Late Little Ice Age Glacier Fluctuations in the Cascade Range
of Washington and northern Oregon

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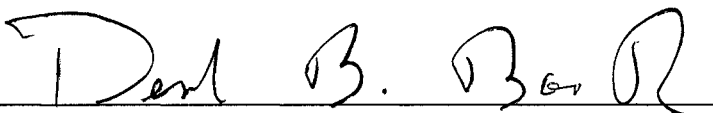
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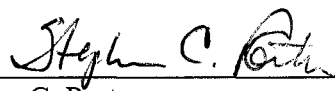Chair of Supervisory Committee:

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Abstract

Late Little Ice Age Glacier Fluctuations in the Cascade Range
of Washington and Northern Oregon

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Chair of the Supervisory Committee:
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During the late Holocene, the large valley glaciers in the Cascade Range of
Washington and northern Oregon advanced and retreated several times, depositing a
series of nested moraines that lie within a few kilometers downvalley of their current
terminal positions. Because glaciers are sensitive to changes in precipitation and
temperature, glacier-length chronologies derived from these moraines are often used as
a proxy record of past climate variation.

Direct observations of glacier extents prior to the widespread collection of air
photos in the 1940s are limited to indirect field data. A regionally applicable lichen
growth curve with an accuracy of ±10 years was developed to characterize the timing of
glacier fluctuations using moraine ages between about 1850 and 1950. The resulting
data show decadal variations in glacier extent and suggest that, since the late 19th
century, glaciers in the Cascade Range of Washington and northern Oregon have
responded synchronously to regional climate patterns.

The poorly constrained ages of pre-19th-century moraines, however, means that these older landforms may be a result of substantially earlier ice advances of indeterminate age(s), and thus they may not reflect regional or global patterns of climate fluctuations. Using historical climate data characteristic of the 20th-century record, a linearized numerical model that produces glacier-length variations from temperature and precipitation data was used to simulate possible length changes that would be anticipated under naturally varying climate conditions. These variations can account for virtually all of the glacier-length fluctuations identified in the moraine record. Attributing the 19th century (or other late Holocene) moraines to distinct climate changes thus requires that any such climatic shift be larger and (or) longer in duration than the observed 20th-century climatic variability. If any systematic climate shifts have occurred, the glacial record suggests that they have been of a magnitude no greater than the modeled natural variability and the moraine record may not provide substantial evidence that they ever existed.

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CHAPTER I

A *Rhizocarpon geographicum* growth curve for the Cascade Range of Washington and northern Oregon.

1.1 Abstract

Lichen thalli measurements from 22 surfaces of known age on mounts Baker, Hood, and Rainier are used to construct a regional *Rhizocarpon geographicum* growth curve for the Cascade Range of Washington and northern Oregon. Growth rates determined by measuring the largest thalli diameters on the same surfaces at Mount Rainier in 1976 and 2002 are used for comparison with lichenometric data from mounts Baker and Hood. Similar lichen thalli diameter vs. age relationships identified in the data from the three mountains suggest the presence of uniform growth rates over the 400-km range. A regional growth curve developed during our study shows three growth phases of successively slower growth: a rapid phase from 8 to 20 years, a linear phase from 20 to 145 years, and a slow phase of unknown duration starting after ca. 145 years. Uncertainty in lichen growth rates beyond 145 years limits projection of the curve beyond that age; however, the age range of the constrained growth curve covers an important period of recent climate variability. When applied in appropriate settings, our growth curve can be used to determine numeric ages to ±10 years for surfaces between 20 and 145 years old in areas where other techniques are not applicable or do not provide unique or well-constrained ages.

1.2 Introduction

In the Cascade Range of Washington and northern Oregon, many glacier forelands have moraines that support substantial *Rhizocarpon geographicum* lichen populations. By applying lichenometric techniques on these landforms, previous studies in the North Cascades (Miller, 1969) and on Mount Hood (Lillquist, 1988) have been used to determine the relative age of Little Ice Age (LIA) and younger moraines. The only calibrated growth curve that can be used to derive numerical ages of lichens in the region was developed by Porter (1981) using *R. geographicum* lichens growing on Mount Rainier. Burbank (1981) applied Porter's curve to surfaces on Mount Rainier and indicated that lichenometric techniques provide more accurate landform ages than tree-ring dating techniques in that study; however, the applicability of the curve beyond Mount Rainier was never tested. Because lichen growth can be affected by many environmental variables, including substrate lithology and roughness, moisture availability, aspect, and duration of snow cover, there is no reason to assume that a growth curve developed from data geographically restricted to Mount Rainier is applicable in adjacent alpine areas of the Cascades.

By using the data presented in Porter (1981) and replicating his methods, we determined the growth rate of *R. geographicum* on Mount Rainier by directly measuring the largest lichens on the same substrates that he used in 1976. The regional similarity of growth rates was assessed by comparing the Mount Rainier data with other well-constrained lichenometric data from mounts Baker and Hood (Figure 1). We find *R.*

geographicum growth rates to be similar over a much larger study area and present a growth curve that can be used to accurately date surfaces in a large number of glacier forelands between mounts Baker and Hood.

1.3 Background

Lichenometry is based on the observation that lichens of many species grow at a quasi-steady rates over spans of centuries to a few millennia. Since *R. geographicum* grows in a radial manner, the thallus diameter is used as a measure of growth. Once a substrate is colonized, the general growth of a lichen proceeds in three phases: 1) a rapid growth phase during which growth proceeds at a logarithmic rate, often called the "great growth period," 2) a linear growth phase during which growth is nearly uniform, and 3) a slow growth phase where lichen growth generally declines until death (Armstrong, 1983; Beschel, 1961; Innes, 1985). Because the growth rate and the duration of the different growth phases are subject to environmental factors, lichenometric dating requires calibration in each region where the technique is applied (Innes, 1986).

By measuring lichen thalli diameters on surfaces of known age, growth rates can be determined and used to construct a growth curve that depicts the size vs. age relationship. However, in order to develop a growth curve, a statistic of a lichen population that best represents the time of substrate colonization must be determined. Researchers differ in their choice of this statistical measure, and differences in the methodologies used to collect and interpret lichen data have resulted in a variety of

opinions on the overall precision and usefulness of this dating technique. In principle, the largest lichen growing on a surface should closely approximate the age of the substrate. However, erosional processes tend to degrade old growing surfaces and expose new areas for lichen colonization so that lichen measurements can only provide an approximate minimum age of the substrate. Despite any limitations of the "largest lichen" technique, this method was chosen for our study because 1) it allows us to integrate data that Porter (1981) used to develop the original Mount Rainier growth curve, 2) Burbank (1981) measured the largest lichen on many landforms on Mount Rainier and showed that the Porter (1981) curve can be used to determine accurate landform ages, 3) our data can be compared with other largest-lichen data obtained throughout the region (Lillquist, 1988; Miller, 1969; Reynolds, 2001), and 4) the application of the technique has been supported in many different settings in the northern hemisphere (e.g., Andersen and Sollid, 1971; Bickerton and Matthews, 1992; Denton and Karlen, 1973; Karlen and Black, 2002).

1.4 Methods

The largest lichen was identified on each moraine and manmade structure at 22 sites on mounts Baker, Rainier, and Hood (Table 1). At each location, the maximum diameter of individual *R. geographicum* lichens with circular or nearly circular thalli was measured on boulders with a surface area > 0.3 m^2 or on rock walls where the largest lichen growing in each 1- m^2 area was recorded. For lichens growing on manmade structures, the largest lichens on individual building blocks were measured. To limit ecological factors that influence lichen growth, all measurements were made at altitudes

between 1195 and 1825 m on exposed andesite and granodiorite rock surfaces away from

trees and dense vegetation cover. Those manmade structures chosen for data collection

were located throughout the altitude range of moraines in glacier forelands to ensure that

there was no bias between the setting and altitude.

Lichen measurements were tabulated at six sites on Mount Baker from five

manmade structures in the Heather Meadows and Austin Pass areas (B1 to B5) and one

moraine in the Easton Glacier foreland (B6 and B7) (Figure 2). The eleven sites on

Mount Rainer (Figure 3) represent five manmade structures (R1 to R5) and six moraines

in the Nisqually Glacier foreland (R6 to R11) (Figure 4). Of the eleven sites where

lichens were measured on Mount Rainier, ten are the same moraines and structures used

by Porter (1981) and one is from an ice-margin position that bore no lichens at the time

of Porter's field study in 1976 (Table 1). However, not all lichens measured by Porter

(1981) survived to the time of this study: lichens growing on the Kautz Creek lahar had

been subsequently overgrown by moss and other vegetation, and lichens growing on the

rock foundations of the Sunrise Gas Station and the Narada Comfort Station were

destroyed during maintenance. Lichen measurements at Mount Hood include data from

three moraines in the Coe Glacier foreland (H1 to H3) reported by Lillquist (1988) and

one moraine identified for this study in the Eliot Glacier foreland (H4) (Figure 5).

Collection of lichen data was restricted to sites where the age of the substrate

could be constrained using maps, photos, historical accounts, dendrochronology, and

tephrochronology. The age of the landforms and structures on Mount Rainier were determined by Porter (1981) using mainly historical information that has accumulated since the designation of the mountain as a National Park in 1899. Mount Hood and Mount Baker also have been the focus of recreation and natural resource extraction for more than 100 years, and abundant historical data are available to help constrain the ages of lichen-bearing surfaces on these mountains.

Because Porter (1981) used landforms and structures that were easily identified at the time of this study, we were able to determine *R. geographicum* growth rates on Mount Rainier based on the direct measurement of the largest lichens in 1976 and 2002. By calculating a regression of the thalli diameter vs. age of the control points from the Mount Rainier data and the 95% prediction interval of that data, we were able to statistically compare relationships between lichen thalli diameter and age on Mount Baker and Mount Hood to those of Mount Rainier.

1.5 Results

Analysis of the thalli diameter vs. age relationship of *R. geographicum* lichens measured on the same ten surfaces at Mount Rainier in 1976 and 2002 indicates a linear growth phase between 20 and 145 years (Figure 6). The average growth rate during this phase is 0.4 mm yr^{-1}. However, average individual rates range from 0.23 to 0.54 mm yr^{-1}, and residuals from the linear regression of the 2002 vs. 1976 diameters (subplot of Figure 6) indicate excursions of as much as 3 mm from linear growth. The lack of an age vs. rate

correlation associated with these variations suggests they are likely the result of natural phenomena affecting lichen growth, as well as inherent error in the identification and measurement of the largest lichen at each location. Regardless of these fluctuations in growth rates, a linear regression of the Mount Rainier data that range between 20 and 145 years results in an R^2 value of 0.99. The thalli diameter vs. age data from Mount Baker and Mount Hood for the same time interval, when fit to the linear regression of the Mount Rainier data, results in R^2 values of 0.90 and 0.95, respectively, and lie on or within the 95% prediction interval (Figure 7).

Three control points were not included in the regression analysis: the zero diameter measurements from the 7-year-old guardrail near Ricksecker Point on Mount Rainier (Porter, 1981) and the 8-year-old wall at the Austin Pass visitor's center on Mount Baker, as well as the largest measurement in the dataset from a late LIA moraine of the Coe Glacier on Mount Hood. A value of 0 mm is not used as a control point because it is not an indicator of actual size but rather a macroscopic presence/absence indicator that is used until lichens become visible sometime between 8 and 20 years. The control point from Mount Hood, constrained at 189 ± 15 years, is not used in the regression analysis because of the potential that it represents a change in the growth rate sometime prior to that age.

1.6 Discussion

Based on the similarity of *R. geographicum* thalli diameter vs. age relationships

within the study area, we suggest a single underlying growth curve for the Cascade

Range of Washington and northern Oregon that can be divided into three phases: an

initial rapid growth phase from 8 to 20 years, a linear phase from 20 to 145 years, and

slow growth phase of unknown duration starting after ca. 145 years (Figure 7). Although

no lichen thalli were measured on surfaces younger than 20 years, a period of initial rapid

growth equivalent to the "great growth phase" suggested by Porter (1981) is inferred by

the absence of lichens on 7- and 8-year-old surfaces and the apparent onset of a linear

growth phase by 20 years. For the portion of the growth curve between 20 and 145 years,

we have treated the data differently than Porter (1981) did in that 1) we reduce the data to

one curve based on the similarity of lichen growth rates on andesite and granodiorite

surfaces in Figure 6, and 2) the thalli diameter vs. age data were not used as minimum

values for positioning the curve. We suggest that the regression of the Mount Rainier data

provides the best growth curve between 20 and 145 years and its use throughout the study

area is justified by the fit of all other age-equivalent data within the 95% prediction

interval (Figure 7). The R^2 value of 0.99 for the regression of the Mount Rainier data

underscores the suitability of a linear model for this period and is supported by similar

linear growth phases of greater than 100 years depicted in other northern hemisphere

growth curves (e.g., Benedict, 1967; Denton and Karlen, 1973) .

The age vs. diameter relationship of the 189-year-old lichen from Mount Hood

deviates from the linear growth phase depicted for lichens between 20 and 145 years and

is used to suggest a transition to a slow growth phase of unknown duration after ca. 145

years. This transition to slow growth is comparable to the pattern of reduced growth rates of ca. 0.1 mm yr^{-1} suggested by Miller (1969) for ca. 150- to 700-year-old *Rhizocarpon sp.* lichens growing in the North Cascades. However, due to the elimination of many early colonizers by factors such as vegetation competition and landform degradation apparent on old moraines at lower elevations throughout the study area, we believe the 189 year-old lichen is not representative of the early colonizers of the moraine on which it is growing. Thus, this lichen only provides a minimum estimate of the thalli diameter vs. age relationship for its age range and does not provide enough information to estimate the position of the curve in the slow growth phase. At no point on the curve do we assume the largest lichen was observed and as more data become available, lichen thalli diameters in the linear and slow growth phases may shift in the direction of the upper limit of the 95% prediction interval shown in Figure 7, thereby more closely approximating the curves of Miller (1969) or Porter (1981).

Due to a short ecesis period of *R. geographicum* compared with the range of 0 to 65 years for trees on Mount Rainier (Burbank, 1981), and the abundance of deglaciated LIA glacier forelands in the Cascades where moraines lack trees (Crandell and Miller, 1964; Sigafoos and Hendricks, 1972), we suggest that our growth curve provides a more precise and accurate method than tree-ring techniques over the same range. However, attempts to apply lichenometric techniques at elevations below the LIA glacier forelands (i.e. on the Kautz Creek lahar (Porter, 1981)) and/or where lichen populations are stressed from increased competition with other vegetation (i.e., on the Bonneville landslide

(Reynolds, 2001)), resulted in lichen thalli vs. age relationships that are not comparable with our growth curve. Despite elevation, our curve should not be used for dating surfaces between 0 and 20 years because this brief rapid-growth phase is only inferred from the data and not represented by any control points. Identification of recent ice-marginal landforms in the abundance of modern satellite images and aerial photographs is likely to result in a more accurate interpretation of recent surface ages than any lichenometric technique. However, when our curve is used to determine the age of surfaces between 20 and 145 years old, we suggest that the 95% prediction interval provides a reasonable error range of ±10 years based on the fit of all control points within that interval. The potential error associated projecting our curve to date landforms beyond 145 years increases to at least ±20 years due to uncertainties in the accuracy of the landform and lichen ages, short-term growth-rate fluctuations, and possible measurement error of the single data point used to interpret the slow growth phase. Without more lichenometric data beyond 145 years, the slow growth phase should only be used as a potential correlation technique or to estimate limiting ages.

The historical accounts, photos, and maps, combined with the availability of well-dated manmade structures and moraines, permit the construction of a regional *R. geographicum* growth curve based on a larger number of control points than are available in most areas of the world. When applied in appropriate settings where 1) lichens are abundant, 2) the substrate is within an appropriate altitude range, 3) vegetation complexity and competition are minimal, and 4) andesite or granodiorite substrates are

stable, our growth curve can be used to determine accurate numeric ages (±10 years) for surfaces that range in age from 20 to 145 years. Although the growth curve resulting from this study is limited to a period of approximately 125 years, it spans an important time interval for those interested in relating glacier-length fluctuations to recent climate variations. Our growth curve constitutes an important alternative dating technique for the study area Because there are many deglaciated LIA forelands in the 400-km range between Mount Baker and Hood where tree-ring and cosmogenic techniques are not applicable, historical records are incomplete, and radiocarbon dates do not provide a unique numeric age,.
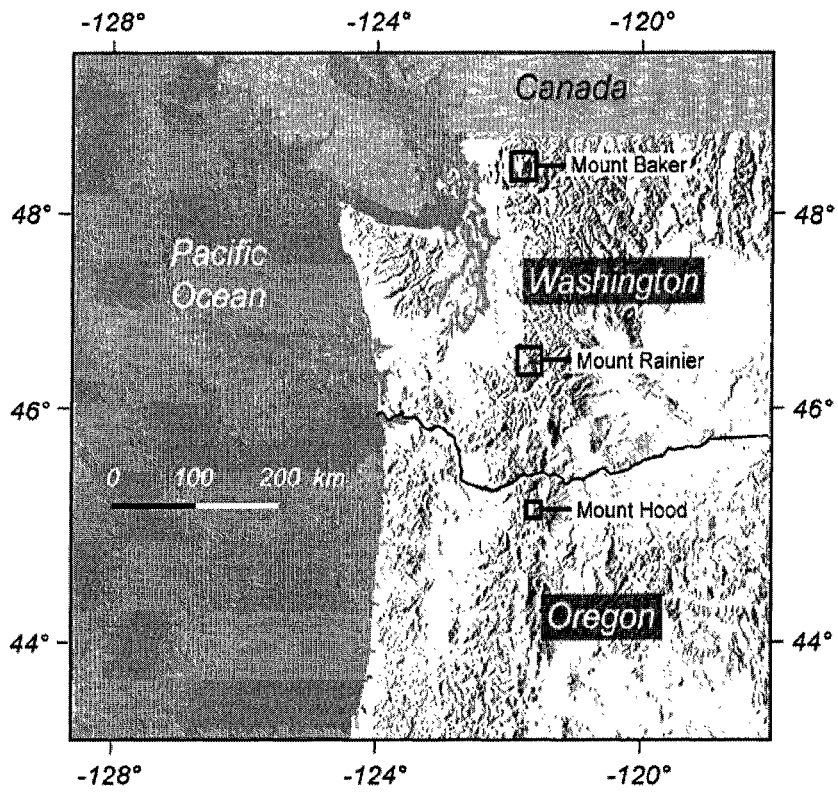
Figure 1.1. Map of the study area showing the three mountains where lichen data were collected.
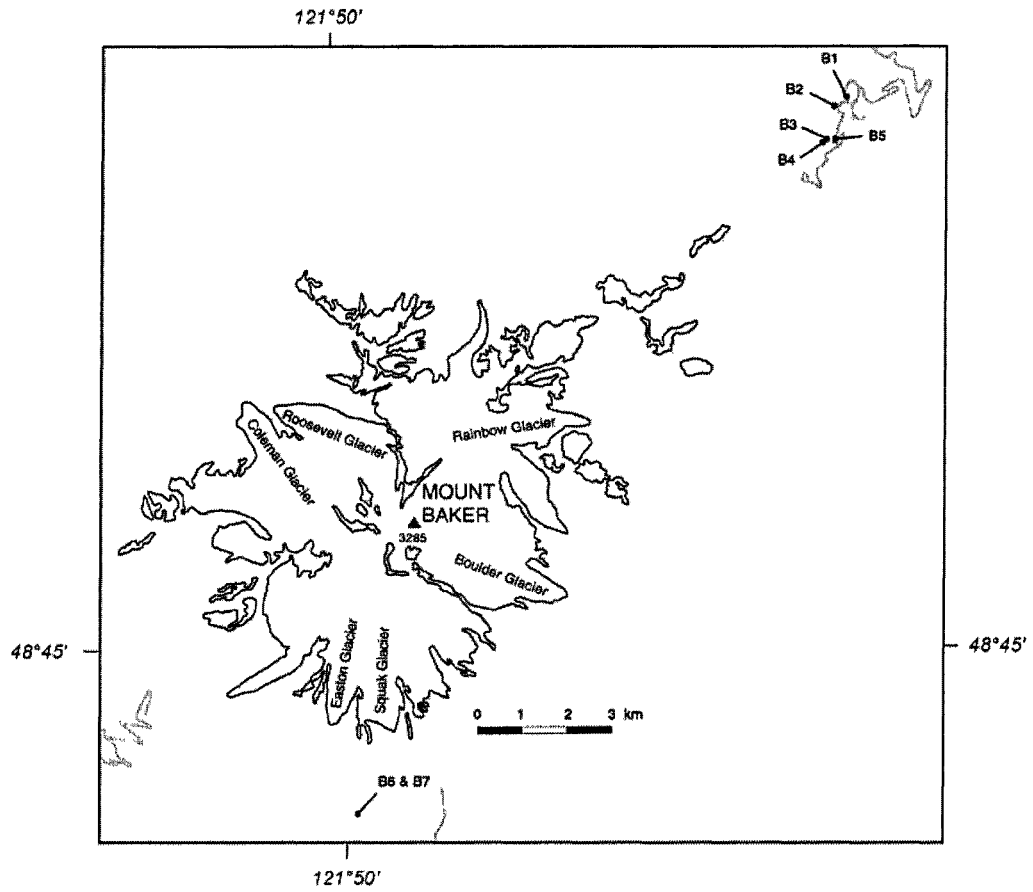
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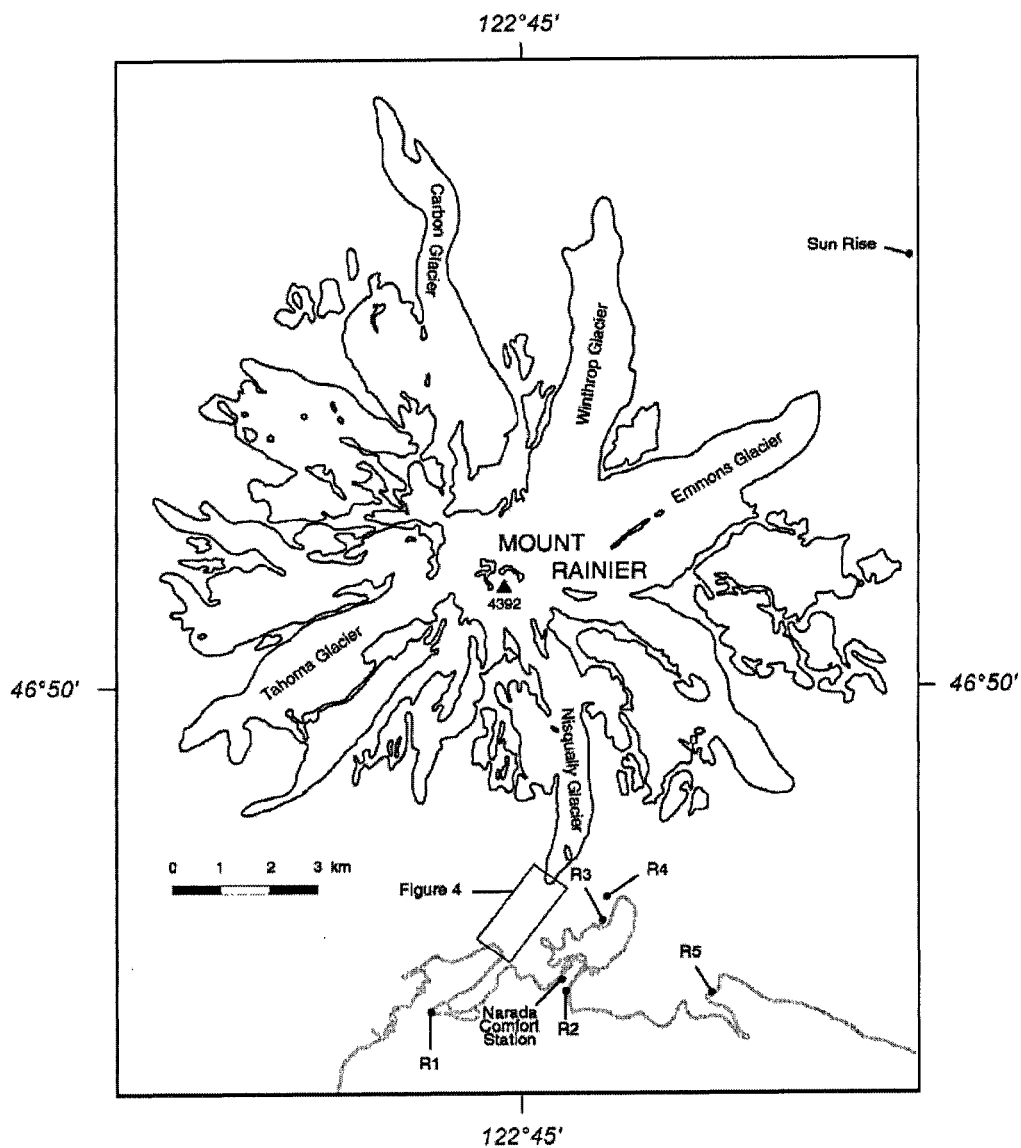
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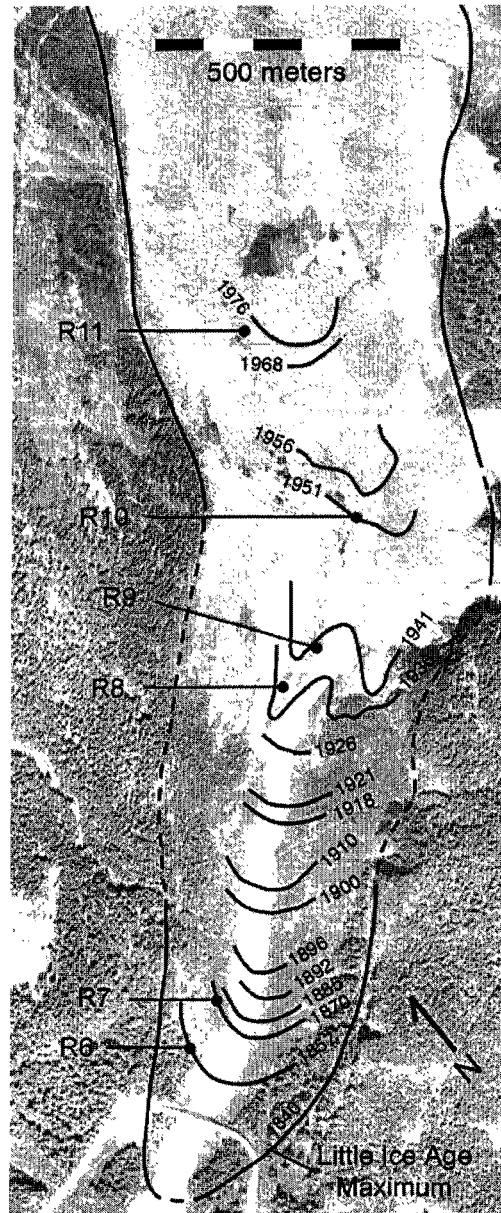
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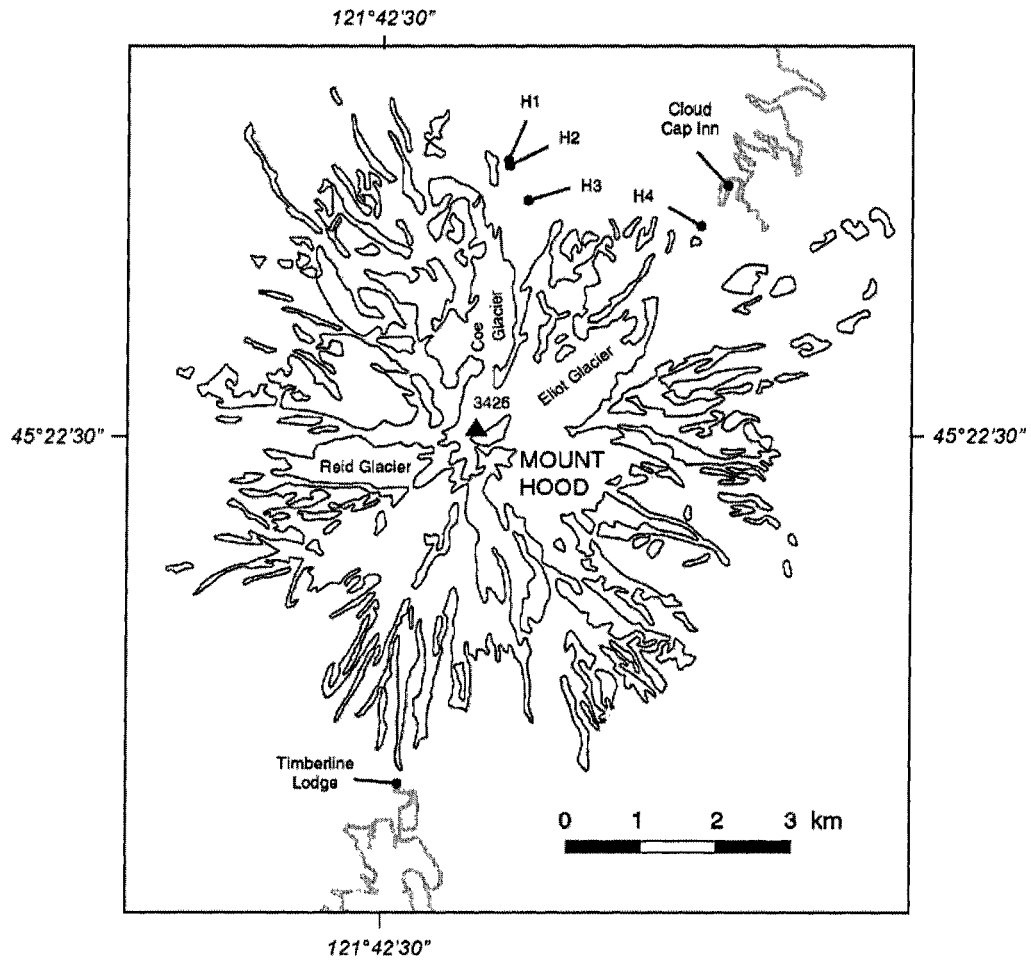
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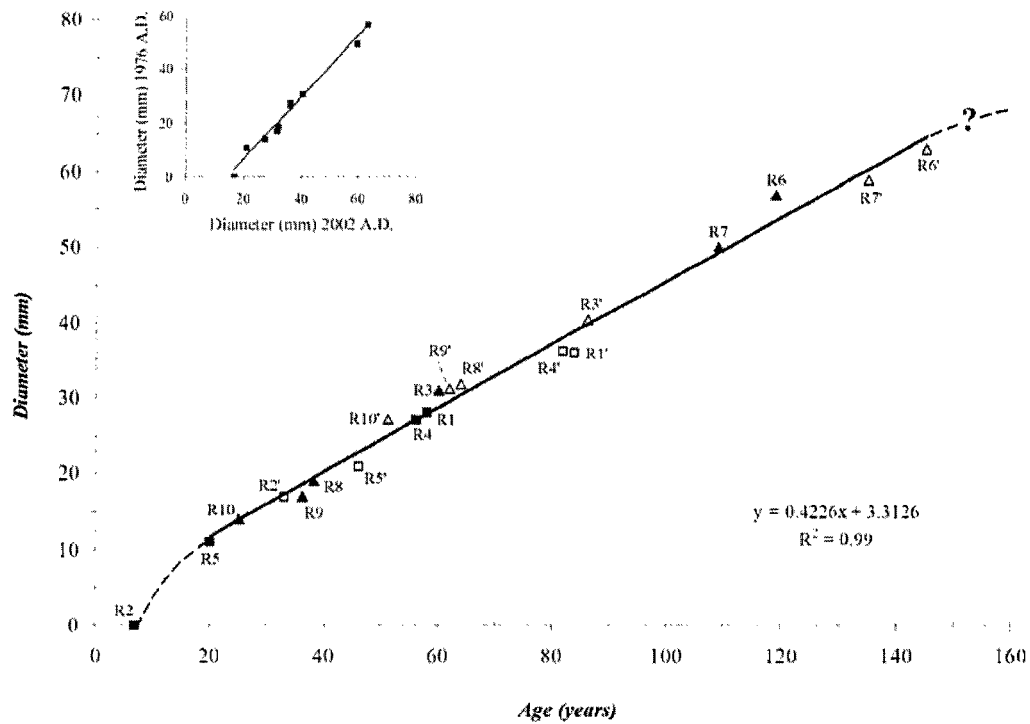
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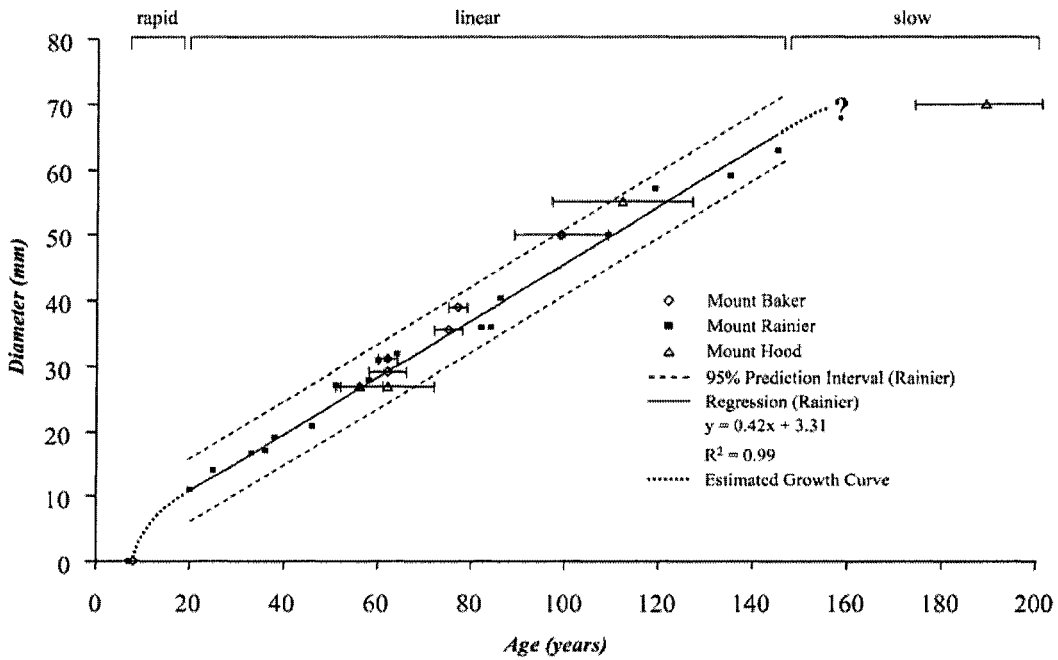
Figure 1.7. Plot of all *Rhizocarpon geographicum* data used in this study, the linear regression and 95% prediction for the Mount Rainier data (from 20 to 145 years), and the interpreted growth curve for the rapid and slow growth phases. Error bars on the Mount Baker and Mount Hood data depict the uncertainty in the age of the substrate.

Area	Control Point	Elevation (meters)	Substrate and Location	Substrate Lithology	Largest Lichen Diameter (mm)	Substrate age when measured (years)	Limiting Age of substrate (A.D.)
Mt. Baker	B1	1280	Bedrock along road between chalet and fee station	andesite	39.0	77	1925 ± 2
	B2	1275	Dam near overflow parking at Mount Baker Lodge.	andesite	35.5	75	1927 ± 3
	B3	1350	Bedrock adjacent to Austin Pass visitor's center	andesite	31.1	62	1940 ± 2
	B4	1345	Wall at the Austin Pass visitor's center	andesite	0.00	8	1994
	B5	1350	Austin Pass picnic area near visitor's center	andesite	29.2	62	1940 ± 4
	B6	1280	Moraine at Easton Glacier	andesite	49.9	97	1900 ± 10
	B7	1290	Rock wall at Easton Glacier	andesite	50.0	97	1900 ± 10
Mt. Hood	H1	1825	Coe Glacier (Lillquist - ECG-O)	andesite	70	189	1800 ± 15
	H2	1700	Coe Glacier (Lillquist - SEC-LT4)	andesite	55	122	1880 ± 15
	H3	1710	Coe Glacier (Lillquist - SEC-LT3)	andesite	27	62	1925 ± 15
	H4	1820	Moraine at Eliot Glacier	andesite	21	55	1946 ± 5
Mt. Rainier	R1	1265	Guardrail near Ricksecker Point (Porter #10)	granodiorite	35.9	84	1918 ± 2
	R2	1492	Guardrail at Inspiration Point (Porter #19)	granodiorite	16.7	33	1969
	R3	1655	Paradise Lodge (Porter #8)	andesite	40.4	86	1916
	R4	1615	Edith Creek Bridge (Porter #11)	granodiorite	36.0	82	1920
	R5	1308	Sunbeam Creek Bridge (Porter #18)	granodiorite	20.9	46	1956 ± 1
	R6	1195	Moraine at Nisqually Glacier (Porter #1)	andesite	63.0	145	1857 ± 3
	R7	1195	Moraine at Nisqually Glacier (Porter #3)	andesite	59.0	135	1867 ± 3
	R8	1285	Moraine at Nisqually Glacier (Porter #14)	andesite	31.9	59	1943 ± 2
	R9	1295	Moraine at Nisqually Glacier (Porter #15)	andesite	31.3	57	1945 ± 2
	R10	1370	Moraine at Nisqually Glacier (Porter #17)	andesite	27.2	51	1951 ± 2
	R11	1375	Moraine at Nisqually Glacier	andesite	11.8	26	1976 ± 2

Table 1.1. Location, elevation, substrate type, measurement, and age data for *Rhizocarpon geographicum* thalli used in this study.

CHAPTER II

The use of geographic and remotely sensed data for identifying potential sites for lichenometric dating

2.1 Abstract

Previous studies have used lichenometry to determine the ages of 51 late Little Ice Age moraines and bedrock surfaces in 19 glacier forelands in the Cascade Range of Washington and northern Oregon. Using a regional growth curve, lichenometry can provide landform ages of ± 10 years for surfaces between 20 and 145 years old, an important alternative to other dating techniques in this region where unknown ecesis periods for tree-ring dating and multiple ages from radiocarbon samples often result in less accurate ages over this time span. Although a regional growth curve is potentially useful throughout the study area, the rate of *Rhizocarpon sp.* growth is sensitive to a variety of environmental conditions. A large area of the Cascade Range is not likely to provide suitable conditions for lichenometric dating, and so much data-collection effort in this topographically and logistically challenging terrain potentially may be wasted on unsuitable localities. Therefore, a spatial and a supervised classification analysis using geographic, climatic, and remotely sensed data are used to identify localities in the study area with conditions similar to the 19 forelands where lichenometry has been successfully applied previously. Results indicate that when applied to lichens growing on igneous and metamorphic rocks at an appropriate altitude range in areas with high precipitation and limited vegetation cover, lichenometric dating using the regional growth curve is applicable for approximately 1100 km^2, or approximately 0.03% of the study area. These

results are important because they provide a rapid, coarse screening method for identifying areas where the technique can be applied without resorting to time-consuming field surveys or air photo analyses. Moreover, knowledge of potential lichenometric dating areas is useful for the variety of geomorphic and environmental applications beyond the moraine-age dating technique discussed in this study.

2.2 Introduction

Over the past four decades, lichenometry has been used to determine the ages of 51 moraines in 19 glacier forelands in the Cascade Range of Washington and northern Oregon (Burbank, 1979; Fuller, 1980; Leonard, 1974; Lillquist, 1988; Miller, 1967; O'Neal and Schoenenberger, 2003; Porter, 1981) (Figure 2.1). Although most of these studies were completed without any indication of the regional applicability of the technique, a recent study by O'Neal and Schoenenberger (2003) provided a calibrated *Rhizocarpon geographicum* growth curve for dating lichen-bearing surfaces throughout the Cascade Range of Washington and northern Oregon. However, because lichens are sensitive to a variety of environmental factors, the extent of the Cascade Range where the growth curve is applicable remained unknown. By applying spatial and classification analyses using geographic, climatic, and Landsat Enhanced Thematic Mapper Plus (ETM+) data, the current study identifies areas in the Cascade Range of Washington and northern Oregon that are likely to support substantial *Rhizocarpon sp.* necessary for applying the regional growth curve.

2.3 Background

Lichenometric dating uses measurements of lichen thallus diameter or other indices of lichen growth to determine the minimum age of surfaces. Beschel (1958; 1961; 1973) first described the technique for determining the ages of recent geomorphic features and it has become especially popular for dating alpine glacial landforms. Although its effective range may in some cases extend to ca. 9000 years (Miller and Andrews, 1972), in areas of rapid growth the method is commonly only effective for a few centuries after colonization due to environmental factors that increase lichen mortality with time (Innes, 1985). Although many critics once argued that the technique is problematic and questioned its accuracy (Jochimsen, 1973; Webber and Andrews, 1973), the widespread development of calibrated growth curves over the last four decades demonstrates that it is possible to use the lichen diameter-age relationship as an accurate measure of surface ages.

Lichenometric techniques are especially important in the Cascade Range where tree-ring dating can be complicated by ecesis periods of as much as 60 years (Burbank, 1979), and calibration of radiocarbon dates yields multiple ages from a single sample at Little Ice Age (LIA) timescales. Historical records (i.e., photographs and maps) can be helpful for dating glacial landforms, but they often lack exact date or locality information. Conversely, where lichens are abundant on Cascade Range moraines, lichenometry can provide a temporal resolution of ±10 years when applied to surfaces between 20 and 145 years (O'Neal and Schoenenberger, 2003; Porter, 1981). This

accuracy is superior to the other techniques used in the Cascades on recent time scales and provides resolution otherwise unobtainable in this region.

The 19 forelands where lichenometry has been applied in the Cascade Range of Washington and northern Oregon (Figure 2.1) share several attributes. Each is: 1) a rocky, igneous or metamorphic surface; 2) in an area that sustains little vegetation; 3) located at or above the lowest active glacier forelands; and 4) in an area of high annual precipitation. Thus, the intersection of the geographic extent of each of these environmental parameters should delineate areas where lichenometric dating using the regional growth curve is likely to work. Field surveys, maps, and air-photo analysis provide cumbersome methods for locating such suitable areas and a more robust technique that could identify these areas rapidly would enable more efficient field studies. Regional data are available regarding bedrock geology, annual precipitation, and elevation, and spatial analyses can be used to intersect the appropriate geographic range of these parameters. However, there are many land cover types present in these areas where *Rhizocarpon sp.* are not likely present in sufficient numbers for dating purposes. Thus, identifying areas with characteristics similar to those where the technique has been applied requires more sophisticated analyses. Landsat ETM+ data are particularly appropriate for this type of study because they are useful for discriminating vegetation types and health, plant and soil moisture measurements, snow and ice, and identifying rock types, and these data are readily available for the study area. A classification

analysis using these data can be used to discriminate among the different land cover types to identify areas appropriate for application of lichenometry.

2.4 Methods

Because of highly similar characteristics among the 19 localities where lichenometry had been previously applied, it is likely that the regional growth curve will only find application in a limited spatial extent of the Cascades. This limited region can be delineated by first selecting areas were where the elevation is higher than a plane that passes through the lowest expanse of rocky surfaces with abundant lichens. These areas lie above a plane that slopes downward 0.08 degrees from 1300 m elevation at 46°N to 1000 m elevation at 49° N, corresponding to the lowest glacier forelands on mounts Hood, Adams, Rainier, and Baker (Figure 2.2a). Second, areas with annual precipitation in excess of 175 cm are selected (Figure 2.2b) (Daly and Taylor, 2000), corresponding to the minimum precipitation at those localities where the technique has been applied. Finally, areas are selected where igneous and metamorphic rocks are the dominate surface lithologies (Figure 2.2c) (Johnson and Raines, 1995). This reduces the effects of different rock types on lichen growth rates; *Rhizocarpon sp.* do not tolerate carbonate lithologies and growth rates can vary significantly on other lithologies (e.g., McCarthy, 1990).

The intersection of the above parameters (Figure 2.2d) is necessary, but not sufficient, for delineating areas for lichenometric dating. This is because the areas that

meet the above criteria comprise a variety of different land-cover types, and some are not

likely to sustain abundant *Rhizocarpon sp.* populations (i.e., glaciers, alder thickets and

old growth forests). Therefore, a supervised classification analysis of remotely sensed

imagery is used to delineate the different land cover types in the study area using ENVI

4.0 (Research Systems Inc., 2004). Six relatively cloud-free ETM+ scenes that provide

seamless coverage of the study area (Table 2.2) were processed for the classification

analysis by reducing to the geographic extent as defined above and correcting for the

topographic effects of shade in each scene using 30-meter digital elevation model DEM

data obtained from the U.S. Geological Survey National Elevation Database.

A supervised classification resembles discriminant analysis in that the

classification of unknown areas is based on the knowledge of reflectance values from

training sites where a distinct land cover type is known. Field analysis indicates that five

general land cover classes can be easily identified in the study area. They include: poorly-

vegetated rocky surfaces, which are areas suitable for lichenometric dating, and montane

forests, grasslands and thickets, freshwater lakes, and perennial ice and snow, which are

not (Table 2.1). Based on field surveys, three training sites were established for each of

the five land cover types (Figure 2.3) and identified in the Landsat scenes. None of the

sites where lichenometric dating was applied previously were used as training sites to

ensure an unbiased test of the classification results.

For each class, the mean and variances of the values for each band are calculated from all the pixels enclosed in the training sites. The spectral signature of each of the five classes is presented in Figure 2.4 where the pixel values for each class, plotted as a function of the band sequence, display a unique spectral signature for each class representative of all of the surfaces that interact with the incoming radiation. Classification proceeds by calculating the Euclidean distance from each unknown pixel to the mean vector for each training class and assigning each to the closest class. In this process any portion of the landscape can be misclassified; therefore, an accuracy assessment was completed by comparing the classes assigned to 200 randomly selected points with knowledge of the terrain obtained from field surveys, maps, and aerial photos.

2.5 Results

Although the intersection of the appropriate elevation, geology, and precipitation delimits approximately 7200 km^2 of the Cascade Range (Figure 2.2d), the supervised classification analysis indicates that only 1100 km^2 of this area are likely to be suitable for lichenometric dating (Figure 2.5). This is approximately 0.03% of the Cascade Range study area. Comparison of the 200 random points with the field and map data indicates that 89% of the areas classified as poorly vegetated rocky terrains were accurately identified, with all errors relating to added inclusion rather than exclusion. The misclassified cells fall into three categories: 1) freshwater lakes with substantial amounts of suspended sediment, 2) active fluvial terrains, and 3) slopes that have been burned recently or sustained mass movements. All 19 glacier forelands in the study area where

lichenometry has been applied are within areas classified as poorly vegetated rocky

terrains, underscoring the success of the analysis in locating potential areas for

lichenometric dating using spatial and remote sensing techniques.

2.6 Discussion

Landsat image classification works well for identifying the different land cover

types in the study area, and other readily available data provide easy screening of other

important environmental factors (e.g., precipitation, elevation, geology). The Landsat

image classification is useful for rapid, coarse screening of areas in the Cascade Range

where the regional *Rhizocarpon geographicum* growth curve is likely to be useful (Figure

2.5). A reasonably restrictive classification analysis captures all of the glacier forelands

where the technique has been applied previously and other such classified areas should be

suitable for lichenometric dating. These results are used to infer that the classified areas

in the Cascade Range of Washington and northern Oregon provide relatively

homogenous environmental conditions that allow for the use of the growth curve over a

large geographic area. A first-order assessment of the applicability of the technique is

significant because of the time necessary to access many of the more remote locations of

the Cascade Range. Although the 30-meter data are appropriate for detecting areas the

size of glacier forelands, researchers interested in smaller areas of interest may require

the same analysis completed with higher resolution data.

A regionally applicable *Rhizocarpon sp.* growth curve is necessary for developing the accurate moraine chronologies necessary for better correlations of climate data with glacier activity in the Cascade Range; however, its utility is broader. A variety of other research topics require an accurate regional growth curve and knowledge of its geographic applicability, such as: determining the ages of earthquake-induced landslides (e.g., Bull et al., 1994), monitoring rock glacier movement (e.g., Sloan and Dyke, 1998), and assessing rates of biomechanical and biochemical weathering on lichen-encrusted surfaces (e.g., Lee and Parsons, 1999). Additionally, the framework for this study should be applicable in many other regions where lichenometric dating techniques have been applied extensively and similar environmental datasets are available.
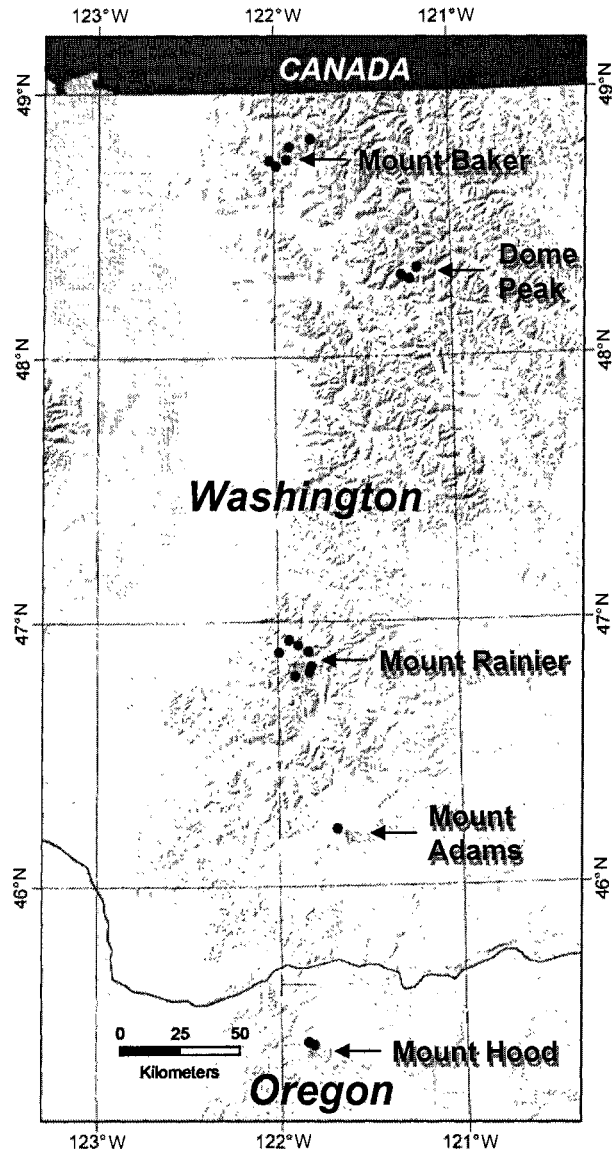
Figure 2.1. Map showing the location of the major peaks of the Cascade Range of Washington and northern Oregon and the location of glacier forelands where lichenometric dating using *Rhizocarpon sp.* has been applied (black dots).
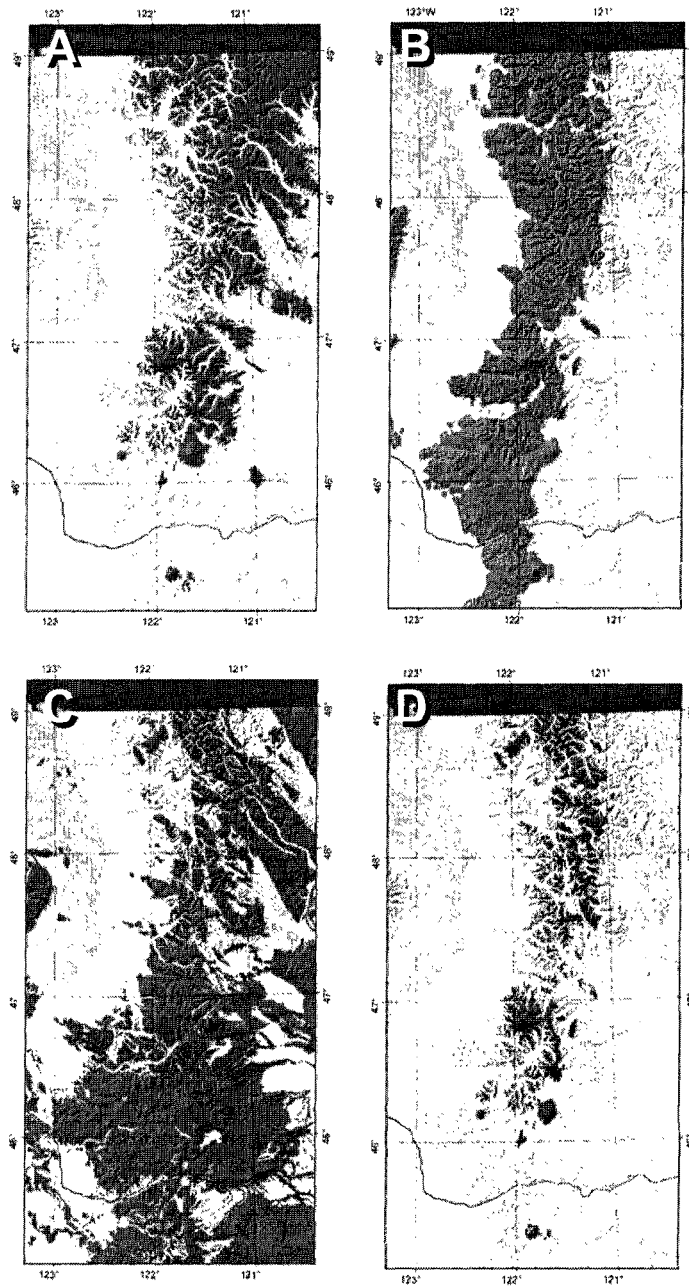
Figure 2.2. Maps of the Cascade Range of Washington and northern Oregon with dark gray areas indicating (A) elevations above a plane incorporating the lowest glacier forelands, (B) areas with annual precipitation is > 175 cm, (C) igneous surface rocks, and (D) intersection of A, B, and C.
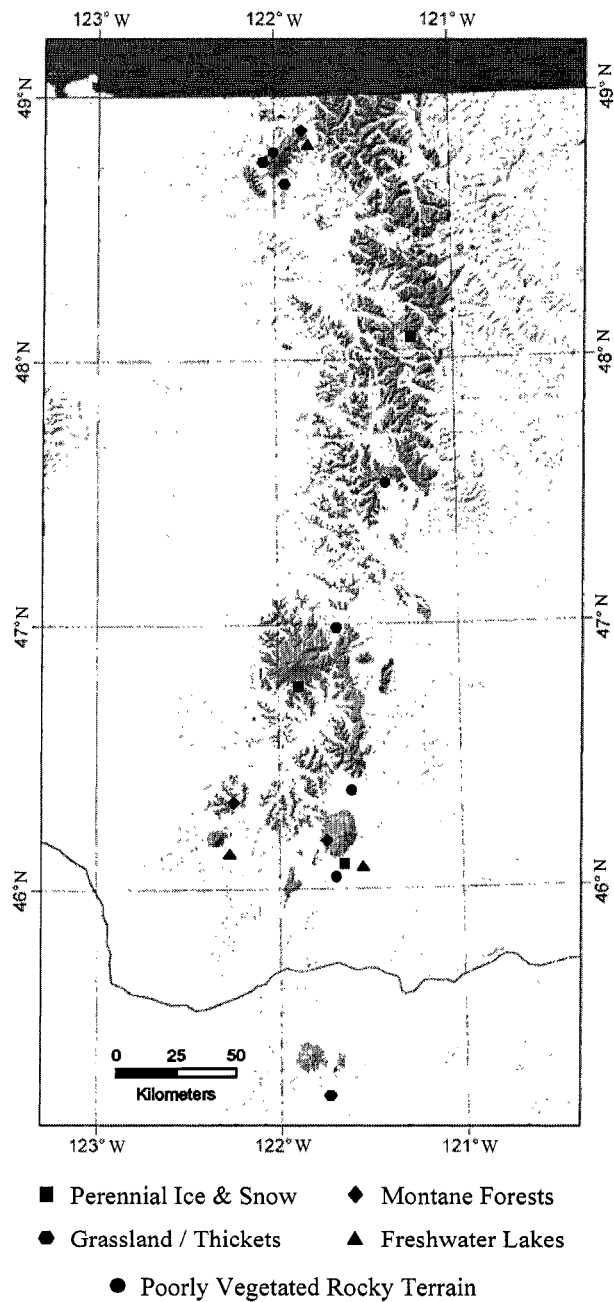
Figure 2.3. Map showing the locations of the land cover training sites used for the supervised classification analysis.
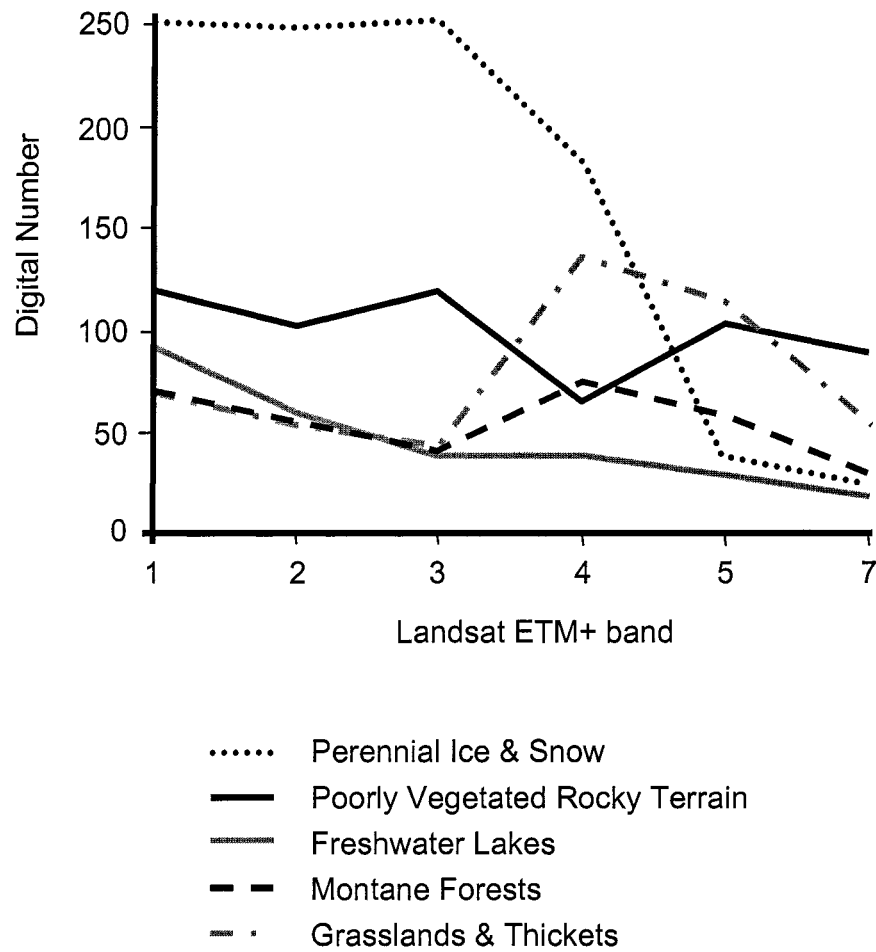
Figure 2.4. Plot of the mean Digital Numbers (DN) for all pixels in each training class vs. the Landsat ETM+ band. Band 1 = 0.45 - 0.52 μm, Band 2 = 0.52 - 0.60 μm, Band 3 = 0.63 - 0.69 μm, Band 4 = 0.76 - 0.90 μm, Band 5 = 1.55 - 1.75 μm, Band 7 = 2.08 - 2.35 μm. Note that the ETM+ Band 6 detects thermal radiation and was not used in this study.
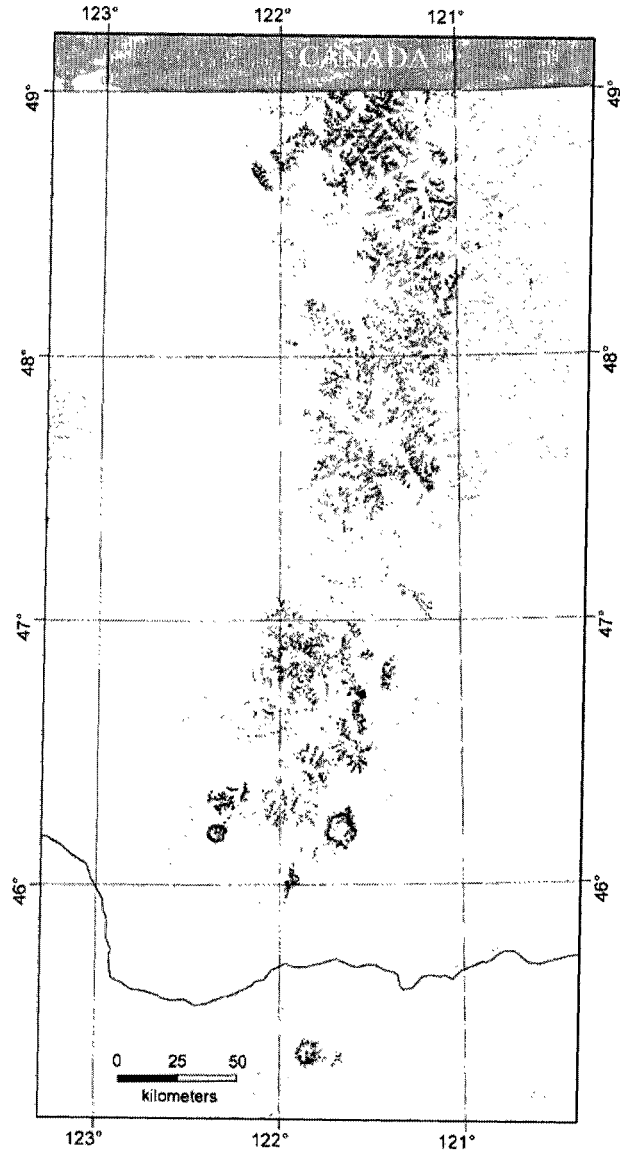
Figure 2.5. Map of the Cascade Range of Washington and northern Oregon displaying areas where the regional *Rhizocarpon geographicum* growth curve is likely to be applicable (black).

Class	Description
poorly vegetated rocky terrain	These areas are in glacier forelands and on some hill and mountain tops. They represent exposed bedrock and/or areas of erosion/deposition of unconsolidated materials where there is a limited amount of vegetation.
montane forests	This class is spectrally variable because of the mixture of vegetation types and ages of forests. The spectral difference between this class and grasslands/thickets is usually obvious but differences from some forests on a steep sunward slopes are often minimal, so some montane forests may be misclassified. However, the outcome does not hinder the key class distinction with poorly vegetated rocky terrain.
grassland and thickets	This class is found near montane forests and represents a mix of grassy alpine terraces, isolated or planted trees, heavy moss cover, grasslands, and thickets of young alder and willow. This class is often fragmented by fresh burns, old burns, and montane forests.
freshwater lakes	This is generally a distinct, easy class to identify; however, there is potential for confusion with topographically shaded or shadowed landscapes and cloud shadows. Some sediment laden water at stream mouths is misclassified as poorly-vegetated rocky terrain.
perennial ice and snow	Glaciers and snow are easy to identify on all of the images, but required a large extent of training areas in order to capture the spectral variation in the different images and the variations between snow and ice on different land forms

Table 2.1. Descriptions of the field conditions for the training classes used for Landsat image classification. *Rhizocarpon sp.* populations are most abundant in the bare-alpine surfaces class.

Scene	Path/Row	Acquisition Date	Scene Center Lat/Lon (decimal degrees)
1	45/26	August 17, 2000	48.870, -119.797
2	45/27	August 17, 2000	47.452, -120.357
3	45/28	August 17, 2000	46.031, -120.894
4	46/26	August 8, 2000	48.863, -121.314
5	46/27	July 7, 2000	47.451, -121.895
6	46/28	July 7, 2000	46.031, -122.432

Table 2.2. Path, row, acquisition date, and scene center coordinates for all Landsat 7 ETM+ scenes used in this study.

CHAPTER III

Rates of moraine degradation determined from lichenometric evidence on Mount Adams, Washington

3.1 Introduction

The exposure age of boulders on a moraine surface can be modeled quantitatively using a simple finite-difference diffusion model (e.g., Hallet and Putkonen, 1994), which characterizes the changes in moraine topography over time as a result of downslope sediment transport. This type of modeling has been used to interpret ranges of cosmogenic boulder ages obtained from Pleistocene moraines and to provide insight into the potential errors when selecting boulders to date (e.g., Putkonen and Swanson, 2003). Although these models ignore the mechanics of landform evolution, they provide an adequate and useful interpretation of landform evolution over time. However, there are a few independent data that support the surface age interpretations from this type of modeling. Because of the cost and labor to obtain cosmogenic boulder ages from moraine slopes, there has been little testing or calibration of diffusion-model results with observational data. Lichenometric dating, however, is based on the same boulder-exposure principle and can be used to obtain a large number of surface boulder ages across moraine slopes with relatively low cost and effort. Although the application of these two dating techniques are aimed at dating moraines of broadly different ages (i.e., typically 10 to 10^3 yr for lichenometry and 10^3 to 10^5 yr for cosmogenic dating), the effects of the degradation process should be pervasive over broad ranges of time and spatial scales.

Many studies have indicated the importance of moraine-degrading processes on boulder exposure age (Calkin and Ellis, 1980; Fuller, 1980; Mahaney and Spence, 1985). However, none has provided a quantitative framework for determining the effects of moraine degradation on lichenometric dating techniques. In this study, a well-calibrated lichen growth curve (O'Neal and Schoenenberger, 2003) allows boulder ages to be determined along two distal moraine slopes in the Adams Glacier foreland on Mount Adams, which enable those boulder ages to be compared with the moraine surface ages predicted from a diffusion model. Moreover, the analysis of the spatial distribution of lichens on the study moraines provides insight into the magnitude of moraine degradation that can be expected in young glacial landscapes, indicates the accuracy of landform age as determined by lichenometry, and suggests the lichen statistic that will likely yield the most accurate landform ages.

3.2 Background

Lichenometry has been used widely over the last four decades to determine minimum ages for glacial landforms. Lichenometrists frequently use the diameter of lichens growing on boulders as a proxy record of exposure age, making the key assumption that some statistic of the population of lichen diameters measures the time elapsed since the landform stabilized. Because of the uncertainties in lichen growth and environmental influences on a lichen population, lichenometry methods have been frequently modified by many users depending on the study objectives, the type of

calibration surfaces available, or the assumed lichen statistic for the most accurate landform age (see Locke (1979) and Noller and Locke (2001) for summaries on different lichenometric techniques).

Differences in the methodologies used to collect and interpret lichen data have resulted in differing opinions on the overall precision and usefulness of this dating technique. Traditional methods look for one or a few of the largest lichens on a substrate since, in principle, the largest lichen should closely approximate the exposure age of the surface in question (so long as the ultimate life-span of the lichen species is greater than the age of the landform). However, because of uncertainties regarding biological and environmental factors that can affect lichen colonization, growth, and mortality, a variety of lichenometric methods have evolved with significant differences in the suggested number of lichens to measure, appropriate sample area, and the most useful statistical parameter of the measured population (Innes, 1984; Innes, 1986; Karlén and Black, 2002; Locke, 1983). Of interest here is a trend in recent studies to utilize either random boulder-sampling strategies or statistical means of measured lichen diameters when calibrating lichen growth curves. However, these approaches depend on the assumption that the primary controls on the lichen population are consistent across the local and/or regional scales used for growth curve calibration, an assumption that is evaluated in this manuscript.

Lichenometry is generally applied with the assumption that boulders are in relatively fixed positions on the landscape and have been exposed to subaerial conditions for similar lengths of time. Differences in the lichenometric ages of boulders on a single moraine are commonly suggested to be the result of poorly understood biological controls on lichen growth and colonization, or external microenvironmental influences on the lichen population (e.g., Haines-Young, 1983). However, in recent years, lichenometry has been used to discriminate the age of diachronous surfaces and deposits formed from closely spaced geomorphic events on dynamic landforms (i.e., talus from rock avalanches (Sancho et al., 2001), river terraces, and boulder mobility on rock glaciers (Sloan and Dyke, 1998), floodplains, and debris flows (Winchester and Chaujar, 2002). Thus, it has become increasingly apparent that different lichenometric ages from a surface can reflect processes that expose and redistribute boulders, even over relatively short periods on the order of one decade or less. As a result of exhumation, burial, and redistribution, boulders on moraines are similarly likely to bear lichens that are not directly representative of the time elapsed since landform construction ceased, but instead represent more complicated exposure histories.

Lichenometry appears to be suitable for analyzing geomorphic controls on boulder exposure ages in the study area because: 1) *Rhizocarpon sp.* is the most abundant lichen at elevations both above and below the study localities; 2) lichens appear at all stages of colonization; 3) *R. geographicum* growth is ca. 0.4 mm/yr in this region, fast enough for the sensitivity of field techniques to differentiate ages of boulders exhumed

and/or redistributed by closely spaced geomorphic events of only a few years; 4) low

lichen frequencies on the boulders of young moraines indicate that competition is not

likely to affect their radial growth pattern; 5) other competitive vegetation is scarce; and

6) the effects of late-lying snow are limited on the southwest-facing slopes studied here.

3.3 Field Methods

The topographic profiles of two distal moraine slopes were measured in the

Adams glacier foreland on Mount Adams, Washington (Figure 3.1). Lichens were

measured on two south-facing lateral moraine segments formed at ca. 50 and 150 years

ago (ages based on tree-rings, maps, and air-photo interpretation). Each boulder position

was surveyed with horizontal and vertical accuracies of ± 10 cm. Based on the

assumption that the largest lichen on a boulder can provide a minimum estimate of its

exposure age, the diameter of the largest lichen on each boulder with a surface area > 0.5

m^2 in an 18-m-wide crest-to-base swath was measured using digital calipers and recorded

along with its surface aspect, substrate composition, and lichen quality (e.g.,

Schoenenberger, 2001). In total, these statistics were determined for 102 lichens on the

50-year-old moraine and 217 lichens on the 150-year-old moraine. In order to avoid the

effects of competition, measurements were restricted to the most-circular thalli that are

completely isolated from other lichens. All boulders studied are andesite (Korosec, 1987),

so variable growth rates related to lithologic differences are not suspected.

3.4 Diffusion Model

After ice retreat, moraine profiles are generally triangular in cross section and at or exceed the angle of repose (Figure 3.2). As these landforms age, the matrix eroded from the crest region is transported downslope and deposited along the slope and at the base, resulting in increasing convexity of the ridge, decreasing concavity of the base, and shortened initial slopes. In this process, boulders at the crest are gradually becoming exposed and possibly unseated, while boulders at the base may be buried progressively. Because moraines are often constructed of poorly sorted sediment, surface erosion in active glacial environments may hinder the arrival vegetation and inhibit soil-forming processes that increase landform cohesion. Therefore, moraines are likely subjected to rapid degradation until the main slope angles are relaxed, or until colonizing biota stabilize the surface.

The evolution of a transport-limited moraine surface profiles can be modeled quantitatively using a simple diffusion model. Mathematical formulas for slope diffusion have been presented by Culling (1960) and Carson and Kirkby (1972), and more directly applied to moraines by Hallet and Putkonen (1994) and Putkonen and Swanson (2003). In all applications, the mass transfer along the surface is equal to the local slope multiplied by a topographic diffusion coefficient. The conservation of sediment leads to an expression relating the rate of change of the local surface elevation to the divergence of sediment flux (S_f),

$$(1) \quad S_f = -\kappa \frac{\partial z}{\partial x}$$

where S_f is the sediment flux, κ is the topographic diffusivity constant in m^2/yr and

represents the erodability of slope sediments, and $\partial z / \partial x$ is the slope inclination. For long

uniform slopes, κ increases linearly with distance downslope (Pierce and Coleman,

1986), and so the topographic diffusivity takes the form of

$$(2) \quad \kappa = \alpha + \beta x$$

where α and β are site-specific constants. For the model presented herein, a topographic

profile of each moraine, perpendicular to the moraine crest, was divided into 1-m bins

(Δx). The elevation change for any bin, Δz_i, can be expressed as

$$(3) \quad \Delta z_i = \left(\frac{\Delta t}{\Delta x} \right) S_{f,i} - S_{f,i+1}$$

where t is the time step in years. If the amount of material entering a bin exceeds what is

eroded, the average elevation of that bin increases and *vice versa*. When equation 3 is

applied to each bin in the profile over for each time step in the model, the result is an

approximation of a diffusive landform-smoothing process. It is assumed that the model

accounts for both the aggregated effects of slow continuous and rapid episodic mass

movements (Martin and Church, 1997).

To calibrate the diffusion equation, one needs to know the initial and final forms to determine the total amount of sediment transport and to calculate the appropriate diffusion coefficient. Assuming an initial triangular cross-sectional form, the diffusion model can be used to determine the change in surface elevation at any point along the moraine profile, the rate at which boulders are exhumed and buried can be calculated, and the duration of boulder exposure at the surface can be determined by dividing the model boulder diameter by the lowering rate. Because the model is not designed to track boulder movement, however, boulders that are completely exhumed must be either assumed to leave the system or accounted for in the surface-age determination. For this study, it is assumed that boulders exhumed at the crest are deposited near the toe of the slope, and thus areas where there is a net accumulation of sediment are probable resting sites for exhumed boulders from the crest and upper slope.

In addition to modeling moraine profiles for comparison with field survey data, the model can also be used to determine the average surface age of hypothetical moraines of different heights as they evolve over time. These data can be used to identify potential systematic errors associated with the collection of lichen data for use in developing and applying lichenometric (and other) dating techniques. To this end, model runs were completed using initial moraines heights of 5, 20, 35, and 50 meters over model durations ranging from 0 to 500 years ($\Delta t = 1$ year in each model run).

3.5 Results

The spatial distribution of the largest lichen diameters on each boulder for both moraines is presented in Figure 3.3. These diameters, when compared to their position on the slope, indicate that the crest is dominated by a large population of recent colonizers, and the oldest boulders are at the toes of the slopes with a general pattern of increasing lichen diameters from the crest to the base of each moraine (Figure 3.3). The size-frequency histograms of both moraines are strongly skewed, with an abundance of small-diameter (younger) lichens and diminishing numbers of larger (older) individuals (Figure 3.4). Although the frequency histogram of lichens downslope is multimodal, a general pattern of decreasing lichen-bearing boulders is apparent at the base of each moraine (Figure 3.5). On both moraines, the largest lichens were growing on the largest diameter boulders that may represent lower slope relicts that have not been moved or buried.

Assuming that the moraine topography immediately after the ice recedes is a steep-sided and sharp-crested landform, which is supported by field observations of recent moraines in the study area (Figure 3.2), a best fit of the modeled profiles to the field data requires a topographic diffusivity of $\alpha = 0.48$ and $\beta = 0.0015$ m /yr, 30° slope angles, and initial heights of 64 m and for the ca. 50-year-old moraine and 57 m for the 150-year-old moraine. The similarity of the modeled and surveyed profiles, as described by the root mean square error, indicate deviations of points from their true position of 8 % for both moraines (Figure 3.6). The amount of crest lowering for the 50- and 150-year-old moraine is 4.7 and 8.0 m respectively, or 8% and 12.5% of the initial moraine height.

The toe of the original triangular form used for the 50-year-old moraine aggrades 2.6 m; the 150-year-old moraine toe aggrades 4.8 m.

The surface ages derived from the modeled profiles are presented in Figure 3.7, where they are compared to the lichenometric ages for boulders along each profile. Although the model-based ages are not fully constrained by the data, they do form an envelope that encloses all of the lichenometrically determined boulder ages. The results of the model runs for theoretical moraines with initial heights of 5, 20, 35, and 50 m indicate that the percentage of a moraine surface that represents the actual moraine construction age decreases substantially on centennial timescales with only 10% of the 500 year old model form equal to the moraine age (Figure 3.8). A difference of 125 years between the mean ages of the 5 m and 50 m landform after 500 years of degradation underscores the importance of moraine height in determining surface exposure ages (Figure 3.8).

3.6 Discussion

The results of this study indicate that a diffusion model offers a useful characterization of moraine profiles that provide guidance on collecting and interpreting quantitative surface-age data, whether lichenometric or cosmogenic. The model results suggest that several meters of crest lowering is possible over 100 yr timescales, which can have dramatic effects on the number and location of boulder surfaces exposed on the moraine slope. When compared to other landscape models, the best-fit diffusivity value is

at the higher end of reported values but is similar to those previously used to model other slopes in humid regions and on debris fans (Anderson and Humphrey, 1989; Kooi and Beaumont, 1996; Koons, 1989). Considering that the study moraines are steep, composed of poorly consolidated sediments, largely void of vegetation, and located in an areas with high annual precipitation (>70 cm yr^{-1}), this value appear appropriate.

The frequency of lichen-bearing boulders and the distribution of lichenometrically determined boulder ages on the study moraines show patterns that are consistent with the model results. The dominance of young lichens at the crest of both study moraines is indicative of constantly emerging boulders as a result of crest lowering. The diminishing frequency of lichen-bearing boulders downslope (Figure 3.5), and the presence of the oldest lichens at the toe of the slope, suggests that many older boulders originally at the toe may have been buried. Although a variety of environmental controls can affect the size distribution of lichens on a slope, the pattern that emerges from the lichen data in this study does not require other biological or environmental factors to explain this distribution. Conversely, the results are fully consistent with the general understanding of the evolution of transport-limited slopes (i.e., Carson and Kirkby, 1972) and are in agreement with the expectations of the moraine degradation model presented by Hallet and Putkonen (1994).

The model moraine-profile data suggest that young and steep landforms experience considerable erosion in the early phase of their evolution, which emphasizes

the dynamic (not stabile) nature of these landforms. The relative degradation over time (amount of degradation/landform height) increases with the initial moraine height—the larger the moraine, the greater the chance that new boulders are exhumed and old boulders are buried. As the ratio of fine-grained matrix to boulders increases, so does the susceptibility of these boulders to exhumation, burial, and redistribution until the slopes reach relaxed angles.

3.7 Importance for Lichenometric Dating

The moraine profile and lichen data presented in this study suggest that slope degradation in active glacier forelands is substantial at the same scales of time and space used in lichenometric dating. The magnitude of moraine profile change can affect the number and distribution of boulder surfaces available for lichen colonization over time, but this is often overlooked when developing and applying lichenometric dating techniques. If the average boulder age is a function of the average surface age, then the mean surface age from moraines of different sizes and diffusivities can result in substantial errors in growth-rate determination and any subsequent landform-age determination. The probability of selecting a random distribution of boulders that will yield an accurate moraine construction age varies with the initial moraine height and slope angle, local diffusivity, and time since construction. This result clearly contradicts suggestions that lichen averages or the statistics of randomly selected boulder can be used to provide consistent dating results, except in the unlikely event that all moraines in a foreland started with and evolved under identical conditions. Even applying the same

technique to both calibration surfaces and unknown surfaces will not produce consistent

results, because these surfaces will not necessarily have had similar degradation histories.

Innes (1986) stated that the averages of the maximum diameters of the thalli are

the most suitable parameter for lichenometric purposes and that increasing the sample

area is important for these results. This study demonstrates that reliable results depend

not only on increased sample area but also on broad sampling up and down the moraine

slope. It particularly emphasizes the importance of the middle and toe of the slope for

finding boulders of the greatest age. Statistical methods that average lichen diameters

from the whole moraine surface can result in significantly younger minimum age

estimates than from using the largest lichen, or from using a subset of the largest lichens

on the landform. Furthermore, vigorous degradation can lead to instances where none of

the original lichens that first colonized the surface survive, and thus the constant supply

of fresh boulders dramatically reduces the estimated limiting age for the landform.

Therefore, a lichen growth curve constructed using anything other than the largest, or

some number of the largest, lichens is likely to result in values that are not comparable

across either local or regional scales.

3.8 Conclusions

Using lichenometric data, observed variation in ages can be readily explained by

the recognized processes of surface degradation, without having to invoke biological or

other environmental forces to explain the lichen distribution. The data suggest that no

original boulders will survive on the crests of young moraines because mass movement has removed all boulders that were originally located there. As the moraine slopes become gentler and the mass transfer rate decreases, the slow surface lowering exhumes new boulders that will always be younger than the moraine age. An important result of this study is that estimates of the degradation on two well-documented moraines are so large that they have to be accounted for in any research based on the preservation of the surfaces. These results are crucial for those who develop, apply, or interpret lichenometric moraines ages. Both field data and model results indicate that moraine exposure-dating techniques require careful data collection, and that lichenometric dating may result in dates that are only a fraction of the age of the moraine, an effect that is amplified with increasing moraine age. Lichen populations are strongly influenced by the duration of boulder exhumation and redistribution (i.e., the size, age, and erodability of the landform) and are likely to be unique for each moraine both within and between glacier forelands.
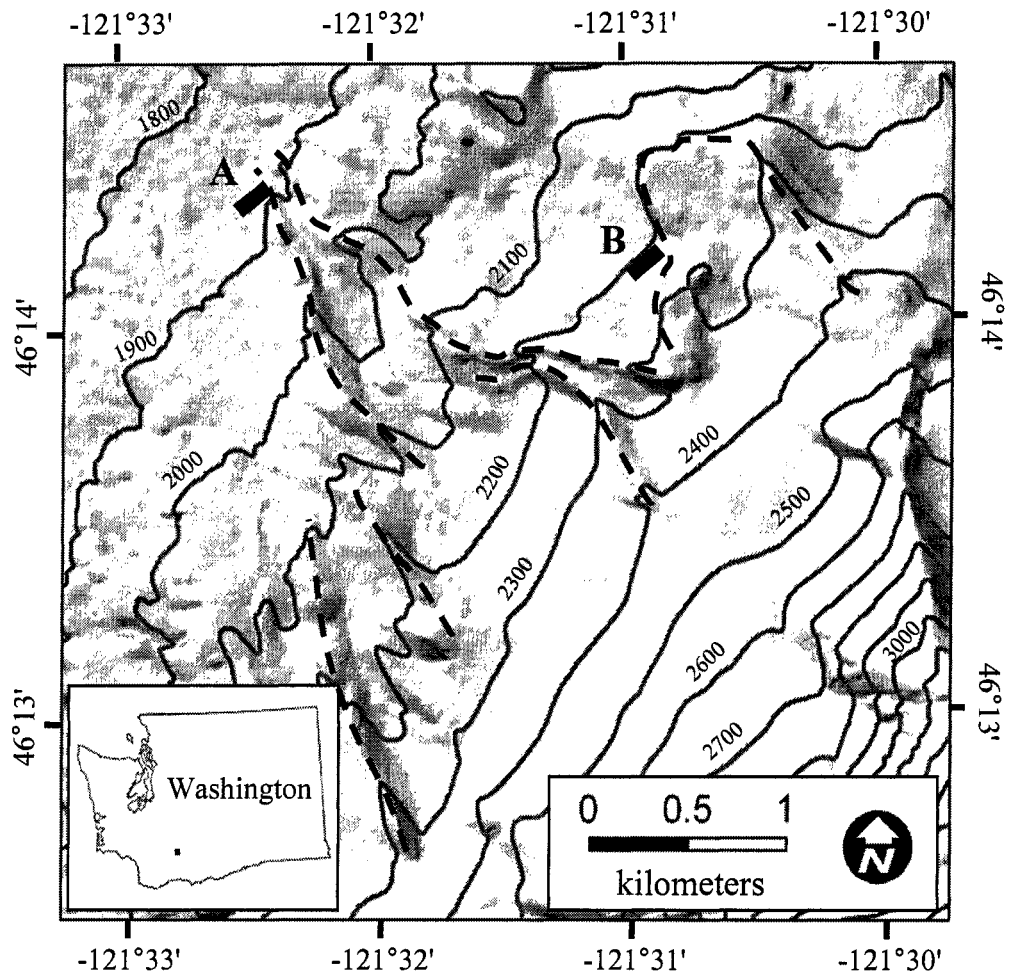
Figure 3.1 Location map of the study area on Mount Adams, Washington. The distal slopes studies on the 50-year-old moraine (A) and 150-year-old moraine are demarked as black boxes. The moraine crests in the immediate vicinity are shown as dashed lines. The contour interval is 100 meters.
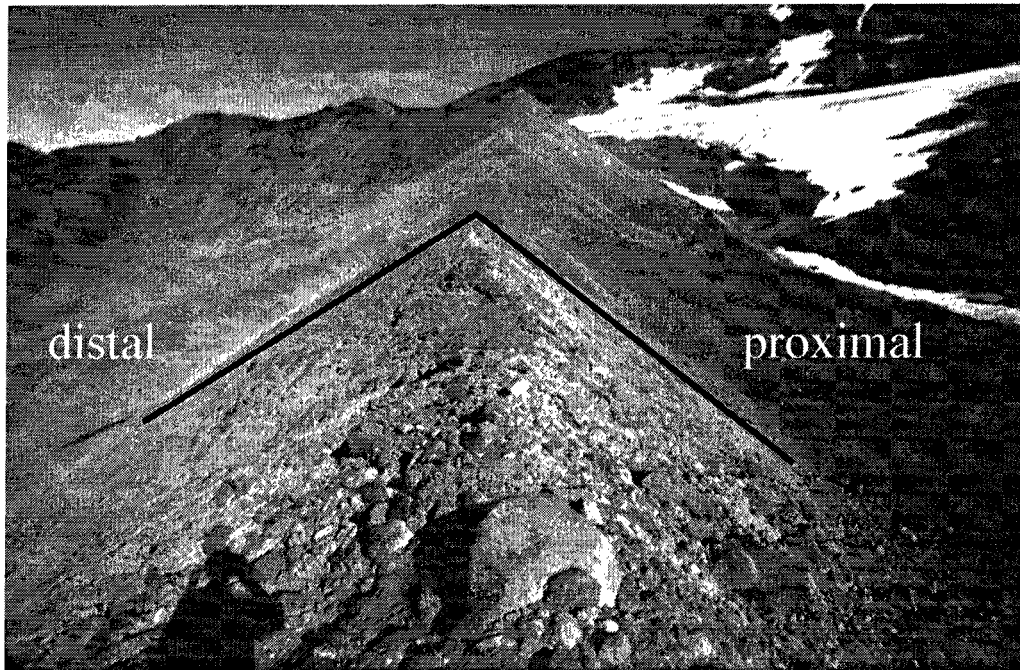
Figure 3.2. This photo illustrates the sharp-crested moraine profile (black line) of a ca 50-year-old moraine at Mt. Adams, WA (photo by Jaakko Putkonen).

A

height   n=102   lichen diameter
□ 60   crest   toe   • 10
□ 40   • 20
▦ 20   ● 30 mm
▦ 0 m

110 meters

B

height   n=217   lichen diameter
□ 60   crest   toe   ·   10
□ 40   •   20
▦ 20   •   30
▦ 0 m   ●   40
                                                            ●   50
                                                            ●   60 mm

130 meters
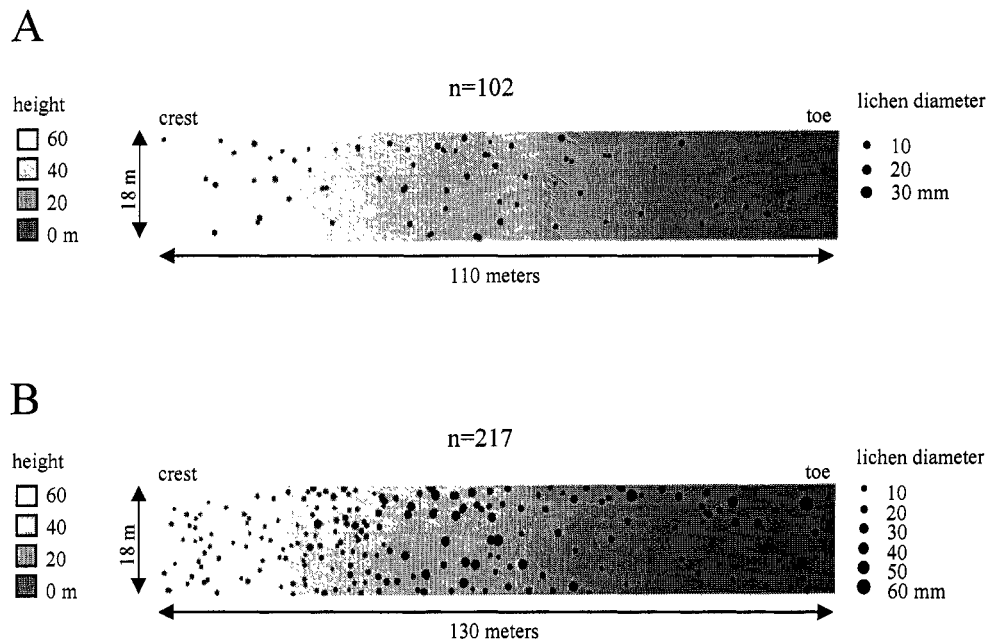
Figure 3.3. Moraine elevation data for the two 18-meter-wide study slopes (half of the profile from crest to flank) with black dots that represent the diameter of the largest lichen measured on each boulder from the ca. 50-year-old (A) and 150-year-old (B) moraines on Mount Adams.
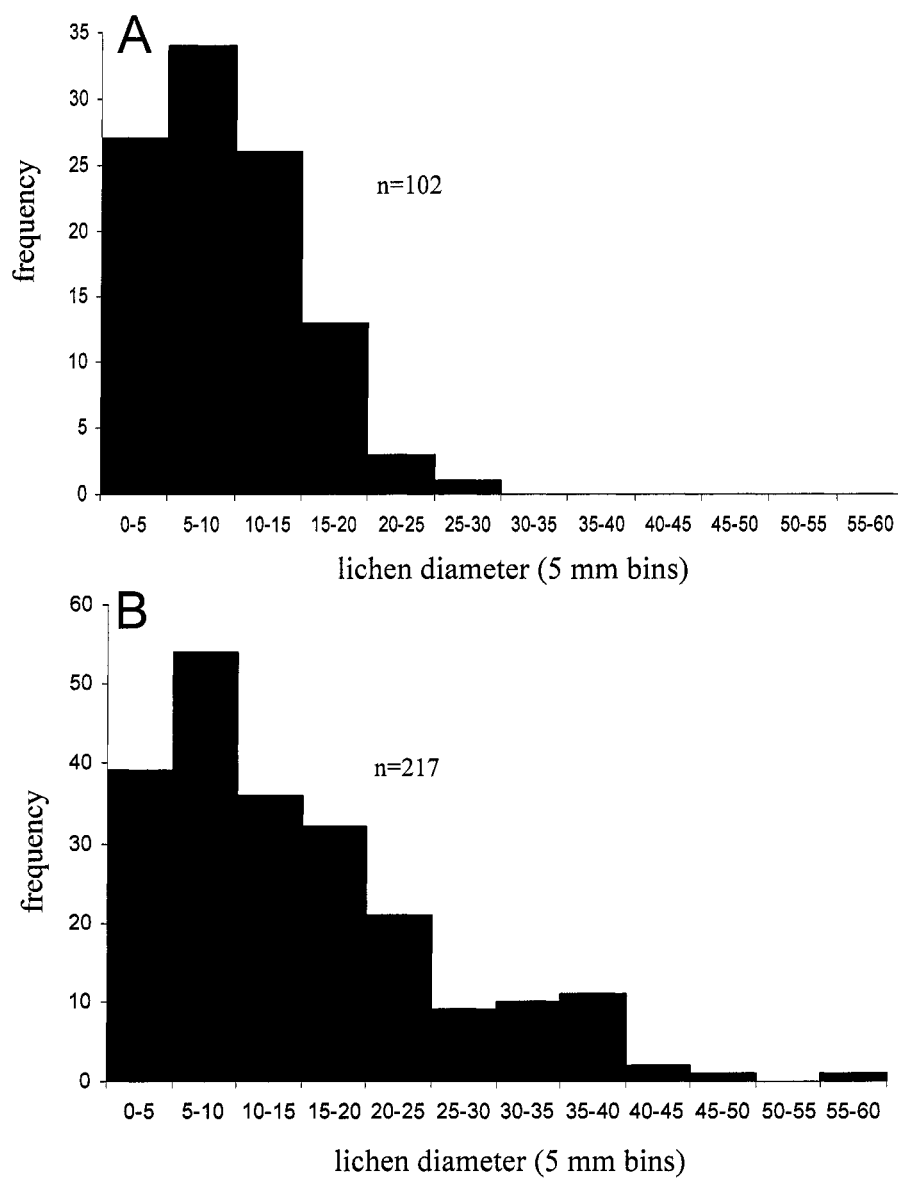
Figure 3.4. Size-Frequency histograms for lichen diameters in the Adams Glacier foreland from the (A) 50-year-old moraine and (B) the 150 year-old-moraine.
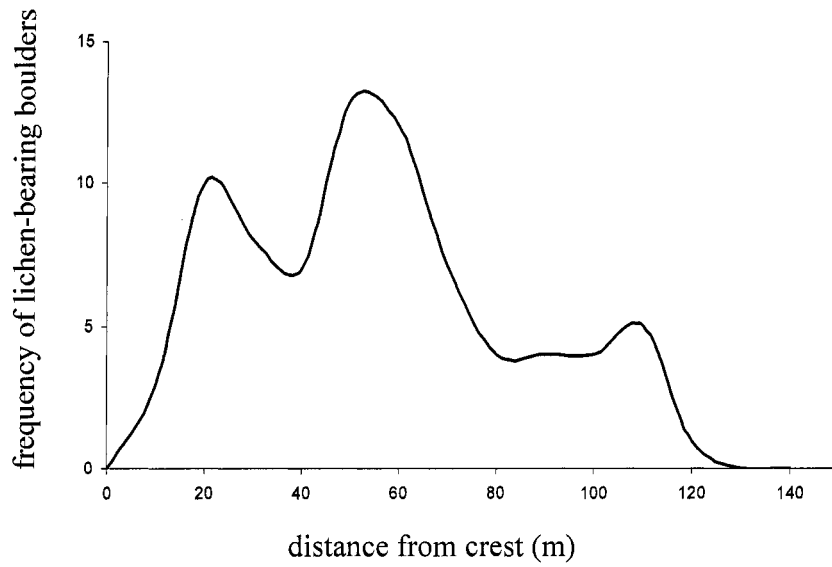
Figure 3.5. Graphs depicting the frequency of lichen-bearing boulders vs. distance down slope for both the 50 (A) and 150 (B) year-old study moraines.
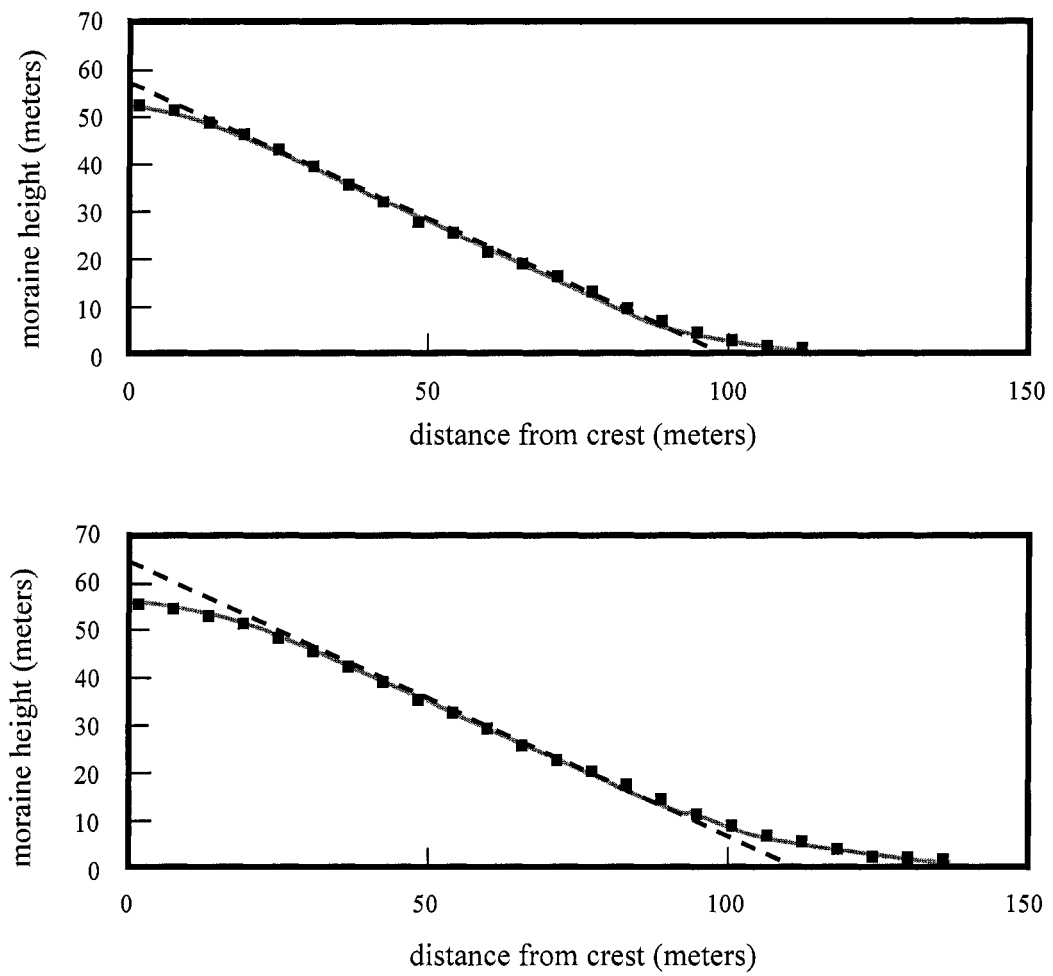
Figure 3.6. Model profiles of the original surface (dashed lines), the final surface (solid gray lines), and elevation points from the field survey profiles (squares).
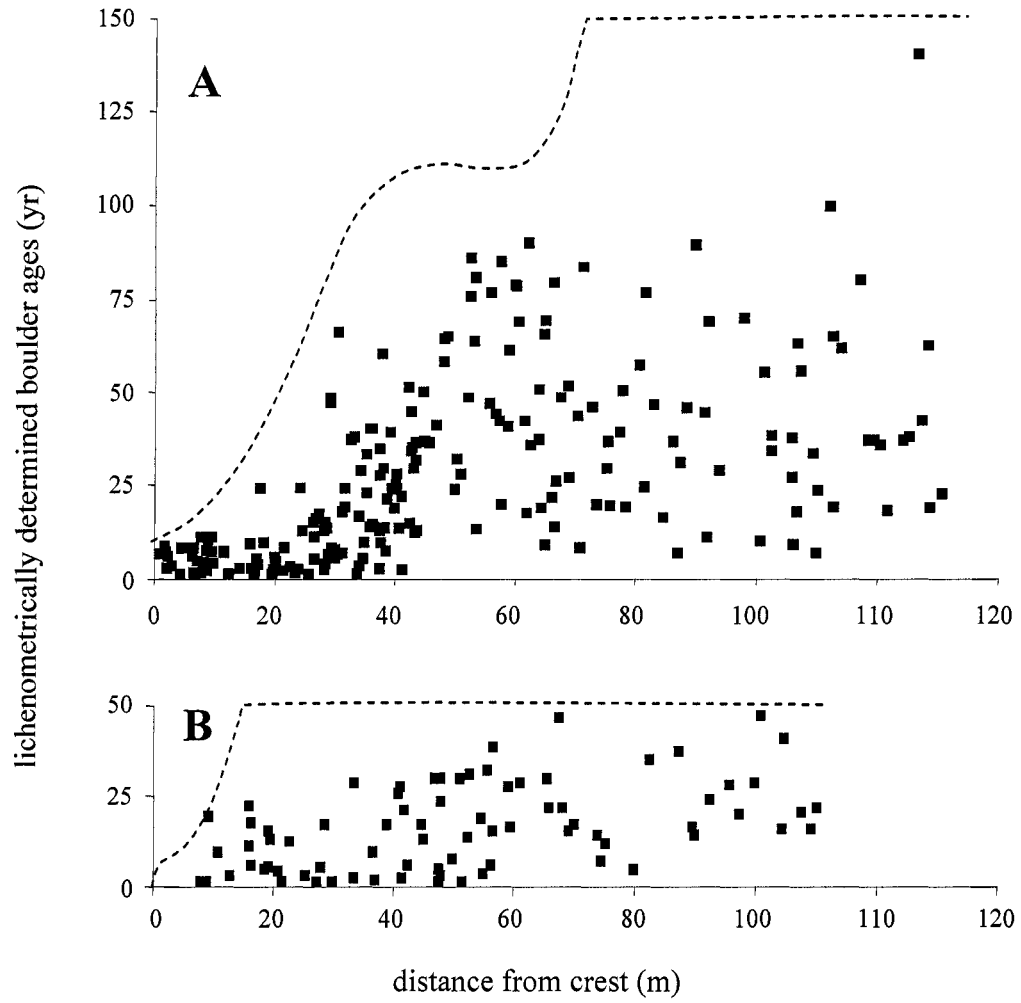
Figure 3.7. Lichen ages and position on the moraine profile for the (A) ca. 50-year-old moraine and (B) ca. 150-year-old moraine. Dashed lines represent the estimated surface ages from the diffusion model.
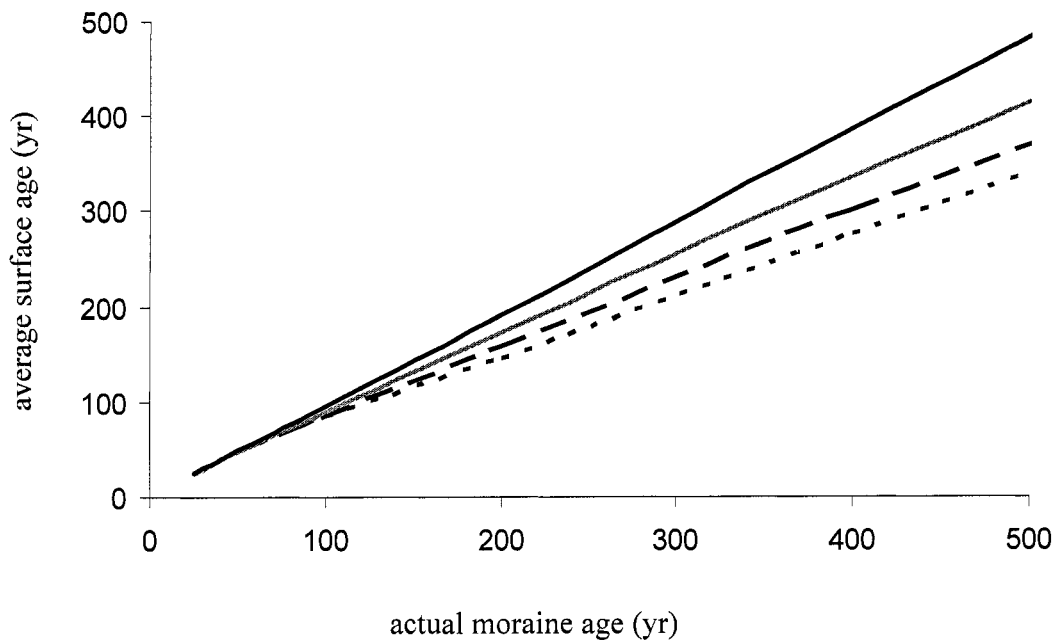
Figure 3.8. Actual moraine age vs. average surface age for modeled moraine with initial heights of 5 m (black), 20 m (gray), 35 m (dashed), and 50 m (dotted) using slope angles of 30°, a = 0.48 and β = 0.0015.

CHAPTER IV

Late Little Ice Age regional climate and glacier-terminus changes in the Cascade Range of Washington and northern Oregon

4.1 Introduction

The purpose of this study is twofold: 1) to inventory late Little Ice Age glacier terminal positions for the Cascade Range of Washington and northern Oregon with more spatial and temporal consistency than previous studies, and 2) to use these expanded data to evaluate their relationship with regional climate variations. Many LIA chronologies of glacier fluctuations have been developed for glacier forelands in the Cascade Range (Miller, 1969; Harrison, 1970; Burke, 1972; Leonard, 1974; Fuller, 1980; Burbank, 1981; Porter, 1981; Driedger, 1986; Lillquist, 1988; Thomas, 1997). However, most of the ice limits identified in these studies were dated using tree-ring and radiocarbon or relative-dating techniques, and for various reasons are not likely accurate representations of the glacier length/age relationship in many forelands. Because of the errors associated with these techniques, previous studies combining glacier-length have likely drawn correlations between glacier advance-retreat patterns based on data that are not accurate for the scale of change that is assumed.

Lichenometric dating using a calibrated growth curve can provide more-accurate exposure ages on a wider range of surfaces than radiocarbon and tree-ring techniques used in the Cascade Range. Because of the abundance of lichens in Cascade glacier forelands, a growth curve recently developed by O'Neal and Schoenenberger (2003)

provides an opportunity to apply a single dating technique for past glacier limits that are less than 200 years old throughout the Cascade Range of Washington and northern Oregon. Moreover, this curve can be used to determine more-accurate surface dates for lichenometric data collected in previous studies, thereby expanding the regional dataset used here. Although the regional growth curve is limited to the last 200 years, this is a period for which there are few observational data of the substantial, overall glacier retreat.

4.2 Lichenometric Techniques

For this study, new lichenometric data were collected from moraines and rock surfaces at five glacier forelands on mounts Adams, Rainier, and Baker (Figure 4.1). The maximum diameters of circular or nearly circular *Rhizocarpon sp.* thalli were measured on all boulders of a moraine with a surface area of 0.3 m^2 or on rock walls where the largest lichen diameter in each 1-m^2 area was recorded. Although a variety of statistical techniques have been used in lichenometric dating, the largest-lichen technique was used here not only because of its widespread use but also because lichenometric data from other studies can be used to expand the regional scope of moraine chronologies (Miller, 1967; Leonard, 1974; Burbank, 1979b; Fuller, 1980; Porter, 1981; Lillquist, 1988; O'Neal and Schoenenberger, 2003). By using chronologies that are based on a consistent and accurate technique, lichenometry provides a mechanism to obtain more regionally comparable and detailed glacier limit ages from each foreland.

Study sites were selected from forelands where late LIA moraines with abundant

lichens are present, moraine chronologies based on other dating techniques are available,

and where calibrated lichen growth curves had not been applied previously (Figure 4.2).

Many forelands from previous analyses were dated using both lichenometric and tree-

ring techniques, and these provide data necessary for comparison of ages derived from

the two techniques. Only moraines formed prior to A.D. 1950 were dated because

observational data and aerial photographs are available for most glacier forelands after

this time, eliminating the need for lichenometric dating of young moraines.

Because most previous lichenometric studies in the region were completed

without a calibrated lichen growth curve and limited to relative dating methods, the new

regional growth curve of O'Neal and Schoenenberger (2003) was applied to all data from

all previous studies (Leonard, 1974; Fuller, 1980, Lillquist, 1989) to compare lichen

chronologies between forelands, and to compare lichen ages to those derived from tree

rings on the same landforms. All lichen ages were determined using the growth curve

equation $a = (D - 2.1179) / 0.436$, where a is the age in years (± 10 years) and D is the

lichen diameter in millimeters (O'Neal and Schoenenberger, 2003).

4.3 Glacier Moraine and Rock Wall Ages

Lichenometric dating was used to provide numerical ages for 16 moraines and

rock surfaces where the technique had not been applied previously, including three

moraines in the Rainbow Glacier foreland (R1, R2, and R3) (Figure 4.2a), three moraines

and one bedrock surface in the Easton Glacier foreland (EA2, EA3, EA4, and EA5)
(Figure 4.2b), one moraine and one bedrock surface in the Boulder Glacier foreland (B4
and B5) (Figure 4.2c), three moraines in the Emmons Glacier foreland (EM3, EM4, and
EM5) (Figure 4.2d), and four moraines in the Adams Glacier foreland (A2, A3, A4, and
A5) (Figure 4.2e). This makes the regional total of 19 forelands where the lichenometric
technique has been consistently applied with 54 dates that can be used to identify past
glacier limits (Table 4.1). The lichens measured on bedrock surfaces were especially
important in this analysis because they provide new terminal position data in areas where
other techniques would not have been applicable. Attempts to use lichenometry on the
pre-1950 moraines of the Eliot (Mount Hood), Deming, Mazama, and Coleman-
Roosevelt glacier forelands (Mount Baker) were unsuccessful because of low lichen
frequencies in these densely vegetated terrains.

In each of the five glacier forelands where lichenometry was used in this study,
the technique provided new glacier length positions. The three moraines in the Rainbow
Glacier foreland (R1, R2, and R3) had maximum lichen diameters of 51, 45, and 34 mm,
equivalent to calendric ages of A.D. 1891, 1909, and 1929 respectively. The diameters of
the largest lichens identified by Fuller (1980) on different sectors of the same moraines,
were 38, 34, and 24 mm, respectively, and result in calendric ages of A.D. 1898, 1904,
and 1930. Tree-ring dates for the same sequence of moraines (Fuller, 1980) are A.D.
1914, 1926, and 1964. Because the foreland was impacted by historic debris avalanches
in 1860 and 1888, there is no clear evidence of mid-19th century or older LIA moraines

(Fuller, 1980). The difference in the lichen diameters from different sectors of the same

moraines in the Rainbow Glacier foreland, from Fuller (1980) and this study in 2004

(Tables 4.1 and 4.2), indicates that lichen growth rates are between 0.4 and 0.5 mm yr^{-1}

over the 25-year period between times of data collection for these studies, comparable to

the 0.4 mm yr^{-1} average lichen growth rate from the control points used in developing the

regional growth curve (O'Neal and Schoenenberger, 2003) and the 0.4 mm indicated for

Rhizocarpon Agg. growing in the southern Columbia Mountains, British Columbia

(McCarthy, 2003).

The Easton Glacier foreland has substantial lichen populations on 19th century

moraine segments with rapidly decreasing lichen frequencies near the early 20th century

positions (Figure 4.2). None of the sampled moraines in this foreland had been dated

previously. The largest lichen diameters on four moraine segments (EA2, EA3, EA4, and

EA5) were 61, 53, 50 and 44 mm respectively, equivalent to calendric ages of A.D. 1869,

1887, 1894, and 1907. The scarcity of lichens on the EA1 moraine, for which Thomas

(1997) obtained a minimum tree-ring date of A.D. 1853, prohibited the use of lichen

dating on that landform.

In the Boulder Glacier foreland, lichens were too scarce on the densely forested

older LIA moraines B1, B2, and B3 to permit lichenometric dating. The largest lichen

from the single moraine that has a substantial lichen population (B4) was 52 mm,

equivalent to a date of A.D. 1890; Burke (1972) provided a minimum tree-ring age of

A.D. 1920 for the same moraine. The largest lichen diameter measured on a bedrock surface (B5) between the 19th century moraine and the mid 20th century ice limits identified by Burke (1972) was 40 mm, resulting in a calendric age of A.D. 1915.

Although Burbank (1981) and Porter (1981) applied lichenometry to several of the large glacier forelands on Mount Rainier, Emmons Glacier was not used in either study in spite of the abundant lichen populations in this foreland. Field surveys from this study identified the largest lichens growing on two lateral moraines (EM3 and EM4) and one terminal moraine (EM5) measuring 74, 68, and 51 mm, respectively; these are equivalent to calendric ages of A.D. 1838, 1852, and 1891. Sigafoos and Hendricks (1972) reported tree-ring dates for EM3, EM 4, and EM5 of A.D. 1848, 1910, and 1900, respectively. These tree-ring ages are consistently younger than lichen ages by 1 to several decades, a likely result of sustained unstable moraine surfaces after ice retreat.

The glacier forelands of Mount Adams are the least studied of those on major peaks of the northern Cascade Range. The lichenometric data collected for this study in the Adams Glacier foreland provide the easternmost example of the application of the technique in the northern Cascade Range. A tree trim-line on a bedrock surface delimits the most recent extent of the Adams Glacier (adjacent to A2 in Figure 4.2e) and traces an ice limit behind the limiting tree-ring date of ca. A.D. 1700 at point A1. Dating younger moraines in this foreland is complicated by the palimpsest topography that resulted from re-entrants that broke through segments of the large lateral moraines in this foreland.

However, four nested moraines behind the ca A.D. 1700 limit (A2, A3, A4, and A5) have maximum lichen diameters of 64, 66, 54, and 41 mm, respectively, equivalent to ages of A.D. 1857, 1862, 1885, and 1914.

Terminus length changes for the 15 glaciers between A.D. 1850 and 1950 are presented in Figure 4.3. Many Cascade Range glaciers advanced during the 1970s and 1980s, and most overrode terminal moraines of the previous few decades (e.g., Harper, 1993; e.g., Nylen, 2001). Thus, several terminal positions from the 1940s in Figures 4.2 and 4.3 are known from photos and observation data and are identified accordingly in Table 4.1.

4.4 Applicability and Limitations of Lichenometric Dating

Although lichenometry can be used in a variety of settings throughout the Cascade Range of Washington and northern Oregon, there are several limitations to its use. First, many moraines where lichenometry was applied in the 1970s and 1980s now have extensive moss cover, dense thickets of alder and willow, or forest cover that increases lichen mortality or inhibits their growth. This is especially true for forelands where late LIA limits reached low elevations (e.g., Carbon, Winthrop, and Nisqually glaciers on Mount Rainier), although upper lateral moraines of these glaciers are not so impacted. Second, because *Rhizocarpon sp.* thalli may die within 5-8 years if annual snow cover exceeds 40 weeks per year (Benedict, 1990); applying the technique may be misleading in areas where the lichenometric clock may have been reset. Porter (1981)

suggested that persistent perennial snow cover of the early 19th century may have killed many preexisting lichens in the region. Third, the lichenometric ages of nested moraines at South Cascade Glacier foreland requires that younger moraines are positioned farther down valley than older moraines (Table 4.2), an impossibility that indicates early colonizers are not always present and that lichenometric dates should be interpreted in the context of the range of dates and techniques applicable in each study locality. Finally, for forelands with limited pioneering vegetation and soil development, LIA moraines may be subject to substantial surface creep and mass wasting. Thus, the degradation these landforms will likely expose, redistribute, and bury boulders suitable for lichen colonization, adding to the difficulty of interpreting lichenometric data.

Comparison of the 27 moraines where both lichenometric and tree-ring data are available indicates that lichenometry results in older limiting ages by as much as 97 years for landforms less than 200 years in age (Table 4.1), and is likely more suitable for determining exposure ages over this period. However, for moraines that have lichenometric ages greater than 200 years old, lichenometry provides younger minimum ages than tree rings by as much as 417 years (Figure 4.4), limiting the usefulness of lichenometry to dating surface exposed during the last two centuries. The moraine-age frequencies determined using both tree-ring dating and lichenometric dating on the same landforms (Figure 4.4) emphasizes the dissimilarity in ages that result from the different accuracies of the two methods. This disparity limits our ability to compare chronologies developed using the two methods (e.g., Heikkinen, 1984). Although both techniques have

their limitations, lichenometry has an advantage in that lichens will grow on exposed

bedrock that can be used to determine the exposure ages of bedrock surfaces after glacier

retreat.

Previous studies have determined that Cascade glaciers maintained advanced

terminal positions from A.D. 1650-1890 (e.g. Miller, 1969; Burbank, 1979a; e.g. Fuller,

1980; Burbank, 1981; Lillquist, 1988; Thomas, 1997), emplacing one or several terminal

moraines that are generally attributed to cold episodes of the LIA (Lamb, 1977).

However, the assigned ages of most of these moraines are based on uncalibrated,

overextended, or poorly calibrated lichenometric growth curves, tree rings from

individuals that are likely not the first generation of colonizers, and the proximity of these

landforms to more recent glacier terminal moraines. Given our poor understanding of the

magnitude of advance and retreat over the late Holocene, there is no reason to assume

that these moraines are assigned to more recent glacier fluctuations (i.e., 13th to 19th

centuries) based on the available age data and their proximity to 19th century moraines.

Thus, without additional weathering profile or tephra data, there is no reason to assume a

relationship between the 19th century moraines from which there is reliable chronological

control, and the older moraines that lie in close proximity to these moraines.

4.5 Comparison of Glacier Length Records and Regional Climate Trends

Recent glacier fluctuation research has focused on reduced time- and space-scales, with

increasing emphasis on the response of individual glaciers to decadal climate variations.

This shift is part of a scientific trend towards explaining glacier fluctuations in terms of the influences of regional short-term climate variations rather than descriptions of how glacier lengths have fluctuated on centennial scales. In the Pacific Northwest, at least two composite climate indices have been developed to provide a measure of decadal climate variability starting at 1890: the Pacific Northwest Index (PNI), developed by Ebbesmeyer and Strickland (1995), and the Pacific Decadal Oscillation (PDO) (Mantua et al., 1997).

The PNI is a century-long terrestrial climate index based on: 1) annual average air temperature at Olga in the San Juan Islands, 2) annual precipitation at Cedar Lake in the Cascade Range; and 3) snow-pack depth on March 15 at Paradise on Mount Rainier. The PNI index suggests two colder and wetter periods from A.D. 1895 to 1924 and 1945 to 1977, and two warmer and drier periods from A.D. 1924 to 1944 and 1976 to 2003.

The PDO index is defined as the leading principal component of North Pacific monthly sea-surface temperature variability (poleward of 20°N) and is manifested as 20- to 30-year-long El Niño-/ La Niña-like warm and cool climate phases that affect both marine and terrestrial climate patterns. Substantial evidence suggests that two full PDO cycles occurred over the period of climate records: two cool phases from A.D. 1890 to 1924 and 1947 to 1976, and two warm phases from A.D. 1925 to 1946 and 1977 to at least the middle 1990s (Mantua et al., 1997; Minobe, 1997). These climate patterns account for approximately 30% of the regional wintertime precipitation variation (Mantua et al., 1997).

The relative patterns of the PNI and PDO are similar, with only a few years separating the timing of the different phases in each index (Figure 4.5). Several studies have identified the response of post-1940s glacier fluctuations with PNI and PDO patterns (e.g., Heikkinen, 1984; Pelto, 1993; Nylen, 2001; Kovanen, 2003); however, prior to this study a regional comparison of 19th to mid-20th century glacier-length records with regional climate has not been possible. A comparison of the glacier length data in Figure 4.3 with the phases of the PNI and PDO in Figure 4.5 indicates a synchronous response of the study glaciers to regional climate variations. This response is manifested by glacier lengths from 1920 to 1945 that were 35 to 70% shorter than their mid- to late-19th century lengths. The timing of the this rapid retreat is ± 15 years and likely reflects the uncertainty in the response time of individual glaciers from differences in insolation, geometry, elevation, ice-thickness, and slope.

All of the 15 glaciers in this study reached their most-recent minimum between 1944 and 1950. Subsequent glacier advances during the cold-wet winter phases of the PDO and PDI from 1950 to the 1970s overrode the glacier limit of these minima (Driedger, 1986; Harper, 1993). Recent analyses of glacier length fluctuations using air-photos from Mount Baker (Kovanen, 2003) and Mount Rainier (Nylen, 2001) identified synchronous glacier advance on these mountains corresponding to the 1944 to 1976 cool PDO phase, with subsequent retreat during the 1976 to 1990 warm PDO phase. When the A.D. 1850 to 1950 data from this study are combined with those of recent glacier

advance-retreat, a consistent pattern of response to regional climate patterns as depicted by the PNI and PSO is apparent in either the rate of retreat between 1890 and 1944 or on the timing of the reversal in the overall advance/retreat trends that followed.

4.6 Conclusions

1. Lichenometry can be used to provide a proxy record of glacier length spanning the last two centuries in areas where observational data are not available or other dating techniques are not applicable.

2. The minimum moraine ages of less than 200 years provided by lichenometric dating suggest that this technique is more accurate than tree-ring methods for this period.

3. Lichenometrically determined glacier length chronologies provide a means of regional comparisons that indicates slow glacier retreat from the 19th century to the early 20th century, with rapid retreat from the early to mid 20th century.

4. When the glacier length records from this study are combined with more recent glacier fluctuation data, it is apparent that Cascade glaciers are sensitive to the decadal climate variations described by the PDO and PDI, a pattern that is often missed when comparing chronologies based on techniques with major differences in their consistency and accuracy. Problems with previous efforts attempting to make this correlation are overcome with a regionally consistent dating technique requisite to address decadal-scale correlations.
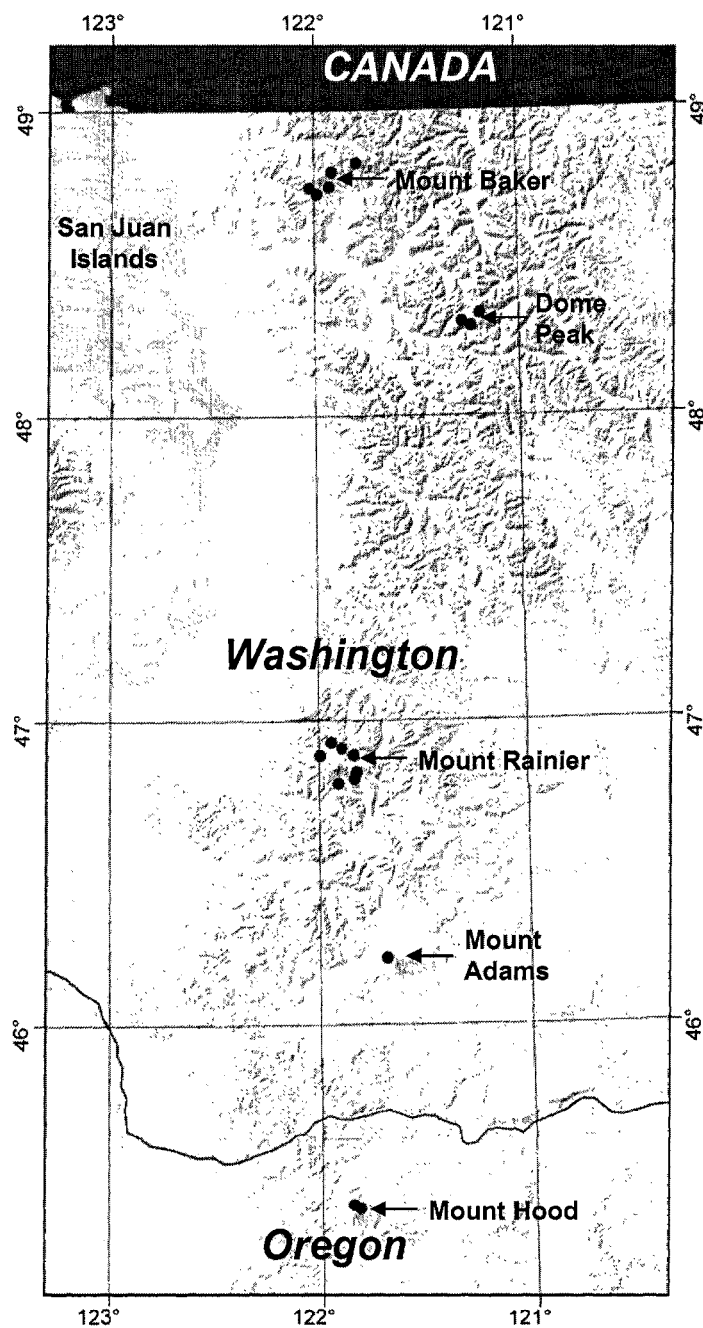
Figure 4.1. Map showing the locations of major peaks of the Cascade Range of Washington and northern Oregon and the location of glacier forelands where lichenometric dating using *Rhizocarpon geographicum* has been applied in this and previous studies (black dots).
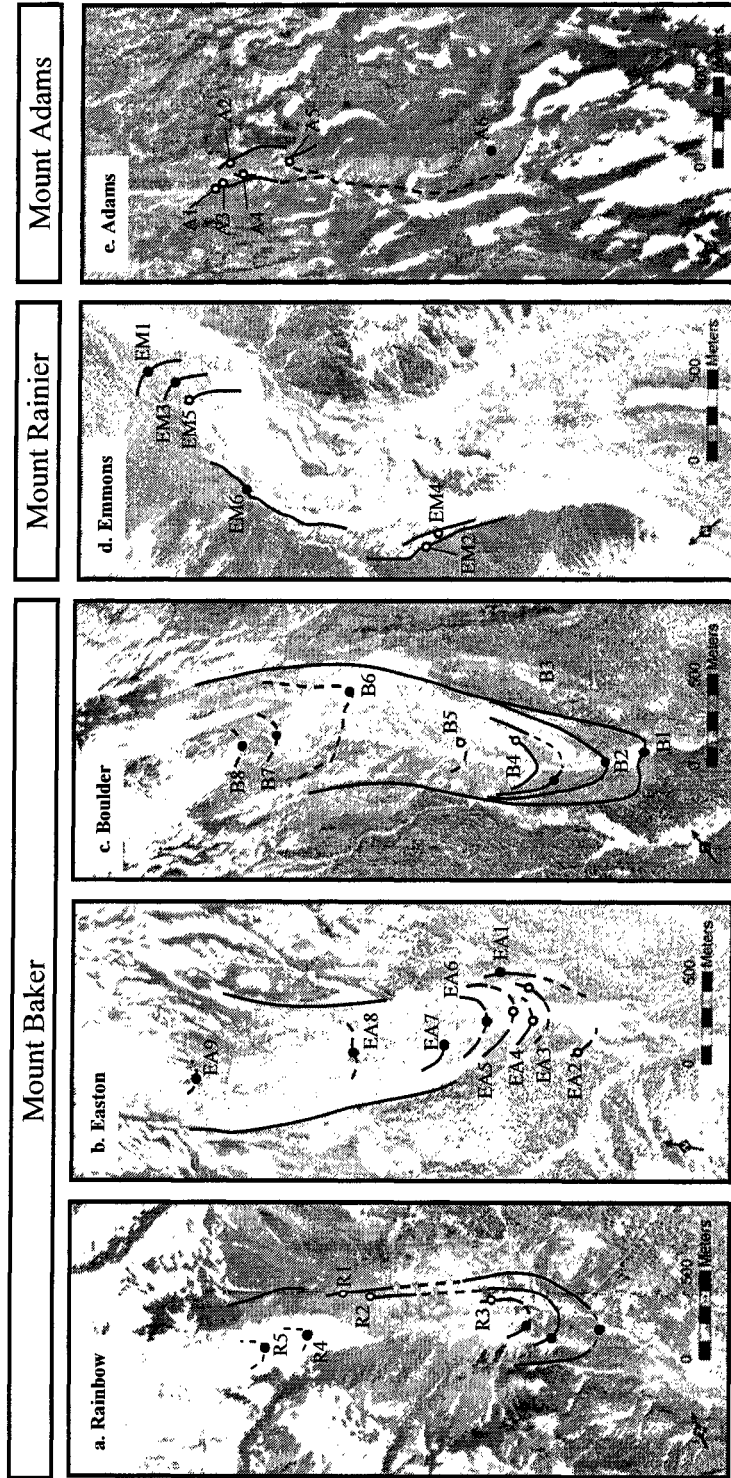
Figure 4.2. The five glacier forelands in the Cascade Range of Washington where lichenometric data were collected for this study. Black dots represent localities of past glacier limits determined by other researchers; white dots represent localities where lichenometric ages were determined in this study.
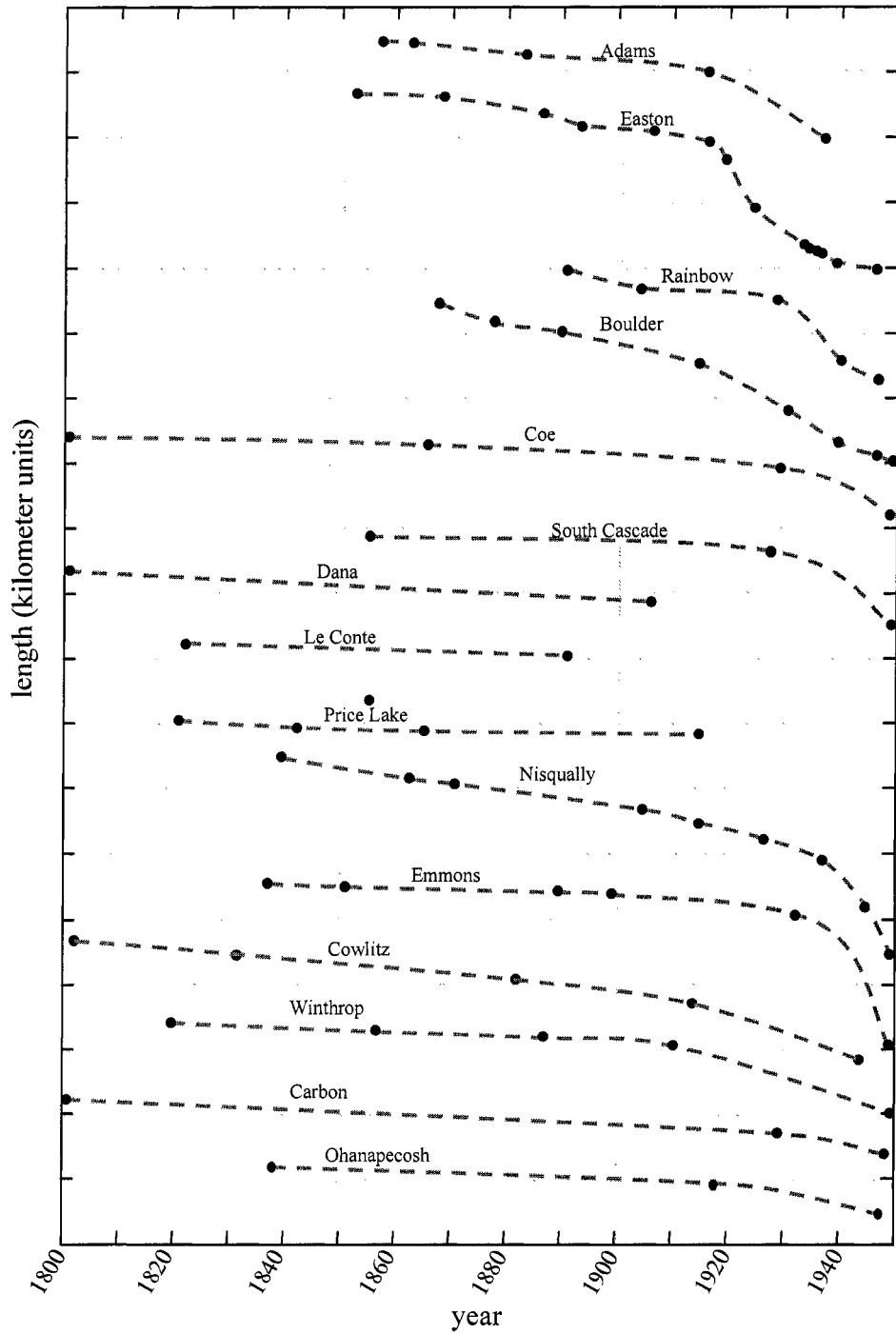
Figure 4.3. Glacier length records for 15 localities with lichenometrically based chronologies. Each dot represents a glacier terminal position with advanced positions are towards the top and retreats are towards the bottom of the graph.
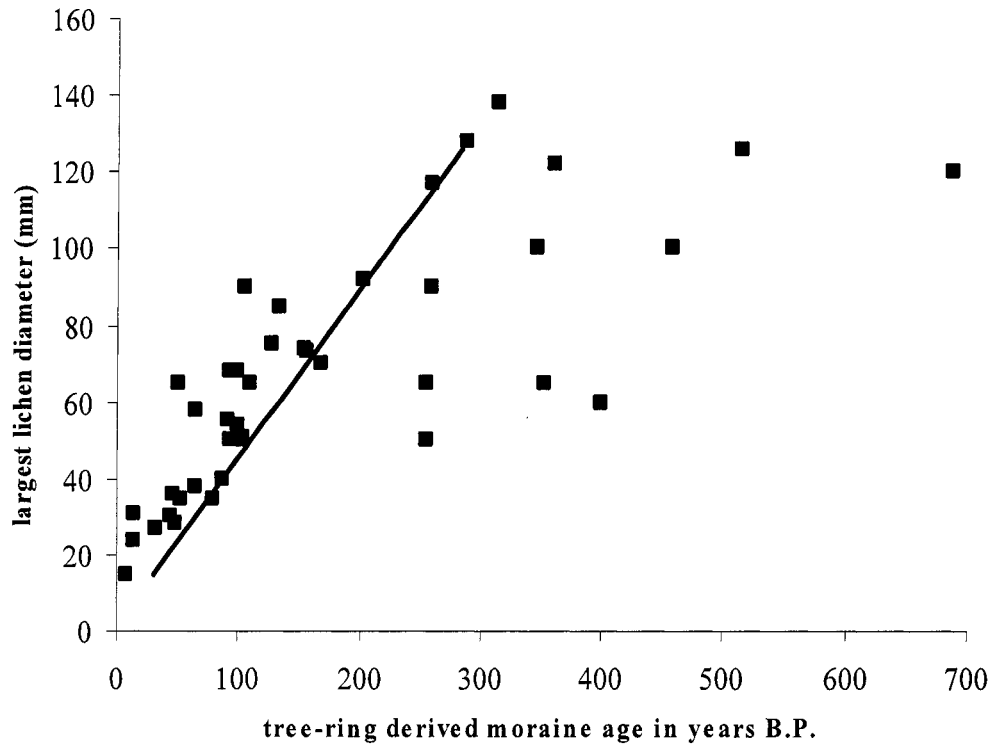
Figure 4.4. Tree-ring ages for moraines presented in Miller (1967), Leonard (1974), and Fuller (1980) on the x-axis with the corresponding largest lichen diameter identified on the same moraine on the y-axis. The black line is the regional growth curve from O'Neal and Schoenenberger (2003).

A

Pacific Northwest Index

5-year average ——   Annual PNI *

B

Pacific Decadal Oscillation Annual Averages

Year
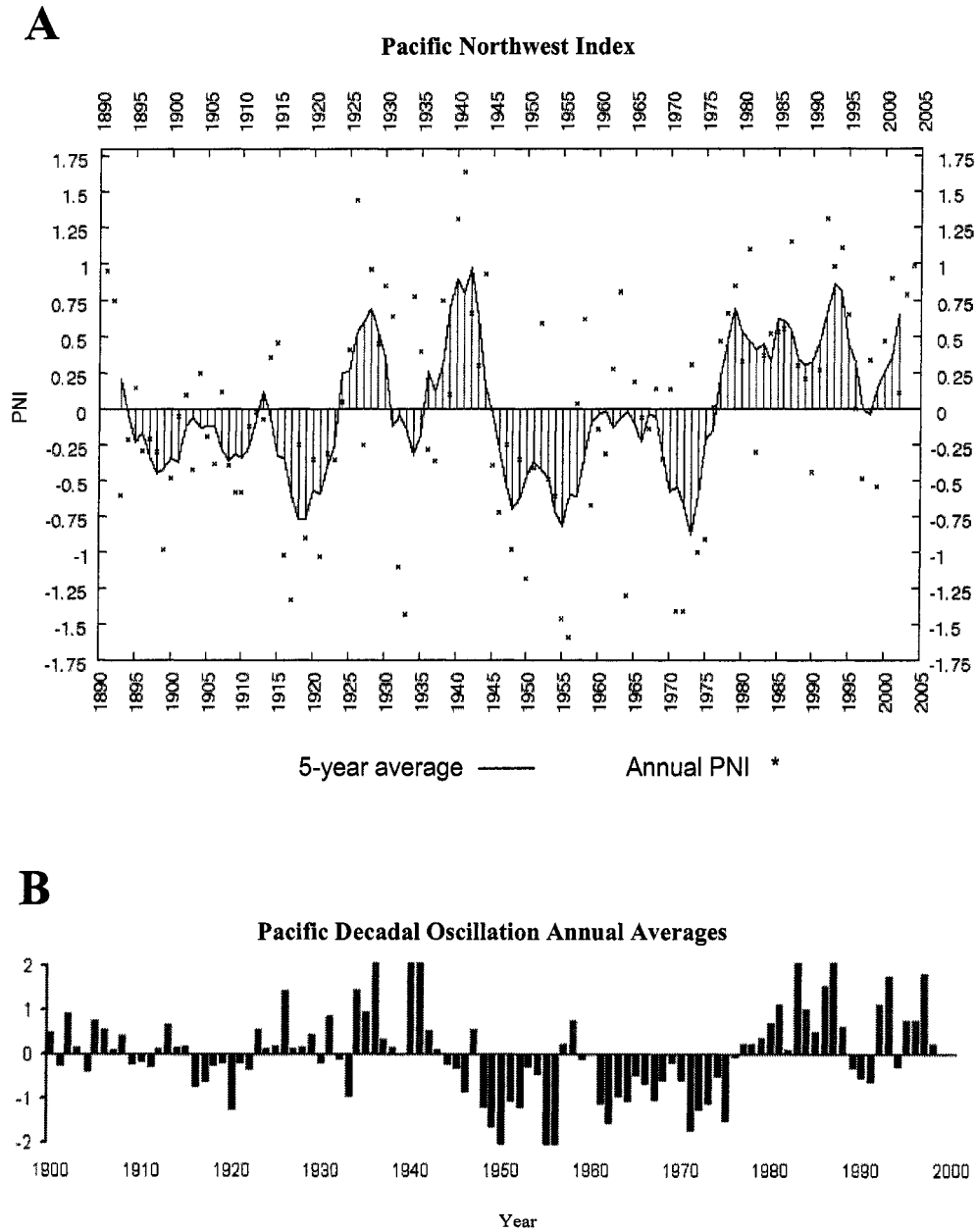
Figure 4.5. (A) The Pacific Northwest Index (Ebbesmeyer and Strickland, 1995) and (B) the Pacific Decadal Oscillation (Mantua et al., 1997).

Glacier Foreland	Moraine Number in Figure 2	Previous Age (A.D) and Dating Technique	Reference for Original Age	Lichen Diameter (mm) - This Study	Regional Growth Curve Age (A.D)
Adams	A1	1700 †	unpublished - this study	-----	-----
	A2	-----	-----	65.6	1857
	A3	-----	-----	63.5	1862
	A4	-----	-----	53.5	1885
	A5	-----	-----	41.0	1914
	A6	1936 ♦	air photo (Jones, 1936)	-----	-----
Emmons	EM1	1745 †	Sigafoos & Hendricks (1972)	-----	-----
	EM2	1745 †	Sigafoos & Hendricks (1972)	-----	-----
	EM3	1848 †	Sigafoos & Hendricks (1972)	73.9	1838
	EM4	1910 †	Sigafoos & Hendricks (1972)	68.1	1852
	EM5	1900 †	Sigafoos & Hendricks (1972)	51.0	1891
	EM6	1900 †	Sigafoos & Hendricks (1972)	-----	-----
Boulder	B1	1588, 1750 †	Burke (1972), Long (1955)	-----	-----
	B2	1868 †	Burke (1972)	-----	-----
	B3	1878 †	Burke (1972)	-----	
	B4	1920 †	Burke (1972)	51.6	1890
	B5	-----	-----	40.4	1915
	B6	1931	Burke (1972)	-----	-----
	B7	1940 ♦	Burke (1972)	-----	-----
	B8	1947 ♦	Burke (1972)	-----	-----
Easton	EA1	1853 †	Thomas (1997)	-----	-----
	EA2	-----	-----	60.6	1869
	EA3	-----	-----	52.81	1887
	EA4	-----	-----	49.5	1894
	EA5	1907 ♦	Long (1955)	44.1	1907
	EA6	1917 ♦	Long (1955)	-----	-----
	EA7	1920 †	Thomas (1997)	-----	-----
	EA8	1925 ♦	Long (1955)	-----	-----
	EA9	1935 ♦	Long (1955)	-----	-----
Rainbow	R1	1900 •†	Fuller (1980)	50.8	1891
	R2	20th century •†	Fuller (1980)	45.3	1904
	R3	20th century •†	Fuller (1980)	34.2	1929
	R4	1940 ♦	Harper (1992)	-----	-----
	R5	1947 ♦	Harper (1992)	-----	-----

† tree core ♦ air photo • lichen measurement

Table 4.1. Moraine age data from all forelands mapped during this study.

location and source of original study	glacier foreland studied	limiting moraine age from tree rings and/or ash layers	largest lichen identified at the time of study (mm)	lichenometric age using the regional growth curve (A.D.)	difference between lichenometric age and other methods
Dome Peak Area, Miller (1967)	South Cascade	1612	65	1822	-210
		1873	50	1856	17
		1916	65	1822	94
	La Conte	1566	60	1833	-267
		1856	65	1822	34
		1886	35	1891	-5
	Dana	1600	75	1799	-199
		1863	50	1856	7
		1917	28	1907	10
	Chickamin	1279	120	1696	-417
		1508	100	1741	-233
		1620	100	1741	-121
		1706	90	1764	-58
		1879	40	1879	0
		1921	30	1902	19
Mount Shuksan, Leonard (1974)	Price Lake	1457	126	1689	-232
		1612	122	1698	-86
		1839	85	1783	56
		1873	68	1822	51
		1908	58	1845	63
		1927	36	1895	32
Mount Baker, Fuller (1980)	Rainbow	1914	38	1897	17
		1926	35	1904	22
		1964	34	1929	35
		1964	31	1913	51
		1970	15	1949	21
Mount Hood, Lillquist (1988)	Coe	1731	65	1843	-112
		1731	50	1877	-146
		1818	70	1831	-13
		1887	54	1868	19
		1882	90	1785	97
		1895	55	1866	29
		1955	27	1930	25
Mount Rainier, Burbank (1980); * data from this study	Carbon	1720	117	1717	3
	Winthrop	1666	138	1668	-2
		1691	128	1691	0
		1823	73	1817	6
	Cowlitz	1849	92	1774	75
		1874	76	1830	44
	North Mowich	1850	72	1819	31
		1865	60	1842	23
	Emmons *	1848	74	1838	10
		1910	68	1852	58
		1900	51	1891	9

Table 4.2. Data from studies where moraine ages were determined using tree-ring measurements or ash layers and lichenometric data were collected from the same landforms. Ages are adjusted to account for the date that the lichens were measured.

CHAPTER V

Climatic determinants of late Holocene glacier-length variations on Mount Baker, Washington

5.1 Introduction

During the late Holocene, the large valley glaciers on Mount Baker (Figure 5.1) advanced and retreated several times depositing a series of nested moraines that lie within a few kilometers down valley of their current termini (e.g., Burke, 1974; Fuller, 1980; Heikenen, 1984; Pelto, 1996; Thomas, 1994). The most recent and well-dated of these moraines mark the maximum glacier advances of the 19th century, with yet older moraines lying just downvalley from the 19th century glacier limits. Previous workers have suggested that late Holocene glacier advances are a result of globally quasi-synchronous, centennial-scale cold-climate phases with subsequent retreats during warmer periods (e.g., Porter and Denton, 1967; Denton and Porter, 1970).

The poorly constrained ages for these pre-19th-century moraines means that it is possible that these landforms may be a result of even earlier advances, and thus that they are not necessarily synchronous or part of a global pattern of climate fluctuations. Long-term climate reconstructions provide conflicting evidence for ca. 100-year-long global "cold phases" that have been cited as the cause for such glacier-length variation (Bradley, 2003; Mann, 1999). Moreover, proxy climate data indicate that the interannual variability in late Holocene temperatures is generally larger than the long-term trends (IPCC, 2001)

and no studies have been able to characterize the expected response of glacier length to

such variability.

Since the most recent advances of the late 19th century, the large valley glaciers

on Mount Baker have retreated between 1300 and 2500 meters, similar to the magnitude

of retreat of large glaciers identified on other major Cascade volcanoes during this time

(e.g., Mount Rainier [Burbank, 1979; Sigafoos and Hendricks, 1971], Mount Hood

[Lillquist, 1989], and Mount Adams [chapter 4 of this thesis]). Recent studies have

suggested that human-driven climate changes responsible for global warming are the

driving mechanism for recent glacier retreat (e.g., Mosley-Thompson, 1997; Oerlemans,

2004). Because moraines merely mark the transition of glaciers from advance to stillstand

or retreat phases, field-based estimates of minimum or typical length fluctuations that

have resulted simply from natural climatic variations are rare. However, studies of alpine

glacier fluctuations in the central Coast Range of Canada (Reyes and Clague, 2004) and

the Great Aletsch Glacier in Switzerland (Haeberli and Holzhauser, 2003) suggest that

length-scale variations comparable to the retreat from 19th century to recent positions are

not uncommon in the last two millennia, with at least two early minima similar to modern

glacier lengths.

To compensate for the lack of direct evidence, a simple analytical model driven

by historical climate data is developed here to simulate glacier length records for five

large valley glaciers on Mount Baker from 1931 to 1990, and it is used to investigate the

influence of natural climate variability on glacier lengths as recorded in the geologic record. Using historical temperature and precipitation records from this period, simulated glacier lengths are determined and compared with geologic reconstructions of past glacier lengths. Moreover, the model is used to estimate the relative importance of varying precipitation and temperature in glacier length fluctuations.

To examine glacier response to climate variation on millennial time scales, the historical climate data are used to generate two-millennia-long realizations of climate variations that are consistent with the observed temperature and precipitation statistics of the 20th century. The simulations illustrate the range of glacier-length variability that would be anticipated under a constant climate with natural fluctuations equal to those observed in the present. This provides a baseline expectation of natural variability against which we might identify any systematic climatic shifts during the late Holocene, as a result of either natural or anthropogenic causes, using the geologic record of Mount Baker moraines. With a better understanding of the glacier-length fluctuations that result from natural climate variability, both the amount and the uniqueness of 20th century glacier retreat can be evaluated.

5.2 Glacier Model

Although unraveling the detailed climate-glacier interactions can be complicated, a relatively simple model suffices to estimate characteristic length variations in response to climate variation using information about the geometry of the glacier, the ice-surface

and bed slope, and how the glacier melts. The annual change in mass for any point on a glacier is the difference between its accumulation and ablation, which is typically expressed as average volume per unit surface area (i.e., thickness) added to or lost from the glacier in a given year. The cumulative change in this mass balance of a glacier directly alters the glacier volume, and it also has an indirect and delayed response in glacier length. Figure 5.2 illustrates these relationships with a simplified diagram of glacier geometry (c.f. Oerlemans, 2001). The ice geometry consists of an accumulation area (A) and an ablation zone (L_{ab}) in a protruding tongue with a characteristic width (W_f). It assumes the glacier has a uniform thickness (H_m) and rests on a bed with a constant slope angle (θ). L is the total glacier length, assumed to be along the centerline, and L' represents a change in glacier length as a result of some climate forcing.

Using simplified representations of glacier geometry like that of Figure 5.2, several studies have presented linear models of how the terminus position of glaciers should respond to changes in climate (e.g., Johanneson *et al.*, 1989; Klok, 2003; Oerlemans, 2001 and 2004). This study also uses a linear model that is identical to those in these other studies in its functional form, but the model formulation here explicitly includes the bed slope and the atmospheric lapse rate (Roe, 2004). This has the advantage that the model can be independently forced with either temperature or precipitation data. The evolution of the terminus position is governed by the following equation:

$$\frac{dL}{dt} = L' \frac{\beta L_{ab} \Gamma \tan\theta}{H_m} + \frac{A}{W_f H_m} P' - \frac{\beta L_{ab}}{H_m} T'$$

(5.1)

where β is the change in melt rate per °C, Γ is the temperature lapse rate in the atmosphere (°C per km), and P' and T' are annual departures from the long-term mean of the winter precipitation, calculated across the entire glacier surface, and the summer temperature, calculated across only the glacier's ablation zone.

5.3 Discussion of Model Physics

Equation 5.1 is a linear, 1st-order differential equation that is readily solved using standard techniques in time increments of 1 year. P' and T' are the forcings on the system, and so Equation 5.1 is equivalent to a 1st-order auto-regressive process. The first term on the right-hand side of this equation presents the normal term of a differential equation that, in the absence of forcing, restores the glacier to its equilibrium state. The second and third terms represent the climatic forcing separated into precipitation and temperature, respectively. This linearized glacier model, common to both Oerlemans (2004) model and that of Appendix A, has a tendency to relax towards the equilibrium state with characteristic timescale or "memory", τ, which is a function of the glacier geometry and the sensitivity of ablation to temperature:

$$\tau = \frac{H_m}{\beta \Gamma \tan\theta L_{ab}}$$

(5.2)

This timescale can also be regarded as that over which the physical glacier system cumulatively integrates the mass balance perturbation. In the model of Johannesson *et al.* (1989), the equivalent timescale is notated by H/b, where b is the terminus melt rate. The denominator in Equation 5.2 plays the equivalent role of b in this model. Increasing the value of β, Γ, tanθ, which affect the change in melt rate per unit distance upglacier, or L_{ab}, the area of the ablation zone, increases the ability of the glacier terminus to accommodate an increase in the mass balance. The time scale of this response is inversely proportional to these parameters. Conversely, increasing the ice thickness (H_m) results in a greater amount of mass that must be removed for a given climatic change.

The model is a gross simplification of a real glacier system, and it is important to emphasize the assumptions. This simplified model does not account for the effects of cloudiness, sublimation, wind, humidity, or orographic precipitation, and thus it only represents a first-order assessment of glacier fluctuations due to climate forcing. Second, the imposed glacier geometry of the model, which neglects any changes in ice thickness, dictates that ice dynamics redistribute the mass-balance perturbations so that all mass added to the accumulation area is effectively added to the tongue. Finally, although this model does not represent any lag in the mass balance perturbation being conveyed to the terminus, the qualitative and quantitative behavior is captured sufficiently well to represent characteristic length variations in response to characteristic climate variations (Harper, 1992; Harrison, 1970; Leonard, 1989; Long 1955).

5.4 Equilibrium Response to Changes in Forcing

It is useful to consider the steady-state response of the glacier system to changes in precipitation and temperature. Equation 5.1 can be rearranged and used to make an estimate of the steady-state response of glacier terminus, ΔL, to a separate change in winter precipitation (ΔP) or summer temperature (ΔT). In steady state $dL'/dt = 0$, and so rearranging Equation 5.1 to solve for the length change ΔL in response only to a change in the average summer temperature, ΔT, gives

$$\Delta L = \frac{\Delta T}{\Gamma \tan \theta} \tag{5.3}$$

Equation 5.3 can be understood as a temperature balance where the product of ΔL and Γ $\tan \theta$ represents the temperature change at the new terminus, which in equilibrium, must equal the imposed temperature perturbation. Note that only the temperature lapse rate and the slope of the bed are required to determine the sensitivity of glacier length to atmospheric temperature changes.

In response solely to a change in winter precipitation, ΔP, Equation 5.1 can be rearranged to give

$$\Delta L = -\frac{A}{W_f \beta \Gamma \tan \theta L_{ab}} \Delta P \tag{5.4}$$

Equation 5.4 is more complicated than 5.3 because both the imposed geometry of the glacier and the melt rate at the terminus are required to account for the accumulation and the area added to the glacier tongue.

The ratio of equations 5.3 and 5.4 can be used to determine the relative forcings of precipitation and temperature (R) in determining glacier length fluctuations:

$$R = \frac{\Delta L_p}{\Delta L_T} = \frac{W_f \beta L_{ab} \Delta T}{A \Delta P} \tag{5.5}$$

The individual contributions of precipitation and temperature to glacier mass balance have been a long-standing issue, and this model provides a simple method for such accounting.

5.5 Model Parameters and Climate Inputs

Most of the model parameters are readily determined or available from the literature. The value of β, the melt rate at the terminus per °C, is assumed to range from 0.5 to 1.7 m °C^{-1} yr^{-1} based on a variety of published values (e.g., Huybrechts et al., 1991; Roe and Lindzen, 2001; Pollard, 1980; Calov and Hutter, 1996). The temperature lapse rate in the atmosphere, Γ (°C m^{-1}), is not consistent and changes with local environmental conditions. For the model used in this study, a range from -6° to -8 °C km^{-1} is considered. Its role is to reflect the change in the terminus temperature that accompanies a change in the altitude of the terminus as the glacier length changes. Parameters related to glacier

geometry were derived using 7.5' U.S. Geological Survey topographic maps (Table 5.1) and past glacier-length data from Harper (1992), Thomas (1994), Fuller (1980), Burke (1974), and more recent data presented in Chapter 4 of this dissertation.

Regional climate data synthesized from 10 stations (Figure 5.3) show a strong regional correlation between stations for both winter accumulation and summer ablation (Figure 5.4), with strong spatial correlations for each parameter year by year. The two different parameters (i.e. precipitation and temperature), however, are not at all correlated with each other (i.e., R=0.01). Although the magnitude of precipitation and temperature is different between localities, the strong year-by-year similarity in the trends of the climate data suggests the presence of a regional signal.

The climate data for the 1930 to 1990 model of Mount Baker glaciers are from the Diablo Dam weather station, approximately 60 km from Mount Baker (Figure 5.3). The precipitation perturbation (P') was calculated as the annual deviation from the average of the October through April 30 precipitation values from 1931 to 1990. The temperature perturbation (T) was calculated as the annual deviation from the average mean monthly temperatures from May 1 through September 30 for the years 1931 to 1990.

Although short-term glacier fluctuations can be modeled using historical climate data over the last 75 years, no climate data exist that support millennial-scale modeling. To assess likely glacier fluctuations on this longer timescale, a 2000-year realization

using normally distributed random values equal to that found in the observed record were

generated using climate data from the Diablo Dam station where $\sigma_P = 0.38$ and $\sigma_T = 1.37$.

These data allow the model to simulate glacier length variations on millennial time

scales, driven solely by climatic fluctuations of a magnitude observed over recent time,

which can be compared to a similar interval of moraine deposition in the geologic record.

5.6 Historical Fluctuations of Mount Baker Glaciers

The historical maps, photos, and reports of Mount Baker glaciers indicate that

they were retreating rapidly from 1931 to 1940, paused, and then began readvancing

between 1947 and 1952 (e.g., Harper, 1992; Long, 1955). This advance continued until

approximately 1980 when these glaciers again began to retreat. Although Rainbow and

Deming glaciers began to advance about 1947, earlier than the other Mount Baker

glaciers, the relative amount of terminal movement between 1947 and 1980 is between

600 and 700 meters for each Mount Baker glacier, underscoring the similar length

responses of these glaciers over this period.

Using the Diablo Dam climate data to drive the model of Equation 5.1, modeled

length changes for Mount Baker glaciers are consistent with the observed length

fluctuations over the period from 1931 to 1990 (Figure 5.5). They account for maximum

changes in glacier length on the order of 600 meters, very similar to the observed data for

this period and 25% of the observed magnitude of the glacier-length changes over the last

two hundred years. The model glacier fluctuations track the general pattern of observed

advance and retreat, but they show a delayed response of ca. 10 years to the advance of 1947, a likely result of the exclusion of a lag time in the model.

For the period of climatic variation between 1930 and 1990, the value of R in Equation 5.5 ranges between 0.9 and 1.1, based on the range of geometric and glacier melt-rate parameters for the study glaciers. These results suggest that the individual components of precipitation and temperature are approximately equal contributors to the length variations of these glaciers, and that neither should be considered in isolation (Figure 5.6).

5.7 Millennial Scale Glacier-Length Variation

Because of the apparent success at simulating glacier-length variation using historical climate data, the model may provide a credible means for estimating length-scale variations during all of the late Holocene. The lengths of the Mount Baker glaciers studied here decreased between 1.3 and 2.5 km from the 19th century to 1990. This retreat was most pronounced at Boulder Glacier and least pronounced at Rainbow Glacier (Table 5.1). Using equations 5.3 and 5.4 with the aforementioned ranges of β, Γ, and average glacier geometries for Mount Baker, the model indicates that a temperature change between 2.8 and 6.3°C or an increase in the annual precipitation between 1 and 3 m yr^{-1} is needed to account for the average change in glacier length since the 19th century. Using white noise with an amplitude equal to 1 σ of the temperature and precipitation values

from the 1931 to 1990 data and characteristic Mount Baker glacier geometries, model

runs result in glacier-length fluctuations of 2.0 km (Figure 5.7).

5.8 Discussion

Using the 1930 to 1990 climate data, simulated glacier-length variations are

similar to observed values over that period suggesting that the model captures the general

pattern of glacier advance and retreat using a range of plausible glacier parameters. These

results also indicate that a simple geometric response model can account for the

magnitude of glacier-length variation seen in the observed geologic record. The advance-

retreat phases and subsequent fluctuations in glacier length on Mount Baker are nearly

equally affected by both summer temperature and winter precipitation.

Within the bounds of the observed natural variability in climate expressed by data

between 1931 and 1990, the 1.3- to 2.5-km length fluctuations on Mount Baker recorded

during the late Holocene can be accounted for by the model without recourse to

systematic shifts in climate. Although a variety of forcings commonly are used to explain

glacier-length fluctuations on centennial to millennial scales [e.g., changes in the strength

of the polar vortex (O'Brien et al., 1995), atmospheric dust from volcanic eruptions

(Robock and Free, 1996), and variations in sunspot activity (Soon and Baliunas, 2003)],

the model results indicate kilometer-scale fluctuations do not require a substantial change

in temperature or precipitation and should be expected simply from natural year-to-year

variations.

To attribute regional (or even global) glacier responses to a systematic climate forcing, we must be compelled to do so. In particular, to attribute the 19th century moraines (or others deposited during the late Holocene) on Mount Baker to a distinct climate change, that change would presumably have to be larger or of longer duration than current climatic variability over the past 75 years, a condition that is not required by the model predictions. Furthermore, any systematic regional or global climate change would be superimposed on top of the natural variability, which would continue to exist as well. This would complicate the identification of any such global signal and require an even greater magnitude of change before it could be recognized unequivocally.

The model presumes that glaciers on low-gradient beds at lower elevations are slower to respond to regional climate variability than those on steeper beds or at higher elevations, but that they are very sensitive to temperature change. Several of the glaciers on Mount Baker, like those on other large Cascade volcanoes, reached low elevations and had low slope angles in the late 19th century. Under an anthropogenic increase in temperature of 1°C, such low-elevation glaciers are simulated to retreat approximately 1 kilometer. If recent global warming is a factor in the recent glacier retreat, a new equilibrium condition for this climate change would result in retreat to steeper slopes at higher elevations where these glaciers would respond more rapidly to climate perturbations (i.e., faster, shorter length-scale responses to local climate variations).

The long-term kilometer-scale fluctuations predicted by the model also provide the opportunity to suggest alternate interpretations or scenarios for moraine ages that are often attributed to poorly dated glacier advances from the 12th to 19th centuries. Many of these older moraines at Mount Baker and in other Cascade glacier forelands with similar physiographic settings and glacier geometries have been dated by dendrochronology using tree species that are at the limit of their lifespan. The range of glacier fluctuations produced by the model, combined with these poor constraints in the actual landform ages, suggest that these moraines may be products of even earlier advances, not necessarily synchronous with each other and certainly not necessarily part of a global pattern of climate fluctuations. Random climatic fluctuations over the past 1000 years may have been ample to produce large changes in glacier length, and until quantative-dating techniques can used to reliably correlate widely separated advances from this interval, these advances cannot be used as the primary evidence for a synchronous signal of regional or global climate change.
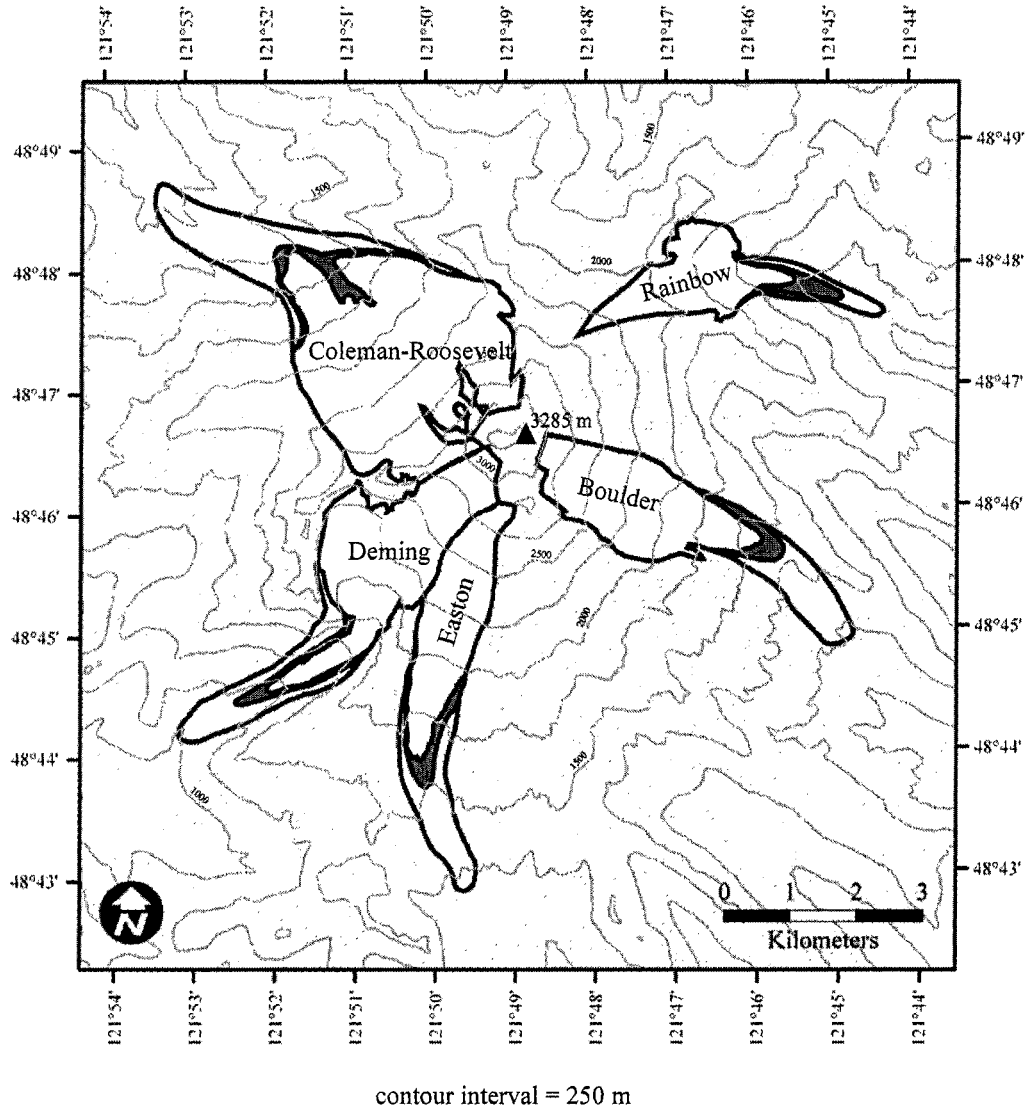
contour interval = 250 m

Figure 5.1. Map of the five Mount Baker study glaciers with 1990 U.S.
Geological Survey 7.5' topographic contours. The 1990 glacier areas are in white.
The dark gray and light gray areas represent the estimated change in glacier
extent since 1931 and the most recent Little Ice Age maximum positions,
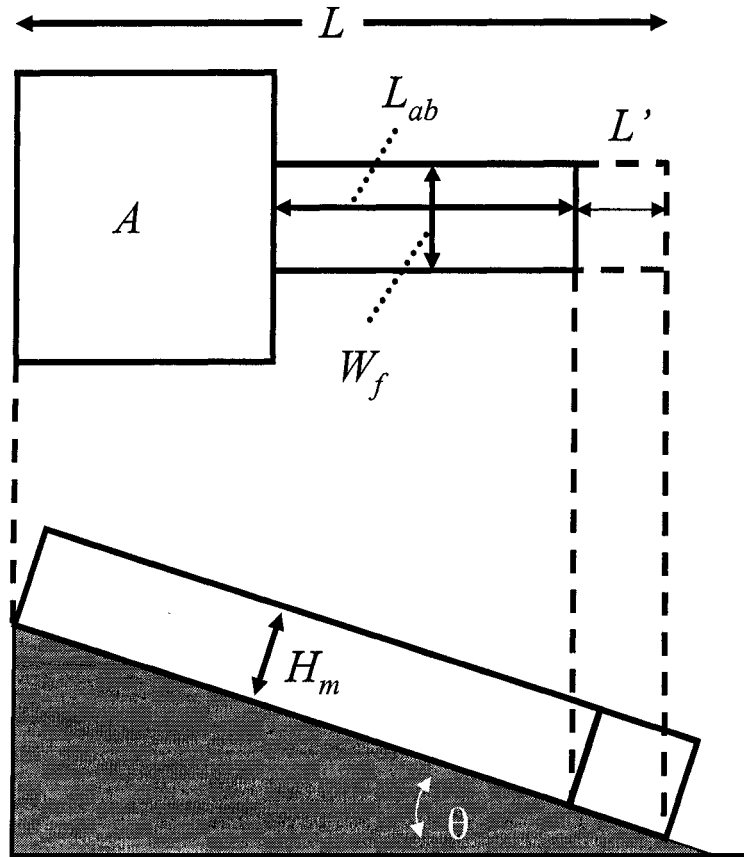respectively.

Figure 5.2. Schematic diagram of a simple model glacier from an aerial view (top) and in profile (bottom) where A is the accumulation area, L_{ab} is the length of the ablation zone, W_f is the width of the tongue, H_m is the characteristic ice thickness, θ is the characteristic slope of the bed, L is the glacier length from the head walls to the terminus, and L' is the a perturbation length that is added as a result of a change in the mass balance.
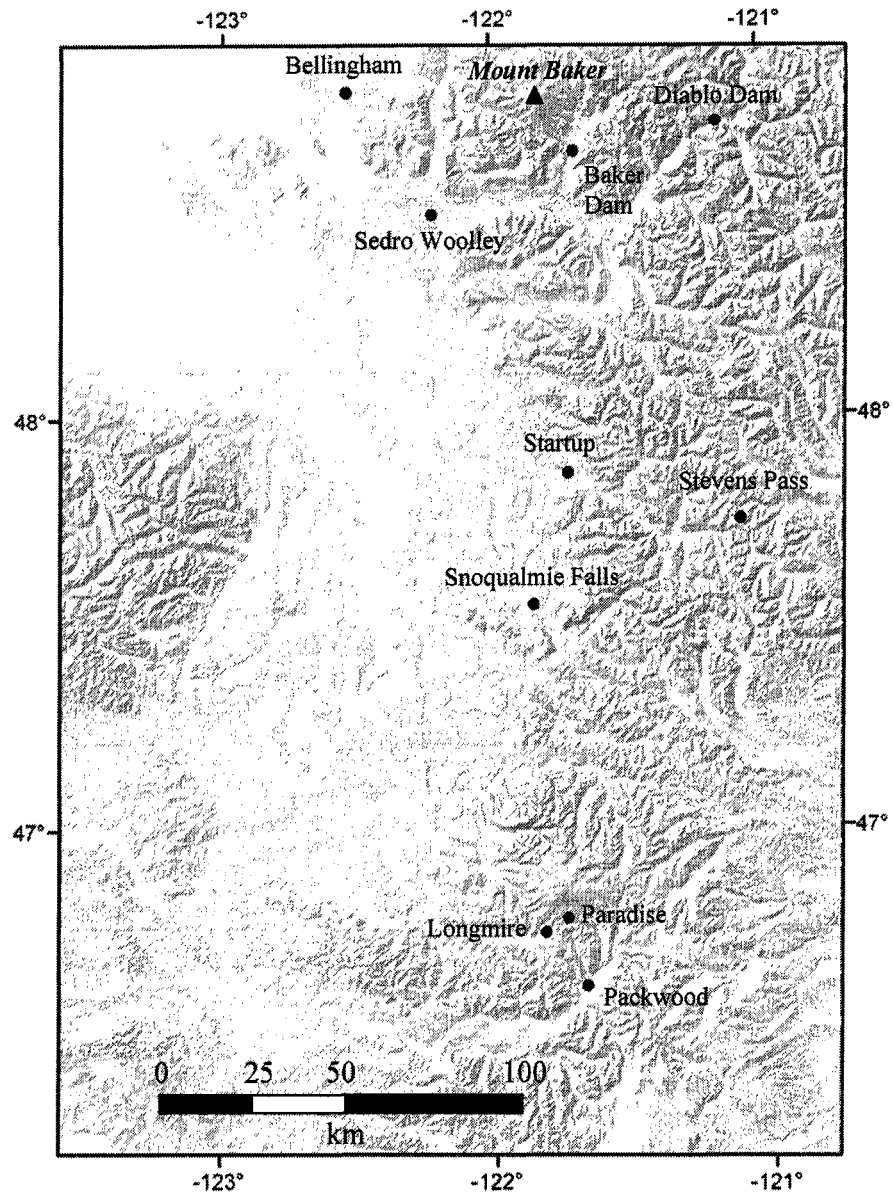
Figure 5.3. A shaded relief map of western Washington displaying the station locations for the climate data presented in this study.
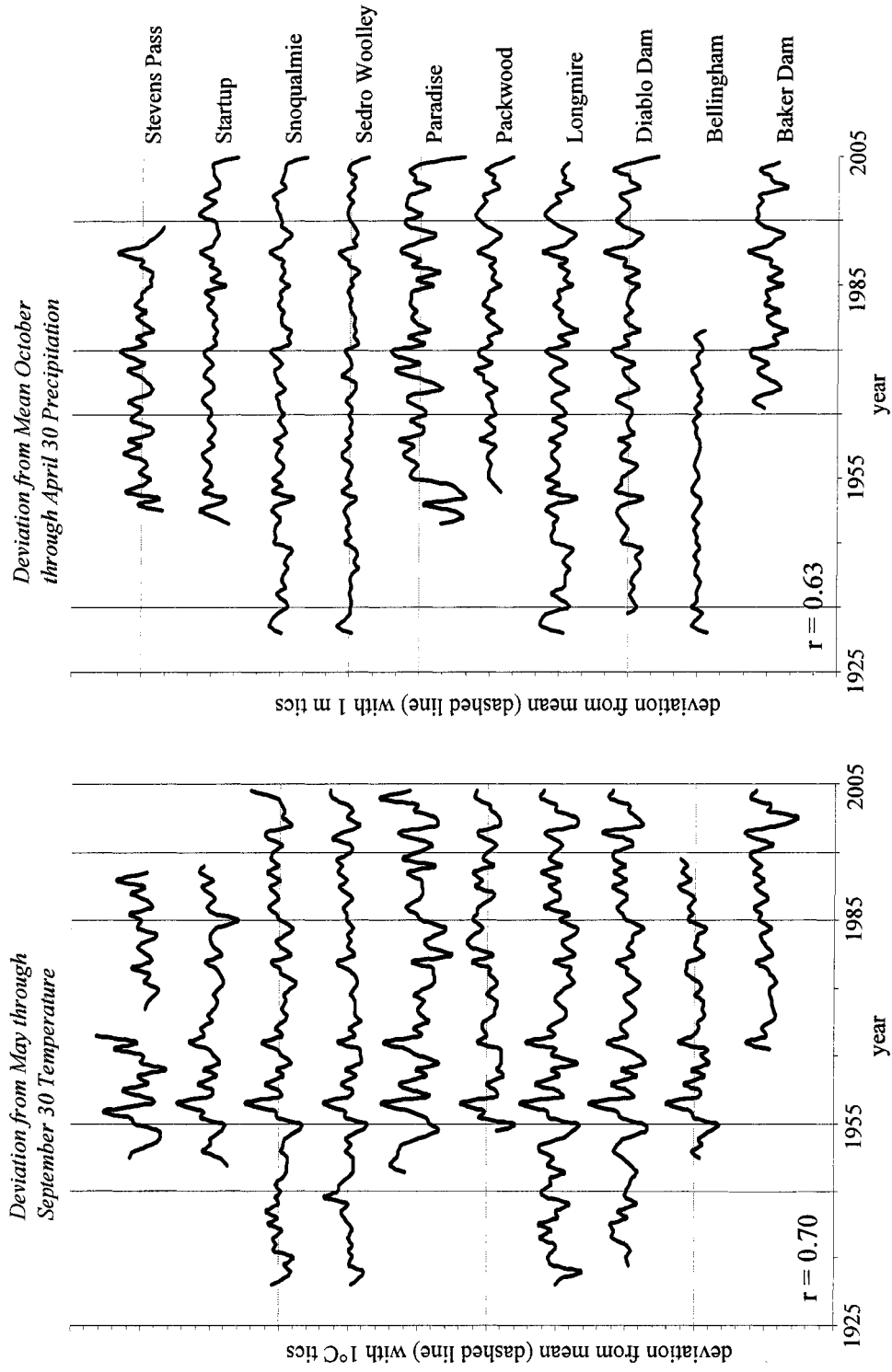
Figure 5.4. Precipitation and Temperature data from 10 stations in the Puget Lowland and Cascade Range of Washington (see Figure 5.3 for station localities)
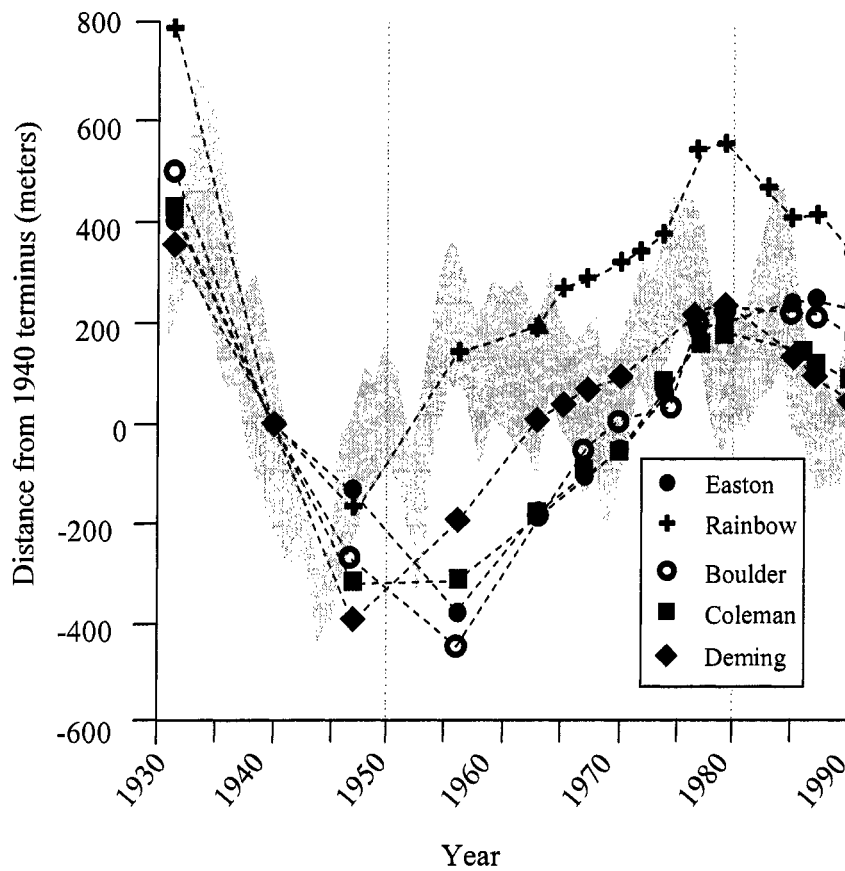
Figure 5.5. Model glacier-length variations from 1931 to 1990 for the five Mount Baker glaciers (gray) compared to historical glacier fluctuation record from Harper (1992) and Chapter 4 of this dissertation.
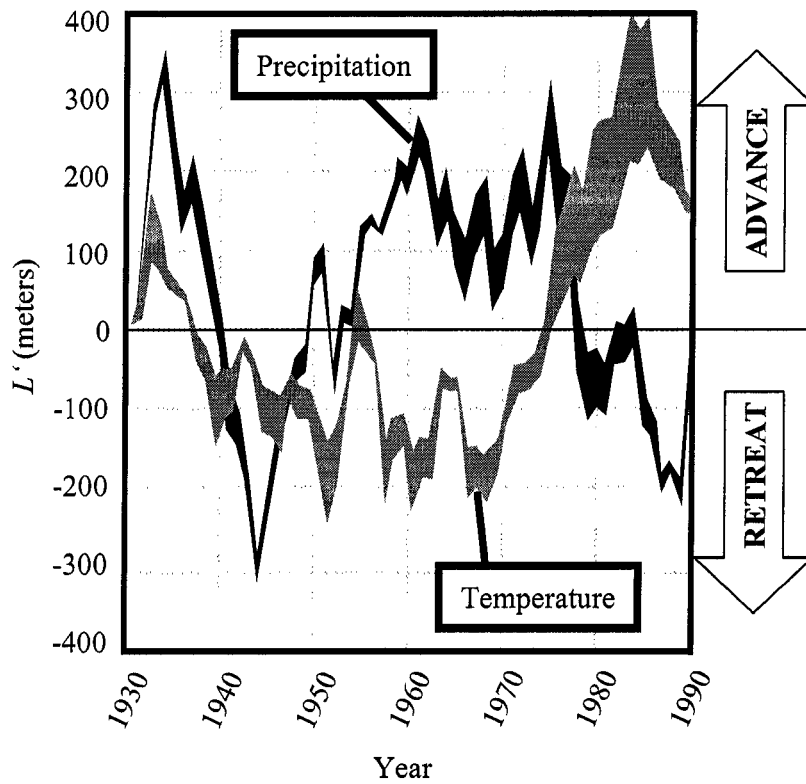
Figure 5.6. Model glacier length perturbations (L') separated by the relative contribution of temperature (gray) and precipitation (black) forcing for a glacier with Easton-like dimensions.
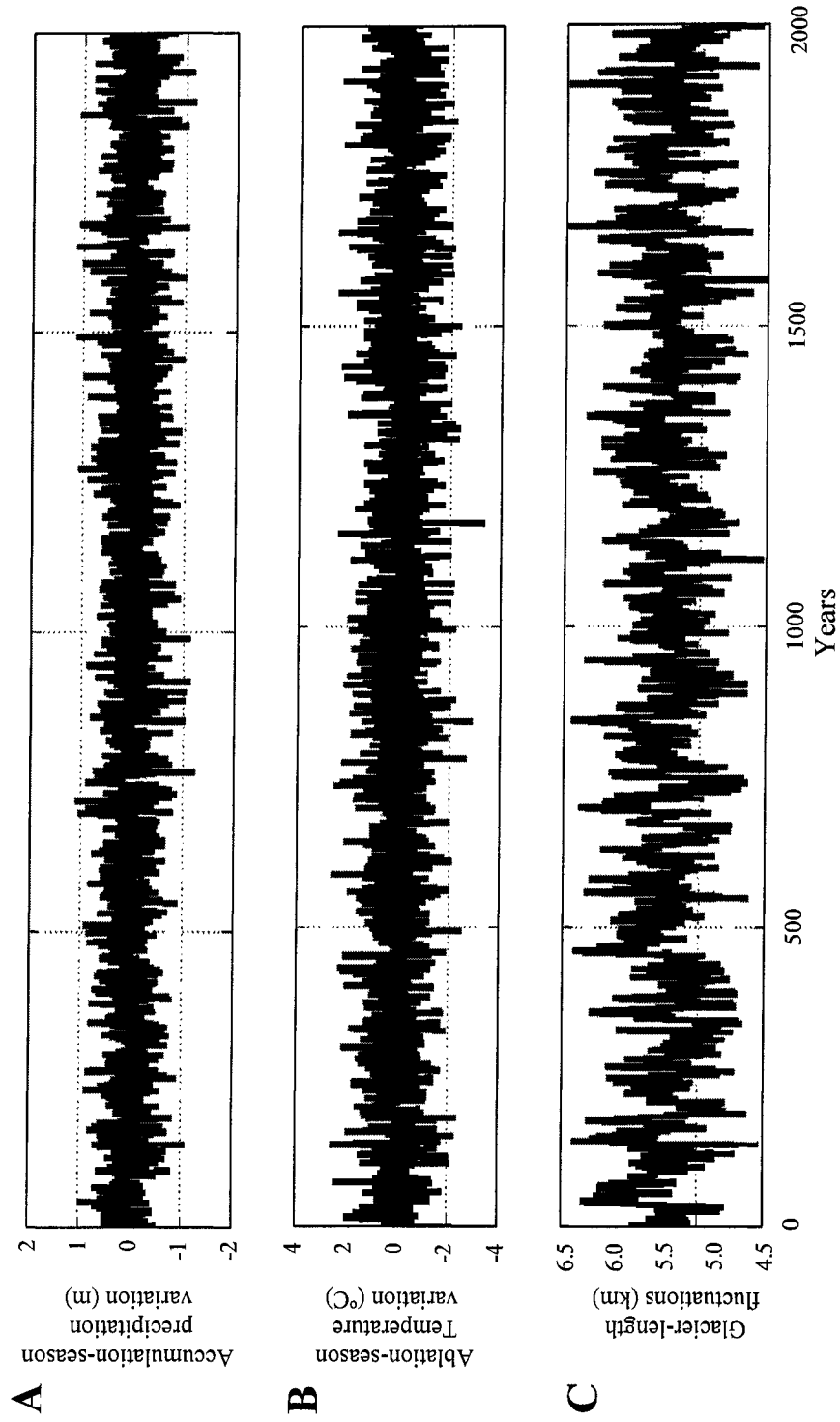
Figure 5.7. Perturbations for (A) precipitation and (B) temperature produced from random values within 1σ of 1931 to 1990 Diablo Dam data. Subset (C) is the model glacier-length fluctuations that result from using average geometry, temperature, and melt-rate parameters from the Mount Baker dataset.

Glacier Name	Little Ice Age maximum length (km)	1930 Length (km)	1990 Length (km)	average slope (θ) (degrees)	average thickness (Hm) (m)	LIA maximum area (A) (km2)	1931 area (A) (km2)	1990 area (A) (km2)	characteristic tongue width (Wf) (m)
Boulder	5.8	4.0	3.7	25	45	5.05	3.95	3.62	550
Coleman	6.5	4.7	4.4	25	39	11.48	9.34	8.89	650
Deming	6.8	5.4	5.1	20	45	6.18	4.89	4.6	450
Easton	6.7	5.5	4.2	19	51	4.37	3.21	2.86	550
Rainbow	5.6	4.6	3.5	18	47	3.02	2.62	2.35	300

Table 5.1. Glacier geometry data that are discussed in the text and used for the model in this study.

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VITA OF MICHAEL AARON O'NEAL

EDUCATION

2005   Ph.D. Geological Sciences, University of Washington, Seattle, WA.

1998   M.S., Geology, Indiana University, Indianapolis, IN.

1993   B.A., Anthropology, Indiana University, Bloomington, IN

PROFESSIONAL EMPLOYMENT

Research

2004 - 2005   Research Scientist – Puget Sound Regional Synthesis Model (PRISM), Dept. of Earth and Space Sciences, University of Washington

2003 -   Assistant to the Editor – Quaternary Research, supervised by Alan Gillespie

2001 - 2005   Research Scientist, Quaternary Geology, Pacific Northwest Center for Geologic Mapping Studies, Dept. of Earth and Space Sciences, University of Washington

2001 - 2005   Research Assistant, University of Washington, supervised by Derek Booth

1998 - 2001   Quaternary Geologist / GIS Specialist, Environmental Section, Indiana Geological Survey: Indiana University, Bloomington, Indiana.

1995 - 1998   Research Assistant, Geology Department, Indiana University-Purdue University at Indianapolis.

1992 - 1993   Field Archaeologist, Glenn Black Laboratory of Archaeology, Indiana University, supervised by Ann Kroll.

1991 - 1993   Laboratory Coordinator (Archaeology Laboratory), Indiana University Department of Anthropology, supervised by Della Collins Cook, Ph.D.

Teaching

2002 - 2005   Fluvial Geomorphology - Field and Lab Instructor, University of Washington, supervised by Derek Booth (2002-3) and Dave Montgomery (2003-5).

1998 - 2000   Adjunct Faculty, Indiana University-Purdue University at Indianapolis. 723 West Michigan Street, Indianapolis, IN 46202. Chairman: Dr. Gabriel M. Filippelli

Courses Presented at IUPUI and the University of Washington

Fluvial Geomorphology Laboratory (G412/426)
Urban and Environmental Geology (G300)
Sedimentology and Stratigraphy Laboratory (G334)
Physical Geology Lecture and Lab (G110/G120)
Introduction to Glacial Geology (G130)
Global Climate Change Short Course (G130)
Environmental Geology Lecture and Lab (G107/G117)
Evolution of the Earth Lecture and Lab (G109/G119)
Global Environmental Change Laboratory (G185)

PUBLICATIONS

Manuscripts

in press   Putkonen, J. and O'Neal, M.A. Quaternary Degradation of Unconsolidated Landforms in the Western North America. Submitted to *Geomorphology*.

in review   O'Neal, M.A. Calendric Ages of Rock Surfaces in the Cascade Range of Washington and northern Oregon Based on Lichenometric Dating. Submitted to *Arctic, Antarctic, and Alpine Research* 12/10

2005   O'Neal, M.A., M. O'Mansky, and J. MacGregor, in review., A diffusion model of earthen wall degradation at the Hopewell Site (33RO27), Chillicothe, Ohio. *Geoarcheology*, Vol. 20, No. 7.

2003   O'Neal, M.A. Multivariate statistical analysis of sediment samples from site 45SJ169, Decatur Island, WA. In: Site 45SJ169 Excavations. State of Washington Department of Ecology. J.K. Stein (ed.).

2003   O'Neal, M.A., K. R. Schoenenberger, A *Rhizocarpon geographicum* growth for the Cascade Range of Washington and northern Oregon, USA. Quaternary Research Vol. 60 No. 2, pp. 233-241.

2001   O'Neal, M.A., L. P. Tedesco, C. Souch, and J. F. Pachut. A pollen zonation of southwestern Florida using multivariate statistical methods and its application to two vertical sedimentary sequences. Bulletins of American Paleontology, 361: Ch. 6.

2001   Hasenmueller, N., T. Branam, N. Bleuer, and M.A. O'Neal. Evaluation of Ground-Water Age and Chemistry Relations in Aquifer Systems in Lake, Porter, and LaPorte Counties of Indiana. Indiana Geological Survey OFS01-21

Manuscripts (continued)

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2000   O'Neal, M.A. and N. Bleuer. Ice-Marginal Moraines of Indiana. Indiana Geological Survey Open File Study 00-6.

2000   Brown, S.E., N.K. Bleuer, M. O'Neal, J. Olejnik, and R. Rupp, Glacial Terrain Explorer. Indiana Geological Survey Open-File Studies, OFS00-08.

1998   Hall, R.D. and M.A. O'Neal. Geology of the deposits of the Bat Room Cave: An Open-File Report for the Indiana State Museum, Indianapolis, IN. 70 p.

1996   Nelson, T.A., Zetwo, M., Klay, J., Blackwelder, P., Alvarez-Zarikian, C., Hood, T., Leal, J., Swart, P.K., Lutz, M., Wanless, H., Trefry, J., Metz, S., Kang, W.J., Tedesco, L.P., Capps, M.A., O'Neal, M.A. The Sediment Record as a Monitor of Natural and Anthropogenic Changes in the Lower Everglades/Florida Bay Ecosystem: Progress Report to NOAA's Coastal Ocean Program, 66 p.

Maps

2004   O'Neal, M. A. Geologic map of the Lake Wooten, Washington 7.5-minute quadrangle: U.S. Geological Survey, unnumbered map as of 09/04, scale 1:24,000.

2004   O'Neal, M. A. Geologic map of the Lilliwaup, Washington 7.5-minute quadrangle: U.S. Geological Survey, unnumbered map as of 09/04, scale 1:24,000.

2001   Bleuer, N.K., O'Neal, M. A., and Olejnik, J., Geologic map of the Arcadia, Kempton, Sheridan, and Tipton, 7.5-minute quadrangles: Indiana Geological Survey OFS.

2000   O'Neal, M.A. Physiographic Map of the State of Indiana. Indiana Geological Survey Open-File Study 00-3, scale, 1:500,000.

2000   O'Neal, M.A. Color Elevation Map of the State of Indiana. Indiana Geological Survey Open-File Study 00-4.

Papers Presented at Meetings

2004 O'Neal, M.A. Moraine degradation processes as a primary control on the size-frequency distribution of a lichen population. GSA Annual Meeting, Denver CO. Geological Society of America Abstracts with Programs, Vol. 36, No. 5, p. 282

2004 Murphy, R.C and O'Neal, M.A. Identifying Late Little Ice Age Terminal Positions on Mount Baker WA. GSA Annual Meeting, Denver CO. Geological Society of America Abstracts with Programs, Vol. 36, No. 5, p. 497

2003 O'Neal, M.A. A Diffusion Model of Earthwork Degradation of the Earthen Walls at the Hopewell Site (33RO27), Chillicothe, Ohio. GSA National Convention Program with Abstracts, Seattle.

2003 O'Neal M.A. And K. Schoenenberger. A *Rhizocarpon geographicum* Growth Curve for the Cascade Range of Washington and Northern Oregon. XVI INQUA Congress, Programs with Abstracts, Reno, NV.

2002 O'Neal, M.A. The Effects of Moraine Degradation on Lichenometric Dating of Little Ice Age moraines. GSA Cordilleran Meeting, Corvallis, OR, Abstracts.

2001 Shimel, S., K. Troost, M.A. O'Neal, D.B. Booth, and K. Blouke. Spatial Database for Enhanced Geologic Mapping in Seattle, WA. GSA Annual Meeting, Boston, MA, Abstracts.

2001 Tedesco, L. P., C. Souch, J.F. Pachut, and M.A. O'Neal. Using Transported Pollen Records to Determine Freshwater Flow in the Shark River Slough, Everglades National Park. GSA North-Central Meeting, Indianapolis, IN.

1999 Zuppann, C.W. and M.A. O'Neal. Three-dimensional modeling of the Ste. Genevieve Limestone Shoal Complex at Owensboro North Consolidated Field, Gibson County, Indiana. Amer. Ass. of Petroleum Geol. Eastern Section Annual Meeting, Indianapolis.

1999 Tedesco, L.P., C. Souch, J.F. Pachut, M.A. O'Neal, and J.M. Arthur. A century of Shark River flow as determined from a transported pollen record. Estuarine Research Federation Biannual Convention, New Orleans, Abstracts, p. 102

1999 O'Neal, M.A., Olejnik, J.R., Bleuer, N,K, and Brown, S.E., GIS based geologic analysis and multidisciplinary data exchange. GSA North-Central Meeting, Abstracts, Posters.

1998 Nelsen, T., Wanless, H.R., Blackwelder, P., Hood, T., Alvarez, C., Swart, P., Trefry, J.H., Kang, W., Tedesco, L.P., and O'Neal, M.A., The sediment record as a monitor of natural and anthropogenic changes in the Lower Everglades. ASLO/ESA, St. Louis, MO.

1997 O'Neal, M.A., Tedesco, L.P., Pachut, J.F., and Souch, C., The use of multivariate statistical methods in delineating surface pollen zones for southwestern Florida. Geological Society of America Annual Meeting, Salt Lake City, Utah.

1996   Tedesco, L.P., M.A. Capps, and M.A. O'Neal. The sediment record as a monitor of natural vs. anthropogenic change in the Everglades/Florida Bay ecosystem: the pollen record, 1996 Florida Bay Science Conference, Key Largo, Abstracts, Posters.

1996   Nelson, T.A., M. Zetwo, H.R. Wanless, P. Blackwelder, P.K. Swart, T. Hood, C. Alvarez, J. Trefry, S. Metz, W.J. Kang, R. Trocine, L.P. Tedesco, M.A. Capps, and M.A. O'Neal. The sediment record as a monitor of natural and anthropogenic changes in the Lower Everglades/Florida Bay ecosystem, Florida Bay Science Conference, Key Largo.

CONTRACT AND GRANT SUPPORTED RESEARCH

2004   GSA Research Grant, The effects of Pacific Decadal Climate Variations on Glacier Mass Balance in the northwestern US.

2004   Stephen's Earth Sciences Grant for Analysis of Glacial Landform Evolution on Mt Adams, Washington, University of Washington.

2003   Mazamas Grant for mapping late Little Ice Age moraines of the Adams Glacier, Cascade Range, Washington.

2003   U.S. Geological Survey EDMAP Grant for geologic and Geomorphic mapping of the Lake Wooten and Lilliwaup Quadrangles, western Washington.

2003   Stephen's Grant for Analysis of Little Ice Age glacier fluctuations on Mount Baker, Washington, University of Washington.

2003   GSA Grant for developing a diffusion model of earthwork degradation at the Hopewell Culture National Monument, Chillicothe, Ohio.

2000   U.S. Geological Survey National Cooperative Geologic Mapping Program, State Map project. Glacial terrain mapping of the Michigan/Indiana corridor and Indiana Heartland.

1999   U.S. Geological Survey National Cooperative Geologic Mapping Program, State Map project. Glacial terrain mapping in the Indiana Heartland.

1998   Indiana Department of Environmental Management, Grant ARN: 99-204. Accelerated Three-Dimensional Glacial Terrain Mapping of Indiana.