"Dendroglaciological Dating of a Little Ice Age Glacial Advance at Moving Glacier, Vancouver Island, British Columbia"

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DENDROGLACIOLOGICAL DATING OF A LITTLE ICE AGE GLACIAL ADVANCE AT MOVING GLACIER, VANCOUVER ISLAND, BRITISH COLUMBIA

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ABSTRACT Dendrochronological investigations at Moving Glacier provide the first calendar-dating of a Little Ice Age glacier advance on Vancouver Island. In 1931, Moving Glacier was within 30 to 50 m of a distinct trimline and terminal moraine marking its maximum Little Ice Age extent. A reconnaissance of the site in 1993 revealed the presence of sheared *in situ* stumps and detrital trunks inside the 1931 ice limit. Sampling in 1994 showed the site was covered by a mature subalpine forest prior to the glacial advance which overrode the site after 1718 A.D. Following this period of expansion, which saw Moving Glacier expand to its maximum Little Ice Age position after 1818 A.D., the glacier apparently experienced only minimal retreat prior to first being photographed in 1931.

RÉSUMÉ *Datation dendroglaciologique de l'avancée du glacier Moving au Petit Âge glaciaire, dans l'île de Vancouver, en Colombie-Britannique.* Des recherches en dendrochronologie menées sur le glacier Moving ont permis de dater l'évolution d'un glacier au Petit Âge glaciaire. En 1931, Le glacier Moving était situé entre 30 et 50 m d'un épaulement et d'une moraine frontale correspondant à sa limite d'expansion maximale au Petit Âge glaciaire. L'exploration du site en 1993 a permis de découvrir des souches et des débris de bois *in situ* à l'intérieur de la limite glaciaire de 1931. Un échantillonnage effectué en 1994 a montré que le site était recouvert d'une forêt subalpine mûre avant l'avancée glaciaire qui a bouleversé le site après 1718 ap. J.-C. Après la période d'expansion, qui a permis au glacier d'atteindre sa limite maximale après 1818 ap. J.-C., le glacier a connu un recul minimal avant d'être photographié en 1931.

ZUSAMMENFASSUNG *Dendrochronologische Datierung des glazialen Vorstoßes am Moving-Gletscher während der kleinen Eiszeit auf der Insel Vancouver, British Columbia.* Dendrochnronologische Forschungen am Moving-Gletscher ergeben die erste Kalenderdatierung eines Gletschervorstoßes während der kleinen Eiszeit auf der Insel Vancouver. 1931 befand sich der Moving-Gletscher innerhalb der 30 bis 50 m einer klaren Abflachung und der Endmoräne, was seiner maximalen Ausdehnung in der kleinen Eiszeit entsprach. 1993 fand man bei der Erkundung des Platzes *in situ* abgescherte Baumstümpfe und Trümmer von Baumstämmen innerhalb der Eisgrenze von 1931. 1994 zeigte eine Probenentnahme, daß der Platz mit einem ausgewachsenen subalpinen Wald bewachsen war, bevor der glaziale Vorstoß den Platz nach 1718 u.Z. verwandelte. Nach dieser Ausdehnungsperiode, in welcher der Moving-Gletscher nach 1818 u.Z. seine maximale Position in der kleinen Eiszeit erreichte, hat der Gletscher offenbar nur einen minimalen Rückzug vollzogen, bevor er 1931 zum 1. Mal photographiert wurde.

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INTRODUCTION

The Little Ice Age is described as a distinct cool period between the Middle Ages and the first half of the nineteenth century (Grove, 1990). At most sites in western Canada, glaciers expanded to reach their maximum Holocene extent in this interval (Osborn and Luckman, 1988). Nevertheless, the Little Ice Age behaviour of glaciers on Vancouver Island is essentially unknown. While Ommanney (1972) suggested these glaciers were sensitive to twentieth century climatic changes, there has been no assessment of the effects of Little Ice Age climatic fluctuations on this set of glaciers. This paper uses dendroglaciology to provide the first calendar-dating of a Little Ice Age glacier advance on Vancouver Island.

Dendroglaciology describes the application of dendrochronologic techniques to reconstruct glacier fluctuations (Schweingruber, 1988, 1993a; Luckman, 1995a). In the southern Canadian Rocky Mountains dendroglaciological procedures have been used extensively on living trees to estimate minimum Little Ice Age moraine ages (*e.g.*,Heusser, 1956; Luckman, 1986; Smith *et al.*, 1995) or to identify intervals when advancing glaciers tilted or damaged trees (*e.g.*, Heusser, 1956; Luckman, 1988). In addition, *in situ* stumps and detrital wood covered at one time by Little Ice Age glaciers have been crossdated to living chronologies to provide the first calendar dating of an early Little Ice Age advance (12th to 14th century) in North America (Luckman, 1995a, 1995b). In comparison, dendroglaciological methods have been used only rarely in the Coast Mountains of British Columbia (*e.g.*, Mathews, 1951; Ricker, 1983; Desloges and Ryder, 1990) and have never been employed on Vancouver Island.

STUDY SITE

Moving Glacier is located in a northwest facing cirque in the Comox Nature Conservancy area of Strathcona Provincial Park (Lat. 49°33'20", Long. 125°23') (Figs. 1 and 2). The glacier (No. 8HD5 [Ommanney,1989]) calves into Milla Lake at 1350 m elevation and was thirty-five years ago one of the largest on Vancouver Island (Ommanney 1972). This distinction is no longer valid, as Moving Glacier has evidently retreated and downwasted far more than many Vancouver Island glaciers (*cf.* Ommanney, 1989).

The historical behaviour of Moving Glacier was described by intergrating vertical aerial photographs and Landsat thematic mapper (TM) imagery into a Digital Elevation Model (DEM) constructed from Terrain Resource Information Management (TRIM) files using the terrain modelling package EMXS™. The data sets generated were then evaluated using terrain analysis functions within PCI™ to describe changes in the topographic and areal extent of the glacier. This analysis showed that the glacier presently covers less than 10% of the area it did during its Little Ice Age maximum, and only 30% of the area it did even 30 years ago (Table I). The glacier terminus is presently positioned 834 m behind its 1931 position and has been receding at rates of between 8.2 to 24.5 m/yr over this period (Table I, Fig. 3).

The Little Ice Age extent of Moving Glacier is marked by a distinct trimline and a small boulderly terminal moraine. The trimline is found along the southeastern shore of Milla Lake, approximately 200 m above the lake surface within a very steep and inaccessible snow avalanche zone (Fig. 4). A terminal moraine (0.5-1 m high) on the crest of a bedrock knoll, midway down Milla Lake (Fig. 2), marks the maximum Little Ice Age advance position. Aerial photographs taken in 1931 (A4013), show the glacier was within 30 to 50 m of this moraine at that point (Fig. 4).

METHODS

A field survey of the site was undertaken in early August of 1994, after the discovery in the previous summer of *in situ* stumps and woody detrital material within a bedrock gully covered by the glacier in 1931 (Fig. 5). Further reconnaissance revealed additional detrital material within or below sections of the terminal moraine, and rooted stumps at various locations on the proximal face of the knoll shown in Figure 2. Living tree-ring chronologies were used to crossdate the detrital wood and describe when the glacier overrode these trees.

Tree-ring chronologies were developed from a stand of living trees at 1400 m, immediately adjacent to the forefield and within 50 m of the local treeline (Figs. 2 and 4). The dominant tree at the site was mountain hemlock (*Tsuga mertensiana* [Bong.] Carr.), with a minor consitutent composed of yellow cedar (*Chamaecyparis nootkatensis* [D.Don] Spach) and amabilis fir *(Abies amabilis* [Dougl.] Forbes).

Two increment cores (at *ca.* 90°) were extracted at breast height from co-occurring mountain hemlock (n=40) and yellow cedar trees (n=25) within a restricted sampling area. After air drying, the cores were mounted in wooden blocks and sanded with progressively finer sandpaper. Annual ringwidths were measured to the nearest 0.01 mm using a computerized WinDENDRO™ image processing tree-ring measurement system (Guay *et al.*, 1992). Where ring definition was uncertain, a measuring stage linked to a digital encoder was used to visually assess the annual increments.

The cores were crossdated to narrow marker rings established during a preparatory examination (Table II) and quality checked using the International Tree Ring Data Bank (ITRDB) software program COFECHA (Holmes, 1992). After crossdating (50-year dated segments lagged by 25 years, with a critical level of correlation [99%] set at 0.32), the chronologies were standardized using a detrending procedure within the ITRDB ARSTAN program (Holmes, 1992). In this instance, each ringwidth series was standardized by fitting it to either a negative exponential curve or a linear regression line, with 50% of the variance established at a wavelength of 128 years.

Floating chronologies were developed from sound samples of the detrital wood. Due to either extensive postglacial rotting or abrasion during transport, no bark was found on any of the samples. The floating series were intially crossdated using COFECHA (50-year dated segments lagged by 25 years, with a critical level of correlation [99%] set at 0.32) and

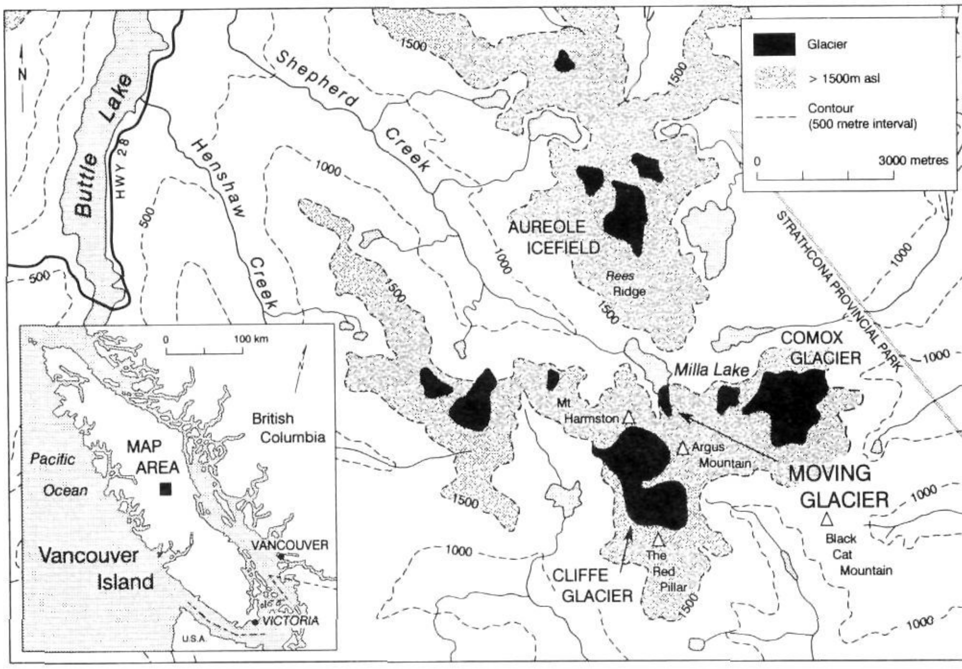

FIGURE 1. Map showing the location of Moving Glacier in Strathcona Provincial Park, Vancouver Island, British Columbia.

Localisation du glacier Moving situé dans le parc provincial Strathcona, dans l'île de Vancouver (Colombie-Britannique).

TABLE I

Historical extent of Moving Glacier

year	data source	distance (m) from 1931 terminus position	average rate of terminus retreat (m/yr)	surface area [% of maximum LIA area] (km^2)	slope of glacier surface
LIA maximum	—	—	—	7.33	—
1931	A4013: 015	—	—	5.67 [77%]	—
1962	BC5086: 058	410	13.2	3.13 [43%]	0.54
1981	BC81071: 039	566	8.2	1.53 [20%]	0.67
1992	TM Data	834	24.4	0.71 [10%]	0.91

The area of Moving Glacier was described by integrating image data from vertical aerial photographs and Landsat thematic mapper (TM) imagery into a Digital Elevation Model. The data sets generated were evaluated using terrain analysis functions within PCI™ to describe changes in the topographic and areal extent of the glacier.

verfied against marker rings within the living chronologies (Table II).

RESULTS

RINGWIDTH CHRONOLOGIES

Most of the living trees sampled at the Milla Lake site were from 300 to 400 years old. Nevertheless, a 620 year old mountain hemlock was sampled and a yellow-cedar was identified with more than 1200 annual rings.

The Milla Lake mountain hemlock chronology extends back to 1374 A.D. and is based upon 30 cores from 20 trees (Table II). The chronology is well replicated for the last 300 years, although only a single core defines the chronology prior to 1506 A.D. (Table II). The results of the COFECHA analysis revealed the chronology has an overall series intercorrelation of 0.509, a mean sensitivity of 0.251 and an autocorrelation value of 0.676 (Table II). As Figure 6 shows, mountain hemlock growth rates declined markedly during the 1500s to mid 1600s, increased until the early 1700s, and decreased again for the remainder of the eighteenth century until the 1830s. An interval of reduced growth followed until the 1870s, when a pronounced interval of improving growth was initiated which persisted until the 1940s.

The Milla Lake yellow-cedar chronology extends back to 798 A.D., with ringwidth measurements from only a single tree describing the interval prior to 1208 A.D. The ringwidth chronology shown in Figure 6 is based upon 38 cores from 22 trees (Table II). The COFECHA analysis indicates the chronology has an overall series intercorrelation of 0.300, a mean sensitivity of 0.252 and an autocorrelation value of 0.696 (Table II). While above average growth rates characterize the

FIGURE 2. View of Moving Glacier from the northern end of Milla Lake, August 1993. Note the trimline on the bedrock knoll bordering the eastern lakeshore which marks the maximum Little Ice Age expansion of the glacier. The stand of trees from which the living ringwidth chronologies were constructed is pictured immediately to the left of the knoll (see Fig. 4).

Vue du glacier Moving à partir de l'extrémité septentrionale du Milla Lake, en août 1993. Noter l'épaulement qui coupe la colline qui borde le rivage est du lac et qui identifie l'extension maximale du glacier au Petit Âge glaciaire. Le peuplement arboréen à partir duquel a été établie la dendrochronologie est situé immédiatement à gauche du monticule (emplacement à la fig. 4).

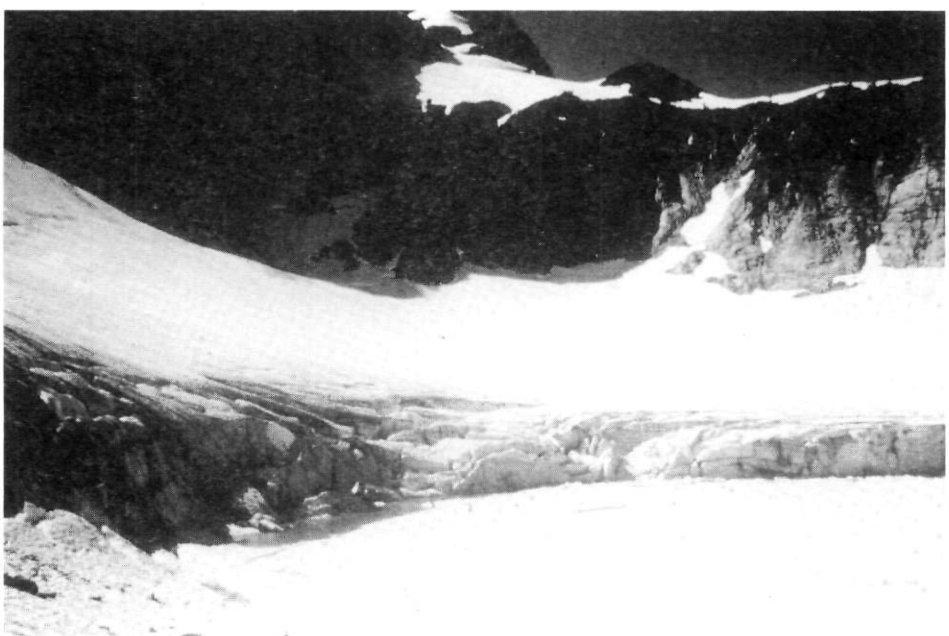

FIGURE 3. Calving terminus of Moving Glacier on July 29, 1968. Note the small figure in the bottom left for scale. Photograph by John Cowlin, Victoria, BC.

Front de vêlage du glacier Moving, le 29 juillet 1968. Le petit personnage sur la marge inférieure de la photographie (à gauche) donne l'échelle (John Cowlin, Victoria, C.-B.).

1510s, 1550s, early 1700s, 1770s, 1790s, mid 1800s, 1910s and 1940s; the 1600s, 1740s, early 1800s, mid 1800s, 1920s, and 1940s were distinguished by below normal rates of radial growth (Fig. 6).

Close examination of the growth trends exhibited by mountain hemlock and yellow-cedar at this site show they share many traits. Particularly notable are the intervals of reduced growth rates in the seventeenth and eighteenth centuries, and a common growth response in the 1830s.

CROSSDATING OF THE FLOATING CHRONOLOGY

Extensive rotting or severely contorted ring sequences reduced the overall sample depth of the floating chronology. Of the 25 samples collected, only 14 contained useful ringwidth sequences and all but one were identified as detrital mountain hemlock on the basis of their anatomic characteristics (Schweingruber, 1993b: 324-325). The single anamalous sample (94015, 371 rings) was identied as a yellow-cedar branch on the basis of its colour, morphology and ringwidth structure (*cf.* Jozsa, 1992). Most samples contained less than 200 annual rings, although two samples had more than 370 rings (94013 and 94015).

Figure 6 shows the position of the detrital ring sequences within the master hemlock and cedar chronologies. Most of the ringwidth measurements were obtained from discs cut out of an assemblage of broken and fragmented trunks (up to

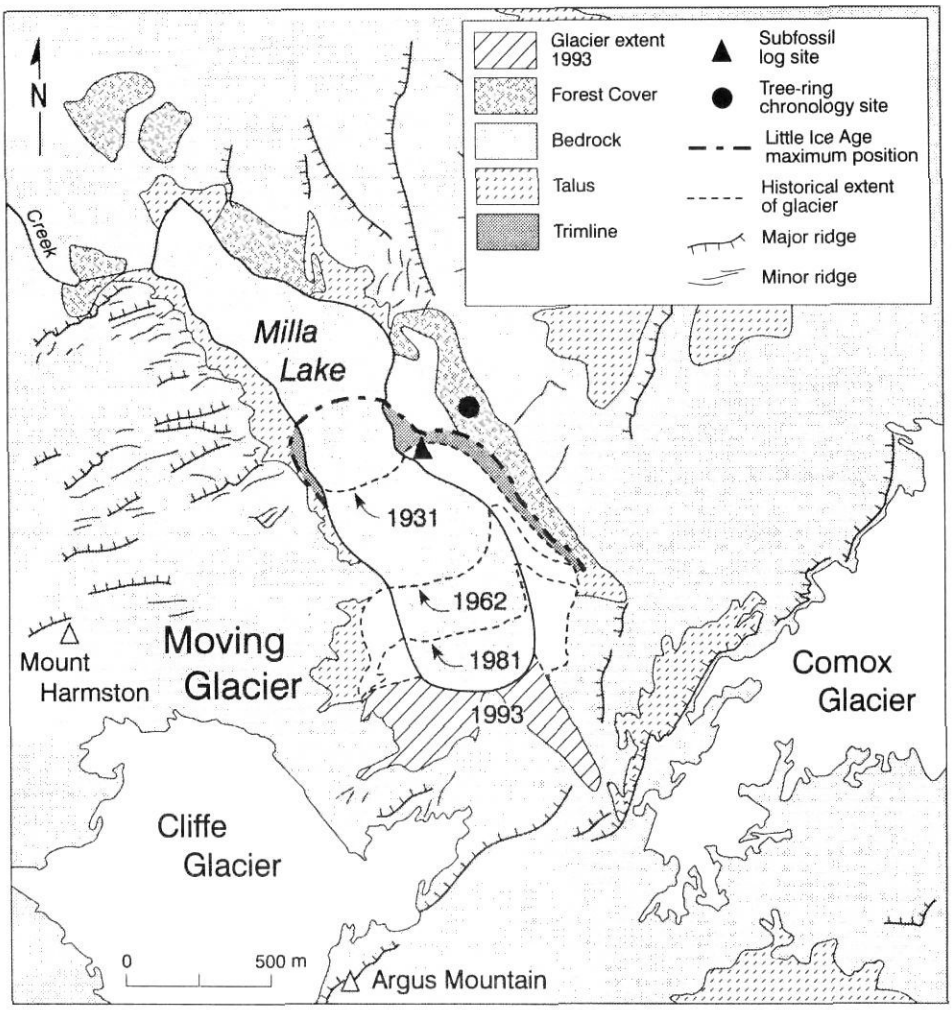

FIGURE 4. Map showing the historical extent of Moving Glacier.

Carte de l'évolution du glacier Moving à travers l'histoire.

FIGURE 5. Detrital assemblage in the knoll gully covered by the glacier in 1931. Moving Glacier flowed up this slope from right to left. Pictured in this group are trunks with perimeter dates ranging from 1616 to 1713 (94021:1533-1687 A.D.; 94022:1486-1616 A.D.; 94023:1658-1713; 94024: 1512-1703).

Assemblage de débris dans un ravin recouvert par le glacier en 1931. Le glacier s'est écoulé le long de la pente, de droite vers la gauche. Figurent dans cet amas des troncs dont les dates à la périphérie varient entre 1616 et 1713 (94021 : 1533-1687 ap. J.-C. ; 94022 : 1486-1616 ap. J.-C. ; 94023 : 1658-1713 ; 94024 : 1512-1703).

2.5 m in length) jammed together at several locations in a steep gully on the proximal face of the bedrock knoll (Fig. 5). Virtually all these boles were found lying with their apical stems oriented upslope, in the direction of glacial flow. Most outer or perimeter rings date to between 1685 and 1713 A.D. (Table III). Although many sheared and rotted stumps bordered the area, the provenance of individual boles was not obvious. Consequently, as the precise growth site of the dated logs could not be determined, this grouping of trunks can only be interpreted to suggest that all were killed after 1713 A.D. (94023, Table III). The wide range in the perimeter dates assigned to this group of samples is believed related to variable surface rotting.

The youngest perimeter date comes from one of two 4 m long detrital logs (94025 and 94026, Table III) found lying on the proximal knoll surface, 30 m west of the site shown in Figure 5. Both logs were found immediately upslope of well-rotted stumps. While the outermost rings were missing from the upper surface of both trunks, excavations beneath the logs revealed the lower half of one log (94025) retained a more complete sequence of perimeter rings. Neither log retained a cover of bark. The relative preservation of sample 94025 and proximity to its growth site provides a close approximation of where the glacier was in 1718 A.D (Table III).

TABLE II

Dendrochronologic characteristics of the two ringwidth chronologies from the Milla Lake site

	Mountain hemlock	Yellow-cedar
number of trees	20	22
number of cores	30	38
interval	1374-1994 A.D.	798-1994 A.D.
interval with two or more series	*1506-1994 A.D.*	*969-1994 A.D.*
years with prominent narrow rings	1534, 1544, 1568, 1572, 1615, 1637, 1659, 1664, 1694, 1703, 1801, 1810, 1838, 1840, 1848, 1866, 1876, 1919, 1921, 1974	1544, 1568, 1615, 1637, 1810, 1838, 1840, 1848, 1866, 1921, 1974
years with prominent wide rings	1574, 1594, 1687, 1704, 1834, 1905, 1915, 1934, 1941, 1965	1704, 1834, 1905, 1915, 1941, 1965
series correlation	0.509	0.300
mean sensitivity	0.251	0.252
autocorrelation	0.676	0.696

The oldest and longest dated ring sequence was from a detrital log (94013) located on the knoll crest. This partial bole was found protruding from beneath the terminal moraine and, after excavation, proved to be the largest of several detrital fragments jumbled together within the moraine. Crossdating of this sample shows the moraine was deposited after 1818 A.D. (94013, Table III). A precise kill date could not be determined due to the lack of bark and rotting of perimeter rings.

DISCUSSION

These investigations show that the bedrock knoll at Milla Lake was covered by trees before the beginning of the eighteenth century. Given the relative abundance of detrital mountain hemlock recovered, it is assumed this stand was dominated by mature 200-400 year-old hemlocks (Table III) with only a minor yellow-cedar constituent. As the oldest dated sample has a pith date of 1354 A.D. (94013, Table III), the site may not have been glaciated by any of the early thirteenth and fourteenth century Little Ice Age advances described elsewhere (*e.g.*, Ryder and Thomson, 1986; Ryder, 1987; Desloges and Ryder, 1990; Luckman, 1994, 1995b).

The death dates of the majority of crossdated detrital logs show these trees were killed by Moving Glacier in the early portion of the eighteenth century. The glacier appears either to have immediately overridden the downed trunks or pushed them into localized depressions, where they were subsequently overridden (Fig. 5). The precise interval over which the trees were killed is impossible to assign due to the loss of outer rings. Nevertheless, the outer dates of two trunks (94023 and 94025, Table III) provide a minimum estimate of between 1713-1718 A.D. for the event. Similar late seven-

TABLE III

Crossdated Milla Lake subfossil samples

No.	Sample	Crossdated Age of Sample	Correlations of 50-year dated segments prior to perimeter crossdate, lagged by 25 years (critical level of correlation 0.32)		
			1-50 years	25-75 years	50-100 years
1	94013	1446-1818	0.35	0.35	0.35
2	94017	1479-1690	0.37	0.44	0.44
3	94018	1578-1705	0.50	0.56	0.44
4	94020	1556-1694	0.47	0.65	0.45
5	94021	1533-1687	0.31	—	0.31
6	94022	1486-1616	0.44	0.34	0.40
7	94023	1658-1713	0.42	NA	NA
8	94024	1512-1703	0.31	0.42	0.49
9	94025	1527-1718	0.40	0.31	0.36
10	94026	1544-1629	0.45	0.59	0.42
11	94027	1531-1648	0.43	0.50	0.32
12	94028	1444-1666	0.41	0.37	0.37
13	94029	1525-1642	—	0.34	0.37
14	94030	1354-1690	0.39	0.38	0.34

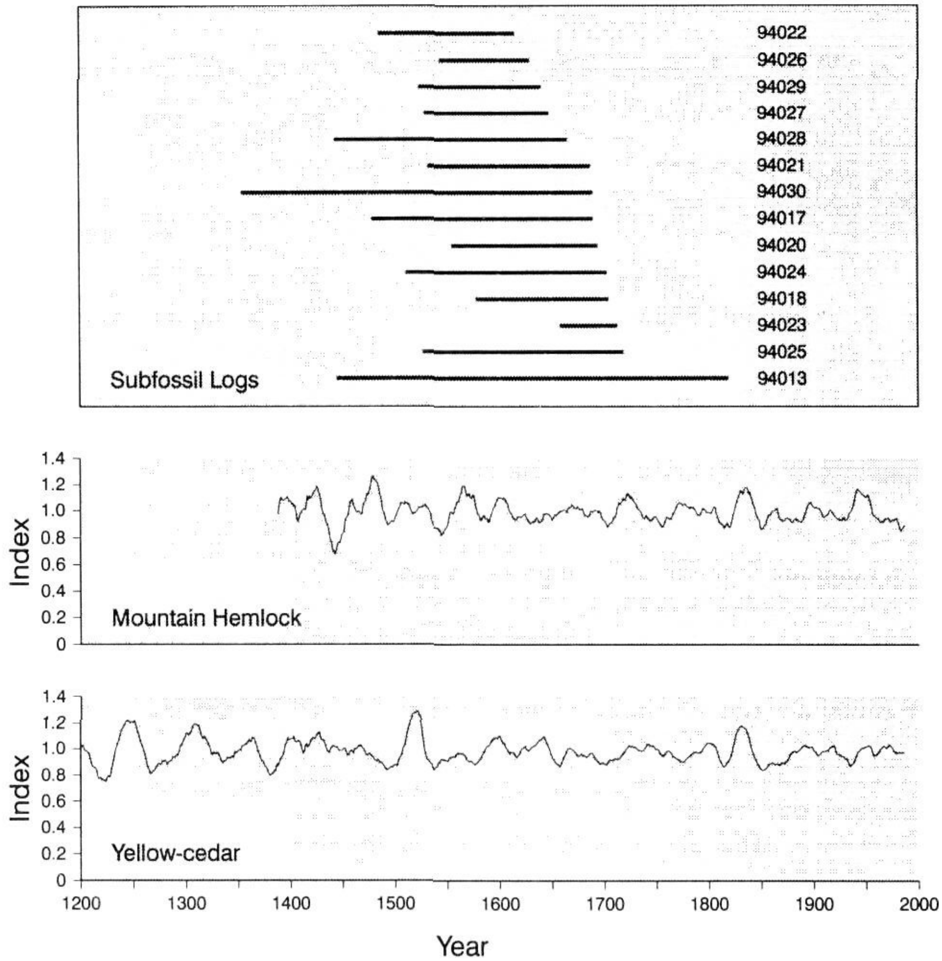

FIGURE 6. Summary of dendrochronological studies at Milla Lake. The upper portion of the figure illustrates the length of the ringwidth record of the crossdated detrital samples. Note that the youngest or oldest portion of each record does not necessarily represent the absolute age of each tree, as many samples had either rotten interiors and/or perimeters. The lower two graphs illustrate the mountain-hemlock and yellow-cedar chronologies prepared from samples of living trees found growing next to the site. The two ringwidth chronologies have been smoothed with a 25-year running mean to emphasize the long-term growth trends.

Résultats abrégés des études de dendrochronologie menées au Milla Lake. Le graphique supérieur montre la longueur des relevés faits sur les échantillons de débris interdatés. La partie la plus ancienne ou la plus récente de chacun des relevés ne représente pas nécessairement l'âge absolu, étant donné la détérioration à l'intérieur ou à la périphérie des tronçons. Les deux graphiques inférieurs donnent les chronologies de la pruche subalpine et du faux-cyprès de Nootka établies à partir des échantillons d'arbres croissant près du site à l'étude. Les deux courbes chronologiques ont été lissées selon une moyenne mobile de 25 ans pour mettre en relief les tendances de croissance à long terme.

teenth to early eighteenth century glacial maxima have been described at various montane locations in the Pacific northwest (*e.g.*, Mathews, 1951; Heusser, 1957; Ricker, 1983; Heikkinen, 1984; Ryder, 1987) and Canadian Rockies (Luckman, 1986, 1995a; Smith *et al.*, 1995).

The terminal position of this eighteenth century advance may be marked by the terminal moraine on the nearby knoll crest. Unfortunately, there is no direct support for this interpretation, as the dendroglaciological evidence shows that the glacier did not advance to this position until after 1818 A.D. (94013, Table III). Given that research at other locations in the region indicates glacial advances in the eighteenth century were followed by a second maximum in the nineteenth century (*e.g.*, Ryder, 1987; Desloges and Ryder, 1990), it may be that Moving Glacier actually went through a period of recession before readvancing to this nineteenth century position. Nevertheless, there is no morphological evidence at the site to suggest that the glacier did in fact override an eighteenth century terminal position. Furthermore, the condition of the detrital boles and stumps in 1994 suggests they were not exposed until after 1931. If this interpretation is correct, Moving Glacier experienced only limited retreat (less than 30 to 50 m) prior to readvancing in the nineteenth century.

The 1931 aerial photographs show Moving Glacier had receded only a short distance from the position it reached sometime after 1818 A.D. (Fig. 5). While the terminal moraine is clearly younger than the minimum date assigned, it is impossible to say whether the glacier remained in this advanced position until it was first photographed. Nevertheless, it is clear that significant recession from this Little Ice Age maximum position did not begin until this century. This observation supports the contention of Desloges and Ryder (1990: 289) that *Little Ice Age climates persisted on the Pacific coast until early* in the twentieth century. Whether this is a reflection of macro scale synoptic circulation patterns or coastal precipitation regimes as they contend, or a mass balance response to climate forcing across the area is still not clear (*e.g.*, Brugman, 1991; Fritts, 1991).

The eighteenth century expansion of Moving Glacier followed regional climatic perturbations in the preceding century (*e.g.*, Schweingruber *et al.* 1991). Reconstruction of these changes in the Vancouver Island region shows the 1600s were characterized by gradually increasing precipitation (Fritts and Shao, 1992) and a series of warm and cool decades (Graumlich and Brubaker, 1986; Briffa *et al.*, 1992; Fritts and Shao, 1992). While the specific effect of these climate fluctuations on the terminus behaviour of Moving Glacier is difficult to ascribe (*e.g.*, Wood, 1988: 410), reduced rates of radial growth within both of the Milla Lake chronologies may be symptomatic of an interval of reduced ablation season temperatures and, perhaps, increased winter snowfalls (Fritts *et al.*, 1979; Fritts, 1991). Similar climate-growth response relationships in the Cascade Range of nearby Washington state, have been interpreted by Graumlich and Brubaker (1986: 231) as indicative of intervals of Little Ice Age glacial activity.

CONCLUSIONS

The dendroglaciological studies at Moving Glacier provide the first calendar dating of a Little Ice Age glacial advance on Vancouver Island. While the condition of the detrital samples prevents the assignment of precise kill dates, the crossdates do show that the glacier was close to its maximum Little Ice Age position by 1713-1718 A.D. No evidence was found of an associated eighteenth century terminal moraine. This suggests that the morainic debris was either incorporated into the terminal moraine deposited after 1818 A.D. or that the glacier maintained an advanced terminus position until a subsequent advance in the nineteenth century. An additional finding of this research was to highlight how little Moving Glacier had receded from its maximum Little Ice Age position by 1931. Although this behaviour may be due to factors other than climatic (*cf.* Wood, 1988; Olermanns, 1989), it does add support for the idea that the Little Ice Age ended somewhat later in this region (Desloges and Ryder, 1990).

The chronology of Little Ice Age glacial activity attributed to Moving Glacier is consistent with that emerging from the southern Canadian Cordillera (Osborn and Luckman, 1988). Further assessment of the Little Ice Age behaviour of glaciers on Vancouver Island will require fieldwork at other locations, as neither the glacial trimline or forefield at Moving Glacier is likely to yield additional insights.

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