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Glaciological and Historical Analyses at the Boundary Glacier, Canadian Rocky Mountains

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The present study focuses on the Boundary Glacier, located on the northeast slopes of Mt. Athabasca. Documentation of terminus retreat and surface velocity and morphology, occurred between 1983 and 1999. Data were collected from the areally dominant northwestern glacier lobe, which contains a steep upper icefall and a gentler terminus region, and from the proglacial valley up to the Neoglacial end moraine. Terminus retreat was measured from proglacial field surveys and remotely sensed data; a network of stake and surface markers were used to collect ablation and surface velocity data; glacier surface morphology was determined from transverse and longitudinal profile surveys.

Longitudinal surface flow velocity ranged between 5.1 and 30.3 m for the years 1983 and 1984; associated emergence velocities ranged between 4.0 and 15.7 m. Surface ablation rates were relatively consistent throughout the glacier ablation zone at approximately 4.0 cmd^{-1}*. Overall, a total terminus retreat of c. 920 m has occurred between 1903 and 1999 at the Boundary Glacier. Morphologically, the northwestern lobe exhibits an almost flat profile in the area below the icefall, but takes on an extreme concave profile near the terminus. Near-terminus accelerated ablation and very low emer-*

gence velocities are causes for the profile change. Generally, the Boundary Glacier shows indications of passivity compared to its recent Neoglacial history.

Introduction

Glacier advance versus glacier retreat depends upon the balance between ice removal through ablation and ice delivery, which is a function surface longitudinal and emergence elocities. Numerous studies of glacier terminus retreat and surface velocity have been reported (e.g., Andreasen and Knudsen, 1985; Aniya et al., 1988; Lawby et al., 1995; Meier et al., 1974). Of these examples, however, only the studies by Lawby et al. (1995) and McCarthy & Smith (1994) were located in the Front Ranges of the Canadian Rocky Mountains. Other glaciological research in the area has largely focused on glacier fluctuations and terminus retreat in the Holocene, and especially during the Neoglacial period (e.g., Luckman, 1986, 1998; Luckman et. al., 1987; Osborn and Luckman, 1988). Furthermore, studies have concentrated on relatively large glaciers, such as the easily accessible Athabasca Glacier (e.g., Raymond, 1971; Savage and Paterson, 1963), and the less accessible Peyto Glacier as summed up in Demuth et al. (1999).

The present study deals with a relatively small valley glacier, the Boundary Glacier, and documents recent surface velocity, ablation, and terminus retreat. Small glaciers are expected to show more immediate responses to local climatic fluctuations, and therefore should provide more detailed terminus recession information. The study uses a combination of detailed field measurements and analysis of a time series of aerial photographs. Terminus retreat has been measured from 1938 to 1999 using proglacial survey points and aerial photographs, whereas surface velocity and ablation were measured during the summers of 1983 and 1984 using a network of ablation/velocity stakes.

Study Site

The Boundary Glacier is located on the northeast slopes of Mt. Athabasca near the southeast margin of the Columbia Icefield at 52°12′N, 117°12′W (See Fig. 1). Presently, the glacier covers an area of about 1.2 km^2 and is 2 km in length. The Neoglacial maximum position of the Boundary Glacier is indicated by a distinctive end moraine located approximately 920 m down valley from the

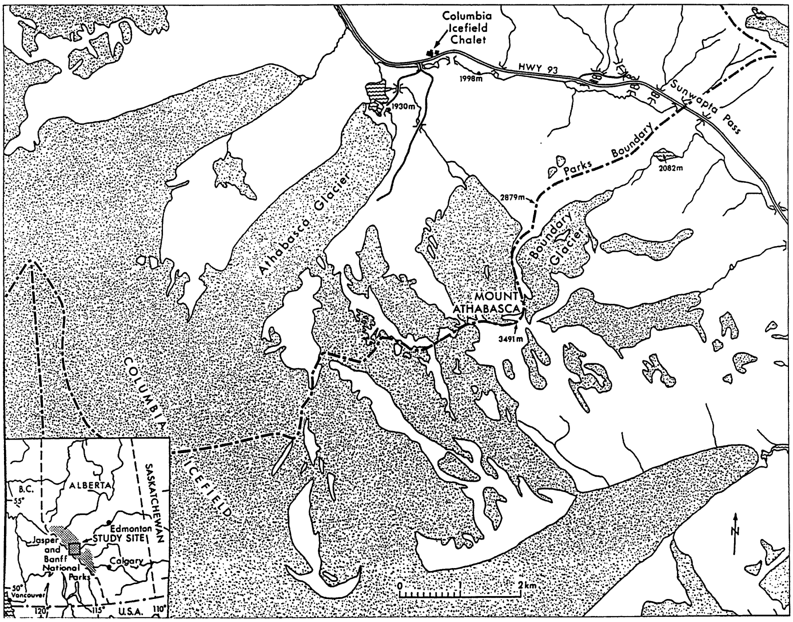

Figure 1 Location of Study Area

present terminus. The glacier extends from 2365 m to 3225 m asl, with lower 300 m of elevation being occupied by the ablation zone. The ablation zone covers an approximate area of 0.3 km^2, and is split into two distinct lobes. Data for the present study were collected from the dominant northwestern lobe, and from the proglacial valley up to and including the Neoglacial moraine. A heavily crevassed icefall, with an average gradient of 320, dominates the upper portion of the northwestern lobe. The lower portion of the lobe has gentler slopes ranging from 12 to 230, and few crevasses.

The Neoglacial advance of the Boundary Glacier has been documented elsewhere by Gardner and Jones (1985). Of importance here are the limiting dates for the advance, which are suggested to be between 3800 and 4200 BP based on radiocarbon dating of buried peat and tree remains. Leonard (1981) further suggested that, based on lacustrine sedimentation records from lakes south of the study site, glacier recession following the initial Neoglacial advances never equaled recession rates during this past century. Radiocarbon evidence presented by Gardner and Jones (1985) indirectly supports this suggestion for the Boundary Glacier. In fact, the terminus recession reported in this paper is considered to be the most extensive since the initial Neoglacial maximum.

Data Collection

Calculations of glacier longitudinal surface and emergence velocity were performed for each stake location; only longitudinal surface velocity calculations were performed at surface marker locations. Glacier longitudinal and emergence ice velocities were determined by triangulation from two fixed survey points, both established on bedrock outcrops located lateral to the glacier terminus. Steel stakes were inserted approximately one metre into the glacier surface along the centreline; painted rock surface markers were located along a line parallel to and approximately 50 m west of the stake line (Fig. 2). Both survey points were located along a line perpendicular to the primary flow direction of the northwest lobe (45°) and therefore to the stake and marker lines. During the 1983 field season, a network of six ablation/velocity stakes and five velocity surface markers were surveyed three times. During the 1984 field season, 18 stakes and four surface markers were surveyed four times. In addition, three stakes and four surface markers from the 1983 field season were still available for re-surveying in 1984, which provided continuous data over one year. Surface ice ablation was measured by changes in the stake length projecting above the glacier surface. These ablation measurements were taken weekly during both field seasons. Longitudinal and transverse surface profiles of the Boundary Glacier west lobe in the ablation zone below the icefall were completed in 1984 and 1999.

Glacier terminus retreat from 1983 to 1999 was measured from large (>2 m diameter) immediately proglacial boulders known to be in stationary positions throughout the field surveys. Also, terminus retreat from the crest of the Little Ice Age end moraine, representing the maximum extent of Neoglacial ice, was calculated from nine sets of aerial photographs (Table 1). The different scales and quality of photos provide different levels of accuracy. All photographs were valuable sources of information, however, the 1938, 1948 and 1949 photos were especially informative due to their larger scale. Enlargements and repeated measurements by two different viewers reduced measurement error from all photos.

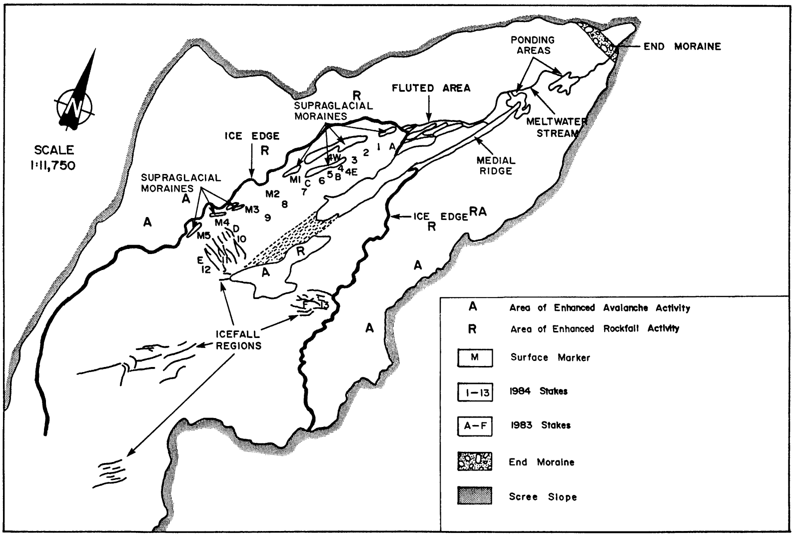

Figure 2 Location of Survey Markers and Survey Stakes

Results

Retreat of the Boundary Glacier terminus from its Neoglacial maximum, as represented by the Little Ice Age end moraine, occurred principally in this century. Terminus positions located from air photos and field surveys are shown on Figure 3. The 1938 aerial photographs indicate that the glacier terminus was approximately 350 m upvalley from the crest of the end moraine. During the next ten years, until 1948, the terminus retreated at an average rate of approximately 10 my^{-1}. If this uniform retreat rate is assumed for the years previous to 1938, the terminus may have began its retreat from the end moraine to the 1938 position circa 1903.

Table 1 Air Photos Used in This Study

Date	*Scale*	*Flight Number*	*Date*	*Flight Number*	*Scale*
1938	1:20,000	A6619	1970	A21547	1:70,000
1948	1:24,000	A11711	1972	A23015	1:66,000
1949	1:24,000	A11729	1979	A25165	1:53,000
1955	1:54,000	A14895	1993	A27990	1:50,000
1966	1:54,000	A19684			

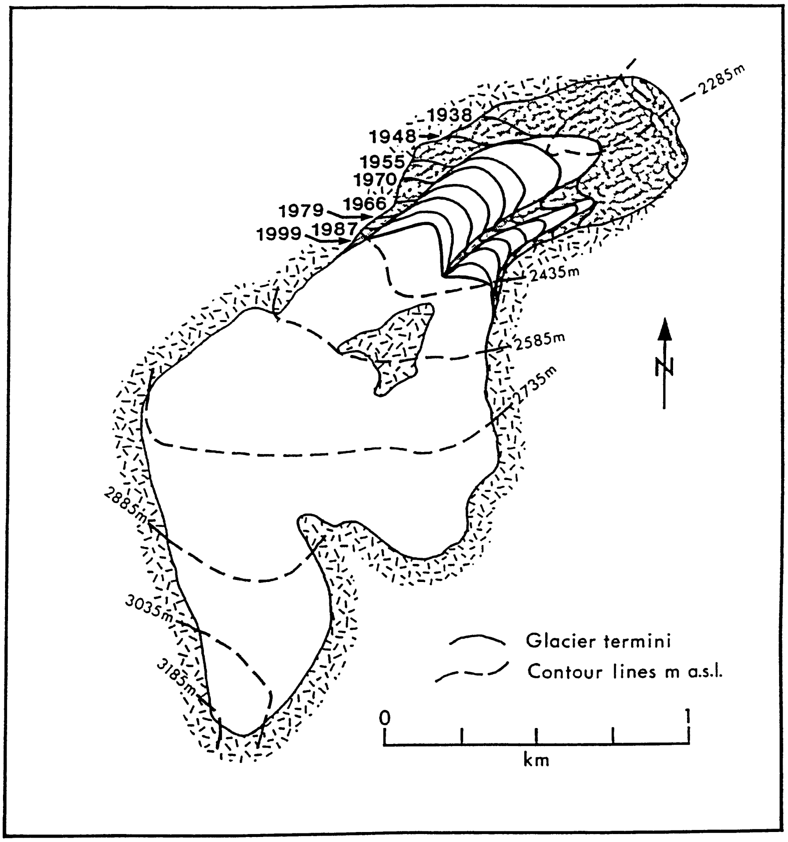

Figure 3 Terminus Positions at the Boundary Clacier, 1938–1999

The retreat rate during the late 1930s and 1940s averaged 10 my^{-1}, increased to 20 my-1 from 1948 to 1956, and decreased to 11 my^{-1} from 1956 to 1966. A brief re-advance, at an average rate of approximately 10 my^{-1} occurred from 1966 to 1970. No terminus fluctuation was recorded between 1970 and 1972, then retreat resumed from 1972 to 1979 at an average rate of 10 my^{-1}. In the last 15 years (1984 to 1999), this rate has slowed to an average rate of approximately 3.7 my^{-1} (Fig. 4). Overall, a total terminus retreat of c. 920 m has occurred between 1903 and 1999 at the Boundary Glacier.

Judging by the height of lateral moraines much of the glacier mass loss during the 20th century occurred through downwasting, as well as backwasting. An estimated loss of 1 to 2 ma^{-1} is possible. The glacier had thinned c. 50 m from its maximum altitude by 1938; it thinned another 90 to 120 m by 1979, and an additional 20 m by

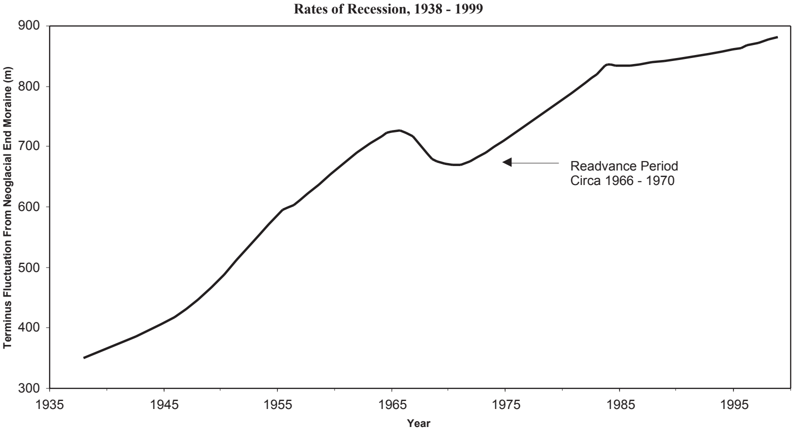

Figure 4 Rates of Recession, 1938–1999

1999. The relatively low slope of the present proglacial valley would cause a significant shift in the Equilibrium Line Altitude, and a sudden increase in the ablation zone area once the climate ameliorated and recession commenced. The frontal recession of c. 920 m occurred in concert.

Areal loss during the 20th century is estimated to have been from a total glacier surface area of 1.64 km^2 at the beginning of the century to 1.20 km^2 in 1999. This represents a total loss of 0.4 km^2, or just over 25%. This latter figure is in keeping with reports by Luckman (1998) for glaciers in the central Canadian Rockies.

With respect to surface velocity, an immediately apparent trend is a downglacier decrease; see Figure 5 and Table 2. Surface velocity decreases from a high of >8.0 cmd^{-1} in the icefall to a low of >1.0 cmd^{-1} near the terminus. These daily rates translate into annual rates of between 5.1 and 30.3 m from 1983 to 1984. The longitudinal profile of the west lobe shown in Figure 6 indicates that the decrease in surface velocity is most likely attributable to surface slope angle. From the base of the icefall, to just above the terminus, the surface slope gradient significantly decreases, thus contributing to decreased surface velocities. Further evidence of decreases in surface velocity below the icefall include glacier longitudinal compression, as manifested by the presence of subtle ogives, and compressed, partly folded ice layers.

The Boundary Glacier surface velocities are somewhat higher than those found for the Rae Glacier, a cirque glacier located in the front ranges of the Canadian Rocky Mountains, by Lawby et al. (1995); measured surface velocities ranged between 1.4 and 5.5 m

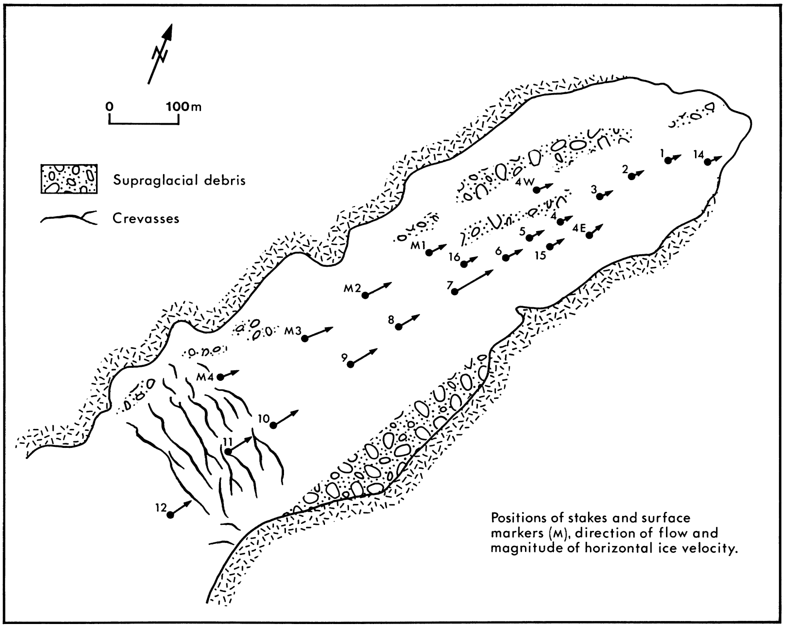

Figure 5 Relative Surface Velocity and Direction of Surface Markers and Survey Stakes

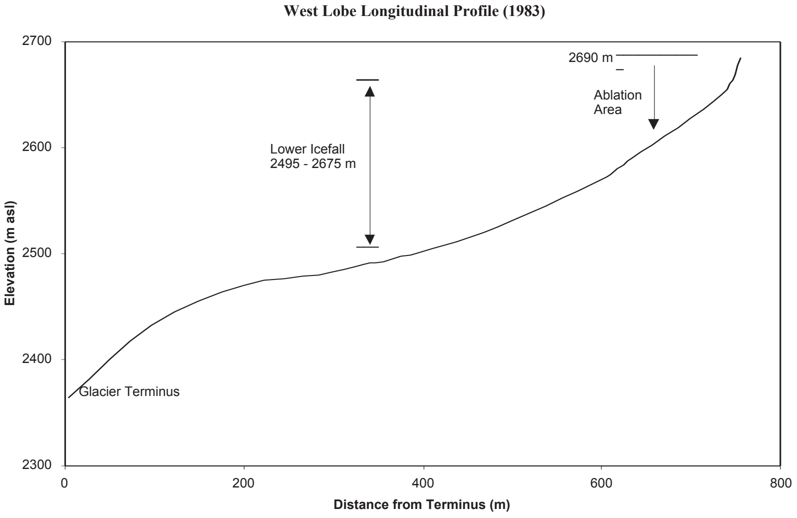

Figure 6 West Lobe Longitudinal Profile (1983)

Table 2 Surface Change Data 1983 and 1984

Elevation (m)	*Stake/ Marker*	*Ve (cm/day)*	*dh (cm/day)*	*Va (cm/day)*	*Vh (cm/day)*
2420	14	0.6	-3.1	-3.7	1.8
2435	1	1.5	-1.7	-3.2	2.3
2455	2	1.1	-2.2	-3.3	1.4
2470	3	0.8	-2.8	-3.6	2.3
2480	4	2	-1.8	-3.8	2
2485	15	2.5	-1.6	-4.1	2.2
2486	5	3.1	-0.9	-4	3.6
2489	6	3.5	0.5	-3	4.9
2495	16	2.8	-.03	-3.1	3.9
2500	M1	n/1	n/a	na/	3.5
2505	7	3	-1.1	-4.1	5.8
2525	M2	n/a	n/a	n/a	7.7
2525	8	3.2	-1	-4.2	6.6
2555	9	4.3	1.2	-3.1	8.3
2560	M3	n/a	n/a	na/	6.7
2590	10	5.1	0.8	-4.3	8
2590	M4	n/a	n/a	n/a	5.3
2635	11	4	0.2	-3.8	7.9
2685	12	4.7	0.6	-4.1	7.2

Vh: horizontal ice velocity
Ve: emergency ice velocity
Va: surface ice abalation
dh: change in surface height

from 1990 to 1991. Alternatively, Raymond (1971) calculated longitudinal surface velocities in excess of 50 ma^{-1} for the Athabasca Glacier, a relatively large outlet valley glacier of the Columbia Icefield. Also, the Boundary Glacier surface rates are relatively lower than the 17.4 to 74.4 ma^{-1} horizontal velocities measured at the Austre Okstindbre valley glacier, Norway by Andreasen and Knudson (1985) between 1979 and 1982. They are much lower than the 100 to 300 ma^{-1} surface flow velocities measured at the Soler Glacier, a valley glacier located in Patagonia, by Aniya et al. (1988) in 1984 and 1986.

Surface flow velocity, in turn, influences a second component of glacier flow, emergence velocity. Emergence velocity tends to compensate for additions and losses of mass from the glacier surface (Andreasen and Knudsen, 1985). Since the vertical emergence velocity is dependent upon the horizontal surface velocity (Gardiner and Dackombe, 1983), the emergence velocities on the

Boundary Glacier also decrease downglacier from the icefall (see Table 2). The maximum emergence velocity of c. 5 cmd^{-1} occurs in the icefall region, and minimums of between c. 1.0 to 1.5 cmd^{-1} near the terminus.

Changes in emergence velocity, as well as surface ablation and elevation are shown in Figure 7. In contrast to the velocities, the surface ablation rate is relatively constant throughout the northwest lobe ablation zone. It has been measured at a steady 4 cmd^{-1} from the icefall to the terminus. Thus most changes in glacier surface morphology occur as a result of changes in emergence velocity not surface ablation. Most importantly, however, this indicates that lowering of the glacier surface below the icefall and near the terminus is a result of reduced ice delivery not higher surface ablation rates.

The transverse profile of the glacier has undergone little change over the past 15 years. A relatively smooth, low relief surface profile exists throughout the lower ablation zone. Accelerated ablation does occur on the peripheries of the glacier lobe, where a

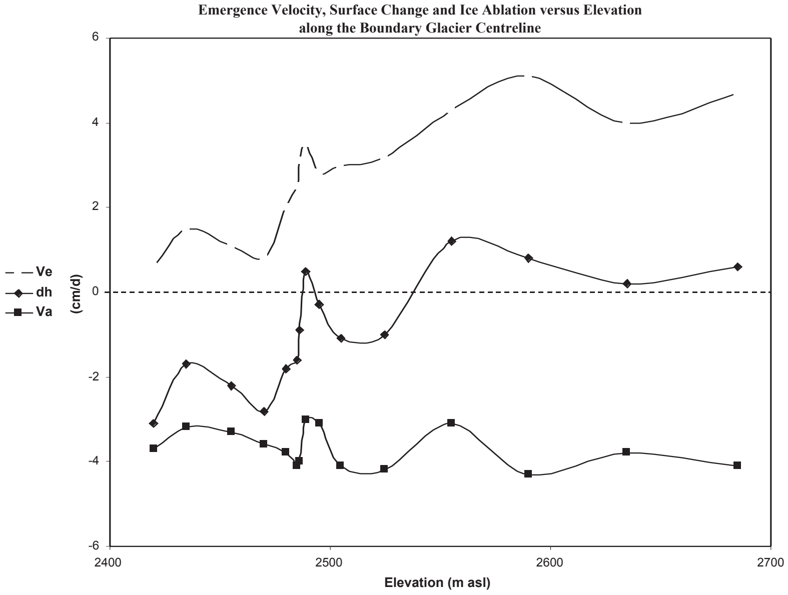

Figure 7 Emergence Velocity, Surface Change, and Surface Ablation versus Elevation

thin cover of rockfall and avalanche delivered debris is found. The thin debris reduces the surface albedo of the ice, and increases the rate of melting. Nakawo and Young (1981) suggest that thin or patchy debris covers of c. 0.5–1.0 cm thick, like those found in this region of the Boundary glacier, maximize ablation. Conversely, the relatively clean central areas of the Boundary Glacier ablation zone should experience lower rates of ablation and surface lowering as a consequence of the higher albedo present.

The longitudinal profile, as measured along the glacier lobe centreline and presented earlier in Figure 6, also has changed little over the 15 years. The slope angle is relatively low throughout the lower ablation area, decreasing from 320 within the lower icefall to 120 at its base, and to 220 near the terminus. These slope angles remain essentially unchanged from 1984 through to 1999.

Conclusions

The present study supports other studies of terminus retreat in this century, notwithstanding a minor re-advance between 1966 and 1970 and a minor standstill from 1970 to 1972 (cf. McCarthy and Smith, 1994). Evidence of the brief re-advance and standstill periods implies a glacier that is as responsive to climatic variations as most other glaciers in the Canadian Rocky Mountains. Future research will focus on defining any possible correlations between climate and glacier response.

Mass output of the Boundary Glacier is low due to relatively low longitudinal ice velocities. Surface ablation rates are uniform across the ablation zone; there is no obvious ablation gradient. The uniformly exposed surface of the glacier and its low profile contribute to the consistency of the surface ablation rates. Present variations in the glacier surface morphology are therefore dependent on variations in emergence velocity, a variable intricately tied to the longitudinal ice velocity. Longer-term measurements of glacier surface velocities are needed to verify the important role played by emerging flow in the Boundary Glacier terminus retreat. Nevertheless, it is apparent from the work completed thus far that the low rate of ice delivery to the terminus area must be considered to be of prime importance in terminus lowering and retreat.

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Tables

Figures