GLACIOLOGICAL STUDIES AT RAE GLACIER, CANADIAN ROCKY MOUNTAINS

Carolyn P. Lawby
Department of Geography
University of Saskatchewan
Saskatoon, Saskatchewan S7N 0W0
Canada

*Dan J. Smith** and *Colin P. Laroque*
Department of Geography
University of Victoria
P.O. Box 3050
Victoria, British Columbia V8W 3P5
Canada

Melinda M. Brugman
National Hydrological Research Institute
Environment Canada, 11 Innovation Boulevard
Saskatoon, Saskatchewan S7N 3H5
Canada

Abstract: Rae Glacier is a small cirque glacier located in the front ranges of the Canadian Rocky Mountains. In 1990 and 1991 field research was completed to describe the physical glaciology of Rae Glacier and to characterize historical glaciological trends at the site. Ablation and surface movement rates were measured using a network of stakes drilled into the glacier and radio-echo sounding was used to describe local ice depths.

Rae Glacier has experienced a significant loss in size and mass during the historical period, owing to a lengthy interval of negative mass-balance conditions. The glacier has decreased in surface area by over 50% and now contains less than 24% of the ice it did at the end of the last century.

Surface-ice velocity varied between 1.4 and 5.4 m from 1990 to 1991. Rates of ice ablation proved to be highly variable, with steeper areas showing up to 50% more ablation. Combined with data on the emergent flow component of the glacier, the ablation data suggest that the glacier presently is unable to replenish the amount of ice annually being lost to ablation. The glacier has a lag time of 5 to 10 years, which confirms that it is sensitive to climatic fluctuations and responds to changes in mass balance within a very short time. This observation is supported by an estimated response time of 42 years. [Key words: glaciology, Rae Glacier, Canadian Rocky Mountains.]

*Corresponding author.

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INTRODUCTION

Glaciological inquiry in the Canadian Rocky Mountains is founded on research efforts at a few comparatively large glaciers (e.g., Meier, 1960; Paterson and Savage, 1963; Raymond, 1971). All of these glaciers are located in the Main Ranges of the Rockies, with most found along the continental divide in Banff, Jasper, and Yoho National Parks (Young and Ommanney, 1984; Brugman, 1991). The behavior of glaciers in the Rocky Mountains outside this region essentially is unknown (Denton, 1975; Ommanney, 1989). Noteworthy in this regard are glaciers found between latitudes 49° and 51° N, along the interprovincial divide between Alberta and British Columbia. Glaciers within this area are among the southernmost in Canada and thus are potentially the most temperature-sensitive grouping of glaciers in the Canadian cordillera.

This southern grouping of glaciers lies almost entirely within the rugged eastern front ranges. Although only a few small glaciers or perennial snowpacks lie south of Mt. Abruzzi (50° 22′ N), northward from this point to Mt. Sir Douglas (50° 45′ N) there is an almost continuous series of small glaciers in Elk Lakes and Peter Lougheed provincial parks (Denton, 1975; Smith et al., 1995). The majority of these glaciers are restricted to summit, cirque, or hanging-valley locations (McCarthy and Smith, 1994), and do not have official names (Ommanney, 1989).

The glaciological behavior of this group of glaciers is still largely unknown. McCarthy and Smith (1994) have shown that many of them downwasted and generally retreated after 1916. A morphometric analysis demonstrated that individual glaciers decreased in area by 15 to 80% and retreated at rates averaging between 20 and 157 meters per year (m/y). This general pattern of terminus retreat was, however, interrupted during three notable wet-cool periods: 1946–1957, 1964–1968, and 1975–1981 (McCarthy and Smith, 1994). Glacial activity during each of these periods was characterized either by reduced or negligible recession or by minor readvances (McCarthy and Smith, 1994).

The purpose of this paper is to report on glaciological investigations carried out at a single glacier in this region. As few studies have been made on small glaciers in the Canadian Rockies, a cirque glacier was selected for study where no previous scientific observations had been undertaken. We speculated that the rapid response of glaciers in this area to short-term climate variations was a reflection of their mass-balance sensitivity (e.g., Grudd, 1990). It was anticipated that a description of the contemporary and historical physical glaciology of the site would enable us to test this hypothesis.

STUDY SITE

Field work for this study took place at Rae Glacier (unofficial name, glacier No. 4: Map 7.2 in Ommanney, 1989) in 1990 and 1991. Rae Glacier is located approximately 75 km southwest of Calgary, Alberta, in the front ranges of the Canadian Rockies (Fig. 1). The glacier is positioned above 2400 m above sea level (a.s.l.) in a high-elevation cirque on the northwest face of Mount Rae.

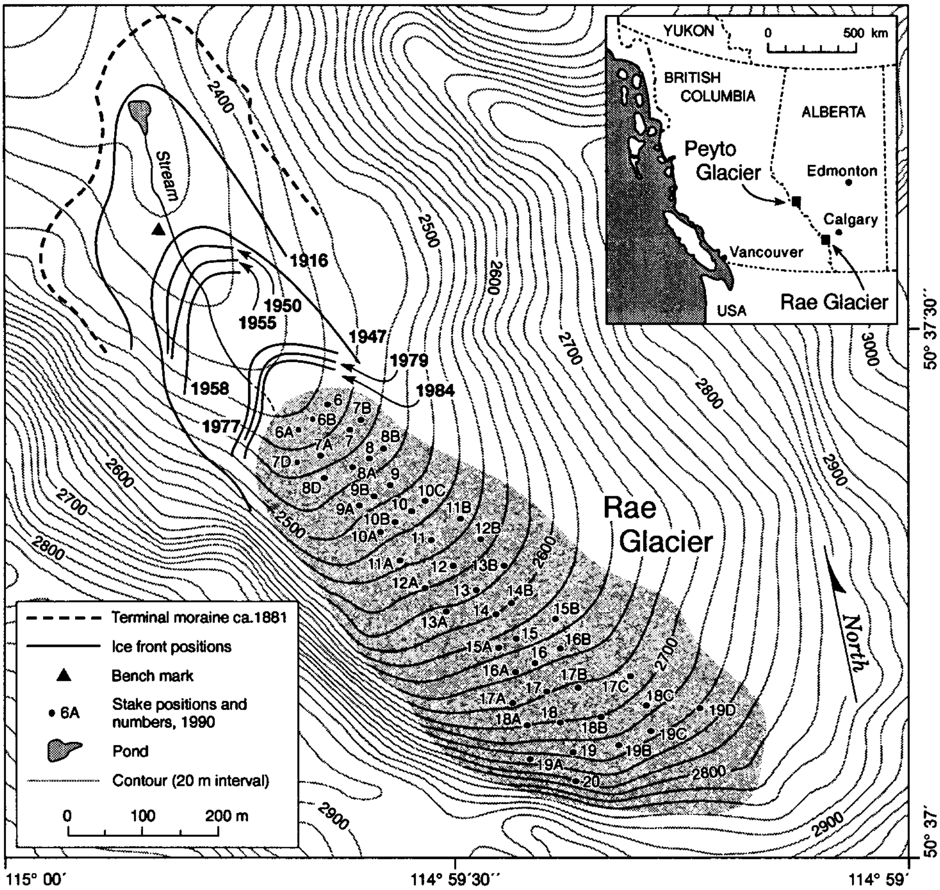

Fig. 1. Location and topographic character of Rae Glacier, Alberta. Shown on the map are the historical terminus positions of the glacier and the location of survey stakes placed on the glacier in 1990.

Rae Glacier is a small, steep (average surface slope = 24°) cirque glacier bounded to the east and west by towering rock walls (Fig. 2). In 1991, Rae Glacier was approximately 700 m in length and had a surface area of 0.23 km^2. The glacier tapers from a width of 350 m in its accumulation area (2790 m a.s.l.) to less than 150 m across at the terminus (2415 m a.s.l.). Numerous transverse crevasses are evident near a prominent bergschrund bisecting the upper part of the accumulation area, and in a steeply sloped area (25–33°) located approximately 200 m down-ice of the bergschrund.

The glacier surface is covered partially by rock debris (up to 0. 5 m in thickness) deposited by rock falls and snow avalanches from the surrounding bedrock cliffs (Gardner, 1980). In areas where the debris cover is thin, ice banding is evident and 200 sedimentary layers were distinguished in 1990.

Rae Glacier has undergone considerable thinning and retreat since the end of the Little Ice Age. Lichenometric evidence from a terminal moraine positioned 450 m

Fig. 2. Rae Glacier, August 1985.

Table 1. Historical Terminus-Retreat Rates at Rae Glacier

Interval Year (date, air photograph no.)	Distance of retreat from last position (m)	Time period (years)	Annual rate of retreat (m/y)
ca. 1881 (estimated)[a]	-	-	-
ca. 1881–ca. 1916 (estimated)[a]	61	35	1.7
ca. 1916–1947 (September; A11100:294)	207	31	6.7
1947–1951 (September 16; AS172-5010:11)	29	4	7.3
1951–1955 (August; A14813:9)	21	4	5.3
1555–1958 (August 25; AS748-5027:83)	18	3	6.0
1958–1977 (August 13; A24804:149)	121	19	6.4
1977–1979 (September 18; AS1960:196)	14	2	7.0
1979–1984 (August 16; AS3083:58)	11	5	2.2
1984–1990 (surveyed; this project)	50	6	8.3

[a] Lichenometric assessment of *Xanthoria elegans* (Link.) Th. Fr. (Smith et al., 1995).

down-valley from the current ice front shows the ice was in retreat by 1881 (Smith et al., 1995). A minor stillstand or readvance deposited an inset lateral moraine along the eastern perimeter of the lower glacial forefield around 1916 (Lawby, 1994). Examination of seven sets of vertical air photographs (1947–1984) shows that the glacier terminus has retreated at an average rate of 5.7 m/y over the last century (Table 1). The highest rate of terminus retreat (7.3 m/y, 1947–1951) corresponds to a period of above-normal summer temperatures in the immediate area (Wig and Smith, 1994).

The climatic character of this region is distinctly seasonal. Air temperatures in the winter months are characteristically cold and continental in nature, although they often are tempered by relatively warm Pacific air masses (Janz and Storr, 1977). In contrast, summer temperatures frequently reach extremes that are more typical of the nearby prairie region (Coté, 1984). Climate records from a valley floor location (Highwood Summit, 2210 m a.s.l.) near the Rae Glacier study site indicate that approximately 60% of the annual precipitation (912 mm) falls as snow (Gardner et al., 1983).

METHODOLOGY

Field research at Rae Glacier began on June 15, 1990, and continued until September 5, 1991. A topographic map of the glacier surface was constructed from survey data collected in 1990. All surveys at the site were tied to a permanent benchmark (2361.1 m a.s.l., Fig. 1) and referenced to an Alberta Forestry Lands and Wildlife ASCM Marker (#1693, 3224.784 m a.s.l.) located on the nearby summit of Mount Rae.

Ablation (1990, 1991) and surface flow (1990–1991) rates were measured using a network of 49 stakes (Fig. 1). The stakes consisted of hollow plastic tubes (9 cm in diameter) of varying lengths (0.4–1.4 m). Extreme rockfall hazards around the perimeter of the glacier surface and numerous crevasses in the uppermost portion of the glacier constrained the spatial placement of the stakes to that shown in Figure 1.

The tubes were positioned in the glacier using a hand-driven ice auger (10-cm-diameter bit) to drill a vertical hole approximately 1 m in depth. By the end of the 1990 ablation season, 38 tubes were installed in the ice. Eleven tubes (portions of rows 17–20, Fig. 1) were placed in the accumulation area and were not used in the process evaluations that follow.

The positions of all of the posts were established using an electronic total station (Sokkisha Set 3) during biweekly surveys. A measure of ice ablation was established by recording changes in the length of the stake above the ice surface. After each ablation reading, the stake was removed and the hole re-drilled.

A topographic map of the Rae Glacier site was constructed from survey data (stake sites, glacier margin and forefield traverses) and elevational information contained within a digital terrain model (DTM) compiled by D. Sauchyn, University of Regina. Approximately 950 grid points were collected and entered into the vector-based SURFER computer mapping program to produce a contour map of the glacier and surrounding area.

Radio-echo sounding was used to describe the total ice thickness at various sites (Fig. 3). The sites were referenced to the survey grid and provide insight into the underlying bedrock topography. The data were collected using a prototype 5-MHz mono-pulse radar unit constructed for the project and a portable 35-MHz oscilloscope. Ice depths were calculated using the technique described in Watts and Isherwood (1978, Equation 3.1) and are considered accurate to within ±5 m.

RESULTS

Bedrock Channel Configuration and Ice Thickness

Radio-echo soundings were made at 30 stations on Rae Glacier and provide the basis for the ice thickness contour map shown in Figure 3. A center-line longitudinal profile indicates that a steeply sloped bowl-shaped depression underlies the glacier (Fig. 3). Basal slope gradients vary from less than 6° near the present terminus to more than 40° below stake 16. The two cross-sections show that the upper basin is asymmetrical in character, whereas the snout of the glacier sits in a more symmetrical channel. While the subglacial topography appears smooth in both the longitudinal profile and cross-sections, local abnormalities in the radio-echo sounding suggests that the glacier floor beneath stakes 14 through 16 may be step-like in character (Fig. 1).

The maximum ice depth (97 ±5 m) recorded in 1991 was found in the central portion of the glacier (Fig. 3). Ice depths decreased sharply upslope and downslope from this point. The two cross- sectional profiles show that the western surface of the glacier is both steeper and higher than the eastern edge.

Surface Ice Velocity

Surface ice velocity was measured during surveys conducted between July 9 and August 17, 1990, and August 2 to September 2, 1991. Of the 38 stakes installed in the

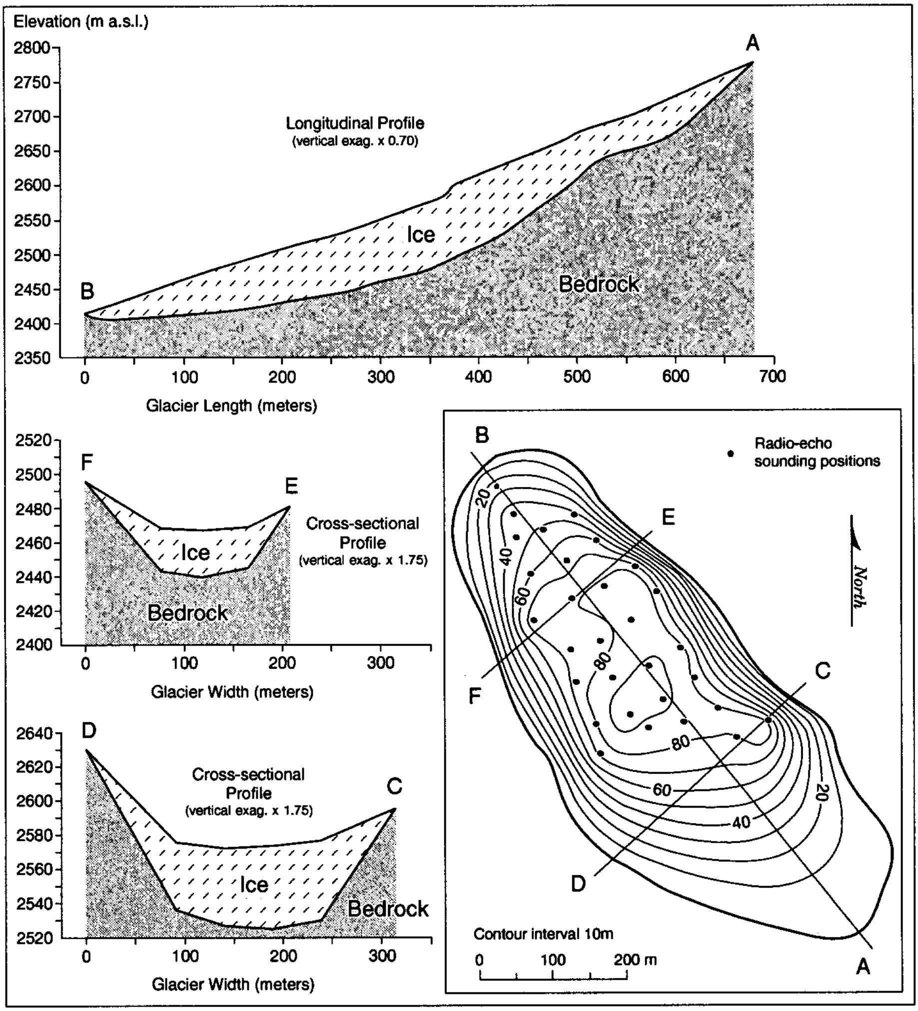

Fig. 3. Radio-echo sounding locations and ice depths of Rae Glacier, 1991. Locations of the cross-sectional profiles are indicated on the accompanying map.

glacier in 1990, 23 were used to describe the annual rate of surface flow and to calculate local emergence velocities (Fig. 4B). Horizontal rates of surface movement are presented that disregard the additional distance covered by the stake owing to the slope of the glacier's surface (Paterson, 1981). Emergence velocities and the related ablation data are presented to show if the ice thickened, thinned, or maintained a steady profile over the study period at each site (Paterson, 1981).

Horizontal surface velocities were lowest near the terminus (1.2 m/y at 6B) and highest (4.6 m/y) in the steeply sloping area (25–32°) below stakes 16 and 17 (Figs. 1 and 4A). Horizontal velocities increased sharply from the terminus (<1.4 m/y) to row 7 (2.5 m/y) and then remained uniform up to row 10 (Fig. 4A). Beyond row 12

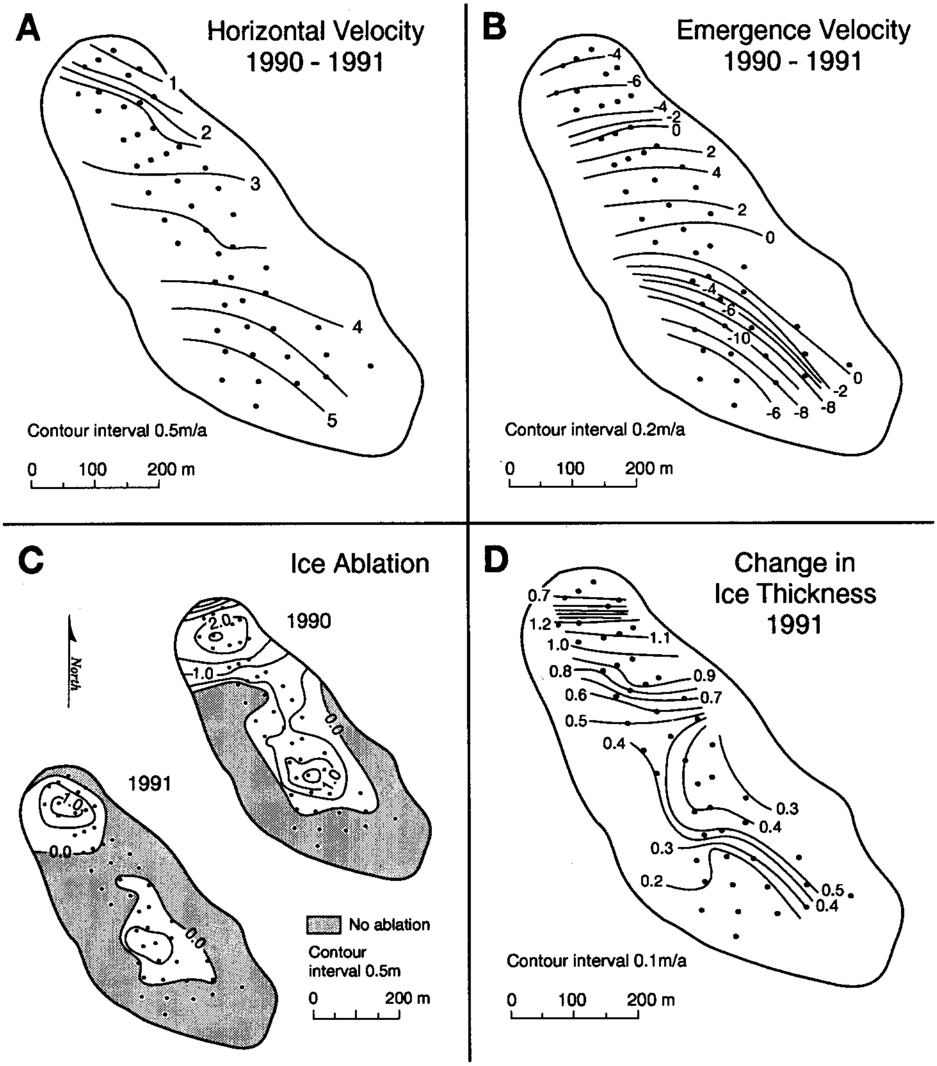

Fig. 4. Annual magnitude of horizontal surface velocity, emergence velocity, and ice ablation on Rae Glacier. The change in ice thickness shown refers to measured losses in elevation from the 1990 datum surface.

surface velocities began to increase sharply from 3.3 m/y at stake 12 to 5.4 m/y at stake 18A (Fig. 4A). These flow velocities are comparable to those measured at cirque glaciers worldwide (e.g., McCall, 1960; Calkin et al., 1985; Theakstone and Knudsen, 1987; Naftz and Smith, 1993), but are an order of magnitude less than those typically recorded at large valley glaciers in the Canadian Rockies (10–200 m/y) (Paterson, 1981).

Velocity Gradients

Velocity gradients in a glacier are expected to vary along its length over time (Nye, 1960; Paterson, 1981). Information on the deformation pattern of ice at Rae Glacier was furnished by examining the longitudinal gradients of velocity along the glacier center line (Nye, 1960). Since basal and internal stress distributions up- and down-glacier from a particular point affect the flow at that location, the longitudinal coupling equation presented by Kamb and Echelmeyer (1986) was used to identify the importance of longitudinal stress gradients to local flow rates along the glacier center line. The term l is the longitudinal coupling length and $2l$ represents the distance up- or down-glacier over which the effects of local slope changes and variations in ice thickness influence flow. Table 2 identifies the center-line stakes used and the various parameters used to calculate l. Basal velocities were assumed to be zero and an average longitudinal shape factor of 0.67 was employed (Lawby, 1994).

The observed longitudinal velocity and ice thickness patterns at Rae Glacier were best explained by a longitudinal coupling length of 200 m and a flow law exponent (n) (Paterson, 1981, p. 85) of 2 (Lawby, 1994). This coupling length indicates that at a specific location, stress gradients 400 m up- and down-glacier affect the flow velocity at that particular point. The coupling length computed for Rae Glacier is almost five times the average ice depth (42 m) and is longer than the ratio of one to three times reported for valley glaciers (Kamb and Echelmeyer, 1986).

The results of this analysis suggest that mass-balance perturbations at Rae Glacier should be transmitted down-glacier very quickly. Since the averaging length ($4l$ = 800 m) over which stress gradients need to be calculated exceeds the present extent of ice at the site, the glacier is considered to be flowing as a single unit, perhaps in a block- or plug-like fashion. Based on these analyses it appears that the response time of Rae Glacier should be relatively short. One measure of this rate is provided by employing a procedure outlined by Paterson (1981, p. 252), who indicates that glacial response times are equivalent to $1/r$, where r is equal to four times the longitudinal strain rate. In light of the coupling length theory suggesting that the stress gradients were effective over the length of the glacier, the longitudinal strain rate was determined over the entire length of the stake network (stake 18 to 6b, Table 2). The change in distance between these points, as a fraction of the original distance (the longitudinal strain rate), was –0.006 over the year of our survey. Interpolation of this change indicates that it will take approximately 42 years for Rae Glacier to adjust fully to a change in its mass balance state.

Ablation

Snow begins to accumulate on the surface of Rae Glacier by late September, and by early June snow depths typically exceed 3 m (Smith, 1995). Although the total winter snowfall (October–March) in 1989–1990 was below normal (143 mm water equivalent) at this site, the total amount of winter precipitation recorded in 1990–1991 (342 mm) was well above average (Lawby, 1994).

Table 2. Rae Glacier Center-Line Slope, Ice Thickness, Annual Horizontal Velocity (± 0.3 m/y), and Vertically Averaged Velocity (for $n = 2$), 1990 to 1991

Stake No.	Distance from glacier head parallel to mean surface (m)	Surface slope (°)	Ice thickness (m)	Annual horizontal velocity (m/y)	Vertically averaged velocity (m/y)
18	138	26	-	4.5[a]	3.4
17	165	32	-	4.6	3.5
16	216	32	67	4.6	3.5
15	257	32	84	4.0	3.0
14	304	27	93	3.5	2.6
13	319	26	90	3.6	2.7
12	388	20	83	3.3	2.5
11	426	20	79	3.0[a]	2.3
10B	487	19	70	2.7	2.0
9	523	22	63	2.3	1.3
8	573	23	48	2.5	1.9
6B	657	18	32	1.2	0.9
Average		24	67	3.3	2.5

[a] Estimates based on velocities from surrounding stake locations.

Ice ablation in both seasons was initiated at two locations on the glacier: close to the snout and on an upper bench below the main accumulation area (Fig. 4C). As the ablation seasons progressed, these areas of exposed ice grew in size but never coalesced because deep snow packs persisted in the low-gradient (20°) central portion of the glacier.

Ice ablation in 1990 averaged 1.14 m and resulted in the release of approximately 116 × 10^3 m^3 of meltwater (Smith, 1995). Although the greatest amounts of ice were lost in the lower portions of the glacier (maximum = 2.64 m, stake 7A, Fig. 4C), significant ablation (1 m) also occurred in an area surrounding stake 16. Glacier ice was not exposed until early August in 1991 and ice ablation averaged only 0.54 m (maximum = 1.54 m, stake 7A, Fig. 4C).

In 1990 the accumulation zone of Rae Glacier was restricted to 52% of the glacier surface. In 1991, the accumulation area increased to cover 84% of the glacier. Following Meier and Post (1962), Paterson (1981), and Kulkarni (1992), the ratio of the accumulation area to the glacier's total area is used to suggest that Rae Glacier experienced a negative mass balance in 1990 and a positive mass balance in the following year.

Relation Between Flow and Ablation

Based on the methods described by Paterson (1981, p. 61), the emergence component of flow at Rae Glacier was determined and represents the net gain or

Table 3. Rae Glacier Center-Line Emergence Angles and Surface and Basal Slopes

Distance from glacier snout (m)	Surface Slope (α, in degrees)	Basal Slope (β, in degrees)	Angle of Emergence (θ, in degrees)
40	18	22	-1
125	23	7	10
175	22	6	25
215	19	21	26
310	20	23	21
380	26	20	26
400	27	24	30
440	32	40	29

loss of ice at the surface (cf. Meier, 1974, pp. 199–200). Values of the emergence velocity were computed for each stake site and were used to prepare the contour map in Figure 4.

Table 3 presents a summary of the angle of ice emergence (θ) along the glacier center line, with respect to basal slope (β) and surface slope (α). If $\theta < \alpha$, the flowline is judged to be emerging, whereas if $\theta > \alpha$, the flowline is regarded as submerging (Paterson, 1981). In addition, Arnold (1981) has suggested that if the flowline angle is above the horizontal, thrusting may be occurring. In the case of Rae Glacier, Table 3 indicates that the majority of stations were positioned in areas of emerging flow. The data also suggest that ice near the terminus may be thrusting over stagnant or slower moving ice.

At most stake sites, the emergence and ablation data indicate pronounced glacial thinning in 1990–1991 (Fig. 4D). Whereas a high rate of thinning (maximum 1.3 m) characterized the area between rows 7 and 9 (Fig. 1), the amount of thinning up-glacier was considerably less (approximately 0.4 m). Only a few stakes in the upper portion of the glacier were positioned in areas where the glacier thickened or maintained an equilibrium profile (Fig. 4D).

Proxy Mass-Balance History

The mass-balance characteristics of glaciers throughout western Canada have been shown to be highly correlated (Reynaud et al., 1984; Letréguilly and Reynaud, 1989; Brugman, 1991). Based on this recognition, it was assumed that any mass-balance variations at Rae Glacier would be broadly comparable to those at Peyto Glacier 150 km to the northwest (see Young and Stanley, 1976) (Fig. 1). In order to test this assumption, the measured mass-balance history of Peyto Glacier was compared to a proxy net mass balance (B_n) reconstructed using climate records (1939–1991) collected at a station located 45 km north of Rae Glacier (KECR, 1380 m a.s.l.). This statistical reconstruction was completed by compiling various seasonal air temperature and precipitation variables into a series of multiple regression equations (cf. Letréguilly, 1988; Lefauconnier and Hagen, 1990). Using this tech-

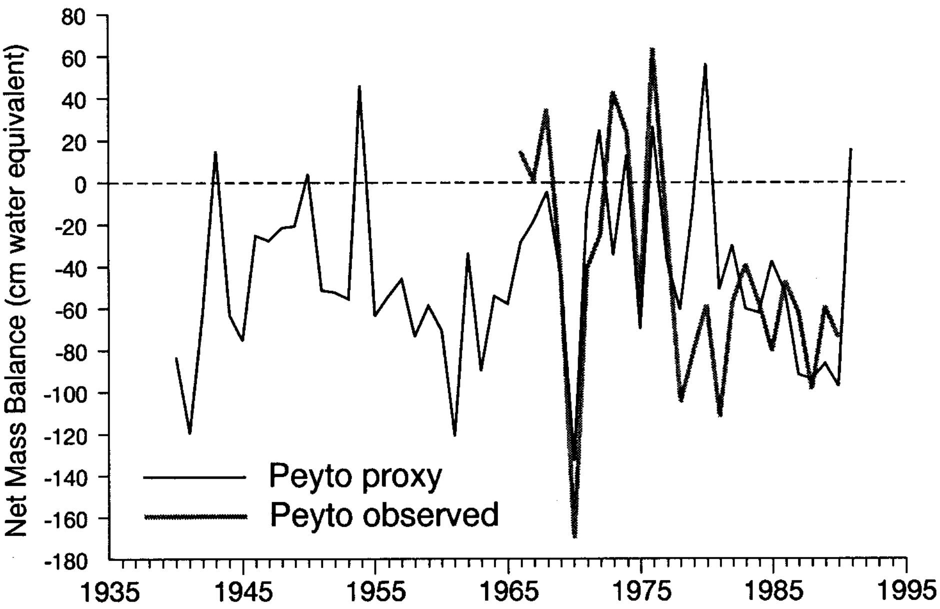

Fig. 5. Observed and proxy net mass balance records for Peyto Glacier. Proxy record is based on climatic information from KECR station and is assumed to represent net mass-balance trends at Rae Glacier.

nique, a combination of total October–March precipitation (P_{10-3}), average June–July temperature (T_{6-7}), and total June–July precipitation (P_{6-7}) successfully explained 53% of the variance in the overlap period between the observed and proxy mass-balance records at Peyto Glacier:

$$B_n = 3826.86 + 3.73P_{10-3} - 351.21T_{6-7} - 3.69P_{6-7}.$$

The entire KECR climate set was input to the equation and a proxy net mass-balance history was constructed for Peyto Glacier for the period of record. Given the relative strength of our comparison and the findings of previous researchers (Reynaud et al., 1984; Letréguilly and Reynaud, 1989; Brugman, 1991), it is assumed that the proxy net mass-balance history for Peyto Glacier shown in Figure 5 approximates the historical conditions at Rae Glacier.

The data presented in Figure 5 suggest that negative balances likely have prevailed for at least 50 years at Rae Glacier. This observation compares favorably with the record of terminus retreat at both Rae Glacier (Table 1) and 18 additional glaciers in the same region (McCarthy and Smith, 1994).

Lag Time

The lag time of a glacier describes the length of time between a mass-balance perturbation and the beginning of its effect on the terminus as indicated by an advance or retreat (Paterson, 1981). In order to analyze the response of Rae Glacier to climatic variation over the historical period, the terminus behavior of the glacier was compared to the KCER weather records and the reconstructed net mass-balance history.

The highest rate of historical terminus retreat observed at Rae Glacier prior to the present study occurred between 1947 and 1950. This interval coincides with a period of generally negative mass balances and also corresponds with high rates of terminus retreat elsewhere in the Rockies (Gardner, 1972; Brugman, 1991). Following this interval, the rate of terminus retreat declined between 1950 and 1955. This interval corresponds to a regional reduction in retreat rates (Osborn and Luckman, 1988; Brugman, 1991; McCarthy and Smith, 1994). At Rae Glacier, this change in behavior is attributed to the above-average snowfalls and below-average summer temperatures recorded over the same time period (Wig and Smith, 1994). It is worth noting, however, that in only one of those years (1954) is there any indication of positive mass-balance conditions.

Beginning in the mid-1970s and continuing to the present, glacier behavior in the Rockies has become increasingly discordant, with some glaciers advancing and others retreating (Brugman, 1991; McCarthy and Smith, 1994). A similar shift in behavior also was apparent at Rae Glacier, where a period of very slow retreat (1979–1984) was followed by an interval of relatively rapid retreat (1984–1990). These observations are supported by the mass-balance reconstruction, which shows several years of positive mass balances during the mid-1970s and increasingly negative balances within the last decade (Fig. 5).

The implication of this comparison is a recognition that Rae Glacier responds quickly to periods of above- or below-normal winter precipitation or summer temperature. Our analysis suggests that Rae Glacier has a lag period of between 5 and 10 years.

Volumetric and Areal Changes

Chronological and topographical data were combined to estimate the historical and present ice volumes of Rae Glacier. The present volume of the glacier was calculated from on-site topographic and radio-echo sounding surveys in 1990 and 1991. Historical volumes were extrapolated from dated terminus positions by assuming the glacier maintained a surface profile similar to its present form. Despite the difficulty of describing the surface profile of the glacier before our survey, the sequence of volumetric data presented in Table 4 is believed to provide at least a relative measure of the continued reduction in the size of Rae Glacier over the last 110 years.

It is estimated that at the close of the Little Ice Age in 1881, the glacier had a surface area of 0.46 km^2 and a volume of at least 3.8×10^7 m^3 (Table 4). Retreat and narrowing of the glacier snout by around 1916 decreased the surface area of the glacier to 0.38 km^2 and reduced its volume to approximately 2.9×10^7 m^3. The 1947 aerial photographs show that the glacier was considerably smaller, with a surface area of 0.32 km^2 and an approximate volume of 2.4×10^7 m^3. At the time of our topographic and radio-echo sounding survey in 1991, the glacier's volume was estimated to be 9.3×10^6 m^3.

Table 4. Historical Changes in the Size of Rae Glacier

Year	Surface area (km²)	Volume (m³)	Volumetric ice loss (m³)	Cumulative ice loss (%)
ca. 1881	0.46	3.8×10^7	-	-
ca. 1916	0.38	2.9×10^7	9.0×10^6	25
1947	0.32	2.4×10^7	5.7×10^6	37
1991	0.22	9.3×10^6	1.5×10^7	76

The results of our analysis show that nearly 37% of the Rae Glacier's Little Ice Age mass had ablated by 1947 and that by 1991 the glacier's volume was only 24% of its 1881 volume. If Rae Glacier continues to recede and downwaste at its present rate, it likely will disappear completely within 35 to 50 years.

CONCLUSIONS

The results of our field surveys show that Rae Glacier is a typical cirque glacier that displays complexity in its surface form and flow. As expected, areas of steeper surface gradients and thick ice proved to have the highest flow velocities. Rates of ablation proved to be highly variable across the glacier. Areas with steep surface gradients became snow-free earlier in the summer and experienced up to 50% more ice ablation. Combined with data on the emergent-flow component of the glacier, the ablation data suggest that the glacier presently is unable to replenish the amount of ice annually being lost to ablation.

The response of Rae Glacier to antecedent climatic fluctuations was manifested in a significant loss in size and mass during the historical period. The glacier's surface area has decreased by over 50% and now contains less than 24% of the ice it did at the end of the last century. The short lag time assigned by the research confirms that this glacier is sensitive to climatic fluctuations and responds to changes in mass balance within a very short time. This observation appears to be supported by an estimate of the response time of the glacier, which indicates that mass-balance perturbations are transferred through the glacier within 42 years.

In summary, it is concluded that Rae Glacier is a climatically sensitive glacier. Nevertheless, it must be acknowledged that the short-term behavior of Rae Glacier is superimposed on what is a much longer time-scale adjustment corresponding to mass-balance changes initiated at the close of the Little Ice Age.

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