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A CHRONOLOGY OF LATE HOLOCENE GLACIER FLUCTUATIONS ON MOUNT RAINIER, WASHINGTON

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ABSTRACT

Lichenometric studies permit close dating for the timing of stabilization of the late Holocene moraines built by North Mowich, Carbon, Winthrop, Cowlitz, and Ohanapecosh glaciers on Mount Rainier. The moraine chronologies indicate synchronous responses among these glaciers during the past 200 yr. Periods of glacier recession began between 1768-1777, 1823-1830, 1857-1863, 1880-1885, 1902-1903, 1912-1915, and 1923-1924. Since the early 19th century, the mean equilibrium-line altitude has risen about 160 m on Mount Rainier.

Minimum ages for earlier glacier variations are based on lichenometric, dendrochronologic, and tephrochronologic data. These data indicate that recessional phases commenced about 1328-1363, 1519-1528, 1552-1576, 1613-1623, 1640-1666, 1690-1695, 1720, and 1750.

Whereas the pattern of glacier fluctuations at Mount Rainier agrees with the general chronologic framework of late Holocene variations from many other areas, comparisons of the detailed moraine chronologies from Mount Rainier for the past two centuries with those from Swedish Lapland indicate several differences in the timing of moraine stabilization. These differences imply some nonsynchrony in Northern Hemisphere glacier variations during the late Holocene.

INTRODUCTION

This study was undertaken in order to establish a more accurate chronology of late Holocene glacier fluctuations on Mount Rainier. Field work was concentrated on the lateral and terminal moraines built by Carbon, Winthrop, North Mowich, and Cowlitz glaciers (Figure 1). Each of these glaciers originates in Mount Rainier's summit ice cap, has an area of 6 to 9 km^2, and has deposited extensive Neoglacial moraine systems in the ablation zone between 1000 and 2000 m altitude. In addition, moraines fronting Ohanapecosh Glacier (1.6 km^2) on the southwest flank of Little Tahoma Peak and several unnamed glaciers (<0.1 km^2) on the north sides of Sluiskin and Crescent mountains were examined. The late Holocene moraines constructed by these glaciers were dated by lichenometry, supplemented by both tephrochronologic and dendrochronologic data.

Preliminary lichenometric studies on Mount Rainier have indicated that the timing of moraine stabilization is probably more accurately determined by lichenometry than by dendrochronology (Porter and Burbank, 1979). Because of the less variable and generally shorter ecesis time for lichens than for

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trees, moraine ages inferred from them are often 10 to 20 yr older than corresponding dendrochronological ages. Many lateral moraines constructed in the 19th and 20th centuries are devoid of trees, but have an abundant lichen cover that permits reliable lichenometric dating. The fact that mature forests are often growing within 50 m of these moraines indicates that proximity to a seed source does not prevent ecesis times from ranging up to 100 yr or more. In contrast to the dendrochronologic histories developed on Mount Rainier (Crandell and Miller, 1964; Sigafoos and Hendricks, 1972), a more synchronous chronology emerges from this lichenometric study.

PREVIOUS INVESTIGATIONS

Several studies that utilized tree-ring counts as age indicators have been conducted on the Neoglacial moraine systems of Mount Rainier (Sigafoos and Hendricks, 1961, 1972; Crandell and Miller, 1964, 1975) and on similar systems in the Pacific Northwest

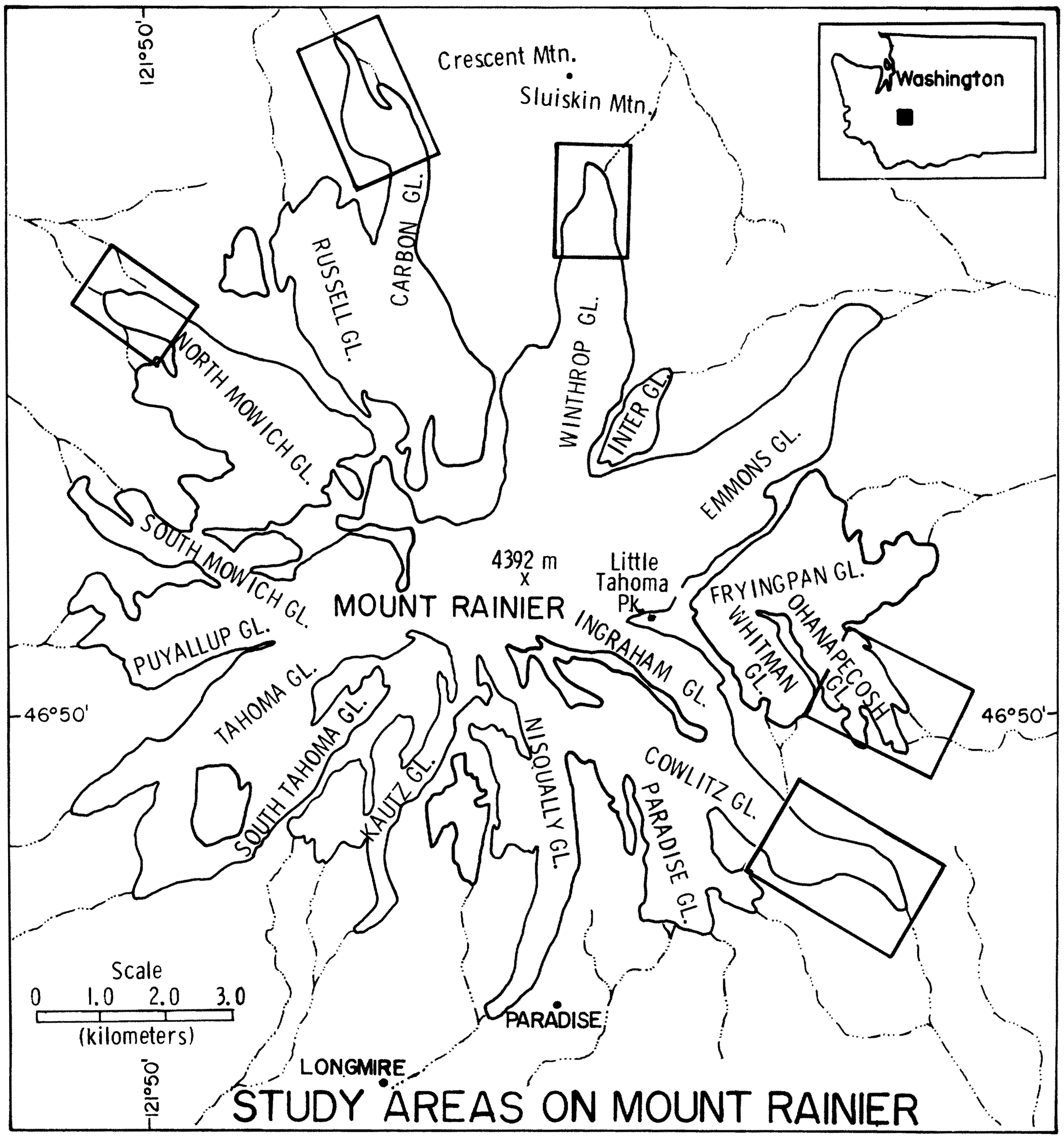

FIGURE 1. Study area (outlined) on Mount Rainier (base from U.S. Geological Survey "Mount Rainier National Park, Washington" topographic sheet).

(Mathews, 1951; Heusser, 1957; Miller, 1969). The dendrochronologic data from Mount Rainier and the spatial distribution of moraines indicate that major recession of glaciers from positions at or near their late Neoglacial maximum extent began between 1822 and 1855 (Table 1). Several earlier broad periods of retreat following major advances are also indicated. However, the accuracy of these dates is affected by several factors, including a poorly known and variable ecesis time, irregular patterns of revegetation, particularly at higher altitudes, and the limited life span of major tree species which may preclude dating of moraines older than 500 to 700 yr.

Lichenometric studies may overcome many of these difficulties. Following the pioneering studies of Beschel (1950, 1961), several more-recent investigations (Beschel and Weidick, 1973; Benedict, 1967, 1968; Denton and Karlén, 1973, 1977; Karlén, 1973; Karlén and Denton, 1976) have demonstrated the utility of lichenometry for dating Holocene deposits. Lichenometric dates can be affected by many of the same limitations as described for tree-ring dates. However, dating of moraines with abundant lichen cover within the altitudinal zones for which the lichen growth curve is valid can minimize these problems. Such lichenometric studies have facilitated the development of more-detailed and accurate chronologies than has been possible in most dendrochronologic and radiometric-dating studies.

TABLE 1
Dendrochronologic ages for moraines on Mount Rainier

Year	Nisqually[a]	S. Tahoma[b]	Tahoma[b]	Carbon[b]	Emmons[b]	Winthrop[b]	Ohanapecosh[b]	Cowlitz[c]
1900					1901			
				1876			1878	
		1864	1857		1854			
	1842	1843	1841	1840			1846	
1800						1822		
								1779
			1761	1763		1760		
					1749		1741	
						1730		
1700								
					1661			
			1640			1655		
			1623		1613			
1600								
					1552			
		1528		1519				
1500								
1400								
								1363
1300								
1200				1217				

[a]Sigafoos and Hendricks (1961).
[b]Sigafoos and Hendricks (1972).
[c]Crandell and Miller (1964).

METHODS OF INVESTIGATION

Botanical Methods

After mapping the glacial geology on aerial photographs at scales of 1:1500 to 1:8000, ages for moraines were determined using lichens, tree-rings, and tephra layers. The lichen growth curve for *Rhizocarpon geographicum* developed by Porter (1981) on the south flank of Mount Rainier formed the basis for all lichenometric dates determined in this study (Figure 2). Lichenometric ages greater than the oldest control point were based on a linear extrapolation of the growth curve. Comparison with growth curves developed in other parts of the world suggests that this extrapolation is probably valid for 400 to 500 yr (Porter, 1981). The techniques of measurement and site selection described by Porter were followed. The maximum diameters of circular or nearly circular lichens were used to date the time of stabilization of the surfaces of interest. Several hundred thalli were examined on each moraine. Typically, the number of thalli in a given size range decreased exponentially as the maximum observed diameter was approached (Figure 3). During this study and similar lichenometric studies in the Alps (S. C. Porter, pers. comm., 1979), it was found that the maximum thallus diameter determined by two workers studying different segments of the same moraine generally varied by 1 mm or less. A precision of 1 mm in the measurement yields an uncertainty of up to 3 yr for surfaces 120 yr old and of 5 yr for those around 200 yr

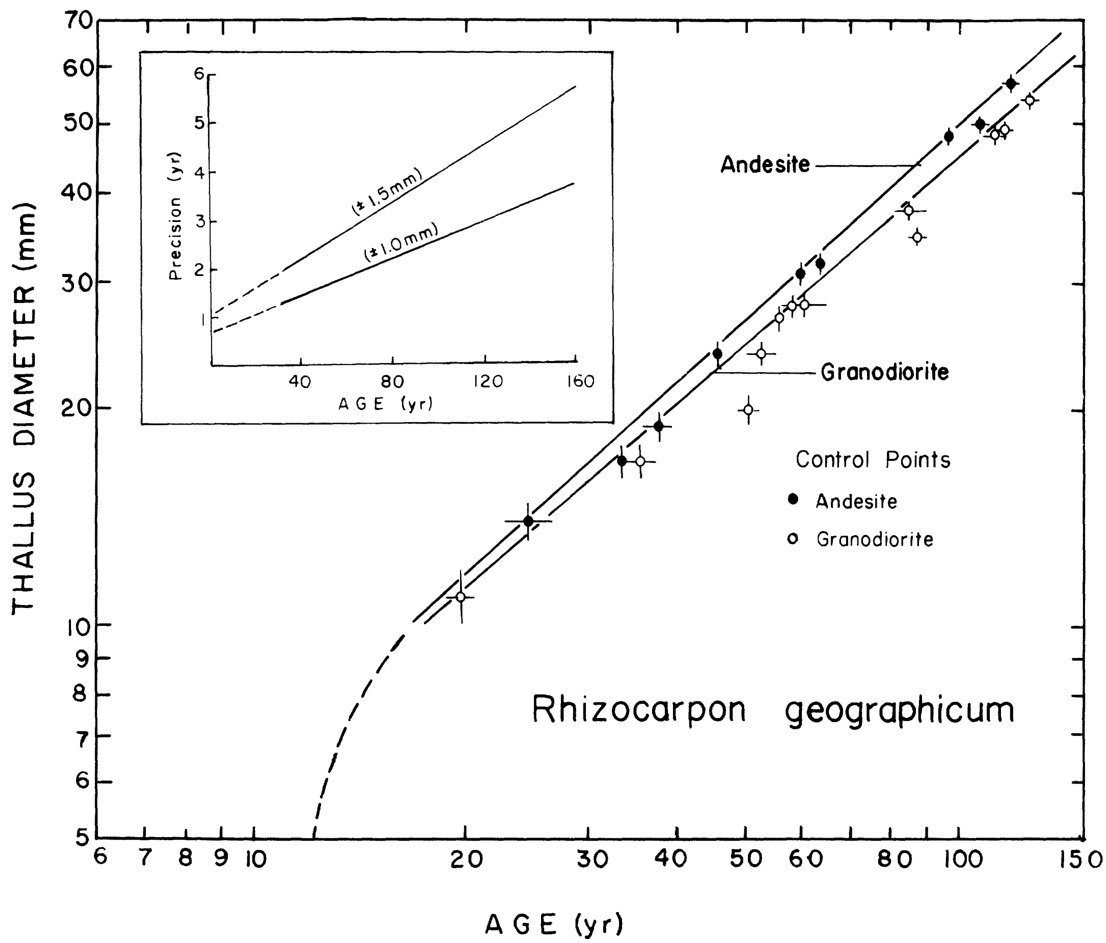

Figure 2. Growth curve for *Rhizocarpon geographicum* at Mount Rainier (after Porter, 1981). Inset shows the estimated error of the lichenometric age as a function of the age of the surface and the precision of the lichen measurement.

old (Figure 2). Lichenometric dates ranging from 300 to 500 yr old should be assigned an uncertainty of 10 to 20 yr. Maximum lichen diameters from historically dated surfaces on the northwest and southeast sides of Mount Rainier conform to the growth curve from the south side and validate its usage all around the mountain between 1000 and 2000 m altitude. On each moraine, measurements were made along the inner slope, the crest, and halfway down the outer slope. Lichenometric ages were assigned only to moraines at least 150 m long which did not show evidence of postdepositional modification due to collapse, rockfall, or accumulation of aeolian sediments, any of which may alter lichen growth rates and the apparent age of a moraine.

Despite the shortcomings of dendrochronology mentioned earlier, tree-ring counts were used to provide minimum dates for forested moraines where lichen growth was inhibited. The techniques described by Sigafoos and Hendricks (1972) were followed in this study. Errors in dating derive primarily from unknown ecesis times and the difficulties of obtaining a core from the true base of the tree and of definitely locating the oldest tree on the moraine. Tree-ring dates provide minimum ages for the times of stabilization of moraines older than 200 yr.

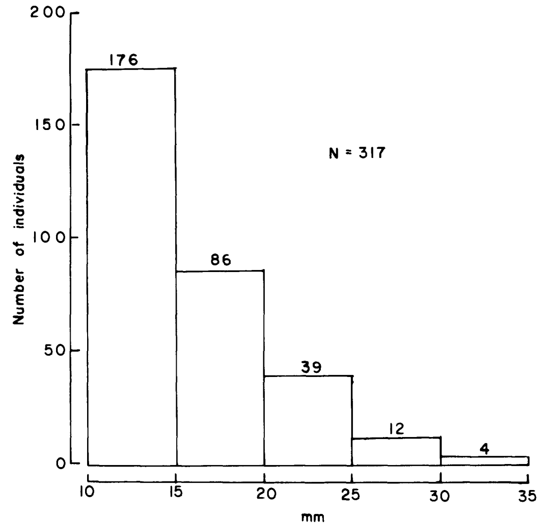

FIGURE 3. Typical size-frequency distribution of *Rhizocarpon geographicum* as found on a Carbon Glacier moraine. The maximum diameter measured on this moraine was 33 mm.

TEPHROCHRONOLOGY

The numerous and readily identifiable tephra layers on Mount Rainier (Mullineaux, 1974) permit broad temporal control of moraine ages. Tephra layers Wn (450 yr BP), C (2200 yr BP), Yn (3400 yr BP), and O (6600 yr BP) served as useful time-stratigraphic horizons. Tephra layers Wn and Yn were erupted from Mount Saint Helens. Layer Wn is a white, coarse sand-sized ash that occurs in beds up to 8 cm thick. Layer Yn comprises very coarse, yellow, pumiceous ash and lapilli that attains a thickness of 2 to 30 cm. Layer O is a silt-sized, orange ash about 2 to 7 cm thick that is a product of the Mount Mazama eruption. Tephras Wn, Yn, and O are distributed throughout most of the study area. Layer C is composed of coarse, brown lapilli that was erupted from Mount Rainier and spread as an irregular layer over the eastern half of the study area. These tephra layers provide bracketing ages for early Garda and Burroughs Mountain advances, as described by Crandell and Miller (1975). Layer Wn is useful for defining areas in which moraines, despite a "fresh" appearance, are older than 450 yr. In addition, moraines that have been constructed during multiple glacial advances can sometimes be identified by the presence of interbedded tephra layers. Sampling for tephra was accomplished through excavation of soil pits and utilization of a 1-m-long soil probe.

The conjunctive use of ash layers, tree-ring counts, and lichen measurements on Mount Rainier permits dating of many late Neoglacial moraines within close limits and allows a limited chronology of glacier fluctuations to be erected.

RESULTS

LICHENOMETRIC AND DENDROCHRONOLOGIC DATES FOR MORAINES

When new debris is no longer being added to a moraine, its surface becomes sufficiently stable for lichens to grow. Since few of the moraines on Mount Rainier have suffered significant mass wasting, lichenometric ages should closely date the time of glacier reces-

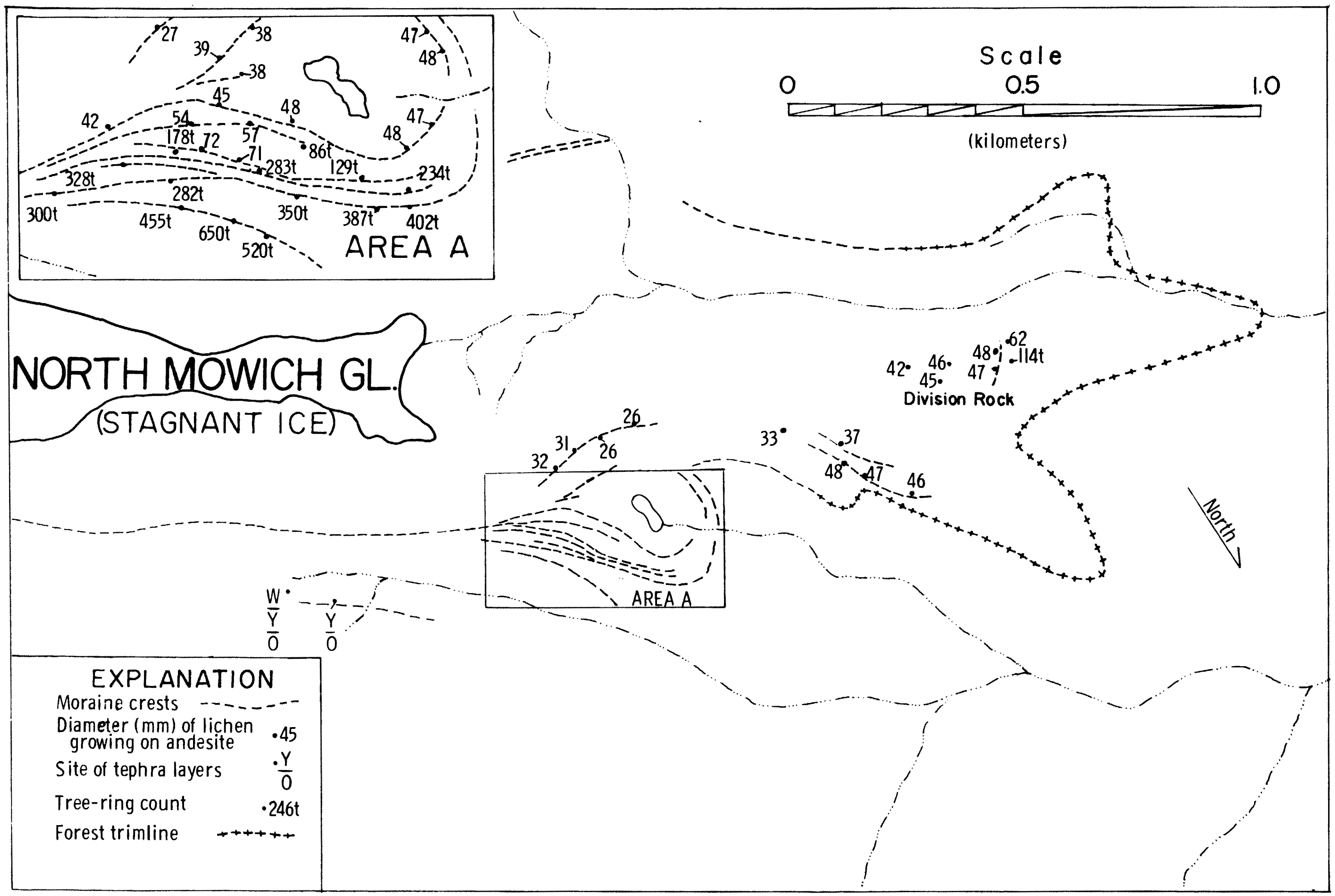

FIGURE 4. Map of lower North Mowich Glacier and associated late Holocene moraines (base from U.S. Geological Survey "Mowich Lake, Washington" 7.5-minute quadrangle, 1971).

sion. Because ecesis times for trees are highly variable, when glaciologic inferences are based on tree-ring counts, this uncertainty in dating should also be considered.

North Mowich Glacier

The terminus of North Mowich Glacier has retreated nearly 2 km from Division Rock since 1880 (Figure 4), and the areal extent of the glacier has decreased more than 30%. The present terminus (1550 m), although active in recent decades, has not readvanced significantly since 1950. Obvious forest trimlines below Division Rock indicate that the glacier advanced below 1240 m altitude during the last century.

This study centered on a series of nested moraines surrounding a small tarn (1630 m) about 1 km east of Division Rock (Figure 4, Area A). These moraines represent the best-preserved record of late Neoglacial advances by North Mowich Glacier (Table 2). The five innermost, concentric moraines support few shrubs or trees, but have an abundant lichen cover. The forested outer moraines have few lichens, but are well suited for dendrochronologic dating of earlier Neoglacial advances by North Mowich Glacier (Table 2). The maximum lichen diameters on the five youngest moraines were 32 mm (equivalent to an age of A.D. 1915), 39 mm (1902), 48 mm (1881), 57 mm (1860), and 72 mm (1826). The four forested moraines yielded dendrochronologic ages of A.D. 1695, 1659, 1576, and 1328 for the innermost ring of the oldest cored tree.

Although tephras Wn, Yn, and O are present nearby, where they mantle moraines of probable late glacial age, an extensive search did not reveal any layer Wn associated with the 1328 moraine. This suggests that local conditions, such as snow cover during an eruption or bioturbation following one, can influence the distribution of tephra. Therefore, although the presence of an ash is a reliable indicator of the minimum age of the feature in question, its absence may not indicate that the feature postdates the eruption.

Table 2
Dates of moraine stabilization on Mount Rainier

Year	N. Mowich	Carbon	Winthrop	Cowlitz	Ohanapecosh
					1955 (a)
		1924 (a)			1923 (a)
	1915 (a)	1914 (a)	1912 (a)	1914 (a)	1915 (a)
1900	1902 (a)	1902 (a)		1903 (a)	
			1885 (a)		
	1881 (a)	1880 (a)		1882 (a)	
	1860 (a)	1863 (a)	1857 (a)		
					1843 (a)
				1830 (a)	
1800	1826 (a)	1823 (a)	1823 (a)		
		1777 (a)		1777 (a)	
			1768 (a)		
			1750 (a)		
		1720 (a)			
1700					
	1695 (b)		1691 (a)		
			1666 (a)		
	1650 (b)				
1600					
	1576 (b)				
---------- scale change ----------					
1500					
1400					
	1328 (b)				

(a) lichenometric date; (b) dendrochronologic date.

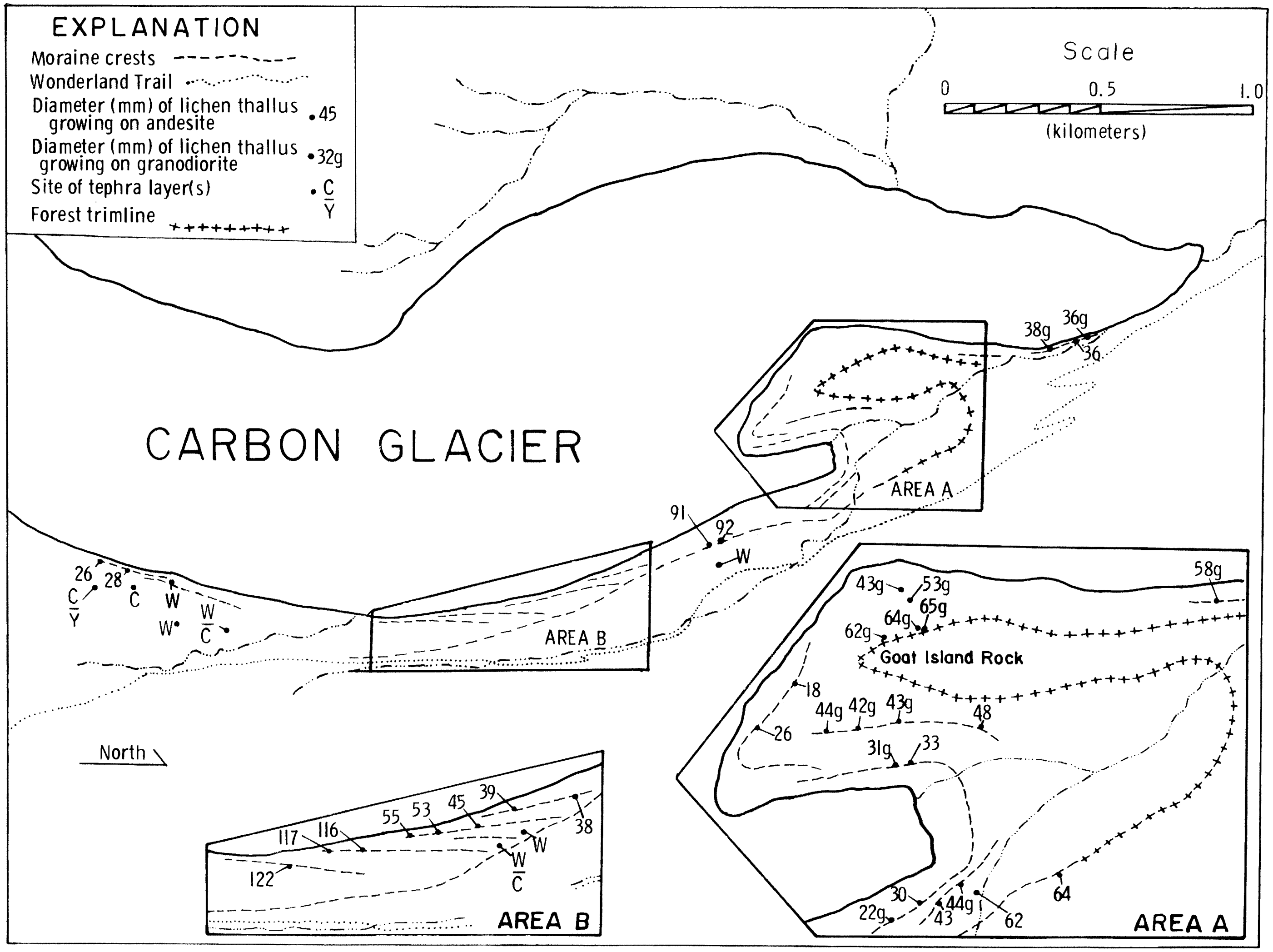

FIGURE 5. Map of lower Carbon Glacier and associated late Holocene moraines (base from U.S. Geological Survey "Mowich Lake, Washington" 7.5-minute quadrangle, 1971).

Carbon Glacier

Carbon Glacier extends to the lowest altitude (1100 m) of any glacier in the conterminous United States. The lower 4 km of the glacier are mantled with a thick blanket of debris derived from rock and ice avalanches. The terminus of Carbon Glacier is very active, having advanced more than 33 m since 1958, and it now lies less than 0.8 km from its maximum Neoglacial position.

Well-developed lateral moraines on the eastern margin of the glacier between 1300 and 1800 m altitude were suitable for lichenometric dating (Figure 5). Near 1650 m, two moraine crests, bearing lichens of 117 mm (1720) and 92 mm (1777), merge to form the major lateral moraine on the eastern margin. Tephra layers Wn and C are found incorporated in this moraine 6 to 8 m below the crest. This indicates that, following the Burroughs Mountain advance between 3500 and 2200 yr ago (Crandell and Miller, 1975), Carbon Glacier remained less extensive for about 2000 yr. However, the recent advances of Carbon Glacier have been at least as extensive as those of the Burroughs Mountain advance, the moraines of which have been overtopped by the 1777 moraine. The presence of layer C requires a reinterpretation of the tree-ring date of A.D. 1217 (Crandell and Miller, 1964) for a lateral moraine that lies beyond the 1777 moraine. This dendrochronologic age may be indicative of the maximum life span of trees at this altitude, rather than times of glacial recession.

Between the 1777 moraine and the glacier, there are several moraine segments that date from 1863, 1903, and 1924, as determined by the oldest lichens found on their crests. Several 65-mm lichens along the prominent trimline around Goat Island Rock indicate that the glacier receded from this position about 1823. Adjacent to the stagnant ice east of Goat Island Rock are moraine crests supporting lichens of 33 mm (1914) and 48 mm (1880).

Because some of the moraine segments surrounding Carbon Glacier are only about 200 m long, dates based on them should be considered minimum ages for moraine stabilization. Despite this limitation, an extensive chronology of moraines has been assembled for Carbon Glacier (Table 2). Direct comparison of this chronology with the dendrochronologic ages determined by Sigafoos and Hendricks (1972) is not possible, because lack of continuity of moraines precludes reliable correlation between different areas. In addition, those moraines dated by Sigafoos and Hendricks lie at a lower altitude than that for which the lichen growth curve is calibrated.

Winthrop Glacier

The second largest glacier on Mount Rainier, with an area of 9 km², Winthrop Glacier extends without interruption from the summit to 1440 m altitude. Below 1650 m, where the active terminus now lies, debris-mantled stagnant ice covers an area of about 1 km². Well-developed Neoglacial moraines surround this region of stagnant ice and include an impressive terminal-moraine complex (Figure 6). Some of these moraines have been dated by dendrochronology (Sigafoos and Hendricks, 1972), but a different chronology emerges from the lichenometric dating (Table 2).

A distinct moraine following the north and west margin of the glacier bears lichens up to 73 mm in diameter and, therefore, dates from about 1823. Between this moraine and the stagnant ice are morainal crests dating from 1912 (34 mm), 1888 (45 mm), and 1857 (59 mm). The moraine adjacent to Winthrop Glacier on its eastern margin supports lichens up to 46 mm (1885) and is considered correlative with the western moraine bearing lichens up to 45 mm.

The extensive terminal-moraine complex, which is better preserved than any other in this study area, contains five moraines that bear lichens up to 138 mm in diameter. Times of stabilization of these moraines, as indicated by lichen size, are 1823 (73 mm), 1768 (96 mm), 1750 (102 mm), 1691 (128 mm), and 1666 (138 mm). Because these dates are based on a linear extrapolation of the growth curve, they should be regarded as minimum ages for the time of glacier recession. Due to sparse reforestation, Sigafoos and Hendricks did not date the 1763 and 1750 moraines located in the terminal complex. Although the lichen and tree-ring ages for the 1823 moraine are essentially the same, the 1691 and 1666 moraines are 69 and 64 yr older, respectively, than the corresponding dendrochronologic ages for these moraines (Sigafoos and Hendricks, 1972).

Cowlitz Glacier

Cowlitz Glacier, heading in a cirque below

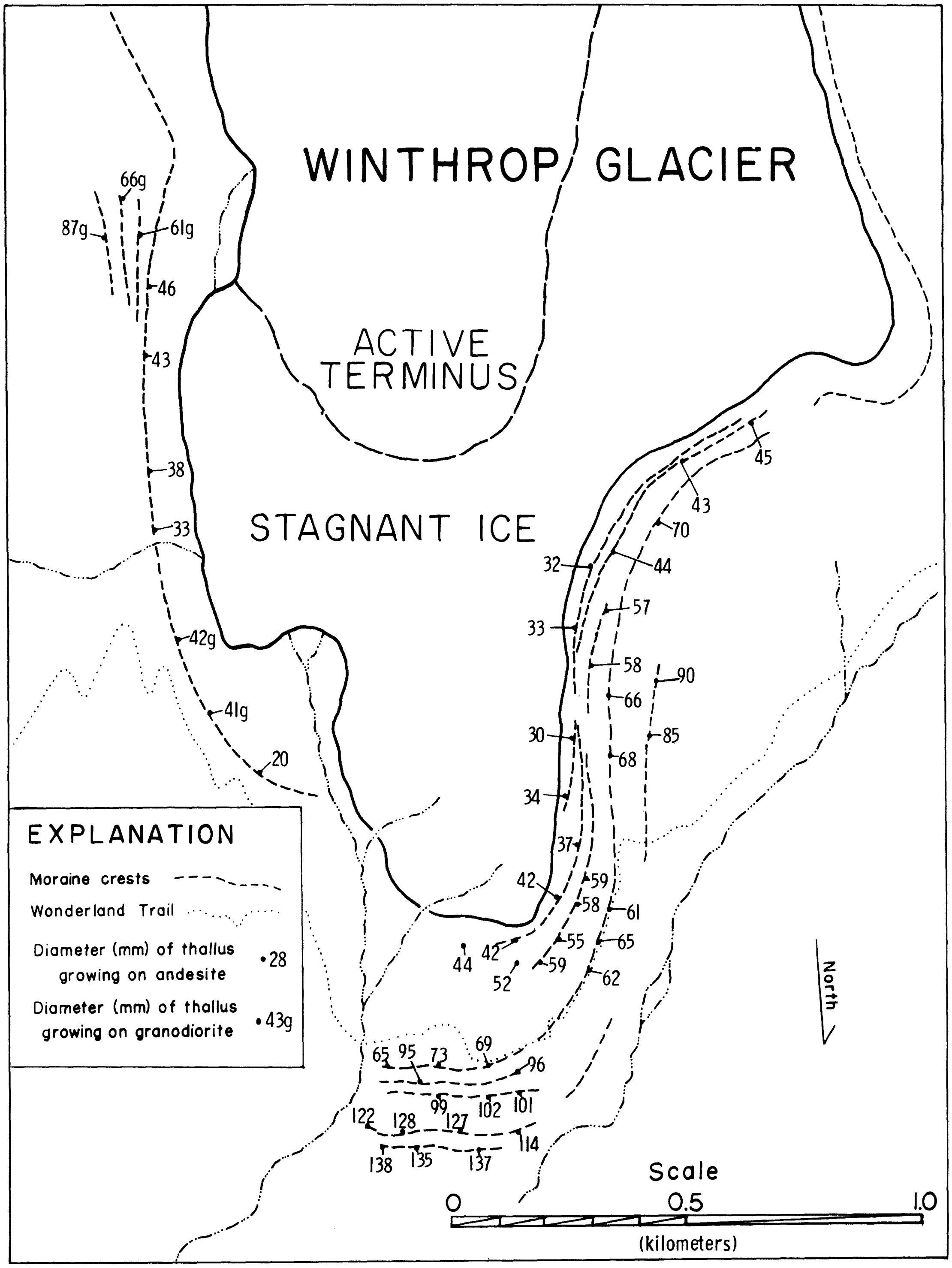

FIGURE 6. Map of lower Winthrop Glacier, the stagnant marginal ice, and associate late Holocene moraines (base from U.S. Geological Survey "Sunrise, Washington" 7.5-minute quadrangle, 1971).

Gibraltar Rock, joins Ingraham Glacier at close to 2000 m altitude. The active terminus now lies at about 1585 m and has been advancing sporadically during the past decade. The area covered by glacier ice is about 35% smaller than 150 yr ago. Only a few remnants of stagnant ice remain in the trough, 2 km long, which has been evacuated by the receding glacier.

Copious rockfall and avalanche debris covers many of the moraines on the north side of the valley and prevents reliable dating of most of them. However, an extensive system of late Neoglacial moraines is preserved on the south side of the valley where lichenometric dating was possible (Figure 7). The outermost, heavily forested moraine has been dated at A.D. 1373 by dendrochronology (Crandell and Miller, 1964). Tephra layer Wn is found associated with this moraine but with none of the younger moraines. The next two, younger moraines support lichens up to a maximum of 92 mm (1777) and 70 mm (1830), respectively, and were formed around a single ice tongue that extended below 1250 m altitude. The terminal moraine that was constructed in 1777 is a good example of a tree-covered moraine immediately adjacent to a mature forest. In this situation, the lichenometric date on the correlative, higher-altitude lateral moraine is essentially identical to the dendrochronologic date. During subsequent recession, the ice tongue divided into two lobes. Three additional moraines concentric to the former southern lobe bear lichens dating to 1882 (47 mm), 1903 (38 mm), and 1914 (32 mm) (Table 2). Still younger moraines are located near the present terminus, but they are cored by ice, are characterized by frequent slumping, and could not be reliably dated.

Ohanapecosh Glacier

Ohanapecosh Glacier, comprising three ice remnants having a total area of about 1.6 km^2, has receded substantially since its maximum Neoglacial advance. Several distinct moraines lie on the northeastern margin of the stagnating ice below the main cirque headwall (Figure 8). The presence of tephra layers O, Yn, and C on the lowest, forested moraine indicates that it is probably of late glacial age. Two forested Neoglacial moraines and an outwash surface 150 m farther upvalley were dated with tree rings by Sigafoos and Hendricks (1972). Tephra layer X, a brown, lapilli pumice that was erupted before 1854 (Mullineaux, 1974), is found on the outwash surface that was dated at 1876. This lag of more than 20 yr is indicative of the variable ecesis time for trees, especially at higher elevations. Four moraine crests in the sparsely vegetated, proglacial zone were dated by lichenometry (Table 2). The prominent moraine adjacent to the forest supports lichens dating to about 1843 (64 mm), and the younger, double-crested moraine yielded lichenometric dates of 1915 (33 mm) and 1923 (29 mm) for its outer and inner crests, respectively. The elongate moraine crest closest to the glacier supports lichens up to 14 mm (1953).

The altitude of these moraines is greater than 1750 m and approaches the upper limit for reliable use of the lichen-growth curve. Moreover, the lichen population is sparse and only a few large thalli were used for each age determination. Consequently, the derived lichenometric ages may not be close limiting dates for moraine stabilization.

Glaciers on Sluiskin and Crescent Mountains

On Sluiskin Mountain, three sharp-crested moraines are concentrically grouped 100 to 150 m below the glacier. Layer C pumice was found beyond these moraines, but not on them, indicating that they are less than about 2200 yr old. Although these moraines probably represent glacier fluctuations during the past several centuries, lichens on the outermost moraine are less than 70 yr old, according to the growth curve.

A single, broad moraine borders each glacier examined on Crescent Mountain. Lichen trimlines are found near the crest of these moraines. *Rhizocarpon* and layer C pumice are plentiful beyond the trimlines, whereas the lichens within the trimlines are sparse. Scattered layer C pumice is also present within the trimlines, and is inferred to have been blown in from the adjacent pumice-covered ground. The observations on Sluiskin and Crescent mountains suggest that the lichen growth curve may not be valid for these higher altitude (> 1750 m) sites or that the expansion of perennial snowbanks may kill lichens periodically, causing irregular distribution patterns.

Summary of Moraine Data

Although times of moraine stabilization

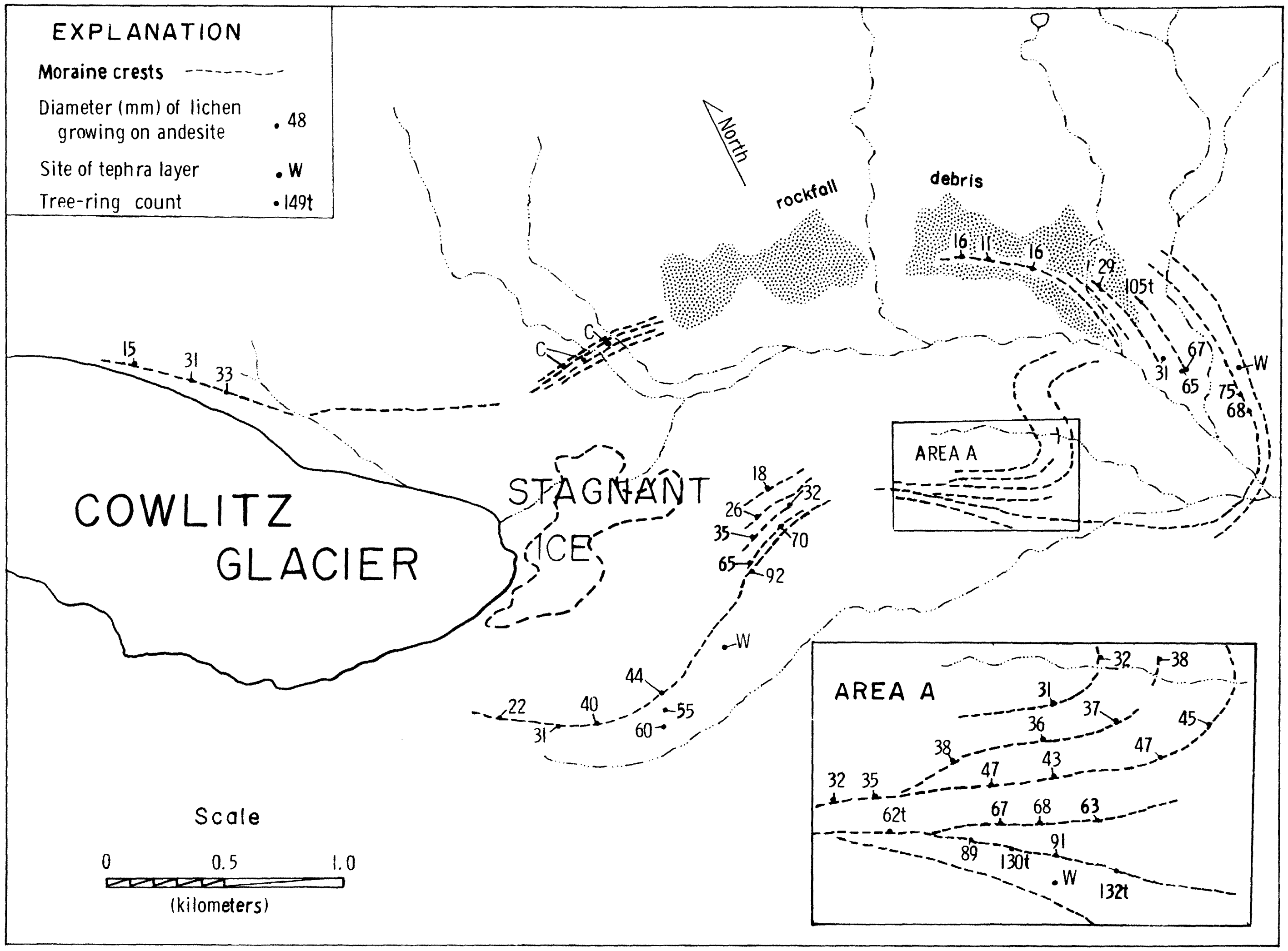

FIGURE 7. Map of lower Cowlitz Glacier and associated late Holocene moraines (base from U.S. Geological Survey "Mount Rainier East, Washington" 7.5-minute quadrangle, 1971).

vary among the glaciers, distinct periods of glacier recession can be discerned from available dates (Tables 1 and 2). The lichenometric data indicate that recessions began about 1768-1777, 1823-1830, 1857-1863, 1880-1885, 1902-1903, 1912-1915, and 1924. Still earlier episodes of retreat occurred around 1750, 1720, 1690-1695, 1640-1666, 1613-1623, 1552-1576, 1519-1528, and 1328-1363, as indicated by lichens and tree-ring counts. Whereas the lichenometric dates for the past 200 yr are considered to date times of glacier recession quite closely, those antedating 1750 are regarded as providing only minimum limiting ages for moraines.

Equilibrium-line Altitudes

Equilibrium-line altitudes (ELAs) were calculated for North Mowich, Carbon, Winthrop, and Cowlitz glaciers. An accumulation-area ratio of 0.6 was assumed (Meier and Post, 1962). The ELA was determined by planimetry of the present areal extent and the reconstructed glacial margins of the maximum late Neoglacial advances. Averaging between glaciers was used to calculate the mean past and present ELAs on Mount Rainier (Table 3). Whereas the present, steady-state ELA is around 2104 $\pm$ 117 m, the ELA during the late 18th and early 19th centuries was around 1943 $\pm$ 63 m.

Although the average rise in the ELA is about 160 m, there is considerable variation between individual glaciers. The calculated ELA for Cowlitz Glacier, which has lost 35% of its former extent, rose about 300 m. In contrast, the ELA rose only 60 m on Carbon Glacier, which has lost less than 6% of its former areal extent. The glaciers that have receded most extensively are those that have a relatively debris-free surface, whereas Carbon and Winthrop glaciers, being mantled with rockfall debris, have retreated much less during the past 200 yr.

DISCUSSION

The utility of lichens for dating moraines constructed during the past several hundred years is amply demonstrated by this study. When conditions of abundant lichen cover,

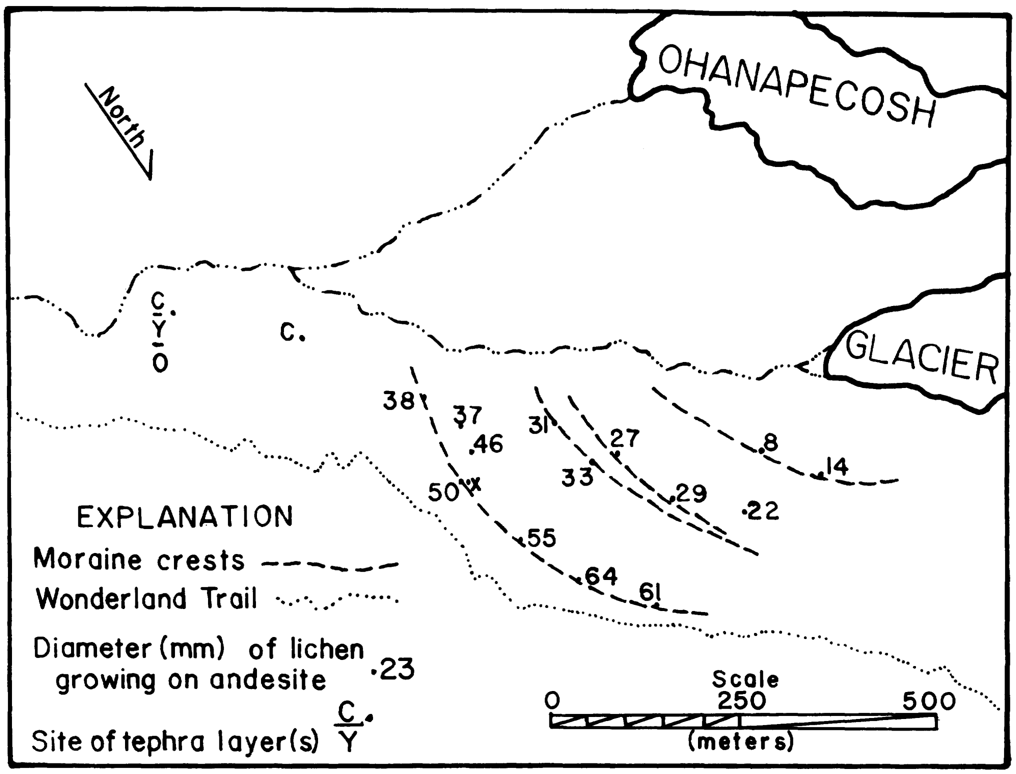

FIGURE 8. Map of lower Ohanapecosh Glacier and associated late Holocene moraines. Layer X (described in the text) mantles the outermost, lichenometrically dated moraine. (Base from U.S. Geological Survey "Mount Rainier East, Washington" 7.5-minute quadrangle, 1971.)

stable moraines, scarcity of other vegetation, and appropriate altitudinal range are met, lichenometric dates can provide close limiting ages for the timing of moraine stabilization and the initiation of recession. Comparisons of lichen ages with dendrochronologic dates for the same moraines on Winthrop, Cowlitz, and Ohanapecosh glaciers indicate a highly variable ecesis time for trees, which range from 0 to greater than 65 yr when compared to lichen dates for the same feature.

Verification of the recessional chronology since 1770 is difficult due to the lack of historical measurements of the glaciers in this study prior to 1930. The terminal position of Nisqually Glacier has been measured periodically between 1857 and 1918 and annually since then (Meier, 1963). The rate of recession prior to 1918 (11.6 m yr^{-1}) is about half as great as the rate between 1918 and 1960 (23.9 m yr^{-1}), at which time the stagnant ice disappeared below the reactivated terminus. Stillstands or minor readvances culminated about 1883 (Harrison, 1956) and either 1903 (Veatch, 1969) or 1907 (Harrison, 1956). Of the glaciers in this study, the greatest decrease in areal extent during the past two centuries is shown by Cowlitz (35%) and North Mowich (30%) glaciers. The moraine chronology indicates that less than one-third of this recession had occurred prior to 1915 and that the rate has at least doubled since then. The similarity to Nisqually Glacier helps to verify the general deglaciation pattern defined in this paper.

More specific verification of the lichen growth curve and the derived lichenometric dates comes from North Mowich Glacier. Observations by I. C. Russell (1898) indicate that the glacier was dividing over the crest of Division Rock (Figure 4) in 1880 and that it had retreated 150 m by 1896. Both trees and lichens on the tip of Division Rock were established prior to 1880. A small moraine constructed 20 m from the crest bore lichens up to 48 mm in 1978, indicating that the moraine stabilized in 1881 ± 3 yr. The maximum observed lichen diameter between 130 and 180 m farther upvalley was 42 mm and is in close agreement with the observed time of deglaciation of this area.

In the late 18th and early 19th centuries, all of the glaciers in this study were at or near their late Neoglacial maximum extent. The dated moraines formed subsequent to that time represent stillstands or minor readvances that punctuated the massive recession that characterized the glaciers between 1830 and 1950. With the exception of Ohanapecosh Glacier where the lichen cover is scarce, an unexpectedly high degree of synchrony is indicated by the lichenometric dates for the past 200 yr. Between 1770 and 1920, there are six groups of dates relating to the commencement of recessional phases in the glacier histories (1768-1777, 1823-1830, 1857-1863, 1880-1885, 1902-1903, 1912-1915). The range within each set of grouped dates increases from 3 yr in the 20th century to 9 yr for the 18th century moraines. This range

TABLE 3

Changes in late Holocene equilibrium-line altitudes and areal extent

	Late Holocene Maximum		Present		Change		
Glacier	Altitude of terminus (m)	ELA (m)	Altitude of terminus (m)	ELA (m)	Altitude of terminus (m)	ELA (m)	Areal change (%)
Carbon	977	1888	1099	1948	122	60	5.2
Cowlitz	1160	1892	1588	2197	430	305	34.6
N. Mowich	1282	2012	1648	2195	366	183	31.5
Winthrop	1404	1981	1645	2080	241	99	8.5
Average	1206 ± 182	1943 ± 63	1495 ± 265	2105 ± 117	289 ± 137	162 ± 108	20.0 ± 15
Rainier average[a]	1258 ± 75	1967 ± 38	1586 ± 62	2125 ± 41	328 ± 48	158 ± 38	19.1 ± 9

[a]Includes additional data from seven other major glaciers.

probably reflects both variability between glaciers and increasing uncertainty in the lichenometric dates on older features.

The fact that these glaciers commenced recession at about the same time suggests that they are responding similarly to climatic phenomena. Because the position of a glacier terminus is a function of the balance between the transfer of ice to the terminus and the ablation of that added mass, recession occurs when the ablation rate exceeds that transfer rate. The study of kinematic waves on Mount Rainier (Meier and Johnson, 1962) indicates that the response of the terminus to increased accumulation is a complex function of glacier velocity and configuration, and consequently, it should vary between glaciers. In contrast, ablation directly and immediately affects the terminal position. The synchrony of glacier recession during the past 200 yr suggests a common response to strong ablation regimes. A comparison of the climatic history since 1850, mass balance calculations, and glacier responses will be described in a forthcoming paper (Burbank, in press).

When all dendrochronologic and lichenometric dates are considered, several periods of moraine stabilization can be defined prior to 1770 (1519-1528, 1552-1576, 1613-1624, 1640-1666, 1691-1695, 1720, and 1750). However, the aforementioned variability in ecesis times requires that these be treated as minimum limiting dates for recession. Future investigations of moraines amenable to lichenometric dating may help to develop a more reliable chronology for this period.

Although there are no moraines dated from the 15th century, there are several dendrochronologically dated moraines from the 13th and 14th centuries (Tables 1 and 2). These moraines represent glacial expansion beyond the extent of the latest Neoglacial maximum advances. However, at Carbon Glacier, the presence of layer C pumice more proximal to the glacier indicates the moraine stabilized prior to 2200 yr ago. This suggests that these moraines should be correlated with the widely recognized Neoglacial advances that culminated 2600 to 2800 yr ago (Porter and Denton, 1967) and that the tree-ring ages are indicative of the maximum life span of trees in this locality.

Examination of the altitudes of the former termini, calculated ELAs, and changes in areal extent (Table 3) reveals considerable variability between glaciers. These variations could reflect differences in local climatic conditions. However, the contrast between adjacent glaciers, like North Mowich and Carbon glaciers, suggests that the smaller amount of recession experienced by Winthrop and Carbon glaciers is a function of the thick debris cover that tends to reduce the rate of ablation on them. At least over the span of 200 yr, reduced ablation due to a blanket of debris has dramatically reduced the magnitude of change in the ELA. Despite the variation among glaciers, the average amount of ELA rise at Mount Rainier since the late Neoglacial maximum (160 m) is similar to the calculated ELA rise for this period in Swat Kohistan (Porter, 1970), New Zealand (Porter, 1975), southern Norway (Matthews, 1977), and the Columbian Andes (Herd, 1974), but is about 50 m greater than the ELA rise calculated for the tropical glaciers of Indonesia (Allison and Kruss, 1977). Assuming a mean lapse rate of 6.2°C 1000 m^{-1} (Porter, 1977), this rise in the ELA is equivalent to a mean annual temperature increase of about 1.0°C since the early 19th century. A similar rise of about 1.0°C in the mean annual temperature since the early 19th century has also been proposed for southern Norway (Matthews, 1977) and Swedish Lapland (Karlén, 1973).

The general pattern of late Holocene glacier fluctuations in other regions of the world, as summarized by Porter and Denton (1967), is similar to the pattern established at Mount Rainier. Glacier expansion began between the 15th and 17th centuries, maximum advances frequently culminated in the late 18th or early 19th century, and these have been succeeded by extensive recession, punctuated by minor readvances. Only a few studies, however, provide detailed chronologies for the past several hundred years. In Swedish Lapland, lichenometric and historical data indicate the late Neoglacial advances began around A.D. 1500 and attained their maximum in the 1600s (Denton and Karlén, 1973; Karlén, 1973). Recessional phases commenced about 1590-1620, 1650, 1680, 1700-1720, 1780, 1800-1810, 1850-1860, 1880-1890, and 1916-1920. Major recession has been experienced between 1920 and 1970.

Although the pattern is similar to that found at Mount Rainier, comparison of the recessional dates indicates that there is some disparity between the two areas. The best-documented differences occur during the past 100 yr. While recession was occurring at Mount Rainier, following the stillstand that ended between 1880 and 1885, most of the Swedish glaciers continued to advance until the 1890s. Whereas the Mount Rainier glaciers were retreating between 1903 and 1910, many of those in Lapland were thickening and advancing from 5 to 30 m (Karlén, 1973). All of the glaciers studied at Mount Rainier were retreating after 1915 (Meier, 1963), while many of the Swedish glaciers continued advancing until 1916 to 1920.

These differences could be due to variable lag times in the response to similar climatic changes. However, in both areas, moraine ages divide into restricted periods of about 5 to 10 yr. This indicates that the regional variability between glaciers is usually not more than about 10 yr. Consequently, even considering the lags imposed by the variable dynamics of different glaciers, the times of moraine stabilization in these two areas are not synchronous during the past 200 yr. Apparently, despite the broad similarities in late Holocene glacier variations, the regional climate and the resultant moraine chronologies are significantly different in detail between these two areas. Further study is needed to determine the relationship between documented climatic change and glacier fluctuations in these regions. Such studies will permit the evaluation of the climatic implications of earlier glacier variations and will facilitate comparisons of regional, hemispheric, and global climatic trends during the late Holocene.

CONCLUSIONS

The evidence obtained from Mount Rainier supports the following conclusions:

(1) Detailed chronologies of late Holocene glacier variations may be established through the use of lichenometry in suitable areas.

(2) During the past 200 yr, the glaciers on Mount Rainier exhibited a high degree of synchrony in their recessional behavior. All glaciers were at or near their late Neoglacial maximum extents in the late 18th or early 19th centuries. Subsequent periods of glacier recession began about 1768-1777, 1823-1830, 1857-1863, 1880-1885, 1902-1903, 1912-1915, and 1924.

(3) Minimum dates for the initiation of earlier recessional events were obtained through the use of lichens, tree rings, and tephra. These indicate recessions commencing around 1519-1528, 1552-1576, 1613-1623, 1640-1666, 1690-1695, 1720, and 1750. The presence of dated tephra indicates that moraines formerly thought to have formed in the 13th and 14th centuries may be attributable to advances that occurred prior to 2200 yr ago.

(4) ELAs have risen an average of 160 m since the early 19th century. This is equivalent to a mean annual temperature rise of about 1.0°C.

(5) In general, the late Holocene glacier fluctuations on Mount Rainier are in agreement with the global patterns described by Porter and Denton (1967). However, detailed comparison of this chronology with ones from northern Sweden indicates some lack of synchrony of glacial events between these areas. This suggests that regional climatic regimes are superimposed on global or hemispheric trends and cause contrasting glacial variations.

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