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DENDROGLACIOLOGICAL INVESTIGATIONS AT HILDA CREEK ROCK GLACIER, BANFF NATIONAL PARK, CANADIAN ROCKY MOUNTAINS

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ABSTRACT Dendroglaciological techniques are used to provide evidence of historical rock glacier activity at Hilda Creek rock glacier in the Canadian Rockies. The research focuses on the sedimentary apron of the outermost morainal deposit, where excavations in 1997 uncovered six buried tree boles that had been pushed over and entombed by distally spilled debris. Cross-sectional samples cross-dated with a local Engelmann spruce tree-ring chronology were shown to have been killed sometime after 1856. Based on the extent of the excavation, the data indicate that Hilda Creek rock glacier has continued to advance along the present ground surface at a rate exceeding 1 cm/year.

RÉSUMÉ *Études dendroglaciologiques menées au glacier rocheux de Hilda Creek situé dans le parc national de Banff, dans les Rocheuses du Canada.* La dendroglaciologie sert ici à fournir des indices de l'activité passée au glacier rocheux de Hilda Creek. La recherche a davantage été axée sur la partie la plus externe du dépôt morainique où des excavations menées en 1997 ont permis de recouvrer six troncs d'arbres enfouis qui avaient été renversés et ensevelis par des débris distaux répandus. L'interdatation des coupes transversales d'échantillons avec la dendrochronologie de l'épinette bleue locale ont permis de situer l'événement quelque part après 1856. L'ensemble des données montre que le glacier rocheux de Hilda Creek s'est avancé le long de la surface actuelle du sol à un taux supérieur à 1cm/an.

ZUSAMMENFASSUNG *Dendroglaziologische Untersuchungen beim Steingletscher von Hilda Creek, Banff National Park, kanadische Rocky Mountains.* Um die zurückliegende Steingletscher-Aktivität am Hilda Creek-Gletscher in den kanadischen Rockies nachzuweisen, hat man dendroglaziologische Techniken benutzt. Die Studie konzentriert sich auf den äußersten Teil der Moränenablagerung, wo im Jahr 1997 durchgeführte Aushebungen sechs vergrabene Baumstämme freigelegt haben, welche durch distal verbreitete Trümmer umgestürzt und begraben worden waren. Die vergleichende Datierung von Querschnittsproben und der Baumringchronologie der lokalen Engelmann-Fichte zeigt, dass das Ereignis irgendwann nach 1856 stattgefunden hat. Auf die Ausgrabung gestützt zeigen die Daten, dass der Hilda Creek-Gletscher sich entlang der gegenwärtigen Bodenoberfläche mit einer Rate von über 1 cm/Jahr fortbewegt hat.

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INTRODUCTION

The geomorphology of rock glaciers in the southern Canadian Rocky Mountains is poorly appreciated (Ommanney, 1976; Luckman, 1981). While research within the last twenty-five years has increased our understanding of their distribution (Papertzian, 1973; Crockett, 1975; Luckman and Crockett, 1978; Smith, 1979) and physical characteristics (Gardner, 1978; Yarnal, 1979, 1982), only a few researchers have sought to discern their contemporary geomorphic behavior (Gardner, 1978; Koning, 1994; McAffee, 1995; McAffee and Cruden, 1996).

The majority of rock glaciers in the southern Canadian Rocky Mountains are thought to consist of a mixture of rock debris and ice (Ommanney, 1976) and thus likely move as a result of some form of permafrost creep (Koning and Smith, 1999). A small number of rock glaciers in the same region are apparently ice-cored (Luckman, 1977; Gardner, 1978) and behave more like debris-covered glaciers (*cf.* Barsch, 1996). Typical in this regard is the Wenkchemna rock glacier in the Valley of the Ten Peaks of Banff National Park first described by Sherzer (1907).

Documentation of rock glacier movement in the Canadian Rockies is based largely upon empirical observation. Limited measurements (1904-1905 AD) by Sherzer (1907) along the frontal slope of the Wenkchemna rock glacier led him to conclude it was advancing downvalley at rate of between 4 and 30 cm/year. Osborn (1975) examined a series of photographs (1902-1974 AD) showing the historic positions of three rock glaciers at nearby Lake Louise and reported rates of frontal advance varying from 30 to 60 cm/year. Far smaller rates of frontal advance were recorded at King's Throne rock glacier, where Koning and Smith (1999) documented 1.6 cm/year of frontal movement between 1988 and 1996.

Dendroglaciology is a research methodology that uses tree rings to study and date the movement of glaciers (Schweingruber, 1996; Luckman, 1988). In most dendroglaciological studies, trees killed or displaced by advancing glaciers are crossdated with reference to a living tree-ring chronology to identify when they were killed (Luckman, 1996, 1998; Smith and Laroque, 1996). While there are numerous reports from the North American cordillera of sites where trees have been killed or buried by advancing rock glaciers (Sherzer, 1907; Roots, 1954; Ragle *et al.*, 1970; Johnson and Nickling, 1979; Jackson and Macdonald, 1980; Blumstengel and Harris, 1988), there has been little attempt to understand the associated pace of rock glacier activity using dendroglaciological techniques (Shroder and Giardino, 1987). For this approach to be successful, a living tree-ring chronology must extend backwards in time past the age of the glacial advance being studied.

In a recent review Luckman (1998) illustrated the application of dendroglaciology to Little Ice Age glacier studies in the Canadian Rockies. We intend to show that dendroglaciological techniques may be equally suitable for describing the activity of selected rock glaciers over the same interval.

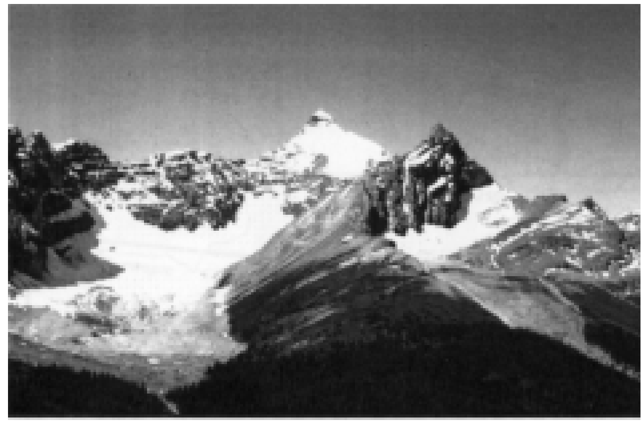

FIGURE 1. View west toward Hilda Glacier on the left and Mount Athabasca in the background, July 1981. The study site is located immediately to the left of where Hilda Creek emerges from beneath the distal sediment apron and traverses the local treeline in the left foreground. Shown in the right foreground is the "Hilda Rock Glacier" examined by Bajewsky (1988).

Vue vers le glacier de Hilda à l'ouest (à gauche) et vers le mont Athabasca, en arrière-plan (juillet 1981). Le site à l'étude est situé immédiatement à gauche de l'endroit d'où émerge le Hilda Creek de sous le dépôt de sédiments distal et traverse la limite locale des arbres à l'avant-plan, à gauche. À l'avant-plan, à droite, se trouve le glacier rocheux de Hilda Creek*, étudié par Bajewsky (1988).*

In this paper we present dendroglaciological evidence of historical rock glacier activity at Hilda Glacier in the Canadian Rockies (Fig.1). Our study was prompted by the discovery of detrital boles found protruding from the terminal ice-cored moraine at Hilda Glacier (Osborn and Taylor, 1975). This debris complex delimits the maximum Holocene extent of Hilda Glacier and was characterized by Heusser (1956: 284) as an active rock glacier based on the presence of "folds of soil ... pushed up along the down-valley periphery". Our excavations in September 1997 within the distal sediment apron of this deposit revealed an assemblage of tree trunks buried below ice-cemented rock debris. The boles were oriented downvalley and were frozen to the underlying soil surface. Based on these discoveries, we hypothesized that the rock glacier had advanced over a group of living trees and that dendroglaciological techniques could be used to identify when this had occurred.

STUDY SITE

Hilda Glacier is a small cirque glacier located below the eastern flanks of Mount Athabasca in the Columbia Icefield area of northern Banff National Park, Alberta (Fig. 2; Table I). Previous research at the site is limited to tree-ring investigations completed by Heusser (1956); proglacial stream studies undertaken by Kang (1982) and Hammer and Smith (1983); and a lichenometric survey by Osborn and Taylor (1975). Hydrological investigations at Hilda rock glacier (*unofficial name*) by Gardner and Bajewsky (1987), Bajewsky (1988) and Bajewsky and Gardner (1989) took place in a cirque basin one kilometre northeast and not within the Hilda Glacier forefield where our research took place (Figs. 1 and 2).

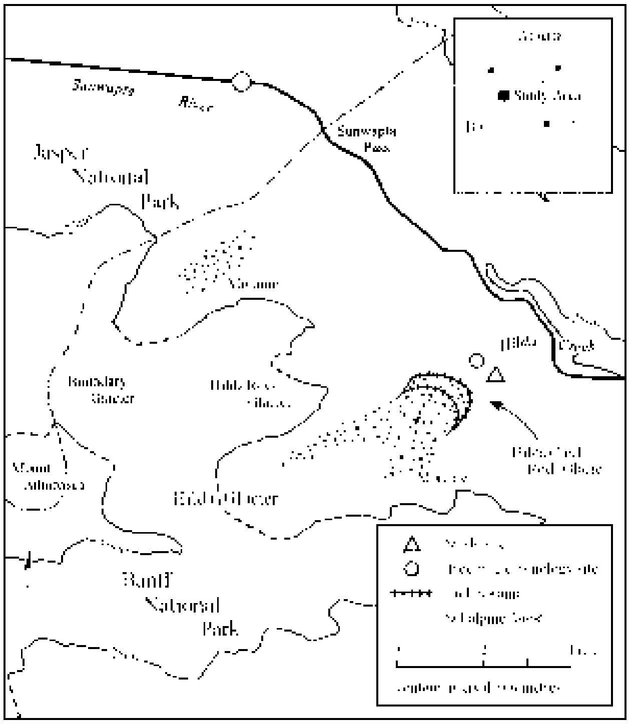

FIGURE 2. Map showing the location of Hilda Glacier and the rock glacier study site in northern Banff National Park, Alberta.

Localisation du glacier de Hilda et du site d'étude du glacier rocheux, dans le nord du parc national de Banff, en Alberta.

TABLE I

Site characteristics, tree-ring statistics for Hilda Creek Picea engelmannii *tree-ring chronology, and detrital wood statistics*

Site characteristics			
location		Lat. 52° 2' N; Long.117° 2' W	
elevation		2 100 m asl	
aspect		NE	
Living tree-ring series statistics			
number of trees		16	
duration of chronology		1586-1997	
series correlation*		0.56	
mean sensitivity		0.18	
autocorrelation		0.8	
Detrital wood statistics			
sample no.	Radius number	crossdated interval (year AD)	correlation with living chronology*
97HG1	1	1765-1856	0.46
97HG1	2	1764-1851	0.36
97HG2	1	1628-1790	0.49
97HG5	3	1588-1715	0.41
97HG5	5	1735-1847	0.37

* significant at the 99 % confidence interval for values above 0.328

Hilda Glacier has receded *ca.* 2 km upvalley from three concentric ridges, the outermost of which extends down below the local treeline (Fig. 3). The two inner ridges are sharp-crested and composed of coarse, unweathered, angular debris lodged in a fine sediment matrix. Upvalley of both ridges, hummocks and thaw pits suggest the differential ablation of stagnant ice (*cf.* Gardner, 1978). Heusser (1956:284) interpreted these deposits as recessional moraines formed by recent "marginal-waning up-glacier" and we support this interpretation. The relative surface ages of the moraines were assessed using regional lichenometric age-growth curves developed for *Rhizocarpon geographicum sensu lato* (Luckman, 1977) and *Xanthoria elegans* (Osborn and Taylor, 1975; McCarthy and Smith, 1995). Based on identification of the largest lichen thalli present, Douglas *et al.* (1997) suggest they are Little Ice Age end moraines that date from *ca.* 1805 and 1911 AD.

The broad, flat surface of the outermost ridge at Hilda Glacier is composed of an open matrix of cobble- to boulder-sized particles (Fig. 3). Occasional thaw pits on the surface of the ridge suggest at least portions of the deposit may be ice-cored (Fig. 3). The degree of weathering and lichen cover present on these particles suggests their deposition predates the Little Ice Age (*e.g.* Luckman, 1988; John, 1989). Numerous large circular *Rhizocarpon geographicum* (up to 300 mm in diameter) found on the surface of the deposit indicate it may be associated with a far earlier Neoglacial advance. The most likely episode is that recorded in the forefield of nearby Boundary Glacier (Fig. 2) between *ca.* 3 800 and 4 200 years BP (Gardner and Jones, 1985).

The research activity reported here focuses on the sedimentary apron of this outer ridge, close to where Hilda Creek emerges from beneath the debris (Fig. 2). The steep (>30 %) sharp-crested character of the frontal margin (Fig. 4), evi-

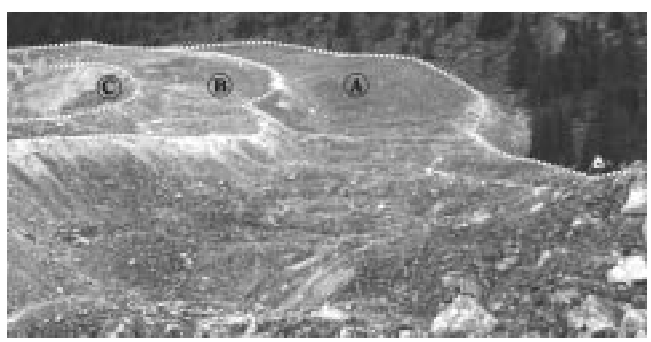

FIGURE 3. View to the northwest looking across the broad, flat surface of Hilda Creek rock glacier (A). A prominent thaw pit is shown in the left foreground. Pictured in the background are the Little Ice Age end moraines deposited by Hilda Glacier in *ca.* 1805 (B) and 1911 (C) AD. Note the stand of *Picea engelmannii,* located adjacent to the rock glacier snout, which was used to develop the living tree-ring chronology.

Vue vers le nord-ouest montrant la grande suface plate du glacier rocheux de Hilda Creek (A). Une importante dépression thermokarstique apparaît au premier plan, à gauche. À l'arrière-plan, apparaissent les moraines frontales abandonnées par le glacier de Hilda au petit Âge glaciaire, vers 1805 (B) et 1911 (C) ap. J.-C. Noter le peuplement de Picea engelmannii, *près du front du glacier rocheux, qui a servi à établir la dendrochronologie des arbres vivants.*

FIGURE 4. Steep frontal margin of the outermost debris complex in the Hilda Glacier forefield. The ice axe sits within our excavation and points downwards to one of the boles recovered from beneath the debris.

Marge frontale escarpée du complexe de débris le plus externe au front du glacier de Hilda. La hache repose dans un des trous creusés dans le cadre de la présente étude et pointe vers un des troncs recouvrés de sous les débris.

dence of near-surface permafrost, and an apron of scattered and overturned boulders splayed beyond the debris snout, all support the interpretation of Heusser (1956) and Osborn and Taylor (1975) that this deposit is a rock glacier. To distinguish our investigations from the Hilda rock glacier of Gardner and Bajewsky (1987), Bajewsky (1988) and Bajewsky and Gardner (1989), we will refer to this site as the Hilda Creek rock glacier.

RESEARCH METHODOLOGY

Preliminary excavations within the distal apron of the rock glacier, at a point *ca.* 50 m southwest of Hilda Creek, led to the discovery of two boles solidly frozen to the pedogenic surface below debris spilled from the rock glacier snout (Fig. 5). Further digging revealed the remains of a total of six

FIGURE 5. Shown is one of the larger boles (97HG1) exhumed from beneath the frozen rock glacier debris. The trunk rests on the buried forest floor and was killed sometime after the 1856 growth year.

Un des plus gros troncs déterrés (97HG1) des débris gelés du glacier rocheux. Le tronc repose sur la surface enfouie de la forêt et a été abattu quelque temps après 1856.

individual trunks lying directly on the underlying pedogenic surface. Although the trunks were of varying size and length, the longest segment uncovered was greater than 2.4 m long. Debris cascading down the unstable steep apron prevented further excavation and so we were unable to locate any associated roots. The trunks appeared to be the remains of trees that were pushed over and entombed by the advancing debris. While the logs displayed some surface mastication and peripheral decay, cross-sections were successfully cut from the three largest boles.

In order to facilitate ring-width measurement and to allow for crossdating (Stokes and Smiley, 1968), the disks were first dipped into a hot paraffin wax bath and allowed to cool. The disks were then polished to a high finish using progressively finer sandpaper. The longest and most intact radii (pith to perimeter) were identified on each disk. The tree-ring widths along each radius were then measured to the nearest hundredth of a millimetre using a computerized WinDENDRO^{TM} (Version 6.1D, 1998) image processing measurement system (Guay *et al.*, 1992; Sheppard and Graumlich, 1996). Where the ring boundaries were difficult to distinguish, a 40X microscope and Velmex-type stage measurement system were employed for ring boundary verification.

In order to establish when the undated detrital samples were killed, increment cores were collected from a stand of Engelmann spruce (*Picea engelmannii* Parry) located immediately adjacent to the Hilda Creek rock glacier (Fig. 2). Engelmann spruce trees characterize the local treeline (*cf.* Luckman and Kavanagh, 1998) and their local antiquity (Luckman *et al.*, 1984) offers considerable scope for crossdating. After air drying, the cores were glued into slotted mounting boards, polished to a high finish and were visually crossdated with reference to a set of regional pointer years (Luckman *et al.*, 1997). The annual ring-widths were measured using the WinDENDRO^{TM} system and the data checked for signal homogeneity using the COFECHA computer program (Holmes, 1983). A standardized tree-ring series was then constructed using a double detrending procedure within the ARSTAN computer program to remove the inherent age/growth trends (Holmes *et al.*, 1986).

RESULTS

The Hilda Creek living spruce chronology spans the interval between 1586 and 1997 AD. Table I presents the principal tree-ring statistics associated with our chronology. The mean series correlation value of 0.56 illustrates the relative strength of the chronology and the mean sensitivity value of 0.18 provides a measure of between-ring variability (Fritts, 1976). Autocorrelation is a measure of the correspondence between successive increments and the value of 0.80 assigned to our chronology suggests that radial growth at the Hilda Creek site is conditioned by factors in preceding growth years (Fritts, 1976). These values are characteristic of climatically responsive, upper elevation tree species in the area (Luckman *et al.*, 1997). There is a significant correspondence (r^2 = 0.66; 1586-1997) between the Hilda Creek chronology and the Athabasca Glacier chronology compiled by Luckman *et al.* (1997), including the presence of notable pointer years in 1746, 1799, 1824, 1844 and 1915.

The bole segments recovered from beneath the rock glacier snout were identified as detrital Engelmann spruce on the basis of the anatomic characteristics of their annual rings (Schweingruber 1993:227-234). The floating series were initially crossdated using COFECHA (50-year dated segments lagged by 25 years, with the critical level of correlation for the 99 % confidence interval set at 0.328) and verified against marker rings within both the Hilda Creek and Athabasca Glacier living chronologies. Figure 6 shows the position of the detrital ring sequences within the Hilda Creek living spruce chronology.

It was not possible to determine the exact year in which the rock glacier first began to encroach upon this stand of trees. There are no conspicuous ring-width anomalies in the cross-sections we examined, nor were there any scars or reaction tissues to suggest when the trees were damaged by boulders sliding down the snout. While the perimeter dates assigned to the three samples range from 1790 to 1856, none of the samples retained any bark and these dates can only be considered as minimum kill dates. Nevertheless, two of the boles (96HG1 and 96HG5) appeared to have relatively intact outer radii and describe kill dates within nine years of each other (Table I). These dates indicate that the trees were killed by the advance of the Hilda Creek rock glacier sometime after the 1856 growth year, at a time when nearby glaciers were reaching their maximum Little Ice Age positions (Luckman, 1988, 1996).

The advance of the Hilda Creek rock glacier into this stand of trees pushed them over, leaving them lying on the forest floor with their apical stems oriented downvalley. Debris spilling off the steep distal slope would have subsequently entombed the logs and continued burying them until their discovery in 1997. Based on the extent of our excavation into the snout (1.75 m), the position of the boles on the buried forest floor and the fact that debris continues to roll and spill off the

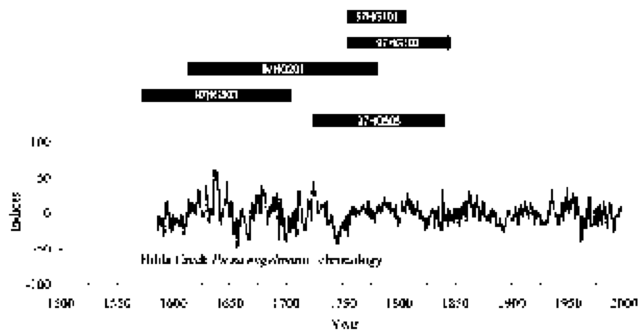

FIGURE 6. Summary of dendroglaciological studies at Hilda Creek rock glacier. The upper portion of the figure illustrates the length of the ring-width record of the crossdated detrital samples. While the youngest portion of each tree record describes the pith date of the sample, the oldest portion of each record does not represent the absolute age of the tree due to the loss of perimeter wood. The lower graph illustrates the Hilda Creek *Picea engelmannii* chronology prepared from increment core samples collected from living trees found growing adjacent to the study site (see Fig. 3). Note that radial growth trends prior to 1700 are described by a single tree.

Sommaire des études dendroglaciologiques menées au glacier rocheux de Hilda Creek. En haut, apparaît le relevé des échantillons détritiques interdatés. Bien que la partie la plus jeune de chacun des arbres donne la date du cœur de l'échantillon, la partie la plus vieille ne donne pas l'âge absolu de l'arbre en raison d'une perte de bois sur le pourtour En bas, le graphique illustre la chronologie de Picea engelmannii *du Hilda Creek établie à partir des échantillons recueillis chez les arbres croissant près du site d'étude (voir la fig. 3). Noter que les tendances de la croissance radiale avant 1700 ont été déterminées à partir d'un seul arbre.*

rock glacier snout, we have interpreted our dendroglaciological findings to suggest that the Hilda Creek rock glacier has advanced downvalley at a rate exceeding 1 cm/year over the last century. While this rate of displacement is lower than that reported in earlier rock glacier studies within the Canadian Rocky Mountains (Sherzer, 1907; Osborn, 1975), it does fall within the range of rates reported recently by Koning and Smith (1999) and other researchers (*e.g.* Blumstengel and Harris, 1988; Dyke, 1990; Sloan and Dyke 1998).

CONCLUSIONS

The terminal moraine complex at Hilda Glacier has a complex geomorphic history that is interpreted to be associated with Neoglacial, Little Ice Age and contemporaneous events. The outermost morainal ridge possibly developed from glacial sediments deposited during an advance of Hilda Glacier in the early part of the Neoglacial. During the intervening millennia, the Hilda Creek rock glacier developed an interstitial core of frozen debris. Glacial advances during the Little Ice Age modified the upper portions of the rock glacier, but never succeeded in overwhelming its downstream extent. Lichenometric measurements show that Hilda Glacier had receded from these Little Ice Age terminal positions by the beginning of this century. Our dendroglaciological investigations show that the Hilda Creek rock glacier was actively advancing into a stable forest cover (>400 years in age) in the latter part of the 19th century and suggest it continues to advance downvalley at a rate exceeding 1 cm/year.

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