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Holocene glacier history of Frank Mackie Glacier, northern British Columbia Coast Mountains

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Abstract

Frank Mackie Glacier repeatedly advanced across the Bowser River valley in northwestern British Columbia to impound Tide Lake during the Holocene. The most recent infilling of Tide Lake was associated with a late Little Ice Age glacier advance and ended around 1930 when the lake catastrophically drained. Over the last century Frank Mackie Glacier has retreated and down wasted to reveal multiple glaciogenic sedimentary units within the proximal faces of prominent lateral moraines. The units are separated by buried in-situ tree stumps and laterally contiguous wood mats deposited on paleosols. Dendroglaciological and radiocarbon dating of these wood remains show that Frank Mackie Glacier expanded into standing forests at 3710-3300, 2700-2200, 1700-1290, 900-500, and 250-100 cal. yr BP. These advances coincide closely in time with the previously established Tide Lake glacier dam chronology and with the Holocene history of other glaciers in the Bowser River watershed. The findings emphasize the likelihood that most glaciers within northwestern British Columbia underwent substantial size and mass balance changes over the last 4000 years, and often spent hundreds of years in advanced positions before retreating.

Keywords: dendroglaciology and tree-rings, Holocene, glacier history, British Columbia,

Boundary Ranges

Introduction

Glaciers worldwide have been retreating following the end of the Little Ice Age (LIA) in approximately 1850 A.D. (Dyurgerov and Meier 2000; Dyurgerov and McCabe 2006). As the pace of this glacier recession and down wasting has increased over the last fifty years (Chapin et al. 2013), valley-side slopes and lateral moraines in many regions are collapsing leading to deformation, rock avalanches, debris flows and slides (Holm et al. 2004). At many sites these slope failures are exposing previously unseen glaciogenic sedimentary units separated by paleosols and the subfossil remains of trees buried during earlier glacier activity. Overwhelmed and killed during discrete glacial advances, the tree remains can be dated using dendrochronological methodologies and/or radiometric techniques (Coulthard and Smith 2013) to provide singular records of the long-term mass balance response to changing climates (Winkler and Matthews 2010).

Recent research focused on glaciers located within the Coast Mountains of northwestern British Columbia (B.C.) draws attention to the limitations in our knowledge of their Holocene behaviour (Menounos et al. 2009; Mood and Smith 2015), especially when compared to the outcome of research within nearby Alaska and the southern Coast Mountain regions (Solomina et al., 2015; 2016). A regional exception is the developing understanding of Holocene glacier behaviour within the Bowser River watershed and adjacent Cambria Icefield area in northwestern B.C. Following on the pioneering work of Clague and Mathewes (1992) and Mathewes and Clague (1993) at Tide Lake and Berendon Glacier, a number of researchers have described multiple advance and retreat intervals from the mid-Holocene through to the LIA in this region (Jackson et al. 2008; Harvey et al. 2012; Johnson and Smith 2012; Osborn et al. 2012; Hoffman and Smith 2013).

In this paper we focus attention on Frank Mackie Glacier where lowering of the ice surface within the last few decades has uncovered the proximal face of prominent lateral moraines alongside the glacier and within the adjacent Bowser River Valley. Only recently exposed, these vertical exposures reveal that the moraines are composed of multiple glaciogenic sedimentary units separated by laterally contiguous wood mats, buried in-situ tree stumps and paleosols. We use ages assigned to the wood samples to describe the Holocene activity of Frank Mackie Glacier, and to advance understanding of the Holocene behaviour of glaciers within the Bowser River watershed and northern Coast Mountains. The study provides greater temporal resolution for Holocene glacier advances in the region and constrains the timing and of duration of these advances.

Study Area

Frank Mackie Glacier is located within the headwaters of the Bowser River watershed in northwestern B.C., approximately 50 km north of Stewart, B.C. and Hyder, Alaska (Fig. 1). Above Bowser Lake, the mountainous headwaters of the watershed straddling the international border with Alaska are characterized by icefields feeding into large valley glaciers including Salmon, Berendon, Frank Mackie, Canoe, Knipple and Charlie glaciers in B.C. (Fig. 1). To the east, Todd Glacier and several smaller glaciers drain from the Todd Icefield into northward-flowing Todd Creek, a tributary of the Bowser River that enters the valley 5 km above Bowser Lake.

The Bowser River watershed is located within the Boundary Range ecoregion (B.C. Ministry of Environment 2013), with the dominant forest cover consisting of mixed stands of subalpine fir (*Abies lasiocarpa*) and mountain hemlock (*Tsuga mertensiana*) trees. At Stewart,

the annual air temperature averages 6 °C and the annual total precipitation exceeds 1840 mm/yr, with more than 30% falling as snow (Environment Canada 2014).

Frank Mackie Glacier extends 10 km down valley from its source at ca. 1400 m asl in the Frank Mackie Icefield to terminate at ca. 600 m asl in 2013 (56°20'28"N, 130°05'16"; Fig. 1). Similar to other glaciers in northwestern B.C. and nearby Alaska (Mood and Smith 2015; Schiefer et al. 2008; Solomina et al. 2015; 2016), Frank Mackie Glacier has retreated and down wasted significantly over the past century (Fig. 2; Table 1). Aerial photographs show that the glacier terminus extended across the Bowser River valley in 1972, but by 2009 the glacier had retreated up valley and was largely constrained to its tributary valley (Figs. 2 and 3).

During the Holocene, Frank Mackie Glacier extended across the Bowser River Valley, damming the river to impound Tide Lake between Frank Mackie and Berendon glaciers (Haumann 1960). At its maximum length of 8.5 km and width of 1.7 km, the lake impounded over 1 km³ of water (Clague and Mathews 1992). Stratigraphic and radiocarbon evidence demonstrate that the glacier dam failed multiple times during the Holocene (Hanson 1932; Clague and Mathews 1996), producing outburst floods whose effects are recorded 28 km downstream in Bowser Lake (Gilbert et al. 1997). The last phase of Tide Lake was associated with a 17th century LIA advance of Frank Mackie Glacier and ended following incision of a kame moraine that impounded the lake until approximately 1930 A.D. (Clague and Mathews 1992; Clague and Mathews 1996). Examination of sediments exposed following drainage of the lake indicate that Frank Mackie Glacier advanced into the Bowser River Valley at least four times during the Holocene (Hanson 1932; Clague and Mathews 1992).

Prior descriptions of the Holocene behaviour of glaciers in the Boundary Ranges result from field studies at outlet glaciers flowing from the Frank Mackie, Todd, Cambria and Andrei

icefields (Hoffman and Smith 2013; Jackson et al. 2008; Mood and Smith 2015). Based on stratigraphic analyses of exposed sediments and drill cores analyses, Clague and Mathews (1992) and Clague and Mathewes (1996) describe advances of Berendon and Frank Mackie glaciers prior to 3000 cal. yr BP, in ca. 2940-2540, 1570-1300, and in 1050-770 cal. yr BP (2700 ± 60 , 1520 ± 50 , and 990 ± 60 ^{14}C yr BP). The peak LIA advance occurred at ca. 350 cal. yr BP (1600 A.D.) and ended at 50 cal. yr BP (1900 A.D.) (Clague and Mathews 1992).

Jackson et al. (2008) report that glaciers flowing from the Todd Icefield advanced prior to 3400 cal. yr BP, in ca. 3340-2930, 2490-2150, and 1550-1270 cal. yr BP (2960 ± 70 , 2300 ± 60 , in 1440 ± 60 ^{14}C yr BP), and during three phases of LIA expansion beginning in 780-560 cal. yr BP (730 ± 60 ^{14}C yr BP). Harvey et al. (2012) indicate that Canoe Glacier expanded into the Bowser River valley in 5450-5050 and 3710-3460 cal. yr BP (4570 ± 50 and 3360 ± 50 ^{14}C yr BP).

Outlet glaciers from the nearby Cambria Icefield (30 km south-east of Frank Mackie Glacier; Fig. 1) advanced down valley during several discrete intervals since the mid-Holocene. The snout of Bear River Glacier advanced into standing trees at least three times from 4220 to 3390 cal. yr BP (3680 ± 60 - 3310 ± 70 ^{14}C yr BP) and at least once in 1060-800 cal. yr BP (1040 ± 50 ^{14}C yr BP) (Jackson et al. 2008; Osborn et al. 2012). Eastward flowing South Flat and White glaciers advanced down valley in 1530-1200 cal. yr. BP (1550 ± 50 - 1280 ± 50 ^{14}C yr BP) and again during 950-540 cal. yr. BP (960 ± 40 - 610 ± 60 ^{14}C yr BP) (Johnson and Smith 2012). At Bromley Glacier thick wood mats within a prominent lateral moraine show that the glacier thickened and overwhelmed standing trees in 2700-2400, 1870-1710, 1390-1300, and 790-690 cal. yr BP (2720 ± 30 , 1850 ± 30 - 1480 ± 30 and 830 ± 30 ^{14}C yr BP) (Hoffman and Smith 2013).

Methods

Field surveys of recently exposed proximal moraine faces were undertaken where Frank Mackie Glacier flows into the Bowser River trunk valley (Fig. 3). Where subfossil wood remains were encountered within the units, representative samples with bark or intact perimeter wood were collected with a chainsaw for dendroglaciological and radiocarbon dating. Increment cores were collected from living trees found growing above the Holocene glacial limit to facilitate tree-ring cross-dating (Coulthard and Smith 2013).

The wood samples were allowed to air dry at the University of Victoria Tree-Ring Laboratory (UVTRL), after which species identification was completed using a 40× microscope and a reference key (Hoadley 1990). Following standardized preparation procedures (Stokes and Smiley 1968), the width of each annual tree ring in the core and subfossil samples was measured along two paths from pith to perimeter using WinDENDRO (ver. 2012). Individual ring-width series were visually cross-dated and verified using COFECHA (Grissino-Mayer 2001), with the living series combined to construct cross-dated tree-ring chronologies using ARSTAN (Ver41d) (Cook and Krusic 2005). Series correlations (Pearson correlation coefficient, r) for chronologies, significant at the 99% confidence level, were calculated with COFECHA for 50 year segments with 25 year overlaps. Series correlation values greater than 0.3281 were accepted as providing statistically significant cross-dates (Holmes, 1983).

Floating (undated) tree-ring chronologies were constructed by cross-dating the subfossil wood, after which an attempt was made to assign an absolute age by cross-dating to living chronologies (Coulthard and Smith 2013). Where cross-dating failed, representative perimeter wood samples from the floating chronologies were radiocarbon dated by Beta Analytic Inc. and the ages provided were used to assign relative calendar ages to the floating chronologies. The radiocarbon ages were converted to calendar years using the INTCAL13 calibration curve

(Reimer et al. 2013) which accounts for temporal fluctuations in the atmospheric $^{14}\text{C}/^{12}\text{C}$ ratio (Walker 2005). The calibrated ages were calculated to 2-sigma standard deviation.

Magnitude and timing of glacier advances were discerned from the stratigraphic position and age of the subfossil tree remains (Ryder and Thomson 1986). In-situ samples were assumed to provide a maximum-age for a glacier advance, whereas detrital samples with unknown provenance were used only in the construction of the floating chronologies. For this study, we considered in-situ subfossil wood samples to include samples found in growth position (i.e. rooted stumps) and large intact boles with bark found within or pressed into a paleosol (Mood and Smith 2015). As all the sites examined were remote from snow avalanche slopes, we presume the boles to be the remains of glacially-killed trees transported only a short distance from where they were rooted (i.e. Le Roy et al. 2009).

Observations

Living tree-ring chronologies

Increment cores were collected from a mixed stand of 200-300 year old mountain hemlock and subalpine fir trees found growing on an open rocky slope positioned above the LIA trim line at 835 m asl ($56^{\circ}19'19''\text{N}$, $130^{\circ}5'57''\text{W}$; Site 4 in Fig. 3). Rotted and only weakly cross-dated ($r < 0.400$), the chronologies constructed from these trees were unsuited for cross-dating the floating chronologies. Instead, we used mountain hemlock (1599 to 2004 A.D.) and subalpine fir (1649 to 2004 A.D.) chronologies constructed from trees found in the Todd Icefield area ($56^{\circ}12'21''\text{N}$, $129^{\circ}35'13''\text{W}$; 955 m asl). Both chronologies are characterized by robust tree-ring statistics, indicating they are well-suited for cross-dating (Jackson et al. 2008).

Site Descriptions

Site 1- Lower moraine

Site 1 consists of a large, bowl-shaped gully set into the proximal face of lateral moraine deposits in the Bowser River valley ($56^{\circ}19'31''\text{N}$, $130^{\circ}5'37''\text{W}$; Figs. 4 and 5). The site is located ca. 850 m south of the glacier. A transect established vertically up the gully, from 700 to 725 m asl, revealed that the moraine is composed of several lithostratigraphic units separated by prominent woody layers (WL) (Fig. 6). The lower portion of the section was comprised of an 8 m thick unit of diamict (unit 1) extending below 700 m asl. Units 1, 5 and 7 were composed of diamict, units 2 and 4 of sand, units 3, 4 and 6 consisted of clay to silt sized sediments, and the upper unit was comprised of mainly gravels (Fig. 6).

A woody layer (WL1) at 700 m asl within the diamict unit, consists of a black, undulating organic horizon containing numerous in-situ boles (Fig. 6), including FM05-0103 which yielded a radiocarbon age of 1760 ± 40 ^{14}C years BP (1810-1570 cal. yr BP, Table 2). Above WL1 at 705 m asl, three upright boles in growth position were located adjacent to the gully wall. FM0501-04 dated to 870 ± 40 ^{14}C years BP (910-700 cal. yr BP) (Table 2).

A second wood mat (WL2) horizontally transects the gully at 715 m asl (Fig. 6). Overlying clay-silt sized sediments and positioned below a sandy unit, detrital wood samples were collected immediately below and above WL2 for cross-dating purposes. A bole (FM0501-10) collected from within WL2 dates to 860 ± 40 ^{14}C years BP (910-690 cal. yr BP, Table 2).

A third wood mat (WL3) was found at 720 m asl, close to the upper extent of the gully. Three in-situ boles were collected for cross-dating directly above a clay-silt unit and below a diamict unit (Fig. 6). FM0501-06 yielded a radiocarbon age of 560 ± 50 ^{14}C years BP (650-510 cal. yr BP, Table 2).

Site 2 - Upper moraine:

Three nested moraine crests at ca. 835 m asl were identified at Site 2 (56°19'16"N, 130°5'43"W; Figs. 3 and 7). A gully eroded through the most proximal moraine shows that it is primarily composed of a massive diamict with a woody layer (WL4) buried within reddish clay-sized sediments. Nine in-situ and four detrital samples were collected between 808 and 818 m asl for cross-dating (Table 3).

Site 3 – Moraine complex/ spill area

Thirty-eight detrital samples were collected (580 to 700 m asl) below the proximal lateral moraine face at Site 3 (56°19'38"N, 130°5'30"W; Fig 3). Included were samples from a small post-glacial landslide, as well as samples contained within debris flow and fluvial deposits transported out of the gully at Site 1.

Site 5 - North lateral moraine

Site 5 is located within lateral moraine deposits along the north side of the glacier terminus at 755-757 m asl (56°20'53"N, 130°05'38"W; Figs. 3 and 8). Exposed within the walls of a prominent gully at Site 5 was an organic mat (~10 cm) with identifiable fir needles and an underlying paleosol buried beneath a thick (>20 m) diamict deposit. Numerous broken boles, oriented down valley, rest on the surface of the organic mat (WL5). One in-situ bole (FM05-24) was killed in 2490 ± 40 ^{14}C years BP (2740-2380 cal. yr BP) and a second (FM05-23) in 2380 ± 40 ^{14}C years BP (2690-2330 cal. yr BP) (Table 2).

Site 6 - Spill area below north lateral moraine

Site 6 consists of a large gully incised through the north lateral moraine (56°20'53"N, 130°05'38"W; Fig. 3). Over 50 detrital samples were collected from within the outwash zone of this gully at 685 to 670 m asl for cross-dating.

Dendrochronological Results

In total, 95 subfossil wood samples were collected for analysis. Approximately one third of the samples were discarded as they could not be internally cross-dated due to the presence of reaction wood, rot and other growth anomalies, or they contained too few rings (<50) for robust cross-dating to a master chronology. This preliminary assessment left 57 samples with internal cross-dating correlations of $r \geq 0.400$ available for constructing floating chronologies. Five additional samples, including two radiocarbon dated samples collected during field surveys at nearby Canoe (Harvey and Smith 2012) and Charlie glaciers (St-Hilaire 2014) were also available and were included in the cross-dating analyses (Table 3).

A total of six floating chronologies were constructed from 44 samples (Table 3). Four floating chronologies (Chron. A, B, C, and D), with interseries correlations values ranging from 0.443 to 0.457, were successfully cross-dated to radiocarbon-dated samples (Fig. 9). Two floating chronologies (Chron. E and F) cross-date to the living chronologies collected by Jackson et al. (2008) in the Todd Icefield area (Fig. 9). To allow for comparison with the absolute dates assigned to Chron. E and F, the relative ages assigned to Chron. A-D were anchored to the mean of the calibrated radiocarbon ages (Table 2). In Fig. 9, error bars are presented to illustrate the potential age range of each sample.

Stratigraphic Interpretation

Recent recession, downwasting and valley-side slumping at Frank Mackie Glacier has exposed the proximal faces of lateral moraines both within the Bowser River valley and the glacier's tributary valley. The stratigraphy of the lower southern lateral moraine (Site 1) indicates that these moraines are composite features originating from fluctuating energy and geomorphic regimes during the late Holocene, as demonstrated by alternating moraine, fluvial and lacustrine sediment units (Figs. 4 and 6). As Frank Mackie Glacier advanced in 1760 ± 40 ^{14}C years BP

(1810-1570 cal) it overrode and buried a standing valley-side forest (WL1) beneath diamict (Unit 1) at Site 1. During a succeeding interval of glacier recession, fluvial sediments consisting of a well-sorted unit of sands were (Unit 2) deposited in an ice marginal stream. The sands grade upward and interfinger into the lowest part of several metres of laminated clay-silt sized sediments (Unit 3) that presumably accumulated within an ice marginal lake or pond. Following drainage of the lake and an interval of at least 187 years, Frank Mackie Glacier advanced toward this location to deposit glaciofluvial sands (Unit 4) that buried and killed the trees at WL2 by 860 ± 40 ^{14}C years BP (910-690 cal. yr BP, Table 2). The sand unit is capped by a diamict (Unit 5) deposited as the glacier advanced over Site 1. Following this early LIA advance the glacier retreated from the site, allowing for the formation of an ice marginal pond into which clay-silt sized sediment accumulated (Unit 6). Following drainage of the pond and establishment of a trees that grew for at least 150 years (WL3), Frank Mackie Glacier advanced across Site 1 in the late LIA to bury the remains of this forest beneath a diamict (Unit 7). The advance occurred by ca. 230-130 cal. yr BP (1720-1820 A.D.) (Table 3), when the glacier had thickened 110 m upwards to the LIA lateral moraine crests identified at the upper extent of the diamict sediments at Site 2 (Fig. 5). It is likely that maximum Holocene ice levels persisted at this elevation until the end of 19th century, given the persistent lack of vegetation and tree re-colonization below the trim line (835 m asl) at sites 1 and 2.

Discussion and Regional Synthesis

Our investigations at Frank Mackie Glacier allow for identification of five discrete glacial advances after 4000 cal. yr BP (Fig. 10). We did not find any evidence of early Holocene glacier activity, such as the episodes reported at Sphaler Glacier 100 km to the northwest in the Andrei Icefield area at 8998-8699 and 7937-7694 cal. yr BP (Mood and Smith 2015) which coincide

with the global 8.2 ka event (Kobashi et al. 2007). Nor did we locate evidence for glacier expansion at 5202-5047 or 4100-4020 cal. yr BP, as found at Canoe and Bear River glaciers, respectively (Harvey et al. 2012; Osborn et al. 2013). If these early and mid-Holocene events occurred at Frank Mackie Glacier, evidence of them has either been obscured by later late Holocene glacier activity or it remains to be discovered.

The earliest record of glacier expansion at Frank Mackie Glacier comes from Tide Lake sediments. Clague and Mathews (1992) describe sedimentary evidence in exposed bluffs and from a drill core taken in the southern section of the Tide Lake basin. Interpreted as resulting from damming of the Bowser River prior to 3000 cal. yr BP, this advance likely occurred around 3710-3460 cal. yr BP when nearby Canoe Glacier expanded into the Bowser River Valley (Harvey et al. 2012). Detrital wood samples from Site 6 cross-date to the radiocarbon dated Canoe Glacier samples, possibly indicating that Frank Mackie Glacier was also advancing and killing valley-side trees during this interval (Fig. 10, Table 3).

A second advance of Frank Mackie Glacier was underway from 2700-2200 cal. yr BP, when a standing forest on the northern lateral moraine at sites 5 and 6 was buried during the deposition of lateral moraine sediments. This advance corresponds to sedimentary records from Tide Lake (Clague and Mathews 1992; Fig. 10), as well as to contemporaneous advances of valley glaciers flowing from the Todd and Cambria icefields (Jackson et al. 2008; Hoffman and Smith 2013; Osborn et al. 2013).

Following the 2700-2200 cal. yr BP advance, Frank Mackie Glacier retreated up valley before readvancing at 1900-1500 cal. yr BP to bury trees colonizing moraine sediments at sites 1 and 3 of the southern lateral moraine (Figs. 9 and 10). Corresponding glacier advances in the Todd Icefield area (Jackson et al. 2008), as well as in the Andrei and nearby Cambria icefield

areas (Johnson and Smith 2012; Hoffman and Smith 2013; Mood and Smith 2015), attest to the regional significance of this first millennium A.D. event (Reyes et al. 2006). Sedimentation and lack of disturbance of detrital wood and conifer needles recovered from Tide Lake sediments, dating from 1700-1290 cal. yr BP, suggest Frank Mackie Glacier remained in an advanced position for several hundred years following this advance (Clague and Mathews 1992).

By 900-500 cal. yr BP, Frank Mackie Glacier was advancing down valley and expanding up the surrounding valley walls during an early LIA glacial event (Figs. 9 and 10), at the same time as Bear River, Bromley, South Flat, Todd, and White glaciers in the Cambria Icefield were also advancing into standing forests (Jackson et al. 2008; Johnson and Smith 2012; Hoffman and Smith 2013; Osborn et al. 2013). This advance appears to have been more extensive than any other within the previous 2000 years, with in-situ stumps at Frank Mackie Glacier (Site 2) found buried beneath moraine sediments over 100 m above the upper limit of sediments deposited during earlier Holocene advances.

Following a brief hiatus that likely included a short-lived interval of terminus retreat and ice surface lowering, as seen by evidence of renewed tree growth (Table 3), Frank Mackie Glacier expanded in 250-100 cal. yr BP to kill and bury a valley-side stand of trees at Site 2 (Figs. 3 and 5). This late LIA advance occurred at the same time as glaciers flowing from the Todd Icefield were killing and burying mature trees (Jackson et al. 2008). Dendroglaciological evidence demonstrates that the magnitude of this late LIA advance was similar to the early LIA advance, with logs buried immediately below the trim line at Site 2. This advance coincides with the Holocene glacier maximum and is recorded across the Coast Mountains (Desloges and Ryder 1990; Menounos et al. 2009; Mood and Smith 2015).

Conclusions

Dendroglaciological and radiocarbon dating of wood remains buried by repeated advances of Frank Mackie Glacier confirm and reinforce prior interpretations of its late Holocene glacier activity. Intervals of glacier expansion at 3710-3300, 2700-2200, 1700-1290, 900-500, and 250-100 cal. yr BP coincide closely in time with the Tide Lake glacier dam chronology established by Clague and Mathews (1992). Taken together, the two records indicate that following each of the five late Holocene expansion events, Frank Mackie Glacier remained in an advanced position, for hundreds of years in some instances, to dam the Bowser River.

The late Holocene history of Frank Mackie Glacier closely matches that established for other glaciers in northwestern B.C. (Menounos et al. 2009; Mood and Smith 2015). It emphasizes these glaciers underwent substantial size and mass balance changes over the last 4000 years, often times spending hundreds of years in advanced positions. Given the rapid response of Frank Mackie Glacier to climate changes over the last century (Table 1), additional research on early to mid-Holocene lateral moraine stratigraphy and dendroglaciology is warranted to fully appreciate the glaciological changes certain to accompany the climate changes projected to occur in northwestern B.C. over the next century.

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Table 1. Historical terminal retreat rates at Frank Mackie Glacier.

Period	Retreat during period (m)	Mean rate of retreat (m/yr)	Imagery Type, Year	Source
1905-1972	50	< 1	Photograph, 1905	1BC6653 (Clague and Matthews 1996)
1972-1997	150	6	Aerial photo, 1972	BC5504-172
1997-2009	342-700	29-58	Satellite image, 2009	Google Earth, Spot
2009-2013	500-888	125-222	Satellite image, 2013	Microsoft Corporation, Bing Maps

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Table 2. Summary of radiocarbon dated samples at Frank Mackie Glacier.

Lab No.	Sample ID	¹⁴ C age (yr BP)	2σ calibrated age (cal. yr BP) ^a	Location	Elev. (m asl)	Sample Description
Beta-217006	FM05-23	2380 ± 40	2690-2330	Site 5, north moraine wall	757	Oriented with direction of glacier flow.
Beta-217007	FM05-24	2490 ± 40	2740-2380	Site 5, north moraine wall	755	In-situ, on organic mat.
Beta-242990	FM05-0103	1760 ± 40	1810-1570	Site 1, gully wall	700	In-situ in WL1
Beta-242991	FM05-0104	870 ± 40	910-700	Site 1, bowl shaped gully,	705	In-situ, upright
Beta-242992	FM05-0110	860 ± 40	900-690	Site 1, hanging at top corner of gully wall/bowl	715	In-situ in WL2
Beta-242994	FM05-0106	560 ± 50	650-510	Site 1, bowl shaped gully	720	In-situ in WL3

^aAges have been calibrated using OxCal 4.2 (Bronk Ramsey and Lee 2013) and the IntCal13 curve (Reimer et al., 2013).

Table 3. Subfossil chronologies established at Frank Mackie Glacier.

Sample ID ^a	Site	Maximum No. rings	Correlation with master chronology, r	Perimeter age ^b (cal. yr BP)	Elevation (m asl)	Location description
Cross-dated to 14C anchored floating tree-ring chronologies						
Chron. A						
FM05-26	6	151	0.514	3227	670-685	detritus in incised gully
FM05-27	6	178	0.409	3239	670-685	detritus in incised gully
FM05-28	6	70	0.451	3371	670-685	detritus in incised gully
KG13-01	Charlie Gl	59	0.523	3490	1080	upright 1.3m bole pressed between till and bedrock
KG13-29	Charlie Gl	140	0.443	3406	989	buried perpendicular in gully
CAN06-02	Canoe Gl	165	0.531	3358		in-situ in wood mat horizon
CAN06-16	Canoe Gl	65	0.493	3355		detrital in wood mat horizon
Chron. B						
FM05-23	5	66	0.46	2521	757	on organic wood mat
FM05-24	5	87	0.46	2421	755	on organic wood mat
FM05-NSfc08	6	107	0.517	2394	670-685	detritus in incised gully
FM05-NSfc17	6	191	0.494	2430	670-685	detritus in incised gully
FM05-NSfc18	6	121	0.463	2482	670-685	detritus in incised gully
FM05-NSfc19	6	175	0.53	2458	670-685	incised gully in north lateral moraine
FM05-NSfc25	6	129	0.451	2495	670-685	detritus in incised gully
Chron. C						
FM05-0103	1	276	0.492	1675	700	in black organic layer, WL1
FM05-0105	1	112	0.597	1777	705	standing upright in bowl gully above WL1
FM05-L	3	168	0.488	1680	580-680	detritus in moraine complex
FM05-Z	3	113	0.455	1673	580-680	detritus in moraine complex
KG13-06	Charlie Gl	100	0.443	1841	1080	detrital wood in moraine colluvium
Chron. D						
FM05-0104	1	187	0.404	805	705	standing upright in line with WL2
FM05-01	2	76	0.618	655	817	in-situ in till of upper gully
FM05-02	2	103	0.482	853	815	in-situ in till of upper gully
FM05-11	2	135	0.57	612	810	detritus in red clay, WL4

FM05-12	2	180	0.531	652	816	in-situ in red clay, WL4
FM05-13	2	78	0.467	750	808	detritus in massive till
FM05-14	2	101	0.504	642	807	in-situ in red clay, WL4
FM05-C	3	145	0.464	784	580-680	detritus in moraine complex
FM05-NSfc01	6	250	0.415	707	670-685	detritus in incised gully
FM05-NSfc02	6	121	0.526	802	670-685	detritus in incised gully
FM05-NSfc05	6	163	0.429	713	670-685	detritus in incised gully

Cross-dated to 14C living tree-ring chronologies

Chron. E

FM05-09	2	99	0.478	223	818	in-situ in red clay, WL4
FM05-A	3	106	0.475	156	580-680	detritus in moraine complex
FM05-B	3	127	0.404	177	580-680	detritus in moraine complex
FM05-F	3	139	0.652	123	580-680	detritus in moraine complex
FM05-I	3	178	0.463	121	580-680	detritus in moraine complex
FM05-J	3	72	0.388	147	580-680	detritus in moraine complex
FM05-NSfc10	6	143	0.494	132	670-685	detritus in incised gully
FM05-NSfc23	6	144	0.382	141	670-685	detritus in incised gully

Chron. F

FM05-08	2	65	0.518	230	818	in-situ in red clay, WL4
FM05-10	2	235	0.481	133	819	in-situ in red clay, WL4
FM05-D	3	133	0.356	153	580-680	detritus in moraine complex
FM05-E	3	176	0.424	131	580-680	detritus in moraine complex
FM05-U	3	82	0.536	219	580-680	detritus in moraine complex
FM05-W	3	288	0.362	128	580-680	detritus in moraine complex

^aCharlie Glacier samples (KG13-01 and KG13-29) from St-Hilaire (2014) and Canoe Glacier sample (CAN06-02) from Harvey et al. (2012).

^bThe relative ages assigned to Chron. A, B, C, and D were assigned by cross-dating to radiocarbon-dated samples (see Table 2). The absolute ages assigned to Chron. E and F were derived by cross-dating with living chronologies collected by Jackson et al. (2008) in the Todd Icefield area. To allow for comparison between the chronologies, the relative ages assigned to Chron. A-D were anchored to the mean of the calibrated radiocarbon age.

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- Fig. 8. Frank Mackie northern lateral moraine, Site 5. Shown is the position of wood layer, WL5, located at the boundary between two diamict units dating to $2490-2380 \pm 40$ ^{14}C years BP (FM05-23, -24).
- Fig. 9. Summary subfossil tree chronologies constructed from Frank Mackie Glacier sites.
- Footnotes:
- ^a Cross-dated samples are grouped with brackets. Each rectangle represents the temporal extent of a sample. Error bars for chronologies A-D represent two standard deviation margin associated with the radiocarbon-dated samples. Chronologies E and F are cross-dated with living tree chronologies.
- ^b Charlie Glacier samples (KG13-01, KG13-06 and KG13-29) from St-Hilaire (2014)
- ^c Canoe Glacier sample (CAN06-02) from Harvey et al. (2012).
- Fig. 10. Summary of radiocarbon ages from Frank Mackie Glacier (this study), Tide Lake (Clague and Mathews 1992), Canoe Glacier (Harvey et al. 2012) and the Todd Valley

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Fig. 1

Fig. 2.

490x259mm (300 x 300 DPI)

Fig. 3.

Fig. 4.

Fig. 5.

Fig. 6.

Fig. 7.

Fig. 8.

Fig. 9.

Fig. 10.