DENDROGEOMORPHOLOGICAL ASSESSMENT OF MOVEMENT AT HILDA ROCK GLACIER, BANFF NATIONAL PARK, CANADIAN ROCKY MOUNTAINS

BY

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ABSTRACT. The results of this dendrogeomorphological study provide evidence of the active movement of Hilda rock glacier, a tongue-shaped rock glacier in the Columbia Icefield region of Banff National Park. Cross-sectional samples were cut from 44 detrital subalpine fir (*Abies lasiocarpa* (Hook.) Nutt.) and Engelmann spruce (*Picea engelmannii* Parry) boles killed and buried by debris spilling off the steep distal slope of the rock glacier. The samples were crossdated using locally and regionally developed tree-ring chronologies, and were shown to have been killed between 1576 and 1999. Our results show that Hilda rock glacier has advanced at an average rate of 1.6 cm/year since the late 1790s, with limited evidence of similar rates of activity extending back to the mid-1570s. This rock glacier activity is believed to be linked to persistent periglacial processes that appear to be independent of the climatic forcing mechanisms known to influence glacier mass balances over the same interval.

Introduction

Despite the prominence of rock glaciers in the Canadian Rockies, there is little understanding of the long-term rate of rock glacier movement in this setting (Luckman and Crockett 1978). While Osborn (1975) estimated rates of frontal advance at a rock glacier near Lake Louise at between 30 and 60 cm/year and Sherzer (1907) showed that the nearby Wenkchemna rock glacier was advancing downvalley at between 4 and 30 cm/year, Koning and Smith (1999) and Carter *et al.* (1999) reported rates of movement of only 1.61 cm/year at King's Throne rock glacier and 1.24 cm/year at Hilda Creek rock glacier, respectively. Collectively these studies provide only a limited perspective into contemporary rock glacier movement, and do not provide any insight into whether their long-term behaviour corresponds closely to the climatically induced fluctuations of glaciers in the region (Smith *et al.* 1995; Luckman 2000).

Dendrogeomorphology is a subfield of dendrochronology in which the study of the annual growth rings in trees and woody plants is used as a basis for calendar dating geomorphic activity (Kaennel and Schweingruber 1995). Dendrogeomorphology is commonly used to provide calendar dated insights into specific geomorphic events, and for describing the frequency and magnitude of various mass wasting processes (Schweingruber 1996). In this study, dendrogeomorphological techniques are used to describe the long-term behaviour of an active rock glacier (e.g. Carter *et al.* 1999).

Study site

Hilda rock glacier is located within the Columbia Icefield region of northern Banff National Park in the Main Ranges of the Canadian Rocky Mountains (Fig. 1). Previous research at the site is limited to a lichenometric survey conducted by Osborn and Taylor (1975) and to hydrological investigations focused on the ephemeral stream that issues from the rock glacier terminus at 2185 m above sea level (a.s.l.) (Gardner and Bajewsky 1987; Bajewsky and Gardner 1989).

Hilda rock glacier originates from a small northeast-facing cirque at 2800 m a.s.l. below Hilda Peak (3000 m a.s.l.). The weathered free face of Hilda Peak contributes avalanche snow and rockfall material, and also provides shade to the upper reaches of the rock glacier. The rock glacier is tongue-shaped and covers an area of approximately 1.5 km^2 (Fig. 2) (Bajewsky and Gardner 1989).

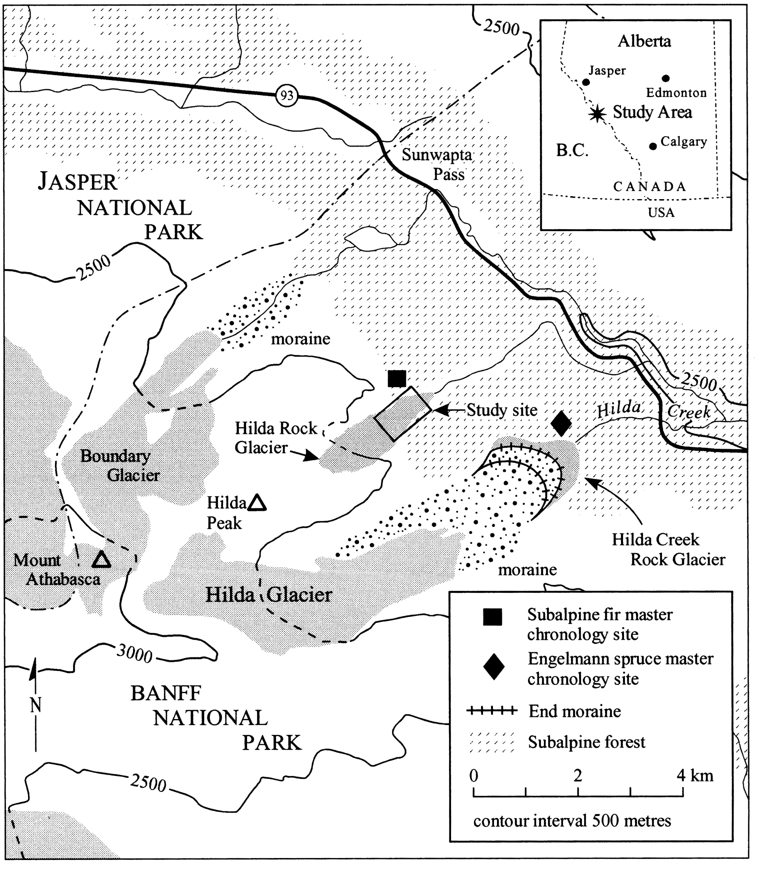

Fig. 1. Location of the study site in Banff National Park, Alberta, Canada.

Fig. 2. View west toward Mount Athabasca and Hilda Peak with Hilda Glacier on the left. Hilda Creek rock glacier is located proximal to the glacier on the left with Hilda rock glacier seen in the foreground right.

Fig. 3. Close-up view of the snout of Hilda rock glacier and its proximity to local treeline.

Fig. 4. Partially buried boles on the south margin of Hilda rock glacier at approximately 2350 m a.s.l.

Active slumping and bulldozing along the rock glacier margin have produced raised lobes of deformed fine sediment on the north margin and buried trees surrounding the periphery. Periglacial creep processes are assumed to play a mass wasting role at the site, as permafrost has been recorded 4 m below the surface at a nearby site (Harris 2001) and has been observed within nearby Hilda Creek rock glacier (Fig. 1; Carter *et al.* 1999).

Methods

Damaged trees and partially buried boles were located at several sites on the northern and southern margins of Hilda rock glacier, approximately 175 m upslope from the terminus (Figs 3 and 4). Excavation of these sites led to the discovery of additional buried boles and, in some cases, associated *in situ* stumps. The distance that the samples were buried was recorded and cross-sections were cut as close to their bases as possible. In the case of *in situ* stumps, the burial depth and distance from the edge of the rock glacier debris apron were also recorded.

Tree cross-sections were sanded to a high polish with progressively finer sandpaper to ensure accurate measurement of tree-ring widths. Samples that lacked structural integrity due to extensive rot or decay were dipped in hot paraffin wax prior to sanding for added structural support. Ring-width measurements were made along the longest intact radius of each sample with either a WinDENDRO™ (Version 6.1d 1998) image-

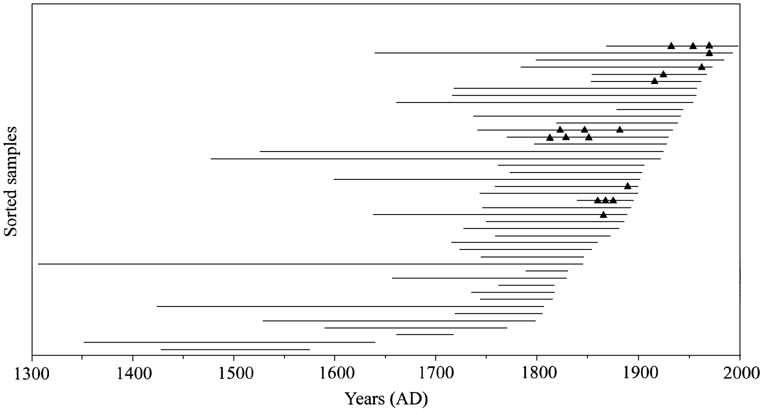

Fig. 5. Death dates and impact dates from the detrital samples in the study. The samples are sorted by death date. The length of the line indicates the age of each detrital sample while wounding events (as measured by impact scars and reaction wood series) are represented by a triangle symbol at the time of wounding.

processing measurement system (Guay *et al.* 1992; Sheppard and Graumlich 1996) or a Velmex-type stage measurement system in conjunction with a 40× microscope.

Minimum kill dates for detrital samples were established by crossdating them to two master chronologies. Engelmann spruce (*Picea engelmannii* Parry) samples were crossdated using the ring-width chronology of Carter *et al*. (1999). The dates assigned to the oldest Engelmann spruce detrital samples were verified using a regional chronology developed by Luckman *et al.* (1997). A local subalpine fir (*Abies lasiocarpa* (Hook.) Nutt.) ring-width chronology was developed to allow crossdating of the detrital fir samples. Increment cores (two per tree) were collected from living subalpine fir trees located adjacent to the north margin of the rock glacier (Fig. 1). The increment cores were air dried and glued into slotted mounting boards prior to sanding. The annual ring-widths were measured and the data checked for signal homogeneity using the program COFECHA (Holmes 1983).

Table 1. Dendrochronological statistics for the living master chronologies used in this study.

Statistic	Subalpine fir[a]	Engelmann spruce[b]
No. of trees	7	16
No. of cores	14	32
Chronology interval	1787–1999	1586–1997
Mean series correlation[c]	0.557	0.560
Mean sensitivity	0.184	0.180
Autocorrelation	0.796	0.800

[a] This study
[b] Carter *et al*. (1999)
[c] Correlation coefficients are significant at the 99% confidence interval for r >0.328

Results

Crossdating

The living subalpine fir master chronology was constructed from 14 cores, and spanned the interval from AD 1787 to 1999. The mean series correlation is significant above the 99% confidence interval (r = 0.557 for 50-year segments) and describes a chronology with a strong coherent group signal (Table 1). The mean sensitivity value is an indication of year to year ring-width variability; the value of 0.184 for the master chronology falls in a normal range for trees in this environment and region (Colenutt and Luckman 1995). The high autocorrelation value (0.796) obtained for this master chronology indicates that annual ring growth for the sampled trees is highly dependent on radial growth in the previous growth year. This value is also within the normal range of autocorrelation for tree species in the region (Colenutt and Luckman 1995).

In total 17 subalpine fir and 27 Engelmann spruce detrital boles were identified. Most samples show significant correlation to their respective master chronologies (see Table 2). Mean sample correlation coefficients for the group of samples were significant at the 99% confidence interval for both subalpine fir (r = 0.343) and Engelmann spruce (r = 0.435). For the subalpine fir detrital samples, the earliest recorded kill date was 1816, while the most recent was in the late stage of senescence in 1999 (Fig. 5). For the Engelmann spruce detrital samples, the earliest recorded kill date was 1576, while the most recent was killed in 1994 (Fig. 5).

A number of detrital samples were strongly correlated with their respective master chronologies after the initial sapling stage, but had weakened

Table 2. Species, mean correlation to the master chronology, death date and distance buried of each sample with calculated rate of rock glacier movement. Rates were only calculated for samples where *in situ* stumps and distance buried (extent of material from the *in situ* stump to the rock mantle edge as measured along the buried bole) could be clearly identified. Species are identifed as ES (Engelmann spruce) or SAF (subalpine fir). Mean correlation coefficients are significant at the 99% confidence interval for r >0.328.

Sample number	Species	Mean correlation to master	Death date (AD)	Distance buried (cm)	Rate of movement (cm/year)
99Y01	ES	0.340	1718	460	1.64
99Y02	ES	0.598	1818	210	1.16
99Y03	ES	0.496	1861	250	1.81
99Y04	SAF	0.208	1816	270	1.48
99Y05	ES	0.494	1799	250	1.25
99Y06	ES	0.353	1955	100	2.27
99Y07	SAF	0.453	1831	250	1.49
99Y08	ES	0.404	1855	250	1.74
99Y09	ES	0.399	1847	250	1.64
99Y10	SAF	0.403	1943	90	1.61
99Y12	ES	0.652	1959	75	1.88
99Y13	ES	0.562	1958	75	1.83
99Y16	ES	0.408	1926	85	1.16
99Y18	ES	0.456	1942	65	1.14
99Y20	ES	0.290	1806	300	1.55
99Y21	ES	0.245	1771	290	1.27
99Y29	SAF	0.420	1931	180	2.65
99Y32	ES	0.341	1985	25	1.79
99Y36	SAF	0.405	1894	180	1.71
99Y37	ES	0.303	1641	450	1.26
99Y38	ES	0.250	1940	110	1.86
99Y39	ES	0.450	1901	145	1.48
99Y41	ES	0.249	1896	150	1.46
99Y42	ES	0.330	1846	200	1.31
99Y43	SAF	0.153	1963	60	1.67
99Y44	SAF	0.273	1968	60	1.94
			Average rate of movement		1.62

correlations over the last 20–30 years of radial growth. Inspection of the detrital samples showed that this behaviour characteristically followed physical disturbance of the tree by cascading debris. In total, 18 impact scars were identified on 10 discs. These impact events induced radial-growth suppression in the subsequent ring widths. Wounding of tree cambium occurred as early as 1814 and as recently as 1971 (Table 3). The data suggest the advancing rock glacier is disturbing tree growth and forcing the trees into a pronounced and extended period of senescence prior to death.

Bole burial

In the case of 26 partially buried boles, excavations into the rock glacier debris apron led to the discovery of associated *in situ* stumps. Fig. 6 illustrates the location of the *in situ* stumps and the associated death dates. Rates of frontal advance were estimated by dividing the total horizontal distance of burial from the *in situ* stump to the debris apron, by the number of years since death had occurred (Table 2). The computed rates of advance average 1.6 cm/year, but range from 2.7 to 1.1 cm/year (Table 2).

Based upon our field observations, two burial scenarios are proposed (Figs 7a and b). Trees with diameters <10 cm are initially wounded by rockfalls cascading down the distal slope as a result of rock glacier advance. This activity results in scarring on the proximal side of tree boles and eventually distal leaning (Fig. 7a (i)). When burial reaches a critical depth, the root-wad is tilted by the advancing rock matrix, growth ceases, and death occurs shortly thereafter (Fig. 7a (ii)). As the rock glacier continues to advance, the boles become increasingly entombed and tilted, to the point where the bole is eventually pushed over to lie on the ground surface (Fig. 7a (iii)).

Trees with trunk diameters of 20 cm or more in-

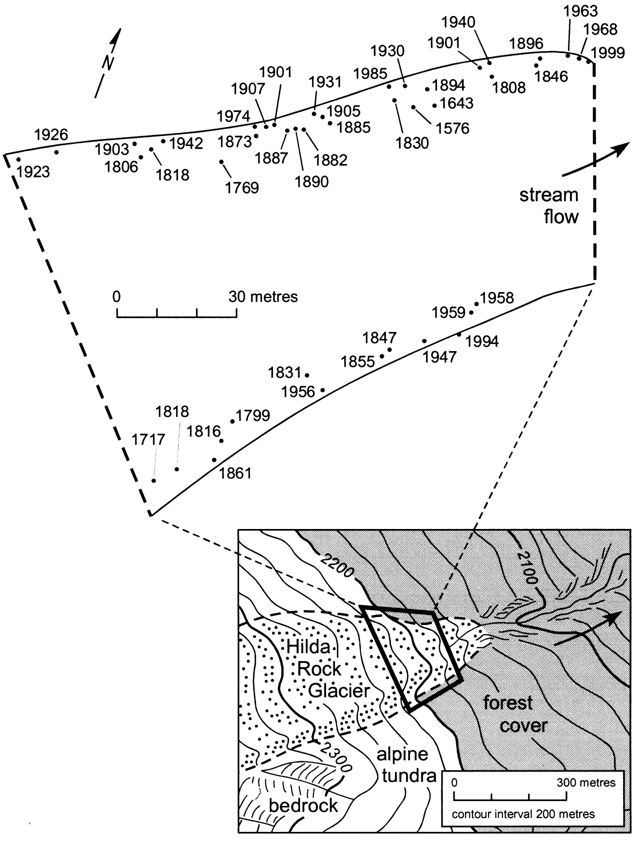

Fig. 6. Map of the perimeter of Hilda rock glacier with the position and the death date of each of the samples shown.

itially appear largely unaffected by the advancing rock glacier. As described above, debris cascades down the rock glacier snout and, while it may damage the base of the tree (Fig. 7b (i)), there is sufficient resistance provided by the bole, from rooting and its mass, that the tree is not tilted (Fig. 7b (ii)). As the rock glacier advances, increased stress is applied to the proximal side of the bole until it eventually shears, leaving the stump upright and *in situ* (Fig. 7b (iii)). Trees with diameters between 10 and 20 cm display both modes of burial and death.

Discussion

Our crossdated tree-ring samples show that Hilda rock glacier has been actively advancing from 1576 to present. On the south flank of the rock glacier, investigations revealed boles that had been killed as early as 1718 and as recently as 1994. Kill dates of samples collected on the north margin of the rock glacier range from 1576 to 1999.

These data suggest that Hilda rock glacier has

Table 3. Dates of impact wounds and death dates for samples with conspicuous impact scars and reaction wood. Species are identified as ES (Engelmann spruce) or SAF (subalpine fir).

Sample number	Species	Year of death (AD)	Impact dates (AD)
99Y11	ES	1994	1971
99Y23	SAF	1974	1962
99Y25	SAF	1901	1889
99Y27	SAF	1890	1866
99Y29	SAF	1931	1851
			1830
			1814
99Y30	SAF	1935	1885
			1848
			1824
99Y41	ES	1896	1876
			1867
			1862
99Y43	SAF	1963	1914
99Y44	SAF	1968	1925
99Y45	SAF	1999	1971
			1956
			1934

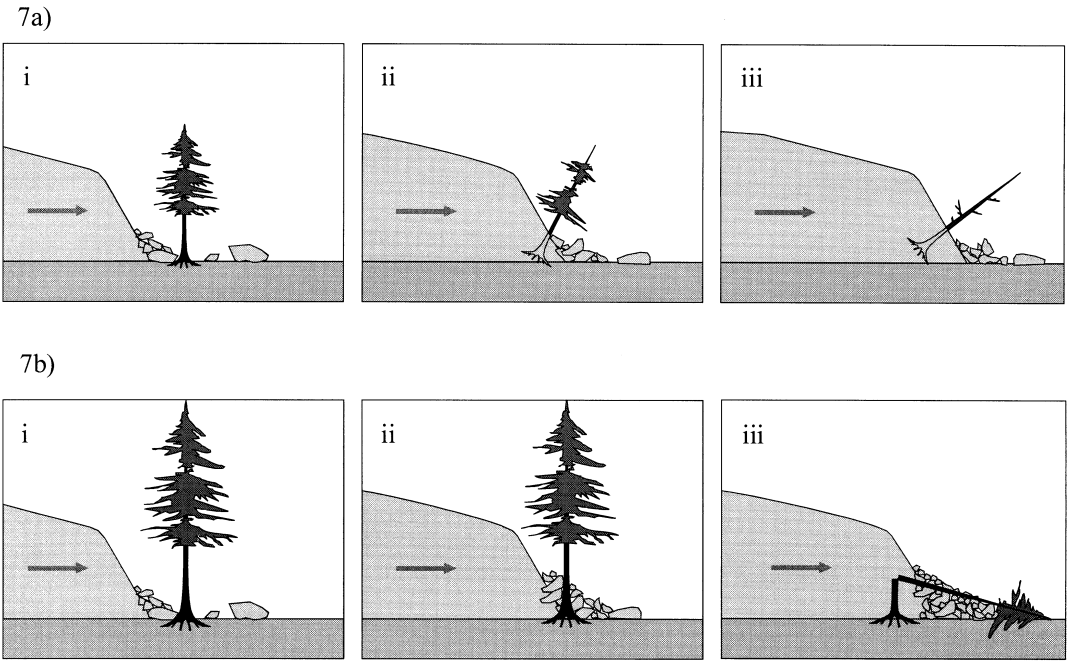

Fig. 7. Conceptual models for the two modes of tree burial observed at the site. The first mode of burial (a) was found to be more common for smaller diameter (<10 cm) trees. The second mode of burial (b) was more common for larger diameter (>20 cm) trees in the study.

experienced an extended period of slow continuous downslope movement from the late 1790s to present (Fig. 5). Prior to this period, data from four crossdated detrital samples suggest similar rates of frontal advance also characterized the behaviour of Hilda rock glacier in the sixteenth and seventeenth centuries. Based on these dendrogeomorphic insights, Hilda rock glacier appears to have been actively advancing at an average rate of 1.6 cm/year for at least the last *c.* 400 years. This rate of movement is similar to that previously measured in the Canadian Rocky Mountains by Koning and Smith (1999). Elsewhere in the North American cordillera, measured surface velocities vary, and are generally an order of magnitude faster than our calculated rate of advance, though some observations show comparable velocities (Wahrhaftig and Cox 1959; Benedict *et al.* 1986; Sloan and Dyke 1998; Konrad *et al.* 1999). Similarly, measured rock glacier velocities outside of North America are generally less than 1 m/yr (e.g. Francou and Reynaud 1992; Sollid and Sørbel 1992; Whalley *et al.* 1995; Humlum 1996; Berthling *et al.* 1998), though higher velocities have been recorded (e.g. Gorbunov *et al.* 1992).

Our calculated rate of advance for Hilda rock glacier is also comparable to those estimated on centennial to millennial scales for other rock glaciers. At the nearby Hilda Creek rock glacier, tree-ring dates on overridden wood suggest that the rock glacier has advanced downvalley at a rate of 1.2 cm/yr since the mid-nineteenth century (Carter *et al.* 1999). For rock glaciers in Svalbard, André (1994) estimated rates of advance for the last 3000 years of 0.8 to 4.5 cm/yr, based on rock glacier length and lichenometric surface ages. Using similar methods, Konrad and Clark (1998) and Sloan and Dyke (1998) inferred movement rates that were generally an order of magnitude higher than ours at rock glaciers in the Sierra Nevada, California and the Selwyn Mountains of northern Canada, respectively. In cases where it was possible to compare measured rock glacier surface velocity to inferred long-term velocity, the available data suggest the two velocities are within the same order of magnitude and statistically indistinguishable (André 1994; Sloan and Dyke 1998).

The long-term behaviour of Hilda rock glacier stands in contrast to the long-term mass balance response of glaciers within this area. Luckman and Kavanagh (2000) describe a 1.5°C rise in mean temperature over the last 100 years, noting that this was accompanied by upslope migration of the local treeline and a lengthy period of negative glacier mass balance conditions. The result of these ongoing climatic changes is a significant reduction in glacial extent that is unparalleled within the last 3000 years in the Canadian Rocky Mountains (Luckman 2000; Luckman and Kavanagh 2000; Osborn *et al.* 2001; Wood 2002). In Banff National Park, Peyto Glacier, for example, has experienced negative mass balance for most of the past 32 years and is rapidly retreating (Dyurgerov 2002). By contrast, our findings show that Hilda rock glacier is currently advancing, and suggest that it has been doing so at a constant rate for at least the last four centuries. This observation indicates that these climate changes have had little influence on the behaviour of Hilda rock glacier or that any climatic response is out-of-step with climate changes influencing the long-term behaviour of glaciers in this region (Luckman 2000). This behaviour may be a result of insulation resulting from the thick mantle of debris that overlies Hilda rock glacier (see Gardner 1978) that results in persistent permafrost conditions (e.g. Potter 1972; Clark *et al.* 1994).

Conclusion

Our findings suggest that Hilda rock glacier has been advancing and slowly burying trees at its margins for the last 423 years. Impact wounds and tree death dates appear evenly dispersed through time, suggesting that trees are killed by a slow advance of the rock glacier rather than by high-intensity, low-frequency rockfalls originating from the distal slope. Our study also suggests that Hilda rock glacier is not responding to ongoing climatic changes in the same manner as glaciers within this region. These conclusions are similar to those reported from rock glacier studies completed elsewhere in the Canadian cordillera (e.g. Sloan and Dyke 1998; Koning and Smith 1999), but provide the first dendrogeomorphic insights into rock glacier movement at the century scale in the Canadian Rocky Mountains.

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