1	275.4	30	29.9	61.6	6.2	0.37	0.09	0.08	0.24	0.04		0.02	0.01
	C1	2-7	7.4	2	1	3	6	0.05	0.10	0.4	0.5	0.2	.02	1.75	.09	225.0	14.7	570.0	12	29.6	88.9	8.3	0.35	0.08	0.07	0.29	0.05	0.01		
	C2	7-30	8.1	1	1	2	2	0.04	0.10	0.5	0.5	0.2	.01	8.10	.11	825.1	13.6	825.9	10	28.8	50.6	10.3	0.38	0.07	0.07	0.42	0.19	0.02		
	C3	30-100	8.1	1	1	2	2	0.03	0.09	0.5	0.6	0.2	.01	9.02	.14	950.2	11.8	786.1	9	29.9	40.4	9.0	0.37	0.07	0.07	0.32	0.06	0.01		
B(48)	Oi/Oe	0-3	5.4	29	4	33	58	2.37	0.11	45.5	82.9	69.2	6.53	91.89	9.23	4603.4	4.2	199.2	>930	557.1	74.9	28.9								
	C1	3-10	6.2	2	1	3	5	0.08	0.10	0.8	2.0	1.8	.09	3.23	.29	582.7	16.7	599.3	93	103.3	83.7	10.8	0.75	0.27	0.28	0.24	0.07		0.05	0.03
	C2	10-30	7.6	2	2	4	3	0.06	0.10	0.5	0.9	0.9	.05	5.82	.11	750.4	16.2	619.7	68	82.7	91.9	12.4	0.72	0.25	0.27	0.39	0.12	0.02	0.02	0.02
	C3	30-100	8.0	2	2	4	1	0.04	0.10	0.5	0.9	1.9	.06	14.51	.15	2120.8	14.9	587.6	78	69.6	89.7	11.3	0.73	0.25	0.27	0.39	0.12	0.02	0.02	0.02
C(73)	Oe	0-4	5.6	15	5	20	35	1.65	0.09	35.0	63.1	76.9	2.92	59.27	6.53	3967.5	3.4	343.3	>930	570.7	86.9	65.6								
	C1	4-12	5.9	1	1	2	5	0.06	0.09	0.8	1.8	2.5	.08	2.91	.30	514.9	14.0	525.3	85	83.2	60.4	6.3	0.84	0.31	0.30	0.45	0.15	0.02	0.07	0.03
	C2	12-32	7.4	1	2	3	2	0.06		0.4	1.0	3.2	.07	4.48	.20	706.8	16.7	579.9	99	99.2	86.2	10.8	1.02	0.38	0.40	0.45	0.15	0.02	0.03	0.02
	C3	32-100	7.9	<1	2	2	0	0.05	0.10	0.5	1.1	2.4	.09	16.47	.16	2393.7	15.4	521.8	108	79.9	99.9	9.8	0.97	0.38	0.42	0.49	0.18	0.02	0.02	0.01
D(85)	Oi/Oa	0-1/1-5	5.4	9	4	13	27	1.80	0.09	37.0	67.4	89.9	2.14	65.83	5.77	4318.9	3.4	428.1	698	481.3	93.0	55.8								
	C1	5-10	5.7	1	1	2	12	0.07	0.09	0.7	1.9	4.7	.09	1.78	.22	326.3	14.6	538.5	95	68.8	44.1	5.7	0.84	0.33	0.31	0.44	0.16	0.01	0.07	0.03
	C2	10-35	6.7	<1	1	1	5	0.03	0.10	0.5	1.4	3.8	.06	3.21	.22	583.5	18.0	564.1	93	91.8	64.7	9.3	0.79	0.31	0.33	0.44	0.16	0.02	0.03	0.02
	C3	35-70	7.6	<1	2	2	5	0.04	0.10	0.4	1.1	2.2	.06	3.90	.20	619.1	16.1	596.4	90	92.6	80.2	9.5	0.84	0.33	0.36	0.44	0.17	0.02	0.02	0.01
	C4	70-100	8.0	<1	1	1	1	0.03	0.10	0.4	0.9	1.1	.07	10.31	.17	1395.2	15.4	573.5	96	81.1	81.5	9.0	0.85	0.34	0.37	0.44	0.18	0.02	0.02	0.01
E(100)	Oi/Oe/Oa	0-1/1-8/8-12	5.0	13	3	16	38	1.92	0.09	47.5	87.1	105.6	2.75	68.01	6.76	4777.1	3.7	384.6	>930	589.8	60.5	36.1								
	AC	12-15	5.5	<1	1	1	4	0.12	0.09	1.7	3.6	4.5	.11	4.29	.41	677.8	5.9	446.1	76	73.9	48.4	3.5	0.47	0.15	0.13	0.31	0.09		0.07	0.03
	C1	15-35	6.7	<1	1	1	4	0.05	0.09	0.6	1.4	3.0	.02	3.17	.16	626.4	16.7	547.3	54	79.6	64.2	8.3	0.72	0.27	0.27	0.36	0.11	0.02	0.04	0.03
	C2	35-60	7.2	<1	1	1	3	0.03	0.10	0.6	1.3	2.0	.02	3.71	.09	520.8	17.6	682.2	30	53.0	58.7	10.6	0.47	0.13	0.13	0.36	0.08	0.02	0.02	0.01
	C3	60-100	7.5	<1	1	1	4	0.04	0.09	0.5	1.1	0.2	.01	2.36	.07	400.9	17.6	863.7	20	43.9	56.5	10.7	0.46	0.10	0.10	0.33	0.07	0.02	0.01	
F(105)	Oi/Oa	0-1/1-5	5.3	23	3	26	48	2.03	0.09	43.1	79.1	103.8	3.32	64.76	8.21	4660.2	3.9	449.9	851	739.1	79.4	62.6								
	A	5-17	5.8	<1	<1	1	6	0.05	0.09	0.7	2.1	3.9	.04	2.52	.21	477.8	12.4	519.2	53	66.7	41.3	5.0	0.73	0.28	0.27	0.43	0.17	0.02	0.06	0.03
	AC	17-32	7.1	<1	1	1	6	0.00	0.10	0.4	1.0	1.8	.02	2.87	.11	512.8	16.7	612.0	44	69.4	64.1	9.6	0.60	0.21	0.22	0.35	0.10	0.01	0.02	0.01
	C	32-100	7.8	<1	1	1	2	0.02	0.09	0.4	0.9	1.6	.03	5.90	.10	854.6	14.5	662.2	60	82.3	78.2	10.3	0.69	0.25	0.27	0.37	0.14	0.01	0.01	
G(108)	Oi/Oe	0-2/2-8	5.2	20	2	22	43	2.06	0.10	45.9	84.2	114.7	3.25	85.15	7.17		4.2	360.1	894	585.1	113.7	73.8								
	A	8-16	5.7	<1	1	1	3	0.11	0.08	1.1	2.3	4.6	.05	3.56	.29	517.6	9.0	468.4	48	55.6	57.2	4.1	0.53	0.17	0.14	0.34	0.09	0.01	0.09	0.03
	AC	16-30	6.9	<1	1	1	5	0.02	0.09	0.5	1.1	2.4	.03	3.27	.15	497.4	16.7	540.7	43	64.6	60.6	8.3	0.49	0.17	0.17	0.37	0.10	0.02	0.03	0.02
	C1	30-70	7.9	<1	1	1	3	0.03	0.10	0.4	1.0	1.0	.02	4.75	.07	673.6	15.7	646.9	39	69.7	74.7	10.4	0.51	0.17	0.18	0.35	0.11	0.01	0.01	
	C2	70-100	8.1	<1	1	1	2	0.01	0.09	0.5	0.9	0.7	.02	9.82	.09	1452.4	13.1	634.5	32	52.4	56.9	8.9	0.45	0.14	0.15	0.30	0.09	0.01	0.01	
1889(110)	Oi/Oe	0-2/2-6	5.5	15	3	18	32	1.93	0.09	41.1	74.7	93.2	1.39	66.51	6.29	4671.6	2.7	336.8	601	601.0	71.5	49.8								
	A	6-22	6.1	<1	1	1	5	0.04	0.09	0.6	1.5	1.5	.02	1.61	.07	310.7	12.2	496.9	23	36.9	45.7	5.7	0.56	0.18	0.16	0.36	0.12	0.02	0.03	0.02
	AC	22-45	7.1	<1	1	1	5	0.01	0.09	0.4	1.0	0.8	.01	1.90	.06	369.2	16.4	605.2	24	53.5	64.8	8.2	0.66	0.22	0.23	0.39	0.12	0.02	0.02	
	C	45-100	7.7	<1	1	1	4	0.03	0.09	0.4	0.7	1.2	.01	3.04	.06	350.2	13.9	625.6	21	50.0	58.7	8.9	0.66	0.21	0.21	0.39	0.11			

Figure 5.4. pH of organic and surface horizons of the mineral soil as a function of age of surface. Sites 1889 and K excluded due to site differences (See text). Logarithmic residuals are depicted for trends.

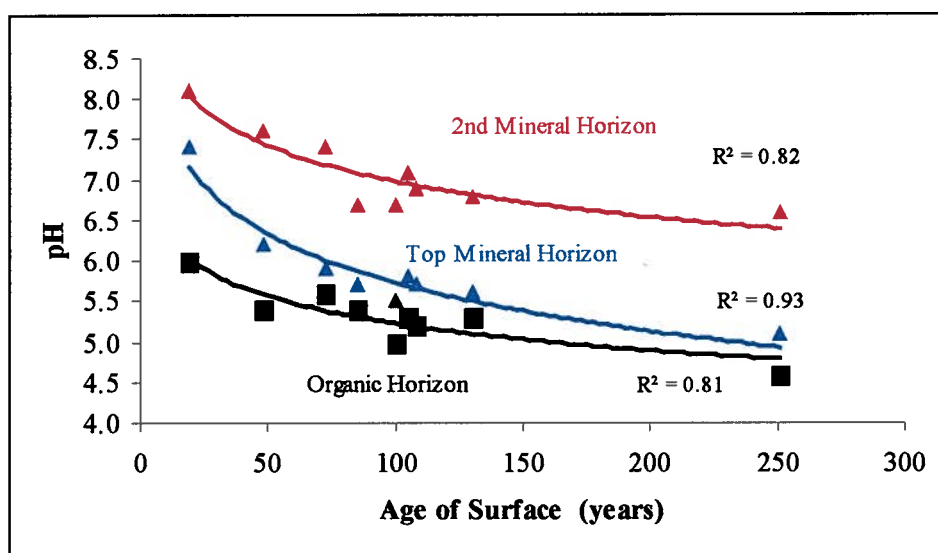


Figure 5.5. Changes in soil pH with depth in nine of the eleven soil sites, where leaf transects were co-located. Sites 1889 and K excluded. Depth in profiles calculated on midpoint of each soil horizon. $N = 1$.

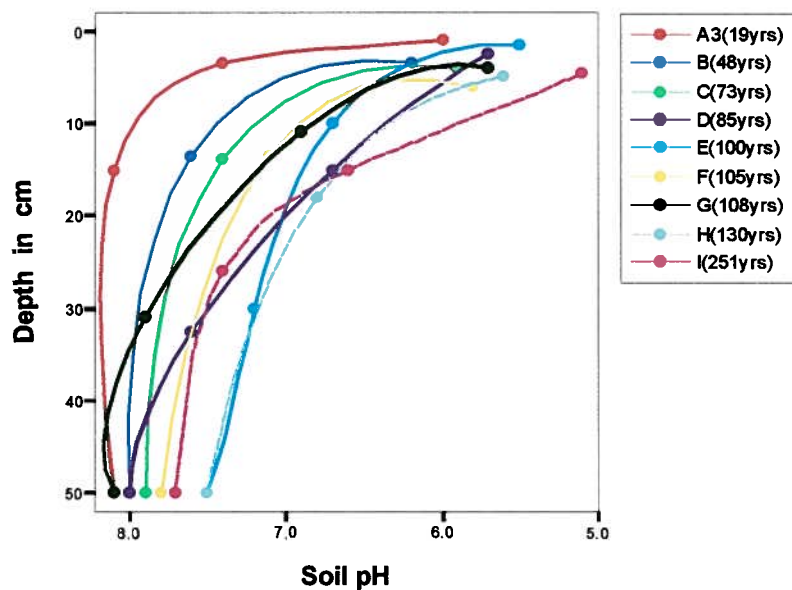


Figure 5.6 a and b Carbon (a) and nitrogen.(b) concentrations (kg m^{-2}) for the organic and mineral horizons (0-10cm and 10-100cm) as a function of time. Linear residuals are depicted for trends.

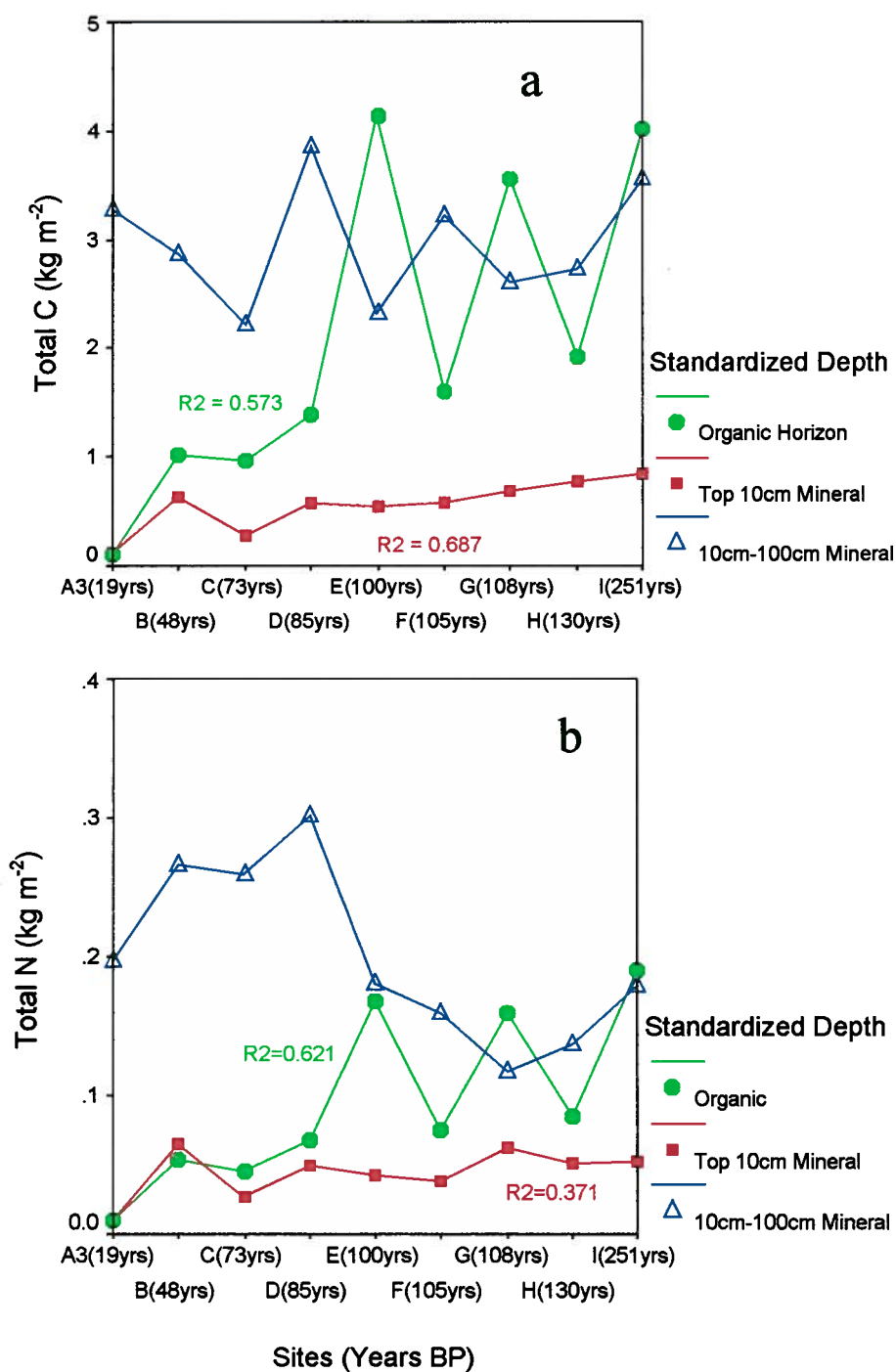


Figure 5.7. Carbon concentration (kg m^{-2}) and pH for the organic horizon as a function of time.

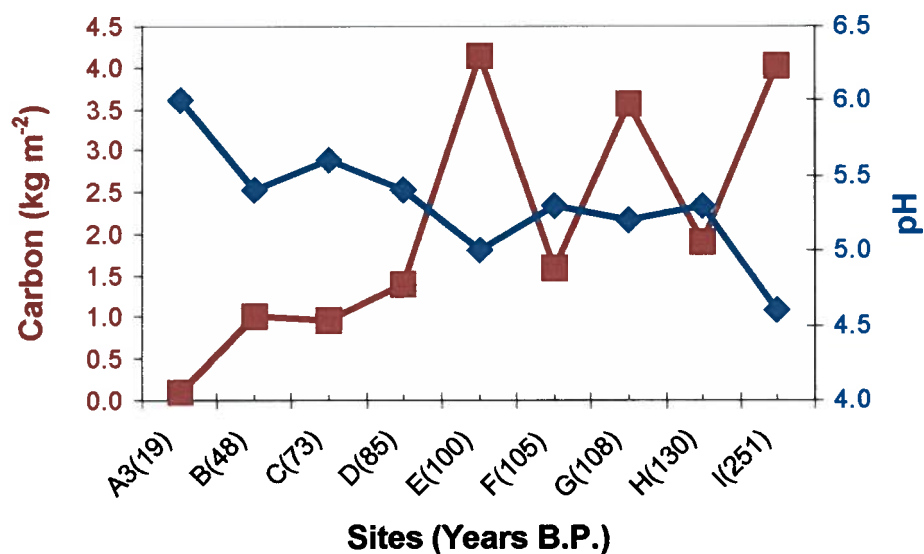
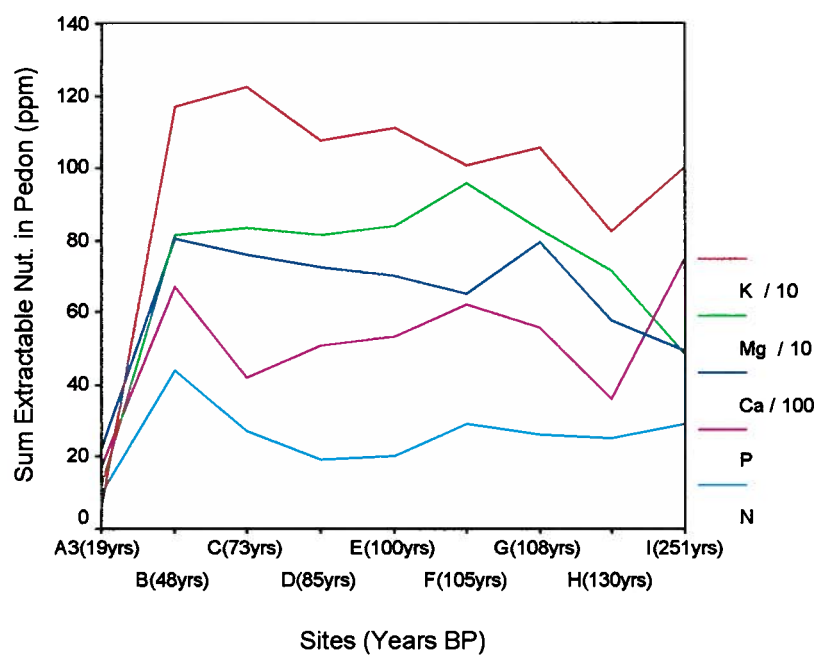


Figure 5.8. Sum of extractable K, Mg, Ca, P and N nutrients in concentration (ppm) to 100cm depth. K and Mg concentrations are divided by 10, while Ca is divided by 100.



6 FOLIAR NUTRIENT RESULTS

Eleven sites were sampled on the Exit Glacier forelands for foliar concentrations. Dates of deglaciation and site age were from historical maps, photographs (sites A-C), or inference from ages of the oldest cottonwood or spruce trees sampled along the ice margin (sites D-J) (Table 3.1). Evidence from tree-rings and soil analysis reveals some sites were established at some time after de-glaciation. For instance, the cottonwood seedling site A3, located adjacent to the modern outwash plain (Fig. 3.2), indicates stabilization of substrate around 1980, but 1961 photography suggests deglaciation about 19 years prior. In this study, the 19-year estimate will be used for foliar nutrient interpretation. Site J was located north of Exit Glacier road and on an abandoned outwash plain. Oldest tree sampled there suggests deglaciation prior to 1904, but trees were difficult to core and unique alder species were encountered. Due to these patterns, this site will not be discussed here. In addition, evidence from soil profiles (See Chapter 5) indicate sites H and I are located on abandoned moraines eroded by past flooding events and are thereby influenced by disturbance. Additionally, the oldest trees sampled from sites F and G suggest deglaciation prior to 1912 and 1903 respectively, however, calculated ice-free dates from more firmly established moraines up and down valley from these sites suggest imprecision on these two sites. Therefore sites F and G have less confident terrain ages and have overlapping ages with site E.

Mineral nutrients Boron (B), Copper (Cu), Sodium (Na) and Sulfur (S) were unreliable as determined from quality control checks during laboratory procedures (Chapter 3) and will not be discussed here. The literature review in Chapter 1 has shown that foliar nutrient concentrations can be affected by many factors other than nutrient supply to the tree. Two of these factors, yearly variability and position on the tree were assessed during this study in order to more accurately interpret the foliar analysis. Details of these assessments are located in Appendix F: "Additional Considerations in Interpreting Foliar Nutrient Variability".

6.1 Comparison of N between Alder and Cottonwood

Nitrogen concentrations in the leaves of Sitka alder remained consistently higher than those of black cottonwood where both species were present (Table 6.1; Fig. 6.1). N concentration in alder leaves were generally highest at sites F and G, surfaces estimated to be ice free between 105 and 108 years ago respectively (Table 4.1). However, due to associated errors in estimating tree age especially at these two sites (See Chapter 4), their substrate ages overlap with the 100 -year-old site. Figure 6.2a indicates the poor linear correlation between time and foliar N ($r^2 = 0.127$; Fig. 6.2a), despite the dramatic differences in composition of the 30 -year-old pure alder stand (A) near the glacier to the older mixed cottonwood dominated sites over 100 years old.

In contrast, N concentrations in leaves of cottonwood were lowest at the exposed gravel outwash site A3, where moss and 0.5 m tall cottonwood predominate (Chapter 2) and foliar N increased in concentration up to and including site C, a 73 -year-old site where a dense alder thicket dominates understory (App. E). N concentrations then decreased at the 85 -year-old site D, followed by a possible increase out to site G (Table 6.1; Fig. 6.1). Differences in foliar N indicate a close linear correlation ($r^2 = 0.568$; Fig. 6.2b) for cottonwood across all the sites ($P < 0.0001$), however, when the youngest site is removed no linear correlation between time and foliar N ($r^2 = 0.004$; $P < 0.03$) exist. Concentration of N at site C remains significantly higher than all other sites ($P < 0.0001$). The unique characteristics of site A3 among all cottonwood sites include exposed outwash, a lack of alder presence, nonvascular (moss) domination and young cottonwood (height < 0.5m; mean age = 5 years). All of these factors are typical of the isolated and patchy areas adjacent to the outwash plain (See Chapter 2; Helm and Allen, 1995), but are not represented in any other sites studied on the outwash plain.

6.2 Macronutrients

The macronutrients for cottonwood and alder displayed several distinct patterns along the Exit Glacier chronosequence. Foliar P in cottonwood were low in the youngest site and increased progressively

out to the 100 -year-old site (E)(Table 6.1). Figures 6.3a and 6.4a indicates a close, linear correlation between time and sites ($r^2=0.667$; $P<0.0001$). Phosphorus concentrations for alder remained relatively unchanged until increasing at the 85 -year-old site, with further increases at site F before declining markedly at site G (Table 6.1; Fig. 6.3a). Although less closely correlated with time ($r^2=0.211$), P concentrations in alder appear to be reciprocal with concentrations in cottonwood for sites where they were co-located (Fig. 6.3a). In at least 3 of the sites (D, F and G), these differences were significant ($P<0.05$).

There were observed significant variations related to substrate age in foliar potassium ($r^2=0.626$; $P<0.0001$; Fig. 6.3b; Fig. 6.4b) for cottonwood. Concentrations of K were lowest in the youngest site and then increased progressively to the older sites. This correlation remains closely linear when the youngest site is removed ($r^2=0.363$) indicating this nutrient is strongly linked with terrain age or tree age across the chronosequence at Exit Glacier. K concentrations in alder remained low through the 73 -year-old site C before generally increasing out to the older sites (Table 6.1; Fig. 6.3b). The significant increase in foliar K between sites C and D reflects only an estimated 10 years in landscape age but a distance of nearly 0.4 km (Fig. 3.2). Although less closely correlated with time ($r^2=0.395$; Fig. 6.5b), alder concentrations remained significantly lower than cottonwood across all sites.

Calcium (Ca), a highly immobile element (Marschner, 1995) showed no significant trends through time for either cottonwood ($r^2=0.002$) or alder ($r^2=0.071$; Table 6.1; Fig. 6.3 c; Fig. 6.4c; Fig 6.5c), although concentrations in alder were generally lower than cottonwood across most sites. There was also an appearance of Ca concentrations varying in a reciprocal manner between species (Fig. 6.3c), but the high standard of error seen for individual sites make trends difficult to discern. This high variability may be partly explained by analytical technique since Ca is a prevalent ion, difficult to control for in the laboratory (Offner, J., personal communication, 1999).

Foliar concentration of magnesium (Mg) was lowest at the youngest site for both species and progressively increased out to the 73 -year-old site C, before decreasing out to the older sites for cottonwood, while Mg in alder increased to site E, before declining sharply out to site G (Table 6.1; Fig.

6.3d). Due to the progressive increase in Mg for alder, the concentrations were more strongly linear with time ($r^2=0.352$; Fig. 6.5d), than those for cottonwood ($r^2=0.045$; Fig. 6.4d).

6.3 Micronutrients

Micronutrients in black cottonwood and Sitka alder foliage displayed several distinct patterns along the moraine chronosequence at Exit Glacier. Foliar zinc (Zn) concentrations were significantly higher ($P<0.0001$) in cottonwood than alder across all sites (Table 6.2; Fig. 6.6 a) with some sites nearly 7 to 8 times greater in concentration. Alder Zn levels on the Exit Glacier forelands are comparable to the younger sites found on the Tanana River chronosequence (Van Cleve et al., 1972), while cottonwood appears to be from 10-30% higher than cottonwood found on several alluvial sites in British Columbia (McLennan, 1990). Within site variability was high for both species (Fig. 6.6 a) but greatest for alder among all sites. I observed that foliar Zn concentrations varied in a reciprocal way across the chronosequence, however, high within-site variability make these trends difficult to assess. There was a slight trend for increasing Zn concentrations through time for cottonwood ($P<0.014$; $y = 0.0997x + 196.94$; $r^2=0.0031$) with sites A3, B and G significantly different ($P<0.05$). Concentrations for zinc in alder and cottonwood were consistent between both sample years.

Iron concentrations for both alder and cottonwood varied similarly in both pattern and concentrations (Table 6.2; Fig. 6.6 b), with a significant increase in concentration from the youngest site to the 50-year-old site (B), then decreasing out to the 100-year-old site (E). Despite these similarities in species, there were no significant trends with time for alder ($r^2=0.001$) or cottonwood ($r^2=0.002$); however site the alder dominated site B (48 -year-old site) showed significantly elevated concentrations of iron ($P<0.0001$; Fig. 6.6b) before progressively declining out to the older sites.

Manganese (Mn) concentration in alder leaves although variable across all sites (Fig. 6.5c), strongly increased through time as evident from the high slope from the linear regression ($y = 0.8365x + 76.798$; $r^2=0.332$; Fig. 6.5 e). Except for relative decreases at sites B and E, there is evident of strong correlation

while cottonwood remains unchanged. In addition, when alder concentrations through time for Mn and Mg (Fig. 6.3 d) are compared, a near opposite trend is apparent, while Mn and Ca varied in similar ways across the chronosequence (Fig. 6.3 c).

Table 6.1. Foliar element concentrations (% dry mass) for alder and cottonwood on along the moraines at Exit Glacier. Transects H, I and J are excluded due to site disturbance post deglaciation (see text). Values are means $\pm$ 1SE. Blank cells not determined.

Sites(Years BP)		Species					
		Alnus sinuata			Populus balsamifera		
		Mean	N	$\pm$ 1 SE	Mean	N	$\pm$ 1 SE
A3(19yrs)	N Conc. (Wt %)				1.49	10	.06
	P Conc. (Wt %)				.101	10	.004
	K Conc. (Wt%)				.76	10	.05
	Ca Conc. (Wt%)				1.42	10	.09
	Mg Conc. (Wt%)				.15	10	.01
A(30yrs)	N Conc. (Wt %)	2.89	10	.05			
	P Conc. (Wt %)	.169	10	.004			
	K Conc. (Wt%)	.70	10	.05			
	Ca Conc. (Wt%)	1.02	10	.05			
	Mg Conc. (Wt%)	.16	10	.01			
B(48yrs)	N Conc. (Wt %)	2.86	5	.13	2.26	5	.10
	P Conc. (Wt %)	.161	5	.008	.156	5	.005
	K Conc. (Wt%)	.68	5	.06	1.01	5	.06
	Ca Conc. (Wt%)	1.15	5	.16	1.50	5	.11
	Mg Conc. (Wt%)	.19	5	.01	.18	5	.01
C(73yrs)	N Conc. (Wt %)	2.82	5	.07	2.61	5	.05
	P Conc. (Wt %)	.166	5	.008	.173	5	.004
	K Conc. (Wt%)	.74	5	.12	1.27	5	.09
	Ca Conc. (Wt%)	1.01	5	.10	1.69	5	.34
	Mg Conc. (Wt%)	.19	5	.01	.19	5	.01
D(85yrs)	N Conc. (Wt %)	2.95	5	.10	2.18	5	.05
	P Conc. (Wt %)	.191	5	.010	.157	5	.007
	K Conc. (Wt%)	1.05	5	.05	1.36	5	.17
	Ca Conc. (Wt%)	1.27	5	.05	1.38	5	.12
	Mg Conc. (Wt%)	.23	5	.01	.17	5	.02
E(100yrs)	N Conc. (Wt %)	2.87	5	.06	2.32	5	.09
	P Conc. (Wt %)	.192	5	.009	.201	5	.019
	K Conc. (Wt%)	.93	5	.12	1.51	5	.15
	Ca Conc. (Wt%)	1.35	5	.11	1.24	5	.05
	Mg Conc. (Wt%)	.26	5	.01	.17	5	.01
F(105yrs)	N Conc. (Wt %)	3.27	5	.07	2.33	5	.13
	P Conc. (Wt %)	.241	5	.020	.168	5	.005
	K Conc. (Wt%)	1.10	5	.10	1.32	5	.12
	Ca Conc. (Wt%)	1.03	5	.06	1.52	5	.17
	Mg Conc. (Wt%)	.23	5	.01	.18	5	.02
G(108yrs)	N Conc. (Wt %)	3.04	5	.06	2.44	5	.07
	P Conc. (Wt %)	.173	5	.003	.223	5	.014
	K Conc. (Wt%)	1.15	5	.11	1.81	5	.09
	Ca Conc. (Wt%)	1.17	5	.08	1.39	5	.05
	Mg Conc. (Wt%)	.19	5	.01	.16	5	.02
Total	N Conc. (Wt %)	2.95	40	.03	2.14	40	.07
	P Conc. (Wt %)	.183	40	.005	.160	40	.007
	K Conc. (Wt%)	.88	40	.04	1.22	40	.06
	Ca Conc. (Wt%)	1.13	40	.04	1.44	40	.06
	Mg Conc. (Wt%)	.20	40	.01	.17	40	.01

Figure 6.1. Concentration of nitrogen (N) in leaves of cottonwood (solid black line with filled symbols) and alder (open red symbols) along the chronosequence at Exit Glacier. Ages represent the time when the surface was ice-free, not necessarily when the substrate was stabilized. The values are means (± 1 SE). Sample size; Sites A and A3 (n=10), Sites B-G (n=5).

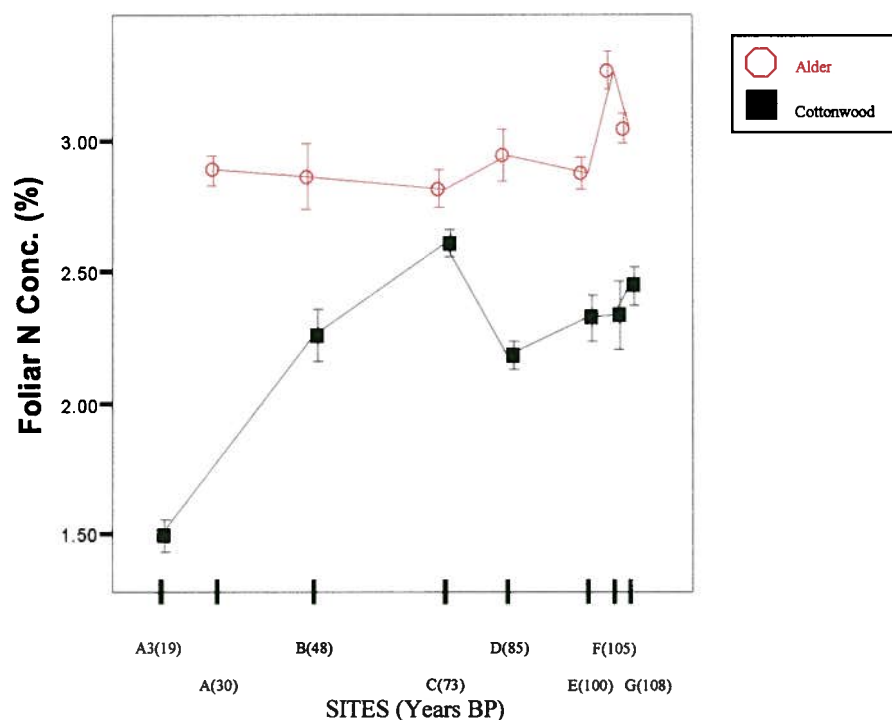


Figure 6.2 a and b. Regressions of Nitrogen (N) for a) alder and b) cottonwood through time (Sites A/A3–G only). All sites with sample size: n=5, except 19 yr old site A and 30 yr old site A3 (n=10).

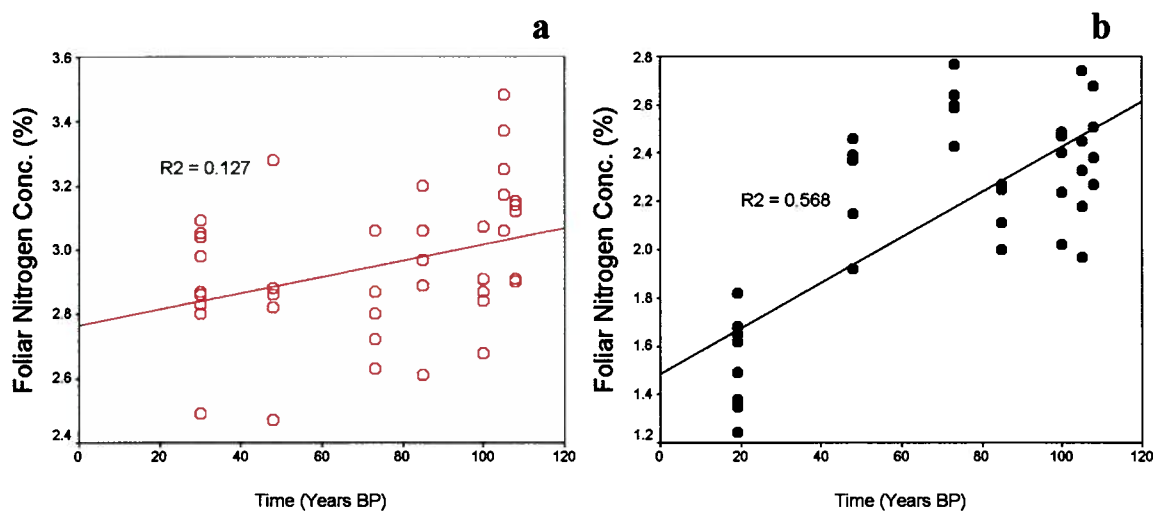


Figure 6.3 a, b, c and d. Concentration of a) phosphorus, b) potassium, c) calcium, and d) magnesium in leaves of cottonwood (solid black line with filled symbols) and alder (open red symbols) along the chronosequence at Exit Glacier. Ages represent the time when the surface was ice-free, not necessarily when the substrate was stabilized. The values are means (± 1 SE). Sample size; Sites A and A3 (n=10), Sites B-G (n=5).

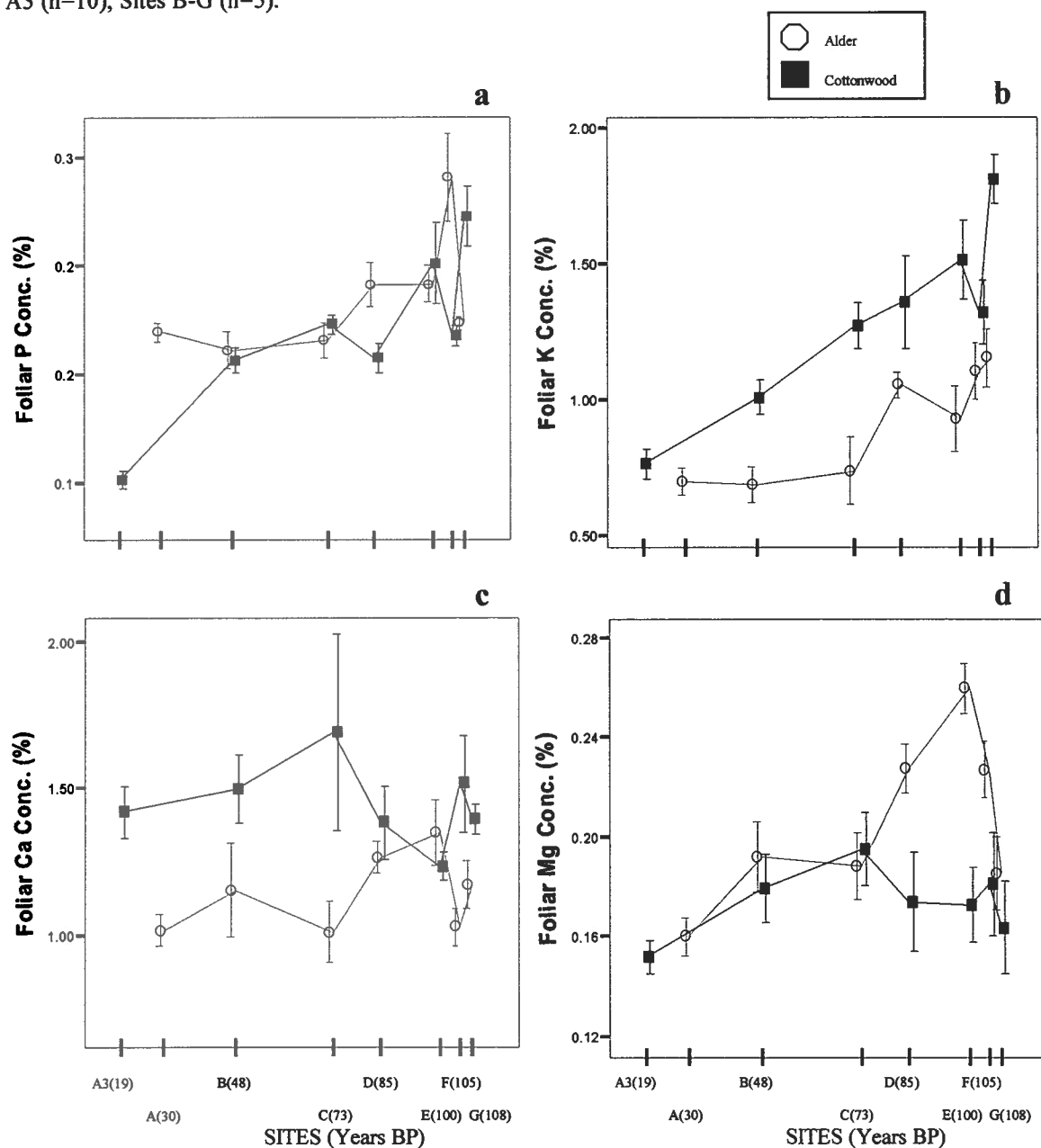


Figure 6.4 a, b, c and d. Regressions of selected macronutrients a) phosphorus, b) potassium, c) calcium, and d) magnesium for cottonwood through time (Sites A – G only). All sites with sample size: $n=5$; except A (19 yr old site: $n=10$).

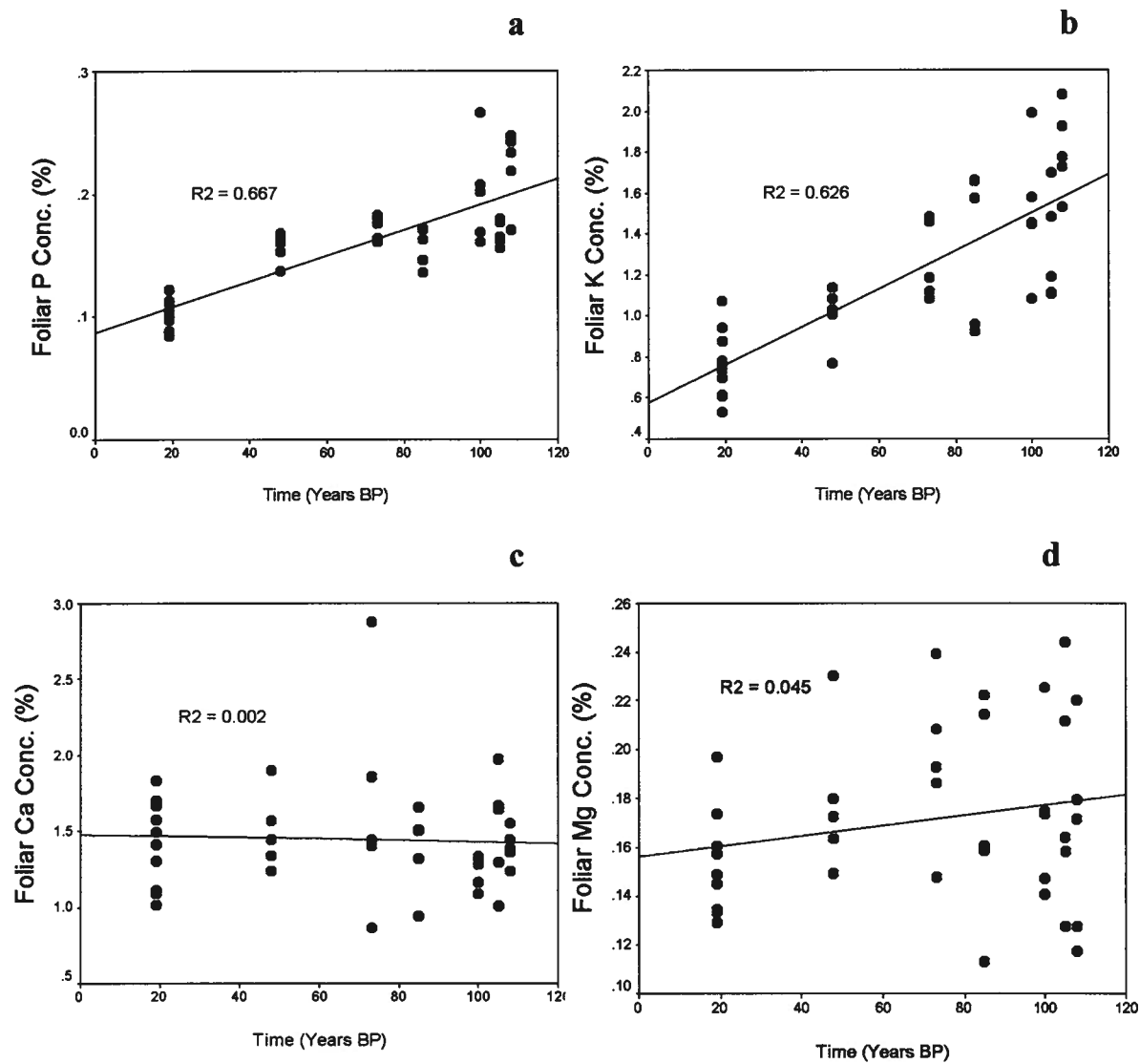


Figure 6.5 a, b, c, d and e. Regression of selected macronutrients a) phosphorus, b) potassium, c) calcium, d) magnesium and e) micronutrient manganese for alder through time (Sites A3 – G only). All sites with sample size: $n = 5$; except A3 (30-year old site = $n = 10$).

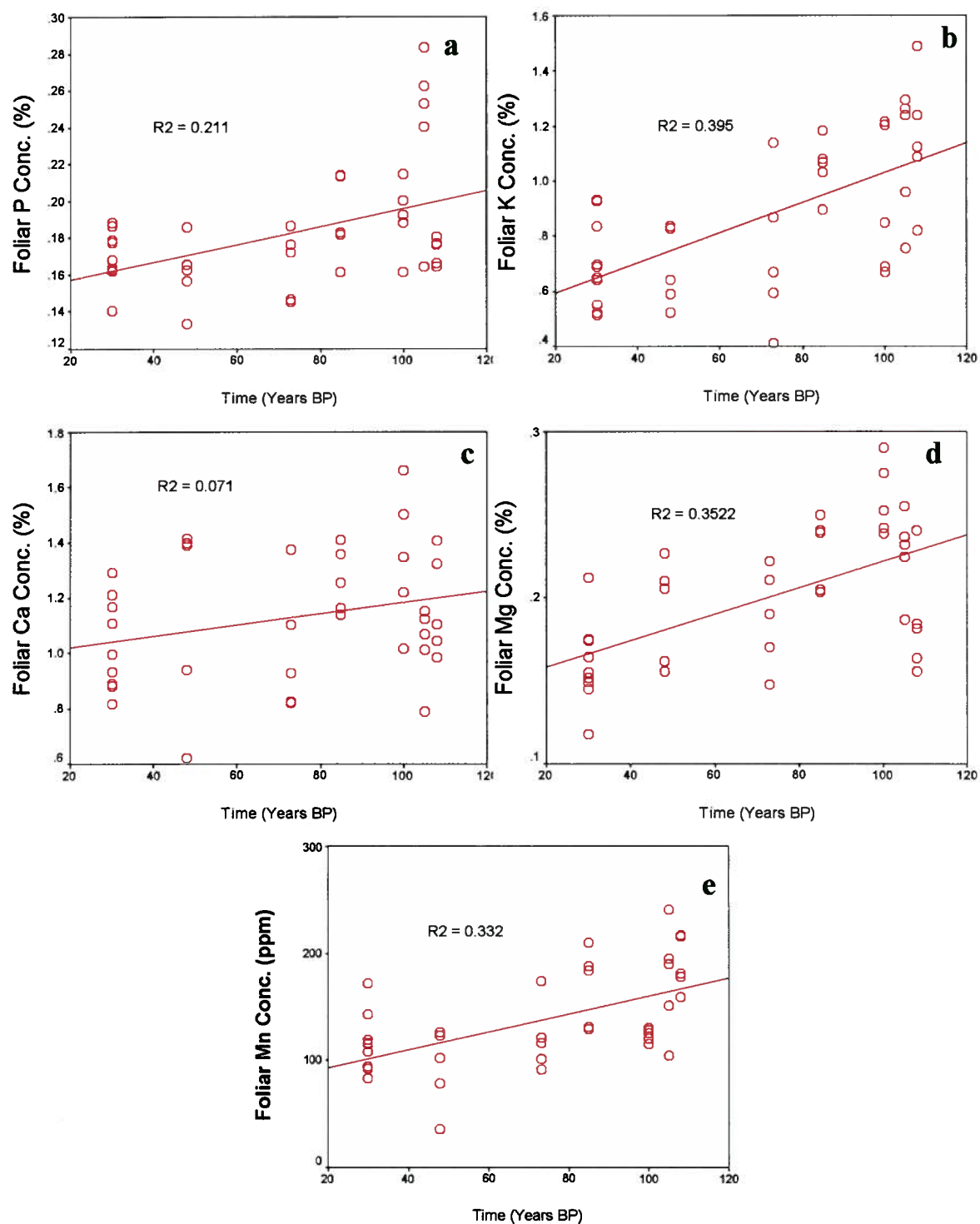
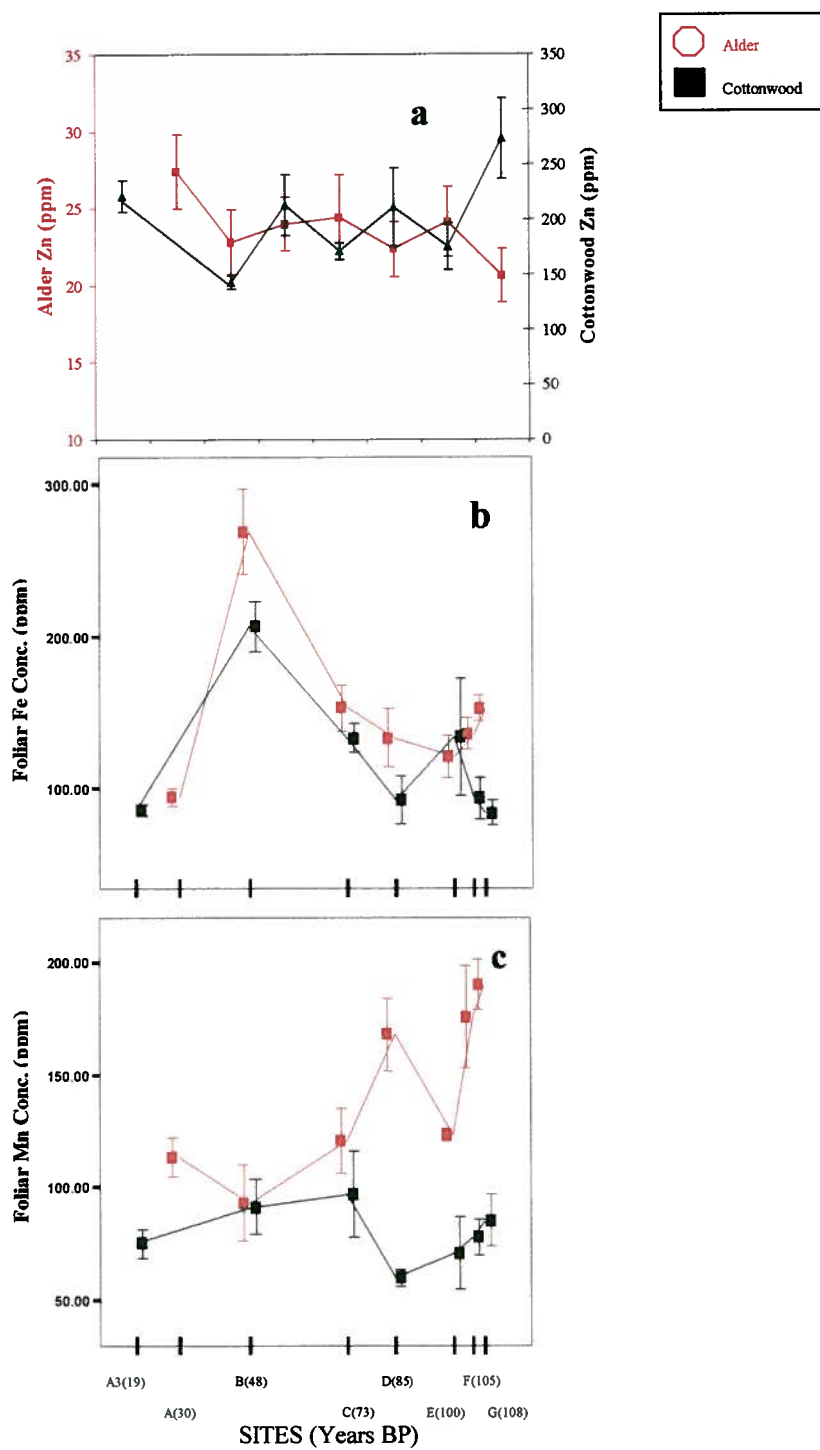


Table 6.2. Concentrations of foliar micronutrients (measured in ppm) in alder and cottonwood from along the moraines at Exit Glacier. Transects H, I and J are excluded due to site disturbance post deglaciation (see text). Values are means $\pm$ 1 SE. Blank cells not determined.

Sites(Years BP)		Species					
		Alnus sinuata			Populus balsamifera		
		Mean	N	$\pm$ 1 SE	Mean	N	$\pm$ 1 SE
A3(19yrs)	Zinc				221.6	10	14.3
	Iron				85.0	10	4.1
	Manganese				74.9	10	6.4
	Copper				4.5	10	.2
A(30yrs)	Zinc	27.4	10	2.4			
	Iron	94.0	10	5.7			
	Manganese	113.5	10	8.5			
	Copper	6.7	10	.3			
B(48yrs)	Zinc	22.8	5	2.1	143.1	5	6.1
	Iron	269.0	5	28.2	206.8	5	16.7
	Manganese	93.3	5	16.8	91.2	5	12.3
	Copper	6.8	5	.7	5.7	5	.3
C(73yrs)	Zinc	24.0	5	1.8	213.2	5	27.3
	Iron	152.7	5	15.0	132.7	5	9.2
	Manganese	120.7	5	14.3	97.3	5	19.2
	Copper	4.8	5	.4	7.2	5	.3
D(85yrs)	Zinc	24.4	5	2.7	171.0	5	7.6
	Iron	132.6	5	19.5	92.1	5	16.0
	Manganese	168.2	5	16.1	59.6	5	3.6
	Copper	5.4	5	.3	4.9	5	.3
E(100yrs)	Zinc	22.4	5	1.8	211.5	5	35.7
	Iron	120.6	5	13.8	133.6	5	38.6
	Manganese	123.5	5	2.7	70.8	5	15.9
	Copper	6.4	5	.7	5.1	5	.3
F(105yrs)	Zinc	24.1	5	2.3	175.6	5	21.6
	Iron	135.8	5	10.0	92.8	5	14.0
	Manganese	175.8	5	22.9	77.7	5	7.8
	Copper	6.6	5	.6	5.4	5	.5
G(108yrs)	Zinc	20.6	5	1.7	273.4	5	36.5
	Iron	152.7	5	8.8	83.1	5	8.5
	Manganese	190.1	5	11.3	85.3	5	11.4
	Copper	5.6	5	.7	7.2	5	.5
Total	Zinc	24.2	40	.9	203.9	40	9.9
	Iron	143.9	40	9.7	113.9	40	8.5
	Manganese	137.3	40	7.1	78.9	40	4.3
	Copper	6.1	40	.2	5.6	40	.2

Figure 6.6 a, b, and c. Concentrations of selected micronutrients a) zinc, b), iron and c) manganese in leaves of alder and cottonwood along the chronosequence at Exit Glacier. Values and symbols as in Fig. 6.1.



7 DISCUSSION AND CONCLUSIONS

This study compared foliar mineral nutrition in *Alnus sinuata* (Sitka alder) and *Populus balsamifera* (black cottonwood) across a successional sequence in the forelands of Exit Glacier. Expectations were that Nitrogen (N) concentrations in leaves were likely to be consistently high within alder, while those of black cottonwood would likely increase across a consequence of successional soil development. Results from this study show foliage concentration in alder were indeed higher than those in cottonwood across all sites, indicating luxury consumption of nitrogen by alder due to association with N-fixing *Frankia*.

Cottonwood N concentrations increased as anticipated, although they remained relatively steady through the chronosequence if the youngest site was excluded. The elevated concentrations at site C may be an artifact of site variability or a reflection of higher growth rates relative to the older sites. It is interesting to note that site C also had relatively high concentrations of clay in the upper mineral layers which may have enhanced greater nutrient availability via greater exchange sites. The foliar N was indeed higher in alder across all sites and these concentrations were comparable to other studies in Glacier Bay (Fastie, 1994), Tanana river floodplain (Van Cleve and Viereck, 1972) from similarly aged sites.

The significant increase in foliar N for alder at site F relative to sites E and G may be either a reflection of the more exposed nature of the site along the edge of the raised terrain leading to higher growth a reflection of the younger terrain age. If site F was indeed colonized around 1900 then this site would be very similar to site E in terms of age.

7.1 Macronutrients

Some nutrients across the chronosequence were found to reciprocate in concentrations between species. The reciprocal nature of P in the leaves of cottonwood and alder (Fig 6.3a) may be due in part to shading effects among sites. An increase in foliar P may be in response to sunlight conditions since P is found in membranes of thylakoids, a component membrane of chloroplasts. Although quantitative

measurements of light admittance through the canopy was not conducted in this study, sites D and F were located on the boundary of raised moraine features. Light penetration may have been higher at these sites than neighboring ones (See Appendix E for photos), thereby increasing foliar P in alder relative to cottonwood. The reciprocal nature of cottonwood at these sites is more difficult to explain, since a lowering of foliar P at the open sites would suggest more light for the upright trees. Another explanation may be that the highly mobile P is limiting these systems, whereby when alder absorbs more phosphorus, this limits the ability for cottonwood to absorb this nutrient. Fertilization field trials on co-located cottonwood and alders may help resolve this question.

Concentrations of calcium differed between species especially at the younger sites at Exit Glacier. Although the within-site variability was higher than those found for P, a sharp contrast between species can be seen at site C and the older sites E-G (Fig. 6.3c). The decrease at site C may be explained by the site quality as it relates to the availability of highly leachable cations. Site C is where the total pool of Ca (4000 ppm to 1 meter) in the pedon decreased from site B, then increased at site D (Fig. 5.8). The majority of Ca at all sites is bound in the organic horizon (Table 5.3) which is mainly litter fall from alder and cottonwood. This decrease in Ca may be due in part to the higher pH found at this site (Fig. 5.7), which strongly regulates the amount of Ca in solution and limits uptake to plants. Alder may be more limited in uptake of Ca, while cottonwood sequesters Ca more efficiently and limits storage in the leaves.

Magnesium, another cation sensitive to leaching was low at the exposed cottonwood seedling site A3 located on an abandoned outwash plain (Fig. 3.2)(Marschner, 1995). Concentrations were at the lower range for optimal growth (mean=0.15; .01 (1 SE)) requirements which may be correlated with the low concentrations of Mg in all horizons for the site (Table 5.3). Magnesium's role as the central atom of the chlorophyll molecule is therefore related strongly with photosynthesis, however, this appears counter-intuitive for leaves extracted from a cottonwood seedlings growing in an open area. This may be partially explained by the relatively small leaf area of these leaves (determined by measurement of long and short

axis of leaves). As calculated on a leaf area basis, the foliar proportion of Mg increases and more closely reflects higher rates of photosynthesis.

Patterns for foliar cations should be influenced most strongly by leaching, which may be most sensitive to sampling leaves during wet periods. Two of the three day sampling period in 1999 were wet, an inevitable consequence of studying at Exit Glacier in the fall. It may be possible that concentrations of cations were washed from leaf surfaces during some sampling periods but this would not explain the reciprocal nature of Ca concentration and relatively high concentrations of K in both species (Fig. 6.3b;c).

7.2 Micronutrients

The strongest correlation among all elements for increasing concentration through time was for the cation manganese (Mn) in alder ($y = 0.8365x + 76.798$; $r^2 = 0.3319$; Table 6.2; Fig. 6.6 c). Such strong correlation with time may be due in part to the N-fixing strategy of alder. Root exudates and their effect on enhanced microbial activity and therefore low pH would enhance adsorption of Mn which is more available in acidic soils (Larcher, 1995). The higher concentrations may then be selectively transported to the leaves of alders where Mn typically accumulates. The values of nearly 200 ppm for alder are well within the range of toxicity recorded for other dicotyledons (Marschner, 1995), however the concentration of Mn in alder at some sites are more than triple than those in cottonwood (Fig. 6.6 c) and in soils (Table 5.3). The low relative concentrations in cottonwood at Exit Glacier would indicate greater utilization of this mineral by alder, a sequestering effect in leaves or inhibitory action from other cations. The evident countertrend witnessed between Mg and Mn for alder is explained by these two cations competition at the cellular level. The inhibitory effect of Mn on Mg uptake is well documented (Marschner, 1995) and it is common to treat manganese toxicity in crops by supplying high amounts of magnesium.

Independent of site and time, Zn was about 7 times higher in cottonwood than alder (192.9 ; $8.0 (\pm 1SE)$; 23.3 ; $.81 (\pm 1SE)$) across all sites and is the greatest difference in elemental concentrations between

species in this study (Table 6.2; Fig. 6.6a) Explaining these differences however is difficult, but may be related to influences of mycorrhizal infection. Ectomycorrhizae (EM) generally facilitate nutrient movement, especially of low mobility nutrients. Alder's EM types may also be lowering the pH in the area immediately surrounding the roots and thereby further increasing the concentrations of some metals. The alders may be able to sequester these metals in the roots and inhibit transfer to the leaves, while black cottonwood, with different types of EM are more tolerant of higher concentrations of metals in their leaves. EM are a quite common means of tolerating heavy metals on old mine sites, but the relations of elemental tolerance tend to vary with the metal and the fungus. Of the two species, alder would be expected to be more metal tolerant partly because it typically grows in lower pH soils than poplar does, and lower pH's are where most metals become more mobile (Helm, D., personal communication, March, 2001) This explanation would be consistent with these results. This species specific tolerance could be tested by excavating roots of the two species at the same time as foliage samples were obtained.

The elevated concentration of zinc for cottonwood found in this study are 10-30% higher than leaves sampled from *Populus trichocarpa* in coastal British Columbia alluvial sites (McLennan, 1990). That study found Zn to be significantly higher in the lower canopy, yet 53 samples would be required to estimate the mean concentration of Zn at 10% β allowable error. Any trends therefore, for this element may be difficult to ascertain due to the low sample number in this study.

Of all the elements analyzed for in this study, iron (Fe), exhibited the highest correlation between species and across sites. Although trends between the two youngest dissimilar sites may be coincidence the proportional variation for most other sites suggests similar responses to the availability of Fe in the soil and uptake. When plants are grown under controlled conditions, about 80% of the iron is localized in the chloroplasts in rapidly growing leaves, regardless of iron nutritional status (Marschner, 1995). The high foliar concentration at site B for both species may represent the rapid growth occurring in both well established alders and young cottonwood trees just beginning to rise above the shaded conditions under

alder (See Appendix E; Site B photo). At older sites, this growth rate may be slower as cottonwood compete for light in the upper portions of the canopy, while alder succumbs to additional shade.

7.3 Complexity in Forelands

The complexity of dating the Exit Glacier forelands became most apparent on sites located on the large forested area down valley from the 1899 moraine and included sites F, G, H and I. The landscape ages assumed for moraines up valley from the LIA max of 1815 were affected by post deglaciation flooding effects. The assumptions of Jenny (1941) that time is the major control, was altered at these sites and therefore confounded the assessment of the chronosequence. The glacier forelands at Exit Glacier are very complex with interactions of past and present environmental controls, and changing fluvial dynamics. The limited raised moraine features (Fig. 4.1) that were sampled in this study may have had boundary effects and characteristics different than those found on larger glacier floodplains.

7.4 Recommendations for Further Study

Every attempt was made to acquire all available aerial and ground photography of Exit Glacier to document glacial activity. Additional photography from 1920 to 1968 would benefit interpretation by: 1) Allowing for better estimates of ecesis intervals and establishing the location of the glacier terminus during these years, and 2) enhancement of visitor experience and interpretation.

Evidence has been given that a more appropriate ecesis interval at Exit Glacier is 25 years for spruce and 5 years for black cottonwood. Additional work on the Exit Glacier and adjacent forelands would increase the precision of this estimate. Additional tree coring along the trimlines above the valley floor would also allow more precise timing of glacial events.

Future nutrient studies along the chronosequence at Exit Glacier could include nutrient throughfall and litter decomposition rate studies as well as estimates of soil organic matter turnover rates using carbon

isotopes (either ^{13}C or radioactive ^{14}C). The presence of a gradient of successional change like that found on the moraines from 1951 to 1899 may provide the controlling factors to improve the understanding of response of organic pools to environmental change. The resultant data would provide a functional relationship between turnover rates in soil organic matter, as well as information on the effects of forest succession in a subarctic maritime climate.

Testing for the turnover rates of the highly mobile nutrients such as P and K in the nutrient limited glacial till may be resolved with fertilization trials at various age surfaces. Although such trials must be assessed on their impact within the forelands located within Kenai Fjords National Park, these tests may resolve the limiting soil nutrients in the alder-cottonwood systems.

Glacier forelands provide a unique laboratory for the study of nutrient dynamics. Although it is not possible to obtain perfect experimental control in such field laboratories, the approach enables a reduction in interactions that occur in more complex landscapes.

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9 APPENDIX A: TREE CORE SAMPLES – ALL FIELD LOCATIONS

APPENDIX A KEY

Tree ID	Each tree sampled in this study is assigned a unique code. Tree ID can be found on labelled core blocks. See page 2 of Appendix A key for examples.
Site	Site name given to area. Letters A-H were used by Ahlstrand (1983). This study used a series of codes in the field to discern between areas. Site names may not correspond to ages determined in this study
Coll.	Person who collected tree cores for sampling. CU: Cusick (this author); AH: Ahlstrand (1983) or WI: Wiles (1992)
Genus	Common Name of tree sampled: POBA: Black Cottonwood(<i>Populus balsamifera</i> ssp. <i>trichocarpa</i>); SIAL: Sitka Alder(<i>Alnus sinuata</i> or <i>Alnus tenuifolia</i>); PISI: Sitka Spruce (<i>Picea sitchensis</i>).
# of Cores	Number of repeat cores collected on same tree. Age of tree determined from best core.
Type	The tree type signifies the reason why the tree was sampled. TL – Core collected from a tree sampled for leaf nutrients. TA – Core collected from tree to determine terrain age of area. This often was subjective selection of the oldest appearing tree. Often times, this tree was collected on or near visible terminal moraine features. CT – Cores collected from three black cottonwood trees. Three trees were chosen from the USFS pullout off of Exit Glacier Road (mile 6.5) to test for differences in leaf nutrients at different levels of the tree canopy. E – Five Cottonwood trees selected along the 1950 Exit Glacier terminal moraine. These trees were cored to test for ecesis interval, or the time to establish a tree once the glacier has moved off of a surface.
Year of Sampling	The calendar date tree was cored. Dates of collection for all Ahlstrand cores were corrected to 1983. All Wiles cores were collected in 1989.
Ring Count	This is the oldest growth ring counted in years. Unless the tree was sampled at the root crown, the earliest growth ring will underestimate the true age of the tree. This is a minimum age for the tree.
Pith Seen	A "good" indicates when a pith was observed. No attempt was made to estimate years to pith when pith is missing. Where the pith was not sampled, a "wide" indicates where the curvature of the rings near the center were wide and several to many years may be missing. A "near" indicates pith was close and possibly only a few years are missing. A "na" indicates that many years may be absent from the count or no sample was taken.
Height Cored (cm)	The height above the mineral layer at which tree/shrub was cored in cm. This measurement multiplied by Age/Ht. Factor (yrs) to correct for sampling height age error.
Age/Ht. Factor (yrs)	The age/height factor in years is an estimate of the time required by the tree to grow to the height at which the sample was taken (Chapter 3, this report; McCarthy, 1983). The following age/height factors were assigned by species: 0.3 yr/cm for spruce and 0.2yr/cm for black cottonwood, 0 yr/cm for alder.
Ecesis	Ecesis correction factors added to ring count to give estimate of tree colonization. * 5 years for Cottonwood * 25 years for Spruce * 0 years for Alder
Oldest Possible Year AD	This calculated calendar year represents the oldest possible date of the surface by dating with tree rings.

Three examples of core block labels. All cores are archived at National Park Service, Alaska Support Office, Anchorage Alaska.

Sitka Alder (*Alnus sinuata*) core sampled from Site A2, 10 meters along tape.
Second core taken from same tree (2) suffix. No. of rings counted = 16.
Diameter of trunk at ground height = 8 cm.

Exit Glacier	9/10/99	J. Cusick	TL
A2_10#2	Alsi	#Rings= 16	DGH(cm)=8

Black cottonwood (*Populus balsamifera* ssp. *trichocarpa*) core sampled for terrain age. Site designated as "MARK_W" and the second core taken in this area.
"C" for cottonwood. No. of rings = 65. Diameter at Breast Height = 46.9cm.

Exit Glacier	9/8/99	J. Cusick	TA
MARK_W02C	Poba	#Rings= 65	DBH(cm)=46.9

Black cottonwood (*Populus balsamifera* ssp. *trichocarpa*) core sampled for terrain age.
Site designated as "MARK_R" and the first core taken in area(01). "C" for cottonwood.
The first core of at least two cores taken on this same tree (suffix "01").
Number of rings = 50. Diameter at Breast Height = 37.1.

Exit Glacier	9/9/99	J. Cusick	TA
MARK_R01C01	Poba	#Rings= 50	DBH(cm)=37.1

Appendix A. Exit Glacier tree core samples. All field locations from all studies.

Tree ID	Site	Coll.	Genus	# of Cores	Type	Year of Sampling	Ring Count	PiTh Seen	Height		Factor (yrs)	Eccesis	Oldest	
									cored (cm)	Age/Ht.			Possible Year AD	Possible Year AD
Closest to Glacier - Leaf Transects Alder - A1, A2														
A2_10#2	A2	CU	ALSI	2	TL	1999	16	good	20	0	0	0	1983	
A2_20#1	A2	CU	ALSI		TL	1999	18	good	15	0	0	0	1981	
A1_10#1	A1	CU	ALSI		TL	1999	19	good	15	0	0	0	1980	
A1_20#1	A1	CU	ALSI		TL	1999	19	good	29	0	0	0	1980	
A2_10#1	A2	CU	ALSI		TL	1999	19	good	17	0	0	0	1980	
A1_10#2	A1	CU	ALSI		TL	1999	20	good	33	0	0	0	1979	
A1_20#2	A1	CU	ALSI		TL	1999	20	good	22	0	0	0	1979	
A2_30#1	A2	CU	ALSI		TL	1999	20	near	17	0	0	0	1979	
A2_30#2	A2	CU	ALSI		TL	1999	20	good	23	0	0	0	1979	
A2_20#2	A2	CU	ALSI		TL	1999	21	near	13	0	0	0	1978	
A2_01C	A2	CU	POBA	TA	1999	21	good	20	4	5	5	1969		
Southeast of Present Terminus - Leaf Transect Cottonwood A3														
A3_10C#1	A3	CU	POBA	TL	1999			na		0	5	5	1994	
A3_20C#1	A3	CU	POBA	TL	1999			na		0	5	5	1994	
A3_30C#2	A3	CU	POBA	TL	1999			na		0	5	5	1994	
A3_40C#1	A3	CU	POBA	TL	1999			na		0	5	5	1994	
A3_50C#2	A3	CU	POBA	TL	1999			na		0	5	5	1994	
A3_10C#2	A3	CU	POBA	TL	1999	5		good	0	0	5	5	1989	
A3_30C#1	A3	CU	POBA	TL	1999	9		good	0	0	5	5	1985	
A3_40C#2	A3	CU	POBA	TL	1999	10		good	0	0	5	5	1984	
A3_50C#1	A3	CU	POBA	TL	1999	10		good	0	0	5	5	1984	
A3_20C#2	A3	CU	POBA	TL	1999	14		good	0	0	5	5	1980	
1951 Moraine - First downvalley terminal Moraine - Leaf Transect B														
B50A	B	CU	ALSI	TL	1999	12		good	24	0	0	0	1987	
B20A	B	CU	ALSI	TL	1999	16		good	20	0	0	0	1983	
B30A	B	CU	ALSI	TL	1999	20		good	23	0	0	0	1979	
B40A	B	CU	ALSI	TL	1999	21		good	13	0	0	0	1978	
B20C	B	CU	POBA	TL	1999	16		good	11	2	5	5	1976	

Appendix A. (continued) Exit Glacier tree core samples. All field locations from all studies.

Tree ID	Site	Coll.	Genus	# of Cores	Type	Year of Sampling	Ring Count	PiTh Seen	Height		Factor (yrs)	Eccesis	Oldest	
									cored (cm)	Age/Ht.			Possible Year AD	Possible Year AD
B10A	B	CU	ALSI		TL	1999	24	good	13	0	0	0	1975	
B01C	B	CU	POBA		TA	1999	19	good	17	3	3	5	1972	
B40C	B	CU	POBA		TL	1999	19	good	15	3	3	5	1972	
B30C	B	CU	POBA	2	TL	1999	23	good	13	3	3	5	1968	
B50C	B	CU	POBA		TL	1999	22	na	24	5	5	5	1967	
MARK_P02C	MARK_P	CU	POBA		TA	1999	25	good	22	4	4	5	1965	
B10C	B	CU	POBA		TL	1999	28	wide	20	4	4	5	1962	
1950_02C	1950	CU	POBA		E	1999	30	good	20	4	4	5	1960	
1950_05C	1950	CU	POBA		E	1999	33	wide	8	2	2	5	1959	
MARK_P01C	MARK_P	CU	POBA		TA	1999	32	near	25	5	5	5	1957	
1950_01C	1950	CU	POBA		E	1999	34	good	20	4	4	5	1956	
H_AH	H	AH	POBA			1983	25	na	0	0	0	5	1953	
1950_04C	1950	CU	POBA		E	1999	38	good	14	3	3	5	1953	
H_WI	H	WI	POBA			1989	37	na	0	0	0	0	1952	
1950_03C	1950	CU	POBA		E	1999	39	good	20	4	4	5	1951	
1926 Moraine - Parrallel to Nature Trail - Leaf Transect C														
C40A	C	CU	ALSI		TL	1999	22	good	18	0	0	0	1977	
MARK_Q12C	MARK_Q	CU	POBA		TA	1999	17	wide	15	3	3	5	1974	
C50A	C	CU	ALSI		TL	1999	26	good	18	0	0	0	1973	
C20A	C	CU	ALSI		TL	1999	29	good	20	0	0	0	1970	
C10A	C	CU	ALSI		TL	1999	36	good	10	0	0	0	1963	
MARK_Q14A	MARK_Q	CU	ALSI		TA	1999	36	good	10	0	0	0	1963	
C03A	C	CU	ALSI		TA	1999	37	good	15	0	0	0	1962	
C30A	C	CU	ALSI	2	TL	1999	37	good	23	0	0	0	1962	
C30C	C	CU	POBA	2	TL	1999	29	wide	20	4	4	5	1961	
MARK_Q11A	MARK_Q	CU	ALSI	2	TA	1999	41	good	56	0	0	0	1958	
C50C	C	CU	POBA	2	TL	1999	32	near	18	4	4	5	1958	
MARK_Q15C	MARK_Q	CU	POBA		TA	1999	33	near	18	4	4	5	1957	

Appendix A. (continued) Exit Glacier tree core samples. All field locations from all studies.

Tree ID	Site	Coll.	Genus	# of Cores	Type	Year of Sampling	Ring Count	PiTh Seen	Height		Factor	Eccesis	Oldest Possible	
									cored (cm)	Age (yrs)			Year AD	Year AD
C40C	C	CU	POBA	2	TL	1999	32	good	28	6		5	1956	
MARK_Q16C	MARK_Q	CU	POBA		TA	1999	35	good	18	4		5	1955	
C20C	C	CU	POBA		TL	1999	35	near	26	5		5	1954	
MARK_Q10C	MARK_Q	CU	POBA	2	TA	1999	37	good	24	5		5	1952	
C10C	C	CU	POBA	2	TL	1999	40	good	23	5		5	1949	
MARK_Q09C	MARK_Q	CU	POBA		TA	1999	40	good	30	6		5	1948	
MARK_Q13C	MARK_Q	CU	POBA		TA	1999	40	near	29	6		5	1948	
MARK_Q17C	MARK_Q	CU	POBA		TA	1999	42	good	27	5		5	1947	
C02C	C	CU	POBA		TA	1999	44	good	27	5		5	1945	
C05C	C	CU	POBA		TA	1999	51	good	17	3		5	1940	
C01S	C	CU	SIAL		TA	1999	33	near	9	3		25	1938	
C04S	C	CU	SIAL		TA	1999	38	good	33	10		25	1926	
1917 Moraine - Moraine S. of Ranger Station														
MARK_Q07A	MARK_Q	CU	ALSI		TA	1999	31	good	27	0		0	1968	
MARK_S01A	MARK_S	CU	ALSI	2	TA	1999	38	good	42	0		0	1961	
MARK_Y05A	MARK_Y	CU	ALSI		TA	1999	38	good	20	0		0	1961	
MARK_Y06A	MARK_Y	CU	ALSI		TA	1999	41	good	25	0		0	1958	
MARK_R02C	MARK_R	CU	POBA	3	TA	1999	37	good	33	7		5	1950	
MARK_Q08C	MARK_Q	CU	POBA		TA	1999	40	good	29	6		5	1948	
MARK_Q06C	MARK_Q	CU	POBA	2	TA	1999	41	good	24	5		5	1948	
MARK_Y04C	MARK_Y	CU	POBA		TA	1999	42	good	27	5		5	1947	
MARK_W07C	MARK_W	CU	POBA		TA	1999	45	wide	22	4		5	1945	
MARK_X01C	MARK_X	CU	POBA	2	TA	1999	44	good	24	5		5	1945	
MARK_S02C	MARK_S	CU	POBA		TA	1999	47	good	27	5		5	1942	
MARK_W08C	MARK_W	CU	POBA		TA	1999	47	good	23	5		5	1942	
G_AH	G	AH	POBA			1983	41	na	0	0		5	1937	
MARK_Q02C	MARK_Q	CU	POBA		TA	1999	48	good	44	9		5	1937	
MARK_R01C	MARK_R	CU	POBA	2	TA	1999	51	near	28	6		5	1937	

Appendix A. (continued) Exit Glacier tree core samples. All field locations from all studies.

Tree ID	Site	Coll.	Genus	# of Cores	Type	Year of Sampling	Ring Count	PiTh Seen	Height		Factor (yrs)	Eccesis	Possible Year AD
									cored (cm)	Age/Ht.			
MARK_U01C	MARK_U	CU	POBA		TA	1999	53	good	23	5	5	5	1936
MARK_Q01C	MARK_Q	CU	POBA		TA	1999	52	good	39	8	5	5	1934
MARK_Q03C	MARK_Q	CU	POBA		TA	1999	52	good	44	9	5	5	1933
MARK_Q05C	MARK_Q	CU	POBA		TA	1999	56	good	36	7	5	5	1931
MARK_Q04S	MARK_Q	CU	SIAL		TA	1999	39	good	19	6	25	25	1929
G_WI	G	WI	SIAL			1989	47	na	0	0	25	25	1917
1914 Moraine - Leaf Transect D													
D40A	D	CU	ALSI		TL	1999		na	0	0	0	0	1999
D50A	D	CU	ALSI		TL	1999		na	0	0	0	0	1999
D10A	D	CU	ALSI		TL	1999	21	good	25	0	0	0	1978
D20A	D	CU	ALSI		TL	1999	38	good	46	0	0	0	1961
D40C	D	CU	POBA	2	TL	1999	44	good	22	4	5	5	1946
D20C	D	CU	POBA	2	TL	1999	44	near	18	4	5	5	1946
D30A	D	CU	ALSI		TL	1999	54	good	24	0	0	0	1945
MARK_O01C	MARK_O	CU	POBA		TA	1999	44	near	32	6	5	5	1944
MARK_V01C	MARK_V	CU	POBA	2	TA	1999	45	good	30	6	5	5	1943
MARK_T02C	MARK_T	CU	POBA		TA	1999	46	near	42	8	5	5	1940
D02C	D	CU	POBA		TA	1999	50	good	24	5	5	5	1939
MARK_T01C	MARK_T	CU	POBA		TA	1999	47	good	38	8	5	5	1939
D10C	D	CU	POBA		TL	1999	51	good	18	4	5	5	1939
D30C	D	CU	POBA	2	TL	1999	52	good	24	5	5	5	1937
MARK_Y02C	MARK_Y	CU	POBA		TA	1999	50	good	38	8	5	5	1936
F_AH	F	AH	POBA			1983	44	na	0	0	5	5	1934
MARK_V02C	MARK_V	CU	POBA		TA	1999	54	good	29	6	5	5	1934
D50C	D	CU	POBA	2	TL	1999	56	good	32	6	5	5	1932
MARK_W01C	MARK_W	CU	POBA		TA	1999	52	good	53	11	5	5	1931
MARK_X02C	MARK_X	CU	POBA		TA	1999	58	good	31	6	5	5	1930
MARK_Y03S	MARK_Y	CU	SIAL		TA	1999	40	wide	24	7	25	25	1927

Appendix A. (continued) Exit Glacier tree core samples. All field locations from all studies.

Tree ID	Site	Coll.	Genus	# of Cores	Type	Year of Sampling	Ring Count	PiTh cored (cm)	Age/Ht. Factor (yrs)	Eccesis	Oldest Possible	
											Year AD	Year AD
MARK_W06C	MARK_W	CU	POBA		TA	1999	62	good	6	5	1926	
MARK_W03C	MARK_W	CU	POBA		TA	1999	60	good	9	5	1925	
MARK_Y01C	MARK_Y	CU	POBA	2	TA	1999	63	good	7	5	1924	
MARK_W02C	MARK_W	CU	POBA		TA	1999	65	good	7	5	1922	
MARK_W05C	MARK_W	CU	POBA		TA	1999	64	good	11	5	1919	
D01C	D	CU	POBA		TA	1999	51	wide	25	5	1918	
MARK_W04C	MARK_W	CU	POBA		TA	1999	64	good	13	5	1917	
F_WI	F	WI	SIAL			1989	50	na	0	25	1914	
1899 Moraine - Leaf Transect E												
E10A	E	CU	ALSI		TL	1999		na	0	0	1999	
E30A	E	CU	ALSI		TL	1999	12	good	0	0	1987	
E20A	E	CU	ALSI	2	TL	1999	15	good	0	0	1984	
E50A	E	CU	ALSI		TL	1999	37	good	0	0	1962	
E40A	E	CU	ALSI		TL	1999	39	good	0	0	1960	
E20C	E	CU	POBA	3	TL	1999	50	good	3	5	1941	
1899_08C	1899	CU	POBA		TA	1999	50	good	5	5	1939	
1909_01C	1909	CU	POBA		TA	1999	52	wide	4	5	1938	
E10C	E	CU	POBA	2	TL	1999	52	good	5	5	1937	
E03S	E	CU	SIAL		TA	1999	33	near	5	25	1936	
E40C	E	CU	POBA		TL	1999	54	good	5	5	1935	
1909_02C	1909	CU	POBA		TA	1999	53	good	7	5	1934	
E02C	E	CU	POBA	2	TA	1999	56	near	4	5	1934	
E_AH	E	AH	POBA			1983	44	na	0	5	1934	
E30C	E	CU	POBA	2	TL	1999	56	good	4	5	1934	
1909_06C	1909	CU	POBA	2	TA	1999	56	wide	7	5	1931	
E50C	E	CU	POBA		TL	1999	59	good	6	5	1929	
1909_05S	1909	CU	SIAL		TA	1999	34	good	11	25	1929	
1899_09C	1899	CU	POBA	2	TA	1999	61	good	6	5	1927	

Appendix A. (continued) Exit Glacier tree core samples. All field locations from all studies.

Tree ID	Site	Coll.	Genus	# of Cores	Type	Year of Sampling	Ring Count	PiTh Seen	Height		Factor	Eccesis	Oldest Possible Year AD
									cored (cm)	Age/Ht. (yrs)			
E04C	E	CU	POBA	2	TA	1999	58	good	43	9		5	1927
1909_04C	1909	CU	POBA		TA	1999	66	good	51	10		5	1918
1909_03C	1909	CU	POBA		TA	1999	64	good	95	19		5	1911
E01S	E	CU	SIAL	2	TA	1999	61	wide	28	8		25	1905
E_WI	E	WI	SIAL			1989	65	na	0	0		25	1899
1894 Moraine Leaf Transect F													
F20A	F	CU	ALSI		TL	1999	15	good	8	0		0	1984
F50A	F	CU	ALSI		TL	1999	19	good	0	0		0	1980
F10A	F	CU	ALSI		TL	1999	20	good	0	0		0	1979
F30A	F	CU	ALSI		TL	1999	21	good	13	0		0	1978
F40A	F	CU	ALSI		TL	1999	27	good	20	0		0	1972
F20C	F	CU	POBA		TL	1999	39	near	20	4		5	1951
1899_07A	1899	CU	ALSI		TA	1999	54	good	17	0		0	1945
F30C	F	CU	POBA		TL	1999	58	near	11	2		5	1934
F02C	F	CU	POBA		TA	1999	61	good	36	7		5	1926
1899_05C	1899	CU	POBA	2	TA	1999	64	good	44	9		5	1921
F40C	F	CU	POBA		TL	1999	70	near	22	4		5	1920
F50C	F	CU	POBA	2	TL	1999	69	near	25	5		5	1920
1899_02C	1899	CU	POBA		TA	1999	66	near	38	8		5	1920
D_AH	D	AH	POBA			1983	59	na	0	0		5	1919
1899_04C	1899	CU	POBA	2	TA	1999	66	good	52	10		5	1918
F10C	F	CU	POBA		TL	1999	69	good	34	7		5	1918
D_AH	D	AH	SIAL			1983	42	na	0	0		25	1916
1899_06C	1899	CU	POBA	2	TA	1999	74	good	32	6		5	1914
1899_03C	1899	CU	POBA		TA	1999	75	near	34	7		5	1912
1891 Moraine Leaf Transect G													
G30A	G	CU	ALSI		TL	1999		na	0	0		0	1999
G10A	G	CU	ALSI		TL	1999	21	good	20	0		0	1978

Appendix A. (continued) Exit Glacier tree core samples. All field locations from all studies.

Tree ID	Site	Coll.	Genus	# of Cores	Type	Year of Sampling	Ring Count	PiTh Seen	Height		Factor (yrs)	Eccesis	Oldest Possible	
									cored (cm)	Age/Ht.			Year AD	Year AD
G40A	G	CU	ALSI		TL	1999	24	good	15	0	0	0	1975	
G50A	G	CU	ALSI		TL	1999	37	good	13	0	0	0	1962	
G20A	G	CU	ALSI		TL	1999	42	good	20	0	0	0	1957	
G02A	G	CU	ALSI		TA	1999	53	near	5	0	0	0	1946	
G30C	G	CU	POBA		TL	1999	54	near	36	7	5	5	1933	
G40C	G	CU	POBA	2	TL	1999	55	wide	28	6	5	5	1933	
1899_01C	1899	CU	POBA	2	TA	1999	60	wide	29	6	5	5	1928	
G10C	G	CU	POBA	2	TL	1999	70	near	13	3	5	5	1921	
G01C	G	CU	POBA		TA	1999	72	good	33	7	5	5	1915	
G50C	G	CU	POBA		TL	1999	78	good	22	4	5	5	1912	
1899_10C	1899	CU	POBA	2	TA	1999	73	good	43	9	5	5	1912	
1899_11C	1899	CU	POBA		TA	1999	76	good	48	10	5	5	1908	
G20C	G	CU	POBA	2	TL	1999	87	wide	20	4	5	5	1903	
1889 Moraine - Soil Pit 1889														
1825_07C	1825	CU	POBA	3	TA	1999	73	good	30	6	5	5	1915	
C_AH	C	AH	POBA			1983	64	na	0	0	5	5	1914	
1825_03C	1825	CU	POBA		TA	1999	79	good	30	6	5	5	1909	
G03S	G	CU	SIAL	2	TA	1999	60	good	20	6	25	25	1908	
G08C	G	CU	POBA	2	TA	1999	82	good	24	5	5	5	1907	
G09C	G	CU	POBA		TA	1999	79	good	43	9	5	5	1906	
1825_04C	1825	CU	POBA		TA	1999	80	near	64	13	5	5	1901	
1825_02C	1825	CU	POBA	2	TA	1999	86	wide	45	9	5	5	1899	
1825_01C	1825	CU	POBA		TA	1999	95	good	33	7	5	5	1892	
1825_05S	1825	CU	SIAL		TA	1999	71	near	37	11	25	25	1892	
1825_06C	1825	CU	POBA	2	TA	1999	93	good	51	10	5	5	1891	
C_AH	C	AH	SIAL			1983	69	na	0	0	25	25	1889	
C_WI	C	WI	SIAL			1989	75	na	0	0	25	25	1889	

Appendix A. (continued) Exit Glacier tree core samples. All field locations from all studies.

Tree ID	Site	Coll.	Genus	# of Cores	Type	Year of Sampling	Ring Count	PiTh Seen	Height		Factor (yrs)	Eccsis	Oldest Possible	
									cored (cm)	Age/Ht.			Year AD	Year AD
Region K- 1869 - Leaf Transect H														
H10A	H	CU	ALSI		TL	1999	19	good	13	0	0	0	1980	
H20A	H	CU	ALSI		TL	1999	20	good	3	0	0	0	1979	
H40A	H	CU	ALSI		TL	1999	21	good	8	0	0	0	1978	
H50A	H	CU	ALSI		TL	1999	31	good	10	0	0	0	1968	
H30A	H	CU	ALSI		TL	1999	33	good	10	0	0	0	1966	
H50C	H	CU	POBA		TL	1999	55	wide	27	5	5	5	1934	
H30C	H	CU	POBA	2	TL	1999	60	good	19	4	5	5	1930	
H40C	H	CU	POBA		TL	1999	61	good	27	5	5	5	1928	
H10C	H	CU	POBA	2	TL	1999	68	near	23	5	5	5	1921	
H20C	H	CU	POBA	2	TL	1999	87	good	51	10	5	5	1897	
G06C	G	CU	POBA		TA	1999	91	good	51	10	5	5	1893	
_AH		AH	POBA			1983	85	na	0	0	5	5	1893	
G04S	G	CU	SIAL	2	TA	1999	67	good	48	14	25	25	1893	
_AH		AH	POBA			1983	87	na	0	0	5	5	1891	
G07S	G	CU	SIAL	2	TA	1999	79	good	44	13	25	25	1882	
G05S	G	CU	SIAL		TA	1999	85	good	41	12	25	25	1877	
REGION_K02S	REGION_K	CU	SIAL		TA	1999	77	good	69	21	25	25	1876	
_AH		AH	SIAL			1983	89	na	0	0	25	25	1869	
REGION_K01S	REGION_K	CU	SIAL	2	TA	1999	96	near	29	9	25	25	1869	
1815 Moraine - LJA Maxima														
B_AH	B	AH	SIAL			1983	119	na	0	0	25	25	1839	
B_AH	B	AH	POBA			1983	143	na	0	0	5	5	1835	
B_WI	B	WI	SIAL			1989	149	na	0	0	25	25	1815	
Distal sites to 1815 moraine, Leaf Transect I														
I20A	I	CU	ALSI		TL	1999		na	0	0	0	0	1999	
I50C	I	CU	POBA		TL	1999		na	0	0	5	5	1994	
I10A	I	CU	ALSI		TL	1999	19	good	66	0	0	0	1980	
													132	

Appendix A. (continued) Exit Glacier tree core samples. All field locations from all studies.

Tree ID	Site	Coll.	Genus	# of Cores	Type	Year of Sampling	Ring Count	P/Th Seen	Height		Eccis	Oldest Possible Year AD
									cored (cm)	Age/Ht. Factor (yrs)		
I40A	I	CU	ALSI		TL	1999	21	good	5	0	0	1978
I30A	I	CU	ALSI		TL	1999	22	good	15	0	0	1977
I50A	I	CU	ALSI		TL	1999	30	good	25	0	0	1969
I01A	I	CU	ALSI		TA	1999	39	good	24	0	0	1960
I20C	I	CU	POBA	2	TL	1999	67	good	22	4	5	1923
I10C	I	CU	POBA		TL	1999	77	good	28	6	5	1911
I40C	I	CU	POBA	2	TL	1999	169	good	58	12	5	1813
A_AH	A	AH	SIAL			1983	148	na	0	0	25	1810
I03C	I	CU	POBA		TA	1999	192	good	58	12	5	1790
A_AH	A	AH	POBA			1983	190	na	0	0	5	1788
A_AH	A	AH	SIAL			1983	195	na	0	0	25	1763
I30C	I	CU	POBA	2	TL	1999	215	good	84	17	5	1762
A_AH	A	AH	SIAL			1983	197	na	0	0	25	1761
I02S	I	CU	SIAL		TA	1999	208	good	61	18	25	1748
NE on the Outwash Plain - Leaf Transect J												
J50A	J	CU	ALSI		TL	1999	16	good	35	0	0	1983
J20A	J	CU	ALSI		TL	1999	26	good	30	0	0	1973
J30A	J	CU	ALSI		TL	1999	37	near	25	0	0	1962
J10A	J	CU	ALSI		TL	1999	44	good	30	0	0	1955
J40A	J	CU	ALSI		TL	1999	45	good	20	0	0	1954
J20C	J	CU	POBA		TL	1999	46	good	40	8	5	1940
J10C	J	CU	POBA	2	TL	1999	63	wide	30	6	5	1925
J30C	J	CU	POBA		TL	1999	66	good	32	6	5	1922
J40C	J	CU	POBA	2	TL	1999	75	wide	33	7	5	1912
J50C	J	CU	POBA	2	TL	1999	79	good	50	10	5	1905
Beyond LJA Maxima - Wiles Living Tree Chronology - near Res. River												
K_AH	K	AH	SIAL			1983	327	na	0	0	25	1631
EXG_WI	EXG	WI	SIAL			1989	400	na	0	0	15	1574

**10 APPENDIX B: AERIAL PHOTOGRAPHY OF EXIT GLACIER, KENAI FJORDS
NATIONAL PARK**

APPENDIX B
VERTICAL AND OBLIQUE AERIAL PHOTOGRAPHY
INDEX OF TERMS

AERO	Aeromap U.S., Anchorage Alaska
ADOT	Alaska Department of Transportation, Anchorage, Alaska
AKSO	National Park Service, Alaska Support Office, Anchorage, Alaska
APFO	U.S.D.A. Farm Services Agency, Aerial Photography Field Office, Salt Lake City, Utah
B/W	Black and White
BLM	Bureau of Land Management, Cadastral Services, Anchorage, Alaska
CIR	Color Infra Red
COLOR	Natural Color
EROS	U.S. Geological Survey, EROS Data Center, Sioux Falls, South Dakota
ESIC	U.S. Geological Survey, Earth Science Information Center, Anchorage, Alaska
KEFJ	Kenai Fjords National Park, Seward Alaska
SEWARD-ENG	City of Seward, Engineers Branch, Seward, Alaska
SEWARD-LIB	Seward Community Library, Seward, Alaska
NASA	National Aeronautics and Space Administration, Alaska High Altitude Photography Program (AHAP)
UAF-GEO	Univ. Alaska Fairbanks, Geophysical Institute, GeoData Center, Fairbanks, Alaska
USAF	U.S. Air Force - Under contract to USGS
USARMY	U.S. Army Map Service - Under contract to USGS
USFS	U.S.D.A., Forest Service, Chugach National Forest, Supervisors Office, Anchorage, Alaska
USFS-J	U.S.D.A., Forest Service, Engineering and Aviation Management, Juneau, Alaska
USGS	U.S. Geological Survey
ICE	U.S. Geological Survey, Ice and Climate Project, Tacoma, WA
UAF-GEO	Univ. Alaska Fairbanks, Geophysical Institute, GeoData Center, Fairbanks, Alaska
	In; Sloan, Charles, E. 1985. Water resources and hydrologic hazards of the Exit Glacier area near Seward, Alaska. Water Resources Investigations Report: 85-4247. U.S. Geological Survey, Anchorage Alaska. [The report is available from USGS Open-File Service Section]
USGS-WR	

APPENDIX B - TABLE 1									
VERTICAL AERIAL PHOTOGRAPHY									
DATE	FLOWN BY	SOURCE ¹	MISSION	ROLL FLIGHT FRAME			SCALE	FORMAT	COMMENTS
				NO.	LINE	NO.			
8/8/1950	USARMY	EROS or ESIC	373			310-311	1:40,000	B/W	Excellent quality Terminus not visible. Poor contrast.
6/25/1951	USARMY	EROS or ESIC	U				1:40,000	B/W	Terminus not visible
9/2/1952	USARMY	EROS or ESIC	655				1:40,000	B/W	Excellent quality
7/1/1961	USFS	APFO	EEV	45	2-4		1:15,840	B/W	Scene ID ABB7140- B000001K
6/28/1973	USAF	EROS or ESIC		1K		5,6	1:64,800	B/W	Excellent quality
7/27/1974	USFS	APFO	2210	1074		95	1:15,840	COLOR	Excellent quality
8/24/1978	NASA	UAF-GEO		2662	576	6724	1:65,000	CIR	
8/14/1984	NASA	UAF-GEO		3387	118	264-265	1:65,000	CIR	
8/14/1984	NASA	UAF-GEO		3388		8522	1:130,000	CIR	
9/2/1985	ADOT	ADOT	Res. River Bridge				1:8,000	B/W	Excellent quality Terminus 1/8" in from edge of photo
7/21/1991	USFS	APFO					1:32,000	COLOR	Grainy, poor contrast
7/10/1993	USFS	APFO	USDA-F 32 6	1090		158	1:32,000	COLOR	
6/17/1995	ADOT	KEFJ				11	1:14,000	COLOR	
9/27/1995	SEWARD-ENG KEFJ		Seward Flooding			4-10	1"=800'	COLOR	
6/16/1996	AERO	AERO	Exit Glacier	1	1-9		1:14,000	COLOR	Excellent quality
	AERO-					46,47,			
6/26/1997	METRIC, INC.	EROS or ESIC	Kenai DOQ effort	1096		55-57		B/W	
8/28/1997	USFS-J	AKSO	Exit Glacier	Multiple	Multiple		1:10,000	COLOR	Digital 35mm
8/14/1998	USFS	APFO	Spruce Bark Project	3	627		1:30,000	CIR	Excellent quality
6/3/1999	BLM	BLM	Exit Glacier	1,2,3			1:8,000	B/W	

See Key for Abbreviations

¹ SOURCE: Physical location of photography as of 1999

**APPENDIX B - TABLE 2
OBLIQUE AND GROUND PHOTOGRAPHY**

DATE	SOURCE ¹	PHOTOGRAPHER	PHOTO		TYPE ²	COMMENTS
			NO.			
ca. 1920	SEWARD-LIB	Unknown			Ground Oblique Unknown camera	Labeled "RESURRECTION RIVER & GLACIER SEWARD ALASKA."
1935	KEFJ	Unknown			Unknown	Small scale. Poor resolution. Labeled on back - July 1935
1948	Anchorage Museum-Archives	Steve McCutcheon	McC 1935-1 A		Aerial Low Oblique 4x5 Horiz. Graphic Air. B/W	Labeled as "Lowell Glacier (A Piedmont). Later called Exit Glacier 1989"
July 14, 1968	Anchorage Museum-Archives	Steve McCutcheon	AMHA 03922,3664,3 962		Aerial Low Oblique. 35mm. Color	Three color slides. Excellent quality
July 14, 1968	Anchorage Museum-Archives	Steve McCutcheon	McC -10266		Aerial Low Oblique 4x5 Horiz. Graphic Air. B/W	Labeled as "Glacier on west side Resurrection Pass (Lowell Glacier) Exit Glacier July 14, 1968"
March 30, 1983	KEFJ	USGS-WR			Aerial Low Oblique B/W Contact Print. B/W	Four photos with snow on ground, but excellent contrast
1984	UAF-GEO	ICE	Roll 84R2 Frames 98-101		Aerial Low Oblique B/W Contact Print. B/W	Series of Obliques, large format camera. Excellent quality

See Key for Abbreviations

¹ SOURCE: Physical location of photography as of 1999

² TYPE: Type of camera and/or film

**11 APPENDIX C: TOPOGRAPHIC MAPPING OF THE EXIT GLACIER FORELANDS,
KENAI FJORDS NATIONAL PARK, ALASKA**

**TOPOGRAPHIC MAPPING OF THE EXIT GLACIER FORELANDS,
KENAI FJORDS NATIONAL PARK, ALASKA**

In 1980, Kenai Fjords National Park was established to perpetually protect the glacier and coastal fjord ecosystems along the Southeastern Kenai Peninsula. In creating the park, Congress stated its purposes as "to maintain unimpaired the scenic and environmental integrity of the Harding Icefield, its out-flowing glaciers and coastal fjords and islands in their natural state... free of human activity which is disruptive to their natural processes." Exit Glacier, one of the out-flowing glaciers, provides visitors with a rare opportunity to approach a glacier on foot, and as the only developed area within the park accessible by road, it is a popular destination, therefore, subject to overcrowding. In 1994 and 1995, portions of the 16 km Exit Glacier Road owned by the U.S. Forest Service and the State of Alaska were improved and paved. The State anticipates paving the remainder of the road to the park in 2001. In 1996, a Development Concept Plan (DCP) was completed by NPS staff, establishing goals and policies for visitor use, interpretation and resource management. One of the critical components outlined in the first year of the study was to develop a map of the area to assist in inventory of the natural and cultural resources at Exit Glacier.

In 1999, with funding support from Kenai Fjords National Park, a mapping project was initiated by the NPS Alaska Support Office to construct a 0.5 meter digital elevation model (DEM), digital orthophotos and 0.5 meter contour topographic map of the Exit Glacier forelands. In early June 1999, photo panels (or premarks) were laid out at predetermined points by NPS and Bureau of Land Management (BLM) personnel. Black and white 1:8,000 vertical aerial photography was flown the following day by the BLM to capture the photo panels for photogrammetric control. In the latter part of June 1999, photo panel positions were surveyed and monumented by the U.S. Forest Service using static GPS survey methods. The acquired photography and GPS coordinates were then used to construct a 0.5 meter contour map of the Exit Glacier terminus, visitor facilities and road corridor, resulting in a database well suited for use in a geographic information system. This report describes the photo panel layout, the BLM aerial photography mission, the

GPS photo control survey performed by the US Forest Service, and the BLM photogrammetric mapping efforts at Exit Glacier, Kenai Fjords National Park, Alaska.

11.1 Photo Panel Premark Layout

Initial mapping plans specified for mapping a 800 hectare area encompassing the Exit Glacier terminus, Harding Icefield trail, visitor facilities and road corridor. This included the entire Exit Glacier valley floor and all proglacial features from the 1951 moraine to the Resurrection River detailed in the previous sections. Pre-planning of the photo panel layout was done by NPS and BLM Cadastral Office personnel in the spring of 1999. Steps included laying out the aerial photography flightlines, photo panel layout, and determination of the number of models or photographic blocks required to tie together the anticipated photography with geographic coordinates collected over photo panel positions.

Sixteen photo panels were laid out on June 1-2, 1999, by NPS and BLM personnel throughout the Exit Glacier forelands on new and pre-existing control (Figure 1). Panel station NPS 10 (SRD 3039) located in the parking lot was an existing USDA Forest Service 3 1/4" aluminum cap set in 1998 and panel station NPS 12 (Jane) was an existing 2" diameter brass cap grouted in bedrock by the University of Alaska Geophysical Institute in 1998 (Figure 2). Both of these controls were previously surveyed by static GPS control. "Jane" monument is part of a geodetic GPS network measuring crustal motion and is considered valid control for high accuracy GPS networks. Photo panel NPS13A was not set, but later surveyed in with GPS control (See GPS section). Photo panel NPS06 was set but considered redundant for mapping purposes and is not depicted in Figure 1. Unusually late-lying snow conditions (0.5 meter depth in places) factored in the placement of some photo panels south of Exit Creek and prevented placement of panels along the Harding Icefield trail and upper glacier area. Access to the northeast portion of the project area (panels NPS03, NPS04 and NPS05) was complicated by high water in streams. All photo panels were constructed of white Tyvex ©, approximately 12 feet long (tip to tip) and 12" wide in the standard form of a cross (Figure 2). Eight-inch gutter spikes, wooden lathe, bailing wire and rocks were used to secure the panel corners. Temporary center points constructed of wooden lathes were installed to mark the location of

the photo panel centers. Panel placement in all areas was aided by the use of waypoints pre determined in a GIS and entered into military GPS receivers (PLGR's) for use in navigation under thick canopy.

11.2 BLM Aerial Photography Acquisition

Concerns of early leaf out of black cottonwood and alder which could occlude portions of the ground led to immediate acquisition of aerial photography on June 3 by the Bureau of Land Management (BLM), Alaska State Office, Division of Cadastral Survey, Branch of Mapping Sciences. The photographs were taken with a Wild RC-8 aerial camera No. 485 with a 6" focal length lens (No. 263) mounted in a twin Cessna 402, using black and white film for maximum resolution. Six flight lines were flown at a nominal scale of 1:8000 scale along a north-south trend line for a total of 54 frames. Two additional flight lines, 7 and 8, were flown at 1:9000 and 1:3000 scale, respectively, along a NW-SE trendline to ensure coverage along the glacier axis and out to the Resurrection Bridge. Weather conditions during the flight ranged from partially sunny conditions to heavy overcast with light rain. Ground conditions included patches of snow partially obscuring low-lying areas south of Exit Creek.

Aerial film was developed by Precision Photo Labs in Dayton, Ohio. Processed photos were assessed for quality by BLM Branch of Mapping Science (Anchorage, Alaska) personnel. Sixteen panels were visible on the photos. However, panel station NPS01 on the extreme northwestern portion of the mapping area had been partially destroyed by a moose but was still visible (Figure 1). Marginal weather conditions during some portions of the flight caused "flat" light, low contrast photos in many areas. In other areas of the mapping area, high contrast environments near snow patches caused overexposure. These photo conditions are discussed further in this section regarding the effects they had on map production.

11.3 GPS Photo Control Survey

This section is excerpted from a project summary report submitted to the National Park Service by Randy Schrank, Project Coordinator, Chugach National Forest, Anchorage, Alaska, in partial fulfillment of a survey conducted to provide survey grade photo control for proposed photogrammetric mapping of the

Exit Glacier forelands. Copies of the entire report are available from the National Park Service, Alaska Support Office, GIS Team, Anchorage, Alaska, 99503 (Schrack, 2000).

GPS was chosen as the preferred method for surveying the photo control. Thick vegetation would have limited efficient use of conventional survey methods due to line-of-sight constraints. In addition, two known GPS control monuments were already set in the area which allowed for more precise determination of relative coordinates. The specialized expertise required for the survey was provided Randy Schrack, Project Coordinator, Chugach National Forest, Anchorage, Alaska.

The GPS network surveyed contained 19 stations including the following two existing Continuously Operating Reference Stations (CORS) : HINCHINBROOK 3 (CHI3) and KENAI 1 (KEN1). Panel stations NPS07, NPS08, NPS09, NPS11 and NPS13 through NPS15 were monumented during the survey with 3' drive rod sections driven to refusal and 3 1/4" diameter aluminum USDA Forest Service caps. Panel Station NPS10 (SRD 3039) was an existing USDA Forest Service 3 1/4" aluminum cap set in 1998, and Panel Station NPS 12 (JANE) was an existing 2" diameter brass cap grouted in bedrock by the University of Alaska Geophysical Institute in 1998. A small number of the stations was monumented with rebar only. Stations along the northern portion of the mapping area were not monumented at all, since it was considered very unlikely they would ever be used again. Panel station NPS13A which was not photo paneled, was monumented due to its line-of-sight location with the Exit Glacier terminus. See Figure 1 for locations of all photo control locations. The final adjusted network includes all monumented panel locations including the seven non-monumented stations.

The survey was performed between June 21 and June 23, 1999, by Chugach National Forest and NPS personnel split into three teams. The project area was approximately 3.6 km x 3.6 km and spanned an area from Resurrection River to the terminus of Exit Glacier and approximately 1.8 km on each side of the Exit Glacier entrance road (Figure 1). Most of the stations were reached by foot and many were accessed by wading across Exit Creek and across several side channels that emptied into Resurrection River. A few stations were reached by vehicle via the Exit Glacier road.

Three dual-frequency Trimble 4000SSi receivers with compact dual-frequency antennas (with groundplanes) and two single-frequency Trimble 4000ST receivers with internal antennas were used throughout the project. Figure 3 shows an example of a receiver set up over a panel station. The two Trimble 4000ST receivers were placed on known GPS control (NPS10 (SRD3039) and NPS12 (Jane)) and left to collect positions continuously throughout the entire project. The three dual-frequency Trimble 4000Ssi receivers were used as rovers by each of the three teams to occupy panel stations around the Exit Glacier forelands. Each roving station was observed for 45-60 minutes using static survey techniques. Every third panel station was double-occupied. The baselines were processed using Trimble's GPSurvey Version 2.30 WAVE processing software and adjusted with Trimnet Plus Version 92.11c software.

The following settings were used during the adjustment process:

Univariate Sigma Scalar = 1.96

Bivariate Sigma Scalar = 2.45

Scalar Weighting Strategy Applied Globally = 12.82

Station Error Weighting Strategy (HI Error) = 0.003 m

Station Error Weighting Strategy (Tribrach Error) = 0.002 m

The geodetic positions of the new panel stations were computed as part of an adjusted network, fully constrained horizontally to National Geodetic Survey (NGS) Continuously Operating Reference Stations (CORS) "HINCHINBROOK 3" and "KENAI 1" using published NAD 1983 (Epoch 1997.0) geodetic coordinates. Elevations were minimally constrained vertically by fixing the ellipsoidal height of CORS station "KENAI 1" using the published NGS height. In the minimally constrained adjustment, all observations that were statistical outliers were removed. The geoid model used during the adjustment process was GEOID96, obtained from National Geodetic Survey. This geoid grid was used in conjunction with Trimble's Trimnet Plus software to arrive at orthometric or ground elevations (Schrank, 2000). Final

adjusted geodetic coordinates in Universal Transverse Mercator (UTM) Zone 6 North and Latitude/Longitude can be found in Tables 1 and 2, respectively.

Relative accuracy within the established control network met the manufacturer's specifications of $1 \text{ cm} \pm 2 \text{ ppm}$ (horizontal) and $2 \text{ cm} \pm 2 \text{ ppm}$ (vertical). Coordinate error ellipses displayed a 1-2 cm horizontal magnitude of error at each adjusted station, and the adjusted network passed the 95% chi-square probability test after outliers were removed (Schrank, 2000). Vertical accuracy of survey grade GPS in this project may be further refined by conducting traditional survey leveling through the project area to compensate for local geoid disturbances (Schrank, R., personal communication, 2000).

Under the guidance of professionals, the geodetic GPS receivers used for survey grade photo control at Exit Glacier provided fast, efficient positioning. With easily transportable equipment, crew sizes were reduced as compared to conventional survey programs. This allowed for multiple observations (double occupancy on control), enhanced accuracy, and redundancy. In addition, no line-of-sight was required between controls, enabling teams to complete the survey in two days despite dense canopy that often limited visibility to 50 meters. Coordinates supplied by survey grade GPS over panel stations provided the necessary control for topographic map construction.

11.4 Exit Glacier Contour Map

The Exit Glacier mapping project was initiated to create a 0.5 m digital elevation model, a 0.5 m contour map and digital orthophotos for incorporation into National Park Service (NPS) geographic information systems (GIS) in anticipation of expanded tourism in the Exit Glacier area. The access road and visitor parking area were a high priority, due to planned use in engineering design. The Bureau of Land Management (BLM), Alaska State Office, Division of Cadastral Survey, Branch of Mapping Sciences, compiled aerial photography and GPS survey control (steps outlined in the previous sections of this appendix) to develop maps for the completion of this project. Due to poor quality aerial photography, however, only the 0.5 m contour map was completed for a small portion of the Exit Glacier forelands. Figure 4 is a fold-out map depicting the final mapping product. Standard photogrammetric methods were

used to aerotriangulate photo models with supplied photo control and to compile features using an analytic stereoplotter.

The map coverage area is bounded on the north by an arbitrary line approximately 100 m north of the Exit Glacier road, on the south by the southern edge of the braided Exit Creek, on the east by an arbitrary line located approximately 50 m east of the east bank of the Resurrection River, and on the west by an arbitrary line approximately 100 west of the Exit Glacier terminus (Figure 4).

The original aerial photography was scanned on a Carl Zeiss, Inc., SCAI high resolution photogrammetric scanner at 21 micron resolution (ground pixel size of 0.168 m). Zeiss Phodis SC scanning software was used to adjust scan parameters for best image appearance. Images were then stored in Zeiss proprietary TLD format. Eighteen photos were then selected from 3 flightlines to encompass all visible photo control points. Fifteen photo models were constructed for aerotriangulation using Zeiss Phodis AT and PAT-B block adjustment software and GPS coordinates of panel locations (Tables 1 and 2). A computed error (sigma naught) associated with the photo models and their placement relative to the cross hairs was calculated at 5.28 microns. This a measure of how well the measured (from photos) panel locations fit surveyed ground positions. This error varies slightly by location, due to physical characteristics of the terrain, and is spread throughout the models only at measured points.

Once the aerial photos were referenced to visible photo controls, photogrammetric compilation of features could then be performed using a Zeiss P3 analytic stereoplotter. Contours were digitized manually by guiding floating marks along the apparent surface of the ground while viewing the photographs in stereo models. Ground surface in large portions of the project area was obscured by vegetation, shadow and/or snow. Contours in these areas were symbolized by dashed lines. Visible planimetric features such as visitor facilities, trails, water bodies, etc., were digitized while viewing the stereo model. Streams less than 0.6 m wide were portrayed as single line entities. Contours with less than 0.9 m horizontal separation were not depicted. All features were then captured in Microstation 95 DGN format and exported as drawing exchange format (DXF) for quality control.

Final accuracy of the map as determined by analytic aerial triangulation does not exceed 0.28 m RMSE (horizontal), while vertical RMSE does not exceed 60% of the horizontal RMSE values. This is a calculated measurement of “human” induced error, most likely associated with picking the centers of photo panels with a mouse and with the placement of floating marks around the terrain. Areas such as the road, bare ground, stream beds and bare ground north of the glacier terminus meet National Map Accuracy Standards (NMAS). However, remaining areas of the map do not meet NMAS standards, due to poor photography (low contrast, poor feature definition), snow cover, and extensive vegetation cover.

Nevertheless, despite the limited mapping area and problems associated with discerning ground features, the contour map provides a high resolution basemap of the most visited areas of the Exit Glacier forelands and will assist resource managers and engineers in documenting and planning future development in the area around Exit Glacier. Survey grade GPS monumentation surrounding the Exit Glacier terminus will provide high resolution local datum control for all future mapping efforts which may include monitoring of the terminus location, geomorphologic and vegetative mapping.

Figure 1. Survey grade GPS photo control points Exit Glacier, Kenai Fjords National Park, Alaska.

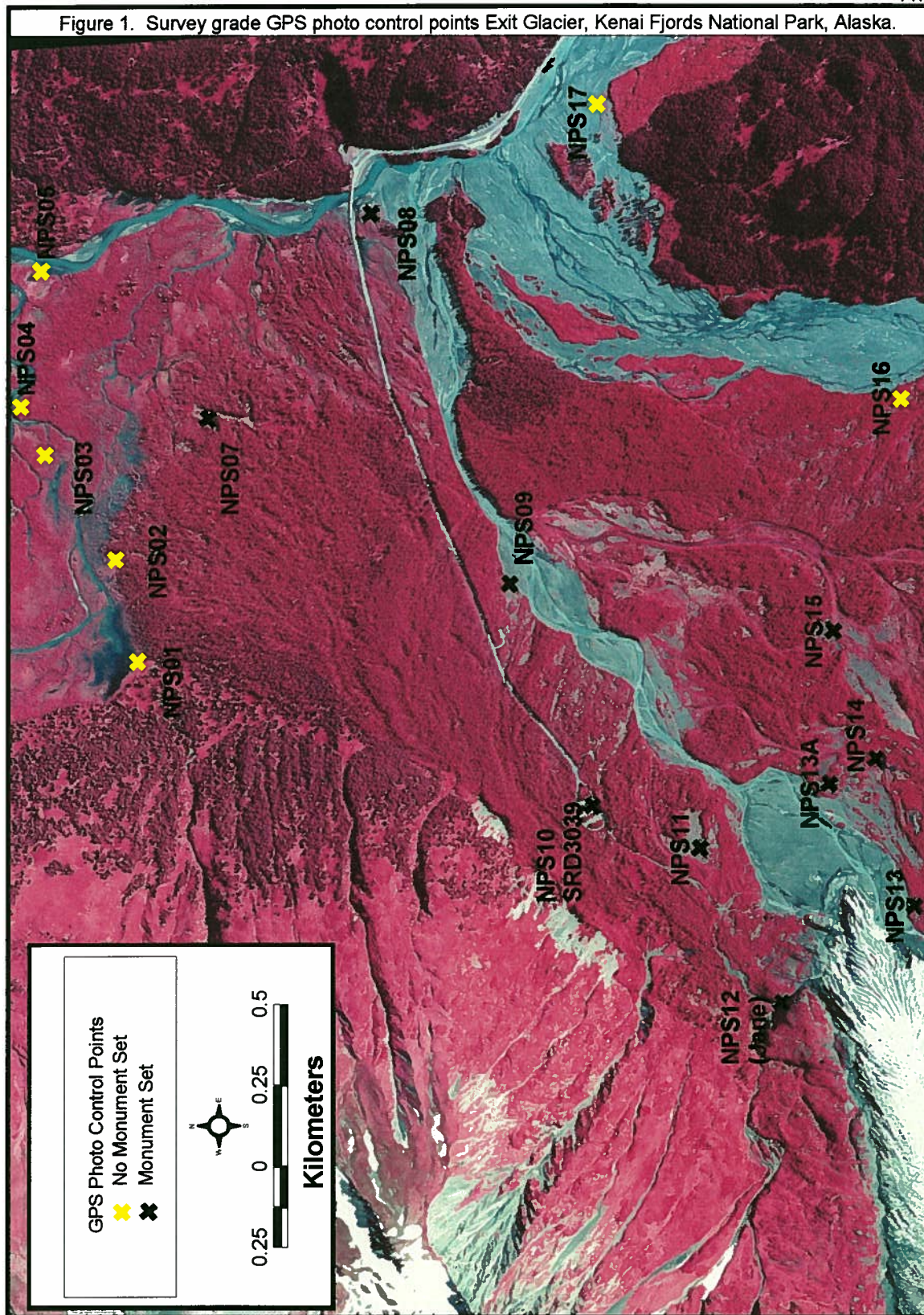


Figure 2. Example of a photo panel placement.



Figure 3. Trimble 4000SSi GPS receiver set up over control NPS13A.



Table 1. Final adjusted geodetic coordinates (UTM) for GPS photo control survey, Exit Glacier, Kenai Fjords National Park, Alaska.

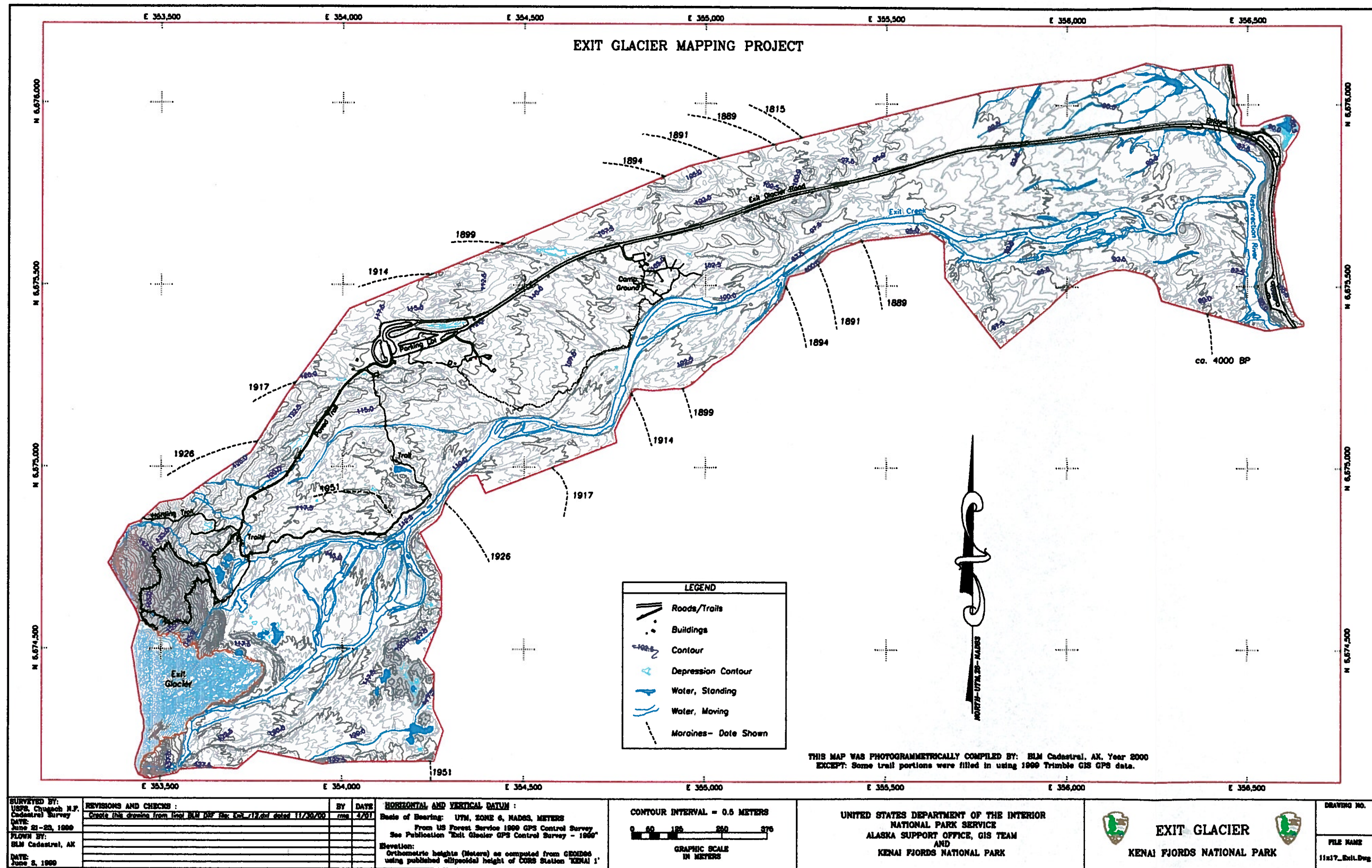
Projection: UTM
 Zone: 6 North
 Linear Units: Meter
 Datum Name: NAD-83 (Epoch 1997.0)

Station Name	Northing	Easting	Orthometric.Ht (meters a.m.s.l.)
NPS1	6676854.891	354846.410	93.41
NPS2	6676894.298	355219.207	92.52
NPS3	6677105.537	355618.302	90.90
NPS4	6677172.600	355795.111	90.61
NPS5	6677049.268	356270.896	89.33
NPS7	6676520.790	355679.976	92.09
NPS8	6675872.257	356346.827	89.15
NPS9	6675522.729	354981.074	102.62
NPS10 (SRD3039)	6675315.991	354160.479	116.04
NPS11	6674954.800	353969.426	117.05
NPS12 (Jane)	6674724.588	353391.254	182.39
NPS13	6674216.933	353682.351	124.87
NPS13A	6674473.518	354150.521	124.60
NPS14	6674299.439	354220.813	121.55
NPS15	6674400.446	354691.054	115.98
NPS16	6674072.030	355491.034	124.85
NPS17	6675031.353	356651.578	87.75

Table 2. Final adjusted geodetic coordinates (Lat/Long) for GPS photo control survey, Exit Glacier, Kenai Fjords National Park, Alaska.

Projection Group: Geographic
 Zone Name: Global
 Linear Units: meter
 Angular Units: degrees
 Datum Name: NAD-83 (Epoch 1997.0)

Station Name	Latitude Deg Min. Sec	Longitude Deg. Min. Sec.	Ortho. Height (m a.m.s.l)	Ellipsoid Height (m)
NPS1	60°12'09.385" N	149°37'07.852" W	93.41	108.187
NPS2	60°12'11.135" N	149°36'43.769" W	92.52	107.309
NPS3	60°12'18.466" N	149°36'18.420" W	90.90	105.685
NPS4	60°12'20.856" N	149°36'07.120" W	90.61	105.390
NPS5	60°12'17.479" N	149°35'35.937" W	89.33	104.123
NPS7	60°11'59.662" N	149°36'12.921" W	92.09	106.895
NPS8	60°11'39.568" N	149°35'28.012" W	89.15	103.986
NPS9	60°11'26.541" N	149°36'55.690" W	102.62	117.440
NPS10 (SRD 3039)	60°11'18.813" N	149°37'48.370" W	116.04	130.852
NPS11	60°11'06.904" N	149°37'59.824" W	117.05	131.872
NPS12 (Jane)	60°10'58.724" N	149°38'36.712" W	182.39	197.191
NPS13	60°10'42.707" N	149°38'16.524" W	124.87	139.696
NPS13A	60°10'51.596" N	149°37'46.839" W	124.60	139.429
NPS14	60°10'46.065" N	149°37'41.832" W	121.55	136.387
NPS15	60°10'49.931" N	149°37'11.608" W	115.98	130.822
NPS16	60°10'40.348" N	149°36'18.906" W	124.85	139.713
NPS17	60°11'12.800" N	149°35'06.111" W	87.75	102.614



12 APPENDIX D: RADIOCARBON RESULTS

APPENDIX D. RADIOCARBON AGES FROM THE EXIT GLACIER FORELANDS. THIS STUDY AND WILES (1992).

Laboratory no.	Radiocarbon Date (BP)	Calibrated Date (age ranges)	Relevance	GPS Location (NAD27 Datum)	Descriptive Local Reference
Beta-144283	3790±60	4155 BC 2205	Soil Pit K1. 78-100cm below surface (Bsb horizon) on top of C1 horizon.	60 11 35.05 (Lat)	At confluence of Resurrection R. and Exit Creek. Soil Pit site K this work
		4395-3980 BC 2445-2030	Age of older stabilized moraine	-149 35 20.42 (Long) ¹	
Beta-144284*	3590±40	3885 BC 1935	Soil Pit K2. 50-67 cm below surface (BC horizon) on top of C1 horizon.	60 11 35.05 (Lat)	At confluence of Resurrection R. and Exit Creek. Soil Pit site K this work
		3980-3835 BC 2030-1875	Age of older stabilized moraine	-149 35 20.54 (Long) ¹	
Beta-148903	890 ±70	780 1170	Outer portion of cottowood? Log in submerged forest, maximum limiting age of midlevel advance?	60 11 04.21 (Lat)	this work
		945-675 1005-1275		-149 37 42.31 (Long) ¹	
Beta-33349	270±50	305 1645	Loc. 1. An alder branch in lateral moraine deposits, maximum limiting age for ice advance**	60 11 17.39 (Lat)	0.5 km due west of Exit Glacier parking lot, on hillside. Wiles, 1992
		470-0 1480-1955		-149 38 19.44 (Long) ²	
Beta-39633	330±50	431, 363, 327 1519, 1587, 1623	Loc. 2. Outer rings of a transported log, maximum limiting age for ice advance**	60 11 05.46 (Lat)	South of Exit Creek, upvalley from 1917 moraine. Wiles, 1992
		500-290 1450-1660		-149 37 13.85 (Long) ²	

* Accelerator Mass Spectrometry(AMS) Method Used

**Wiles (1992)

¹ Position derived from differential GPS

² Position derived from map position on 1:40,000 scale photo (See Wiles, 1992)

**13 APPENDIX E: SOIL PROFILE DESCRIPTIONS OF EXIT GLACIER, KENAI FJORDS
NATIONAL PARK**

Site A3 Pedon - 1980

- A • 0-2 cm; black (N2.5/) extremely gravelly loamy sand; weak medium granular structures, very friable; loose, non-stick and non-plastic; common fine and medium roots; abrupt smooth boundary.
- C1 • 2-7 cm; black (N2.5/) extremely cobbly sand; single grains; loose, non-sticky and non-plastic; many very fine and fine, and few medium roots; clear wavy boundary. (5-10 cm thick).
- C2 • 7-30 cm; black (N2.5/) extremely cobbly sand; single grains; loose, non-plastic and non-sticky; common very fine and fine roots; clear wavy boundary.
- C3 • 30-100 cm; black (N2.5/) extremely cobbly sand; single grains; loose, non-sticky and non-plastic; few fine roots.

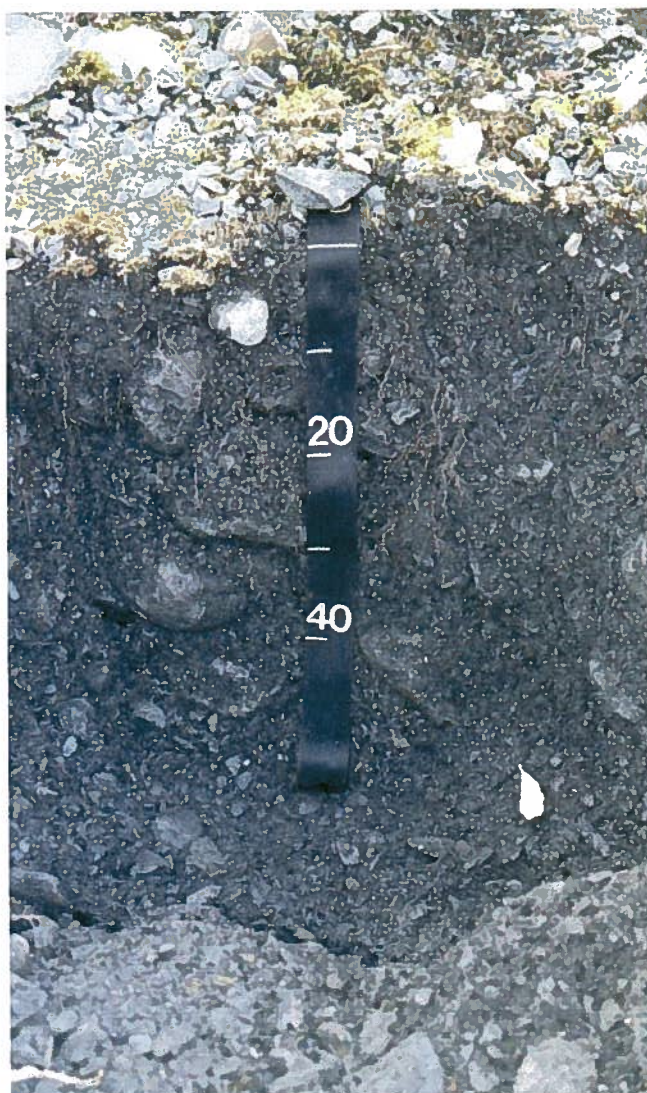


Table 1. Final adjusted geodetic coordinates (UTM) for GPS photo control survey, Exit Glacier, Kenai Fjords National Park, Alaska.

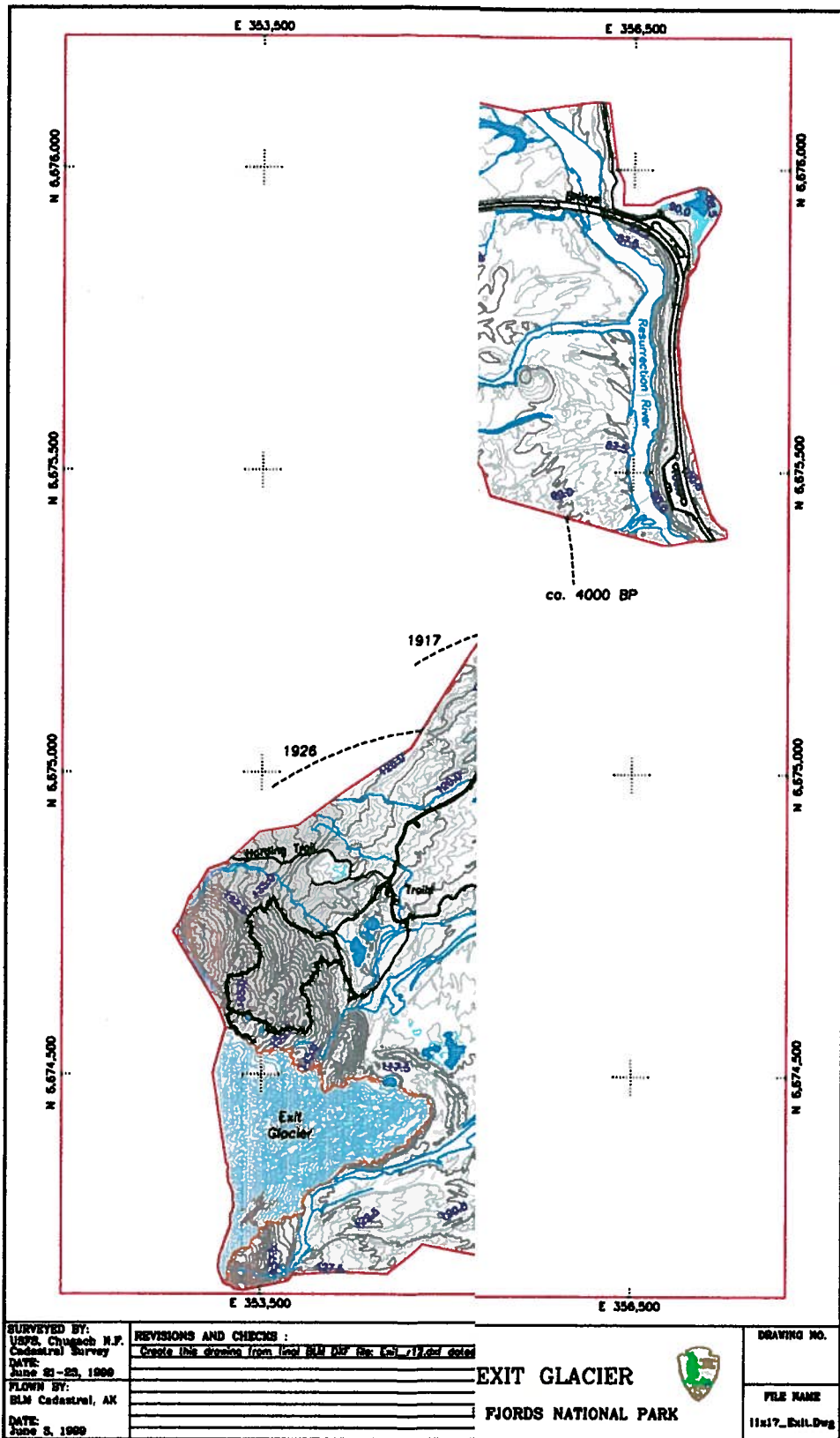
Projection: UTM
 Zone: 6 North
 Linear Units: Meter
 Datum Name: NAD-83 (Epoch 1997.0)

Station Name	Northing	Easting	Orthometric.Ht (meters a.m.s.l.)
NPS1	6676854.891	354846.410	93.41
NPS2	6676894.298	355219.207	92.52
NPS3	6677105.537	355618.302	90.90
NPS4	6677172.600	355795.111	90.61
NPS5	6677049.268	356270.896	89.33
NPS7	6676520.790	355679.976	92.09
NPS8	6675872.257	356346.827	89.15
NPS9	6675522.729	354981.074	102.62
NPS10 (SRD3039)	6675315.991	354160.479	116.04
NPS11	6674954.800	353969.426	117.05
NPS12 (Jane)	6674724.588	353391.254	182.39
NPS13	6674216.933	353682.351	124.87
NPS13A	6674473.518	354150.521	124.60
NPS14	6674299.439	354220.813	121.55
NPS15	6674400.446	354691.054	115.98
NPS16	6674072.030	355491.034	124.85
NPS17	6675031.353	356651.578	87.75

Table 2. Final adjusted geodetic coordinates (Lat/Long) for GPS photo control survey, Exit Glacier, Kenai Fjords National Park, Alaska.

Projection Group: Geographic
 Zone Name: Global
 Linear Units: meter
 Angular Units: degrees
 Datum Name: NAD-83 (Epoch 1997.0)

Station Name	Latitude Deg Min. Sec	Longitude Deg. Min. Sec.	Ortho. Height (m a.m.s.l)	Ellipsoid Height (m)
NPS1	60°12'09.385" N	149°37'07.852" W	93.41	108.187
NPS2	60°12'11.135" N	149°36'43.769" W	92.52	107.309
NPS3	60°12'18.466" N	149°36'18.420" W	90.90	105.685
NPS4	60°12'20.856" N	149°36'07.120" W	90.61	105.390
NPS5	60°12'17.479" N	149°35'35.937" W	89.33	104.123
NPS7	60°11'59.662" N	149°36'12.921" W	92.09	106.895
NPS8	60°11'39.568" N	149°35'28.012" W	89.15	103.986
NPS9	60°11'26.541" N	149°36'55.690" W	102.62	117.440
NPS10 (SRD 3039)	60°11'18.813" N	149°37'48.370" W	116.04	130.852
NPS11	60°11'06.904" N	149°37'59.824" W	117.05	131.872
NPS12 (Jane)	60°10'58.724" N	149°38'36.712" W	182.39	197.191
NPS13	60°10'42.707" N	149°38'16.524" W	124.87	139.696
NPS13A	60°10'51.596" N	149°37'46.839" W	124.60	139.429
NPS14	60°10'46.065" N	149°37'41.832" W	121.55	136.387
NPS15	60°10'49.931" N	149°37'11.608" W	115.98	130.822
NPS16	60°10'40.348" N	149°36'18.906" W	124.85	139.713
NPS17	60°11'12.800" N	149°35'06.111" W	87.75	102.614



SURVEYED BY:
USFS, Chugach N.F.
Cadastral Survey
DATE:
June 21-23, 1999
FLOWN BY:
BLM Cadastral, AK
DATE:
June 8, 1999

REVISIONS AND CHECKS :
Create this drawing from final BLM DWP file Exit_17.dwg dated

EXIT GLACIER
FIORDS NATIONAL PARK



DRAWING NO.

FILE NAME
Exit17_Exit.Dwg

12 APPENDIX D: RADIOCARBON RESULTS

APPENDIX D. RADIOCARBON AGES FROM THE EXIT GLACIER FORELANDS. THIS STUDY AND WILES (1992).

Laboratory no.	Radiocarbon Date (BP)	Calibrated Date (age ranges)	Relevance	GPS Location (NAD27 Datum)	Descriptive Local	Reference
Beta-144283	3790±60	4155	Soil Pit K1. 78-100cm below surface (Bsb horizon) on top of C1 horizon.	60 11 35.05 (Lat)	At confluence of Resurrection R. and Exit Creek. Soil Pit site K	this work
		4395-3980	Age of older stabilized moraine	-149 35 20.42 (Long) ¹		
Beta-144284*	3590±40	3885	Soil Pit K2. 50-67 cm below surface (BC horizon) on top of C1 horizon.	60 11 35.05 (Lat)	At confluence of Resurrection R. and Exit Creek. Soil Pit site K	this work
		3980-3835	Age of older stabilized moraine	-149 35 20.54 (Long) ¹		
Beta-148903	890 ±70	780	Outer portion of cottowood? Log in submerged forest, maximum limiting age of midlevel advance?	60 11 04.21 (Lat)		this work
		945-675		-149 37 42.31 (Long) ¹		
Beta-33349	270±50	305	Loc. 1. An alder branch in lateral moraine deposits, maximum limiting age for ice advance**	60 11 17.39 (Lat)	0.5 km due west of Exit Glacier parking lot, on hillside.	Wiles, 1992
		470-0		-149 38 19.44 (Long) ²		
Beta-39633	330±50	431, 363, 327	Loc. 2. Outer rings of a transported log, maximum limiting age for ice advance**	60 11 05.46 (Lat)	South of Exit Creek, upvalley from 1917 moraine.	Wiles, 1992
		500-290		-149 37 13.85 (Long) ²		

* Accelerator Mass Spectrometry(AMS) Method Used

**Wiles (1992)

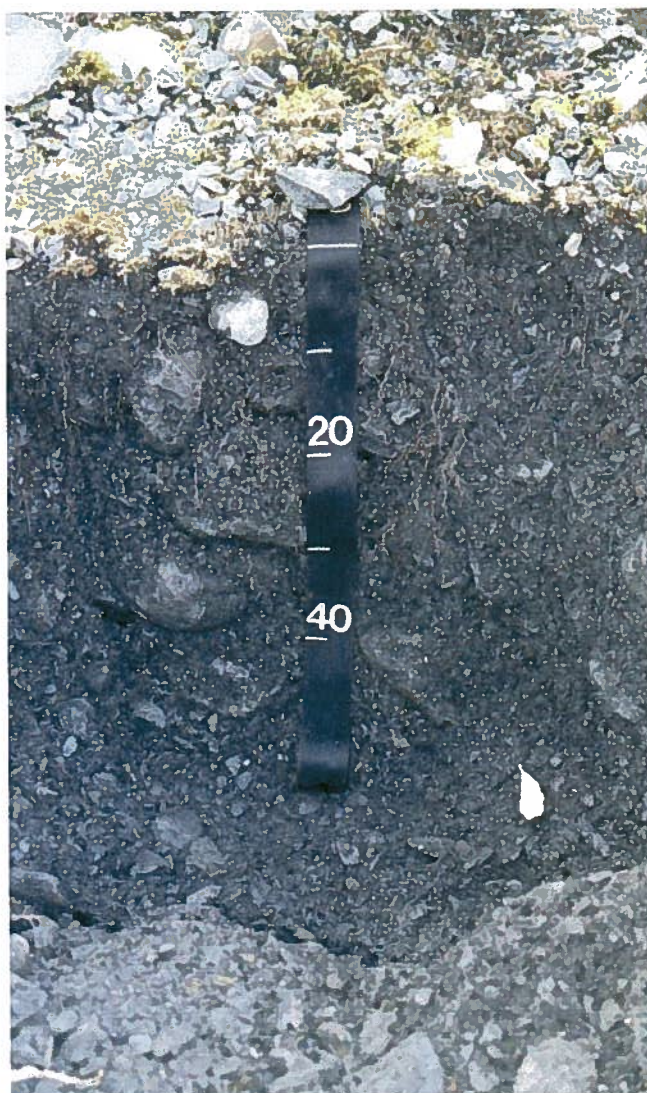
¹ Position derived from differential GPS

² Position derived from map position on 1:40,000 scale photo (See Wiles, 1992)

**13 APPENDIX E: SOIL PROFILE DESCRIPTIONS OF EXIT GLACIER, KENAI FJORDS
NATIONAL PARK**

Site A3 Pedon - 1980

- A • 0-2 cm; black (N2.5/) extremely gravelly loamy sand; weak medium granular structures, very friable; loose, non-stick and non-plastic; common fine and medium roots; abrupt smooth boundary.
- C1 • 2-7 cm; black (N2.5/) extremely cobbly sand; single grains; loose, non-sticky and non-plastic; many very fine and fine, and few medium roots; clear wavy boundary. (5-10 cm thick).
- C2 • 7-30 cm; black (N2.5/) extremely cobbly sand; single grains; loose, non-plastic and non-sticky; common very fine and fine roots; clear wavy boundary.
- C3 • 30-100 cm; black (N2.5/) extremely cobbly sand; single grains; loose, non-sticky and non-plastic; few fine roots.

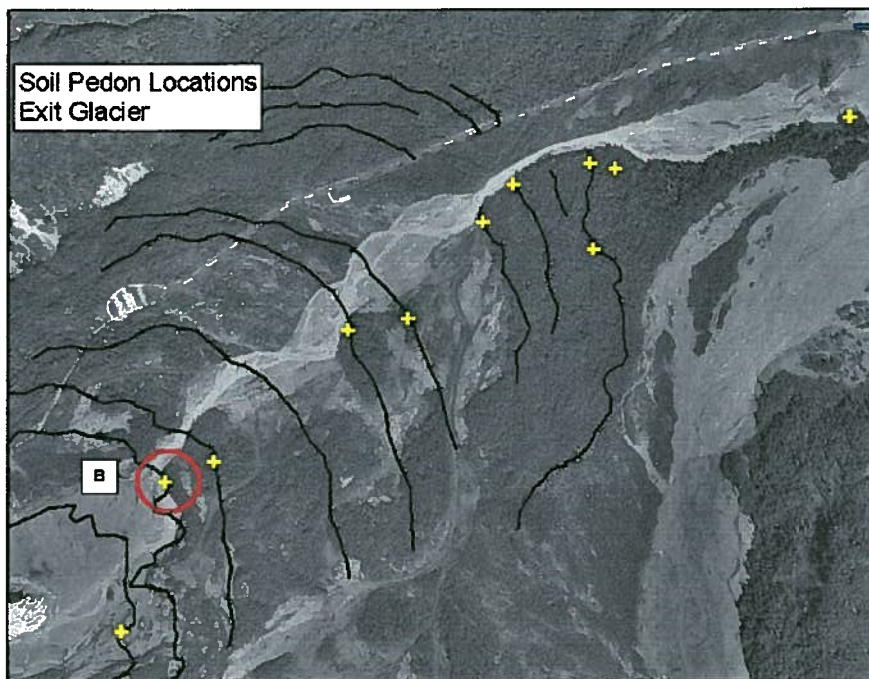


Site B Pedon - 1951

- Oi/Oe • 0-3 cm; black (7.5YR2.5/1) mucky peat; weak fine platy structures, very friable; many very fine, fine, medium, and common coarse roots; abrupt smooth boundary.
- C1 • 3-10 cm; dark gray (N4/) very cobbly sandy loam; massive structure; firm, non-sticky and non-plastic; common very fine, fine, and medium roots; clear wavy boundary.
- C2 • 10-30 cm; dark gray (N4/) extremely cobbly sandy loam; massive structure; firm, non-sticky and non-plastic; few very fine, fine, and medium roots; diffused smooth boundary.
- C3 • 30-60 cm; dark gray (N4/) extremely cobbly sandy loam; massive structure; firm, non-sticky and non-plastic; few very fine and fine roots.



Site B Pedon - 1951 cont.

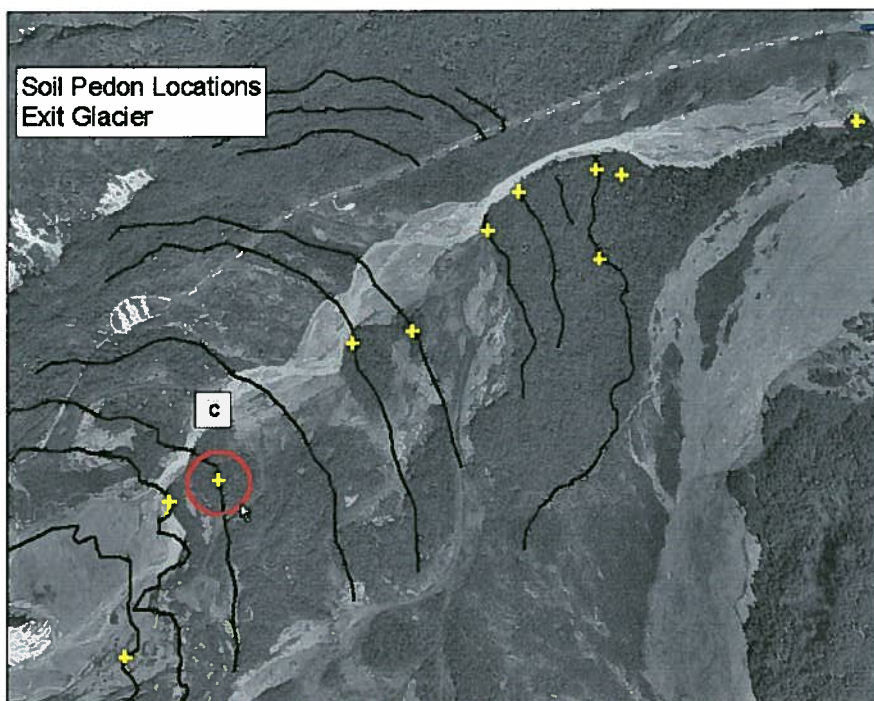


Site C Pedon - 1926

- Oe • 0-4 cm; black (5YR2.5/1) peaty muck; moderate fine platy structures, friable; many very fine, fine, medium, and common coarse roots; abrupt smooth boundary.
- C1 • 4-12 cm; dark gray (N4/) extremely stony loam; 40% stone, 25% cobble and 20% gravel; weak medium subangular (60%) and massive (40%) structures; friable, slightly sticky and slightly plastic; common very fine, fine, and medium roots; clear wavy boundary.
- C2 • 12-32 cm; dark gray (N4/) extremely stony loam; 40% stone and 25% cobble and gravel; massive structure; firm, slightly sticky and slightly plastic; few very fine, fine, and medium roots; diffused smooth boundary.
- C3 • 32-80 cm; dark gray (N4/) extremely stony loam; 45% stone and 25% gravel; massive structure; firm, slightly sticky and slightly plastic; few very fine and fine roots.



Site C Pedon - 1926 cont.

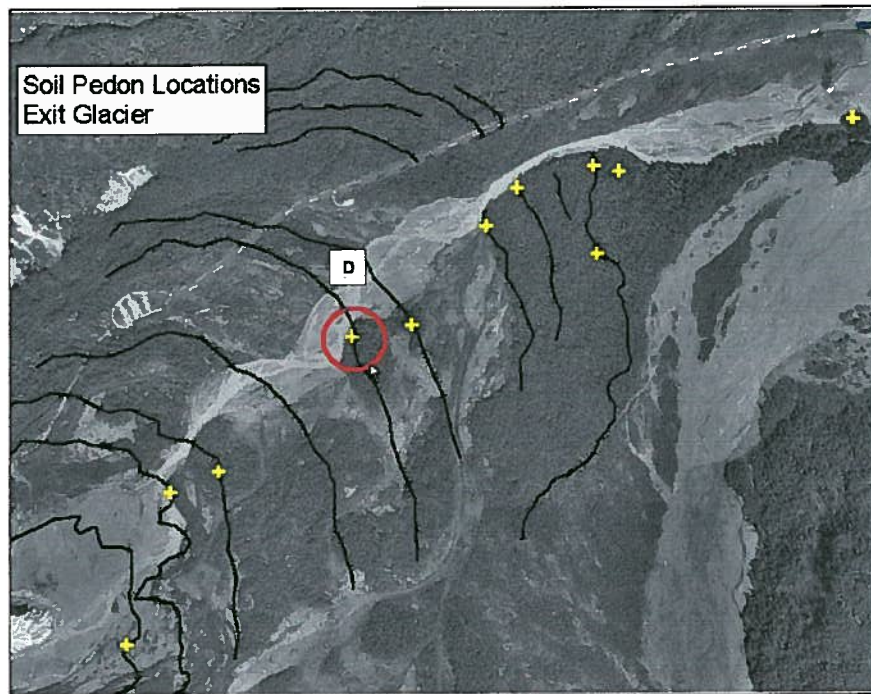


Site D Pedon - 1914

- Oi • 0-1 cm; peat; litter layer
- Oa • 1-5 cm; black (5YR2.5/1) muck; moderate medium platy structures, friable; many very fine, fine, medium, and few coarse roots; abrupt smooth boundary. (4-8 cm thick)
- C1 • 5-10 cm; dark gray (N4/) very cobbly sandy loam; moderate medium granular structures; friable, slightly sticky and slightly plastic; common very fine, fine, medium, and few coarse roots; clear wavy boundary.
- C2 • 10-35 cm; dark gray (N4/) very cobbly sandy loam; moderate medium subangular structures; friable, slightly sticky and slightly plastic; few very fine, fine, and medium roots; diffused smooth boundary.
- C3 • 35-70 cm; few old root remains; dark gray (N4/) very cobbly sandy loam; moderate medium subangular structures grading into moderate medium reticular structures; friable, slightly sticky and slightly plastic; few very fine, fine, and medium roots; few old root remains diffused smooth boundary.
- C4 • 70-120 cm; dark gray (N4/) very cobbly sandy loam; moderate medium subangular structures; friable, slightly sticky and slightly plastic; few very fine and fine roots; few old root remains.



Site D Pedon - 1914 cont.

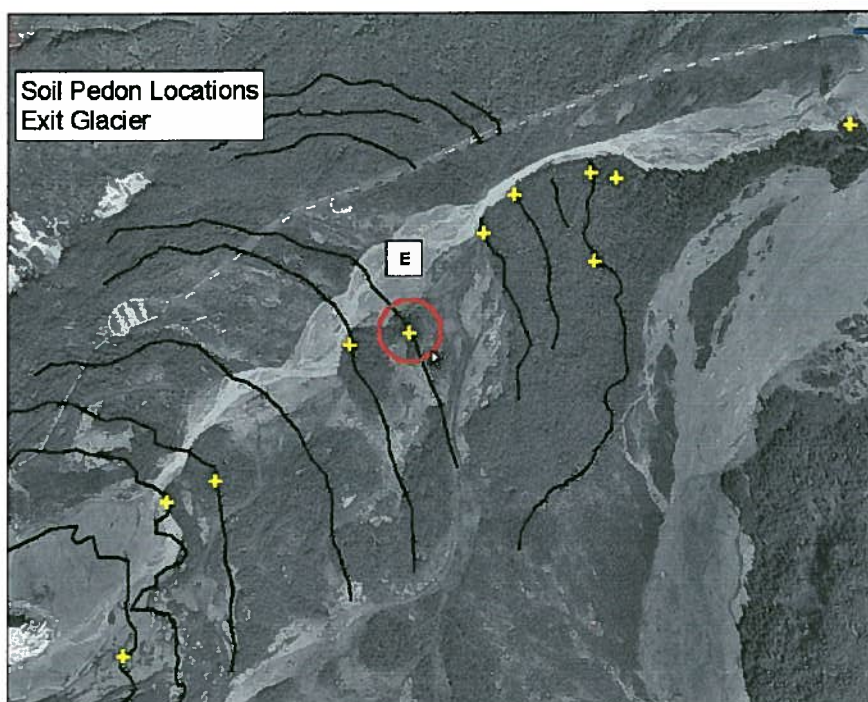


Site E Pedon - 1899

- Oi • 0-1 cm; peat, litter layer.
- Oe • 1-8 cm; black (7.5YR2.5/1) peaty muck; moderate medium platy structures, friable; many very fine, fine, medium, and coarse roots; abrupt smooth boundary.
- Oa • 8-12 cm; black (5YR2.5/1) muck; moderate medium granular structures, friable; many very fine, fine, medium, and coarse roots; abrupt smooth boundary. (10-13 cm thick)
- A&O • 12-15 cm; 70% dark gray (N4/) extremely cobbly sandy loam and 30% black muck; 35% cobble and 30% gravel; weak fine subangular blocky structure in mineral part and weak medium granular structure in organic part; friable, slightly sticky and slightly plastic in mineral part and very friable non-sticky and non-plastic in organic part; many very fine, fine, and common medium roots; gradual smooth boundary.
- C1 • 15-35 cm; dark gray (N4/) extremely cobbly sandy loam; 35% cobble and 30% gravel; weak fine subangular blocky structure; friable, slightly sticky and slightly plastic; common very fine, fine, and medium roots; few old roots; gradual smooth boundary.
- C2 • 35-60 cm; very dark gray (N3/) extremely cobbly loamy sand; 70% rock fragment; single grained; loose, non-sticky and non-plastic; common very fine, fine and medium roots; few pockets of organic matter and dead roots; gradual smooth boundary.
- C3 • 60-90 cm; very dark gray (N3/) extremely cobbly sand; 70% rock fragment; single grained; loose, non-sticky and non-plastic; few very fine, fine and medium roots.



Site E Pedon - 1899 cont.

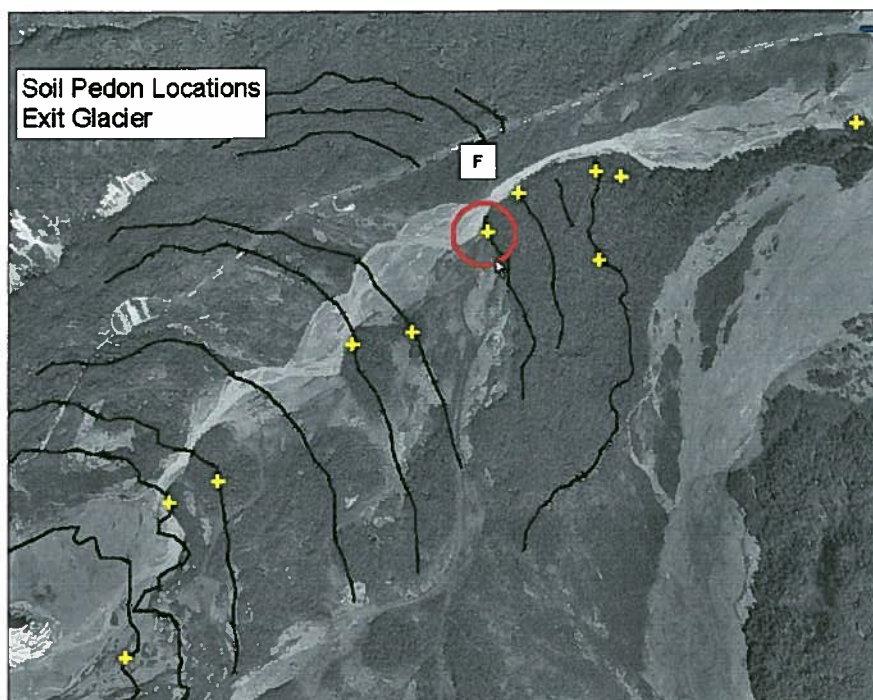


Site F Pedon - 1894

- Oi • 0-1 cm; peat, litter layer.
- Oa • 1-5 cm; reddish black (2.5YR2.5/1) muck; moderate medium granular structures, friable; many very fine, fine, medium, and few coarse roots; abrupt smooth boundary.
- A • 5-17 cm; 70% dark gray (N4/) and 30% dark gray (2.5Y4/1) very cobbly sandy loam; 30% cobble and 15% gravel; moderate medium granular structure; friable, slightly sticky and slightly plastic; many very fine, fine, common medium, and few coarse roots; common small pockets of decayed organic matter; clear wavy boundary.
- AC • 17-32 cm; dark gray (N3.5/) very cobbly sandy loam; weak fine subangular blocky structure breaking into weak fine platy structure; friable, slightly sticky and slightly plastic; common very fine, fine, and medium roots; few small pockets of decayed organic matter; clear wavy boundary.
- C • 32-90 cm; very dark gray (N3/) very cobbly sandy loam; weak medium granular structure; friable, slightly sticky and slightly plastic; few very fine and fine roots.



Site F Pedon - 1894 cont.

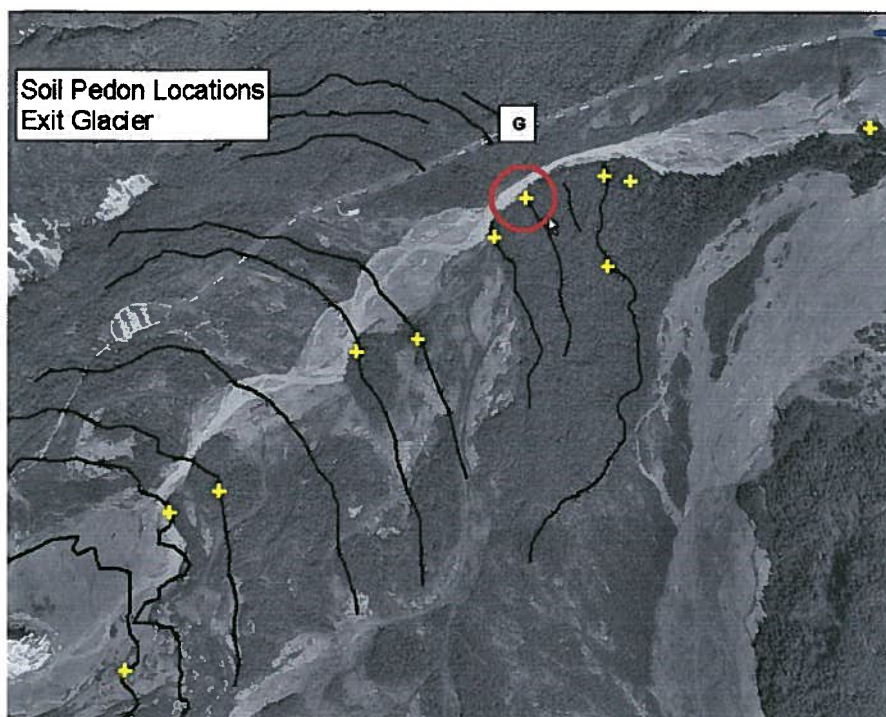


Site G Pedon - 1891

- Oi/Oe • 0-2 cm; black (5YR2.5/1) mucky peat; moderate fine platy structure; abrupt smooth boundary.
- Oa • 2-8 cm; reddish black (2.5YR2.5/1) muck; moderate medium platy structure breaking into weak medium granular structure; friable; many very fine, fine, few medium and coarse roots; abrupt smooth boundary. (6-10 cm thick)
- A • 8-16 cm; very dark gray (2.5Y3/1) very cobbly sandy loam; 55% rock fragment; moderate medium granular structure; friable, non-sticky and non-plastic; many very fine, fine, and few medium roots; clear wavy boundary. (5-12 cm thick)
- AC • 16-30 cm; dark gray (N4/) very cobbly sandy loam; 10% stone and 50% cobble and gravel; weak medium subangular blocky and weak medium granular structures; friable, slightly sticky and slightly plastic; common very fine, fine, and few medium roots; clear wavy boundary.
- C1 • 30-70 cm; dark gray (N4/) very cobbly sandy loam; 20% cobble and 40% gravel; weak medium subangular blocky structure; friable, slightly sticky and non-plastic; few very fine, fine, and medium roots; gradual smooth boundary.
- C2 • 70-120 cm; dark gray (N4/) very cobbly sandy loam; 25% cobble and 40% gravel; weak medium granular structure; friable, non-sticky and non-plastic; few fine and medium roots.
- Remarks: (1). microrrhize hyphae common between 10-55 cm.
(2). Few rocks with spotty iron stains. (3). Color change noted in A.



Site G Pedon - 1891 cont.

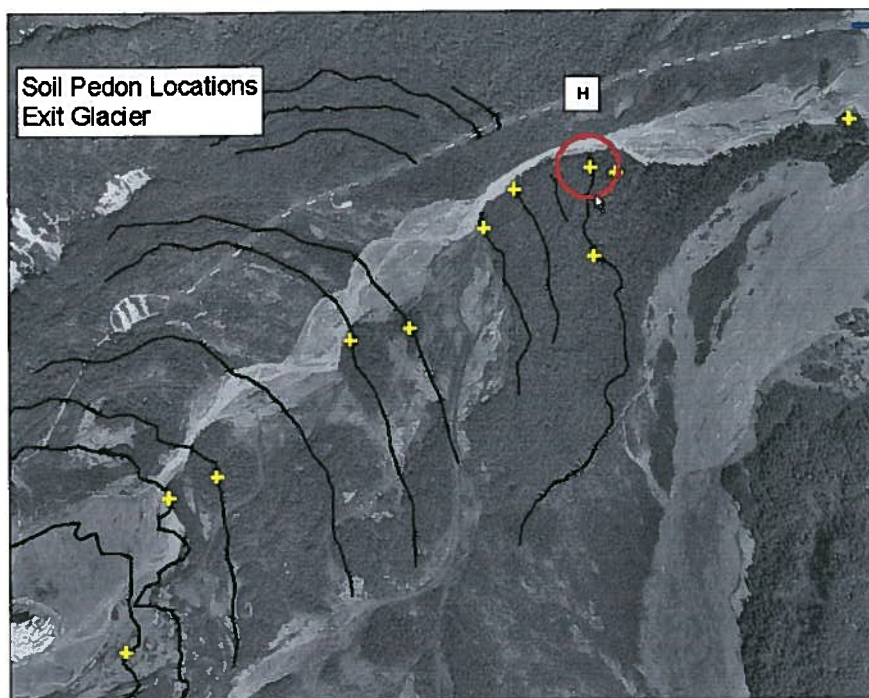


Site H Pedon - 1869

- Oi • 0-1 cm; peat; litter layer; abrupt smooth boundary.
- Oa • 1-6 cm; black (10YR2/1) muck; moderate fine granular structure; friable; many fine, medium, and coarse roots; abrupt smooth boundary.
- A • 6-16 cm; black (10YR2/1) extremely cobbly sand; 55% rock fragment; moderate medium granular structure; friable, non-sticky and non-plastic; many very fine, fine, and few medium roots; abrupt wavy boundary. (10-20 cm thick)
- AC • 16-42 cm; very dark grayish brown (2.5Y3/2) extremely cobbly sand; 50% cobble and 20% gravel; single grain, non-sticky and non-plastic; common very fine, fine, and few medium roots; clear wavy boundary. (10-25 cm)
- C • 42+ cm; dark gray (N4/) extremely cobbly sand, 55% cobble and 20% gravel; single grain, non-sticky and non-plastic; few fine roots.

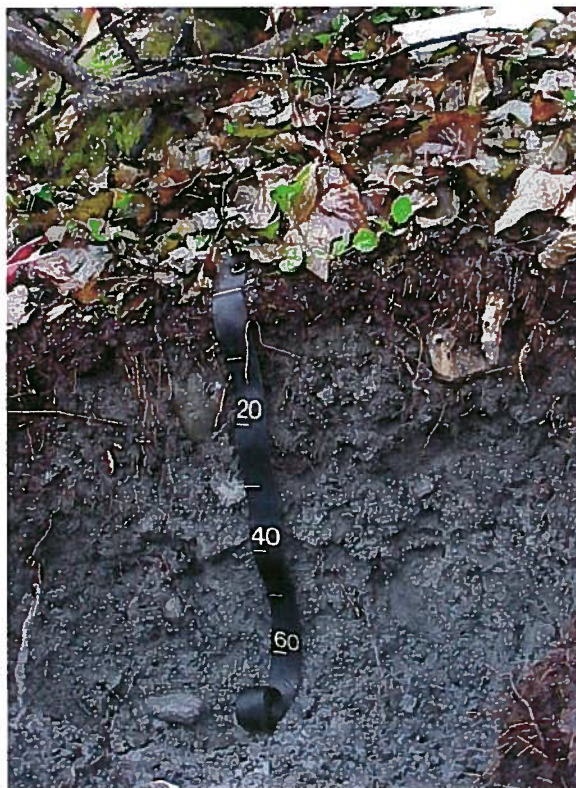


Site H Pedon - 1869 cont.

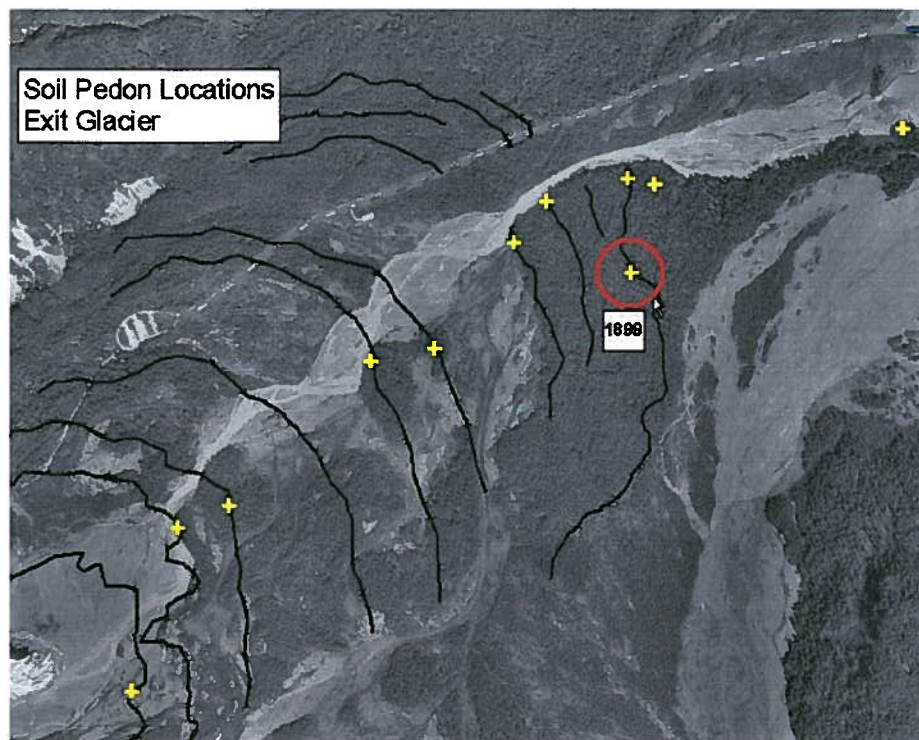


Site 1889 Pedon

- Oi • 0-2 cm; black (5YR2.5/1) peat; moderate fine platy structure; very friable; abrupt smooth boundary.
- Oe • 2-6 cm; black (5YR2.5/1) mucky peat; weak medium platy structure; very friable; many fine, medium, and common coarse roots; abrupt smooth boundary.
- A • 6-22 cm; very dark gray (N3/) very cobbly loamy sand; 30% cobble and 25% gravel; single grain; loose, non-sticky and non-plastic; common very fine, fine, and medium roots; clear wavy boundary.
- AC • 22-45 cm; dark gray (N4/) very cobbly loamy sand; 30% cobble and 20% gravel; single grain; non-sticky and non-plastic; few very fine, fine, and medium roots; clear wavy boundary.
- C • 45-80 cm; dark gray (N4/) very cobbly loamy sand, 55% cobble and 20% gravel; single grain; non-sticky and non-plastic; few fine roots.
- Remarks: Most gravel and cobble stones are rounded and few are subangular. Few rocks in the A and AC horizons have iron stains on top and humus coatings (2.5YR3/2) on the bottom. White granular formed from fungus hyphae in the bottom of AC horizon.



Site 1889 Pedon

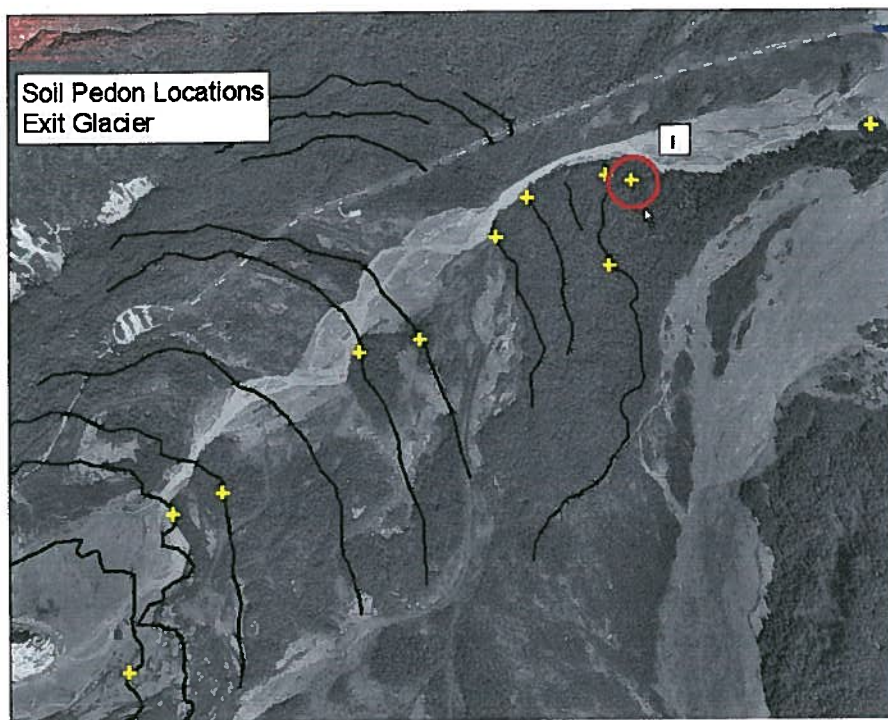


Site I Pedon - ca 1748

- Oe • 0-9 cm; very dark brown (7.5YR2.5/2) mucky peat; moderate medium platy structure; very friable; many very fine, fine, medium, and coarse roots; abrupt smooth boundary.
- A • 9-18 cm; black (10YR2/1) very gravelly sand; single grain structure; loose, non-sticky and non-plastic; many very fine, fine, common medium, and few coarse roots; clear smooth boundary.
- AC • 18-39 cm; black (10YR2/1) very gravelly coarse sand; single grain structure; loose, non-sticky and non-plastic; common very fine, fine, and medium roots; gradual smooth boundary.
- C1 • 39-61 cm; very dark gray (N3/) very cobbly coarse sand, 25% cobble and 20% gravel; single grain structure; loose, non-sticky and non-plastic; many fine, medium, and coarse roots within buried stumps and woody debris; abrupt smooth boundary.
- C2 • 61-100 cm; very dark gray (N3/) gravelly sand; single grain structure; loose, non-sticky and non-plastic; horizontal lying decayed woody debris and twigs.
- Remarks: Water table: 90 cm



Site I Pedon - ca 1748



Site K1 (Disturbed) Pedon - ca. 4000 BP

- Oi • 0-8 cm; very dark brown (7.5YR2.5/2) peat; moss roots; many fine, medium, and few coarse roots; abrupt smooth boundary.

- Oa • 8-11 cm; black (10YR2/1) muck; weak medium granular structure; very friable; many very fine, fine, common medium and coarse roots; abrupt smooth boundary.

- E • 11-13 cm; gray (10YR6/1) sandy loam; weak medium subangular blocky structure; very friable, slightly sticky and slightly plastic; smeary; common very fine, fine, medium, and few coarse roots; abrupt wavy boundary.

- Bhs • 13-20 cm; very dusk red (2.5YR2.5/2) sandy loam; moderately fine granular structure; friable, slightly sticky and non-plastic; smeary; common very fine, fine, and medium roots; abrupt wavy boundary.

- Bsl • 20-60 cm; dark brown (7.5YR3/2) sandy loam; weak fine subangular blocky structure breaking into weak fine granular structure; friable, slightly sticky and non-plastic; very smeary; common very fine, fine, and medium roots; clear irregular boundary.

- Bs2 • 60-73 cm; dark brown (7.5YR3/2) sandy loam; 5% gravel; weak medium subangular blocky structure; friable, slightly sticky and non-plastic; very smeary; common fine and medium roots; abrupt irregular boundary

- Eb • 73-78 cm; grayish brown (10YR5/2) sandy loam; 3% gravel; weak medium subangular blocky structure; friable, slightly sticky and non-plastic; moderately smeary; common fine and medium roots; abrupt irregular boundary

- Bsb • 78-100 cm; dark brown (7.5YR3/2) gravelly sandy loam; 16% gravel; weak fine subangular blocky structure; friable, slightly sticky and non-plastic; moderately smeary; common fine roots; abrupt smooth boundary

- 2C • 100-200 cm; dark grayish brown (2.5Y4/2) very gravelly sandy loam; 40% rock fragment including 8% cobble; strong medium reticular structure; firm, slightly sticky and slightly plastic; very few fine roots; compact till.

- Remarks: Gravel in Bhs hprizon has Fe-humus coating with color of 2.5YR2.5/2. All rock fragment in 2C horizon have silt cap on top and bottom clean. Silt cap has color of 10YR6/3. Strong reticular structure in 2C horizon suggests periglacial feature: ice lense formation.

Site K2 (Undisturbed) Pedon - ca. 4000 BP

- Oi • 0-5 cm; very dark brown (7.5YR2.5/2) peat; moss roots; common fine, medium, and few coarse roots; abrupt smooth boundary. (4-8 cm thick)

- Oa • 5-11 cm; very dusky red (5YR2.5/2) muck; weak medium granular structure; very friable; many very fine, fine, common medium and few coarse roots; abrupt wavy boundary. (4-15 cm thick)

- E • 11-16 cm; grayish brown (10YR5/2) silt loam; weak fine subangular blocky structure; very friable, slightly sticky and slightly plastic; smeary; common very fine, fine, and medium roots; abrupt irregular boundary. (0-9 cm thick)

- Bhs • 16-30 cm; reddish black (2.5YR2.5/1) sandy loam; 10% gravel; moderately fine granular structure; friable, slightly sticky and non-plastic; smeary; common very fine, fine, and medium roots; abrupt irregular boundary. (1-19 cm thick)

- Bs • 30-50 cm; dark reddish brown (5YR3/2) gravelly sandy loam; 20% gravel; weak fine subangular blocky structure breaking into weak fine granular structure; friable, slightly sticky and slightly plastic; moderately smeary; common very fine, fine, and few medium roots; clear wavy boundary. (10-20 cm thick)

- BC • 50-67 cm; dark gray (10YR4/1) gravelly sandy loam; 30% gravel and 25% organic debris (5YR4/4); weak medium subangular blocky structure breaking into weak medium granular structure; friable, slightly sticky and slightly plastic; smeary; old root mat consisting of many old fine and medium roots; abrupt irregular boundary. (0-25 cm thick)

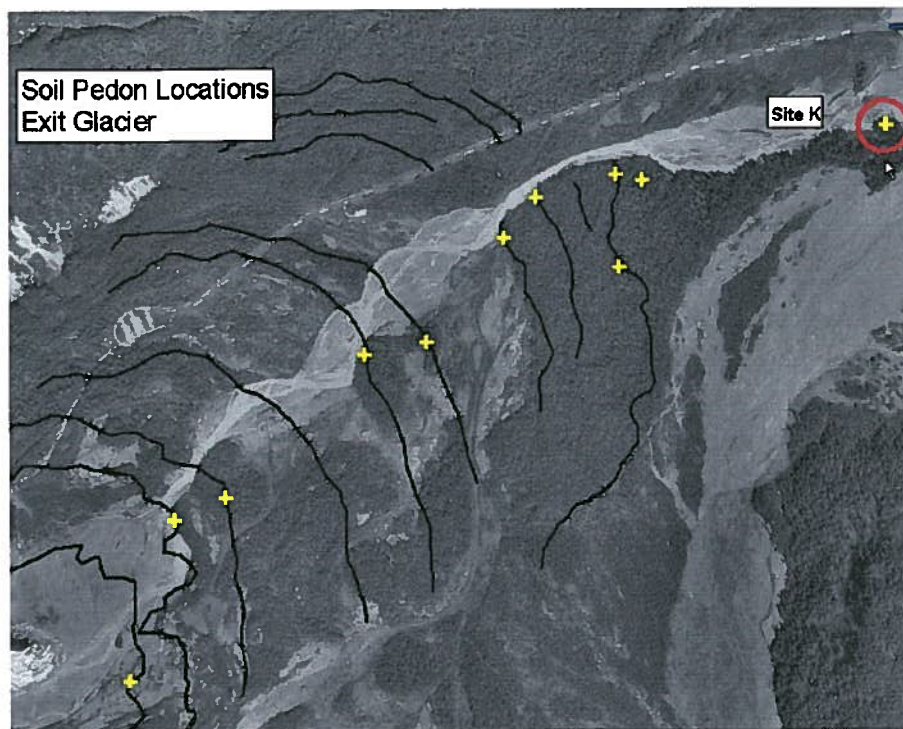
- 2C • 67-200 cm; light olive brown (2.5Y5/4) very gravelly sandy loam; 40% fractured sedimentary rock, 5% cobbles, and 15% round rock fragment; moderate fine reticular structure in upper 90 cm, strong medium reticular structure in 90-100 cm and weak medium reticular structure below 100 cm; firm, slightly sticky and slightly plastic; very few fine roots; compact till.

- Remarks: Gravel in Bhs horizon has Fe-humus coating with color of 2.5YR2.5/2. All rock fragment in 2C horizon have silt cap on top and bottom clean. Silt cap has color of 10YR6/3. Strong reticular structure in 2C horizon suggests periglacial feature: ice lense formation.

Site K2 Pedons - ca. 4000 BP



Site K2 Pedons - ca. 4000 BP



**14 APPENDIX F: ADDITIONAL CONSIDERATIONS IN INTERPRETING FOLIAR
NUTRIENT VARIABILITY**

ADDITIONAL CONSIDERATIONS IN INTERPRETING FOLIAR NUTRIENT VARIABILITY

The literature review in Chapter 1 has shown that foliar nutrient concentrations can be affected by many factors other than nutrient supply to the tree. Two of these factors, yearly variability and position on the tree were assessed during this study in order to more accurately interpret the foliar analysis of black cottonwood and Sitka alder along the Exit Glacier forelands.

14.1 Yearly Variability and Seasonal Affects

Inter-year and seasonal differences were one of the variables this study attempted to control by re-sampling trees from 1998 using precise GPS. In addition, leaves were sampled 20 days and 1 year apart between years so a seasonal re-sample was conducted to test for differences between sampling routines (Chapter 3).

A paired samples T test was first utilized to group all 30 samples and test for differences in leaf elements between all 1998 and 1999 samples. For both cottonwood and alder, zinc and iron decreased significantly between years (Figure 1 a and b), while carbon in alder significantly decreased between years (Fig. 1 c). A similar decrease between years for each species is seen.

Testing if sampling in 1998 near the end of August resulted in a fall senescence affect, both species were tested with a paired samples T test using 20 samples (n=10 alder; n=10 cottonwood) re-sampled in 1999 at approximately the same time of year (Fig. 3.1; August 26,1999). Analysis revealed essentially the same elements were significantly different for both species as those when comparing all samples.

Multivariate analysis of 1999 data re-sampled on the north side of Exit creek grouped by when the sampling occurred (August 6; n=5 and August 26; n=10) was conducted to see if one could compare the 1998 and 1999 data given that 20 calendar days separated both sampling times (See Fig. 3.1). These tests revealed that P in cottonwood was significant, while N, and Cu in alder, were significantly different ($P<0.001$) between sampling times within the same year.

14.2 1998 Results

Several approaches used in the 1998 sampling season, limited the usefulness of the data and detection of patterns in foliar nutrient concentrations. Only leaves reached from the ground were sampled, thereby limiting cottonwood trees to those under 4 meters tall and up valley from the 1899 moraine (Fig. 3.1). In addition, the haphazard approach to sampling was not restricted to areas free of detectable fluvial disturbance and thereby dates of surfaces were unreliable. Despite this approach the exploratory methods in 1998 provided some information on foliar nutrient controls. Site differences were classified into the following groups: 1) proximity to road, 2) distance from glacier, 3) plant exposure, 4) plant height, and 4) presence on raised landform surfaces.

When alder samples were grouped according to distance to the Exit Glacier road (Fig. 3.1), both sulfur ($P=0.024$) and copper ($P=0.007$) were significant. Samples from both road versus non-road were from sample populations with unequal variances, so the power of univariate analysis for both groups could only explain 62% and 77% of the variance.

Foliar concentration of iron in alder was significantly influenced by position on landform ($P=0.015$) while plant exposure and height had affect on foliar concentrations of S ($P=0.05$) and K ($P=0.006$). Foliar concentrations of C ($P=0.017$), N ($P=0.006$), Fe ($P=0.0001$), and S ($P=0.039$), were all significant for alder by distance from the glacier. Black cottonwood sampled in 1998 indicates correlation between foliar N ($P=0.031$) and landform age as well as plant height and zinc concentration ($P=0.018$). Significant difference between foliar zinc in cottonwood (mean=290ppm; st.dev=119;n=71) relative to alder (mean=38ppm; st.dev=12;n=217) was also observed as in the 1999 samples ($P<0.0001$).

14.3 Canopy Effects

In order to compare variation among the transect sites, canopy position was recorded for all sites. Of the 45 trees that were sampled for nutrients (excluding the 10 A3 seedlings), 5% were obtained from the

upper one-third, 24% from the middle one-third, and 15% from the lower one-third of the canopy. Across sites, the upper one-third was sampled once at site F. The middle one-third canopy trees were sampled at least once in all sites.

In order to assess the possible affect that canopy height may have on foliar mineral concentrations, three trees were sampled near the Exit Glacier forelands at a USFS pullout 8 km from the Seward Highway (Fig. 2.1) from three canopy levels; the upper one-third, middle one-third and lower one-third of each tree. There were no significant differences in foliar mineral content among canopy heights from the three trees sampled. Although not significant ($P=0.76$), iron exhibited decreasing concentration with canopy height ($r^2=0.576$). When the mean concentrations of foliar iron for cottonwood is compared between the foreland area (mean = 122.28; std. dev.; 62.51; $n=40$) and the canopy test area (mean = 532.52; std. dev.; 117.94; $n=9$) there is significant difference between these two areas ($P < 0.0001$), and significance between canopy levels ($P = 0.003$). Other elements that are significantly different between these areas include N ($P=0.014$), C/N Ratio ($P=0.018$), Cu ($P=0.000$), K ($P=0.008$), P ($P=0.031$) and Zn ($P=0.0001$). Such differences between these areas indicate the choice of the roadside location for the canopy test may have poorly represented the trees on the foreland due to either road dust, or provenance, however, the low sample number in these tests may make comparisons difficult.

Figure 1 a, b, and c. Inter-year comparison of selected foliar mineral nutrients a) zinc, b) iron, and c) carbon for alder (open red symbols) and cottonwood (solid black line with filled symbols). Sample size = 15 for each species and year.

