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Abstract: This paper reports the 1989 re-mapping of Lemon Creek Glacier, Alaska, and, in conjunction with 1948 and 1957 maps of the glacier, calculation of 9-year and 32-year changes of glacier mass and terminal position. As in the earlier maps, the new map is at a scale of 1:10,000 with a 5-m contour interval for the glacier surface. Changes between 1957 and 1989 were determined by use of the geodetic method for determining mass balance. Net water equivalent change was -118.71×10^6 m^3. The glacier's respective 1957–1989 area and volume losses were 0.878×10^6 m^2 and -131.90×10^6 m^3 (14.6%). The terminus retreated an average 700 m.

INTRODUCTION

This paper reports the 1989 re-mapping of Lemon Creek Glacier, Alaska, and in conjunction with 1948 and 1957 maps of the glacier, determination of 9-year and 32-year changes of glacier mass and terminal position. Lemon Creek Glacier, a relatively small valley glacier about 6 km long located in the southwestern corner of the Juneau Icefield, Alaska (Fig. 1), has been a benchmark for interpretation of glacier behavior and associated climatic influences in the marine Coast Range environment of southeastern Alaska for more than 40 years. From 1953 through

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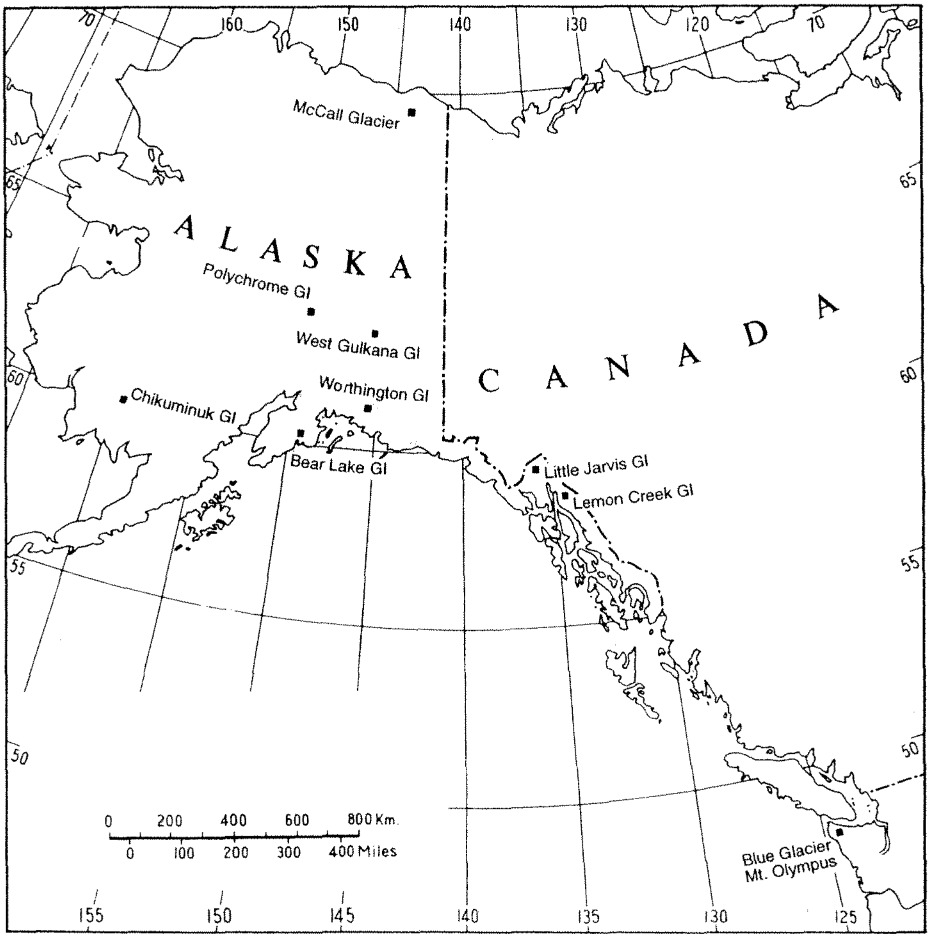

Fig. 1. Locations of the nine American glaciers mapped during the International Geophysical Year, 1957–1958. From American Geographical Society (1960).

1958, the glacier was the focus for several glaciological and glacio-climatic investigations; field research in 1957 and 1958 was directly associated with the International Geophysical Year (IGY). These activities were under the operational umbrella of William O. Field's Department of Exploration and Field Research at the American Geographical Society.

The 1953–1958 research included: (1) investigations of glacier dynamics (Nielsen, 1955); (2) gravimetric measurements (Thiel et al., 1957); glacier mapping (American Geographical Society, 1960); (3) mass balance and glacier flow studies, which included a series of progress reports by LaChapelle (1955, 1956) and publications by Wilson (1959), Heusser and Marcus (1964b), Marcus (1964), and Zenone (1962); late Holocene history of the glacier (Heusser and Marcus, 1964a); and glacier climatology (Hubley, 1955, 1957). Subsequent studies of Lemon Creek Glacier have included seismic measurements (Prather et al., 1968), analyses of geomorphological and fluvioglacial processes (Marston, 1983; Miller, 1972, 1975), and energy balance climatology (Wendler and Streten, 1969).

An important element of the 1950s work was construction of two topographic maps of Lemon Creek Glacier at a scale of 1:10,000 and a 5-m contour interval. The glacier was one of nine American glaciers mapped by the American Geographical Society (1960) in conjunction with the IGY (Fig. 1). These were intended to provide the bases, when compared with future maps, to determine glacier dimensions and mass change. James B. Case (1958) produced the 1957 IGY map of Lemon Creek Glacier (Fig. 2). Marcus (1964), using earlier aerial photography, constructed a map for 1948.

The selected IGY glaciers were small alpine systems considered to be representative of various glaciological environments in the western United States. They ranged from Blue Glacier on Washington's Olympic Peninsula, through Lemon Creek and Little Jarvis glaciers in southeastern Alaska, to five others ranging poleward from the Gulf of Alaska to West Gulkana Glacier in the Alaska Range and McCall Glacier in the Brooks Range (Fig. 1). The glaciers were selected because of their geographical distribution, relative accessibility, and the prevailing wisdom at the time—espoused by the distinguished Norwegian glaciologist Hans Ahlmann—that small glaciers were the best medium through which to interpret glacier behavior and to understand related climatic interactions. Because accessibility was an issue, the glaciers were situated at relatively low elevations.

Lemon Creek Glacier exemplifies this pattern. It is about 6 km long and its maximum width approaches 2 km. In 1989 its surface area was 11.728 km^2. The glacier flows to the north from around 1500 m, dropping to around 600 m above sea level. According to gravimetric and seismic measurements, it attains a maximum thickness of over 200 m some 1500 m downglacier from its head; ice exceeds 150 m depth from about 400 m below the head to just above the icefall (Figs. 2 and 3). Further, it is easily reached within one or two days by foot or ten minutes by helicopter.

1989 LEMON CREEK GLACIER MAP

None of the IGY glaciers were re-mapped until West Gulkana Glacier in 1987, resulting in a published map and the computation of change in mass balance over three decades (Marcus and Reynolds, 1988; Chambers et al., 1991). Subsequently, it was decided to extend the new mapping net through 7° of latitude south to Lemon Creek Glacier. Original survey photography and data, field notes, and diapositives of U.S. Navy aerial photography taken on September 18, 1957 were retrieved from storage at the United States Geological Survey and the Byrd Polar Research Center, Ohio State University. In consultation with Aeromap U.S., who flew the aerial photography mission, eight ground control points were selected for the new map. Cairn Peak was the only station reoccupied from the original 1957 survey.

The ground control grid was surveyed in July 1989, during a five-day period of clear weather. Distance and angle measurements were by AGA Geodimeter and Wild T2 theodolite. Survey markers—1 × 10 m vinyl strip crosses—were centered

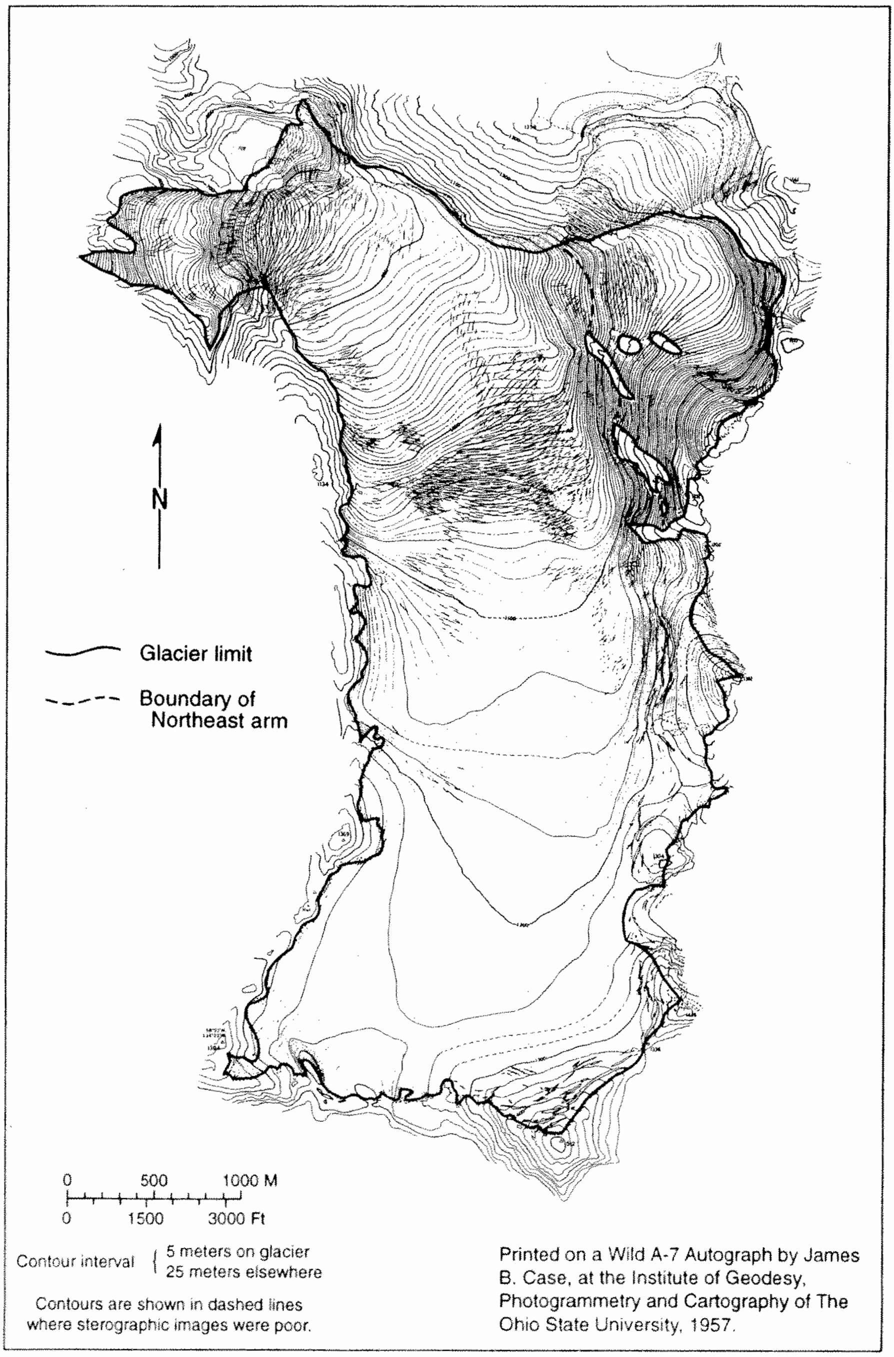

Fig. 2. Reduced version of the 1957 1:10,000 map of Lemon Creek Glacier. From American Geographical Society (1960).

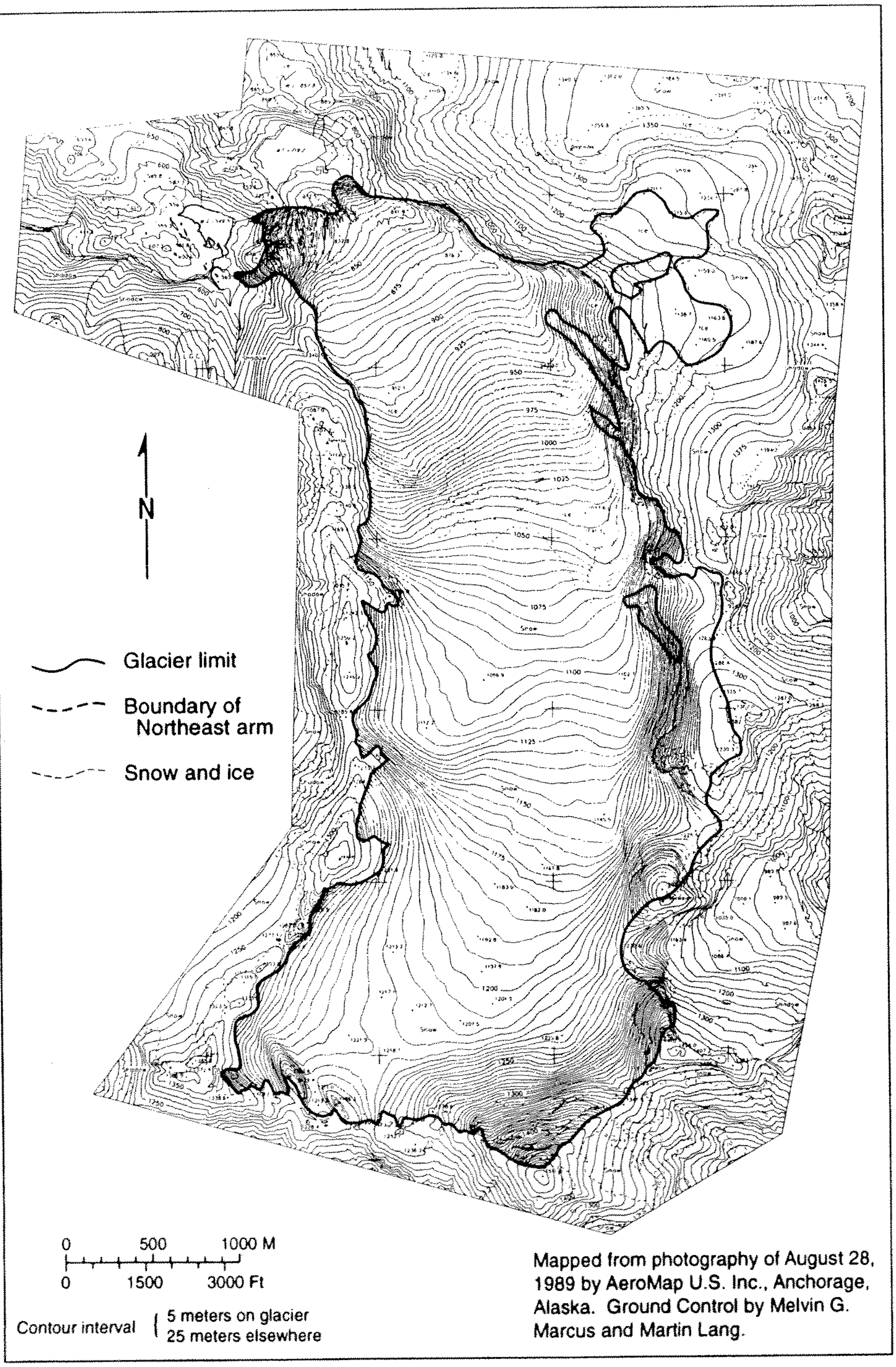

Fig. 3. Reduced version of the 1989 1:10,000 map of Lemon Creek Glacier.

over each control point following the ground survey. These remained in place until aerial photography was flown on 28 August 1989; the eight control points were clearly visible in the air photos.

The 1989 control points were calculated in an orthogonal grid with reoccupied (from 1957) Cairn Peak as the point of origin. The net was subsequently linked to a USGS benchmark 25.85 m to the southwest and 7.37 m lower than the point of origin. To enhance error control, x, y, and z coordinates were independently calculated at both Arizona State University (by traditional survey geometry) and the Universität der Bundeswehr München (by the least squares program KINAUS). The differences were negligible; the German figures yielded only a 0.00001 percent greater distance over the length of the glacier.

Black and white aerial photography at a scale of 1:30,000 was flown, utilizing a certified, six-inch focal length cartographic camera (Fig. 4). A line of four stereo-pairs was obtained. The final map was photogrammetrically plotted at Aeromap U.S. at a scale of 1:10,000, with a 5-m contour interval over glacier surfaces and a 25-m interval elsewhere (Fig. 3). These replicated the scale and contour intervals for the 1957 IGY map of the Lemon Creek Glacier. Both inked and scribed masters of the map were generated. The full-color, 1:10,000 map is included in a pocket in the back of this volume.

MASS BALANCE MEASUREMENTS

Most direct measures of glacier behavior involve determination of mass balance, which is defined as the net water gain or loss for a glacier during any assigned time period, usually one or more glacier years. There are several ways to determine mass balance. These have been enumerated most recently in the manual *Glacier Mass Balance Measurements* by Østrem and Brugman (1991) and include the geodetic method, which compares two or more topographic maps through time; stratigraphic and fixed-date methods, both of which employ direct field measurement of annual accumulation and ablation; and the method using equilibrium line altitude (ELA)/accumulation area ratio (AAR).

This paper focuses on the geodetic method, which utilizes the old and new Lemon Creek Glacier maps and identifies mass changes over multi-year periods through superimposition and comparison of maps at the same scale and contour interval. This procedure was refined by Finsterwalder (1952, 1960) and subsequently used in North America by, among others, D. Haumann (1960), Konecry (1966), and Chambers et al. (1991). It also was used to determine the 1948–1957 Lemon Creek Glacier budget (Marcus, 1964). Advantages of this method are that mass balance can be calculated over several years without annual field observations and that the entire glacier is surveyed and not subject to errors associated with field sampling methods. The obvious drawback is that annual mass changes cannot be determined nor their short-term relationship to climate assessed.

1957–1989 Mass Balance

The 32-year mass balance for Lemon Creek Glacier was determined by the geodetic method, calculating volume changes from contour line displacement

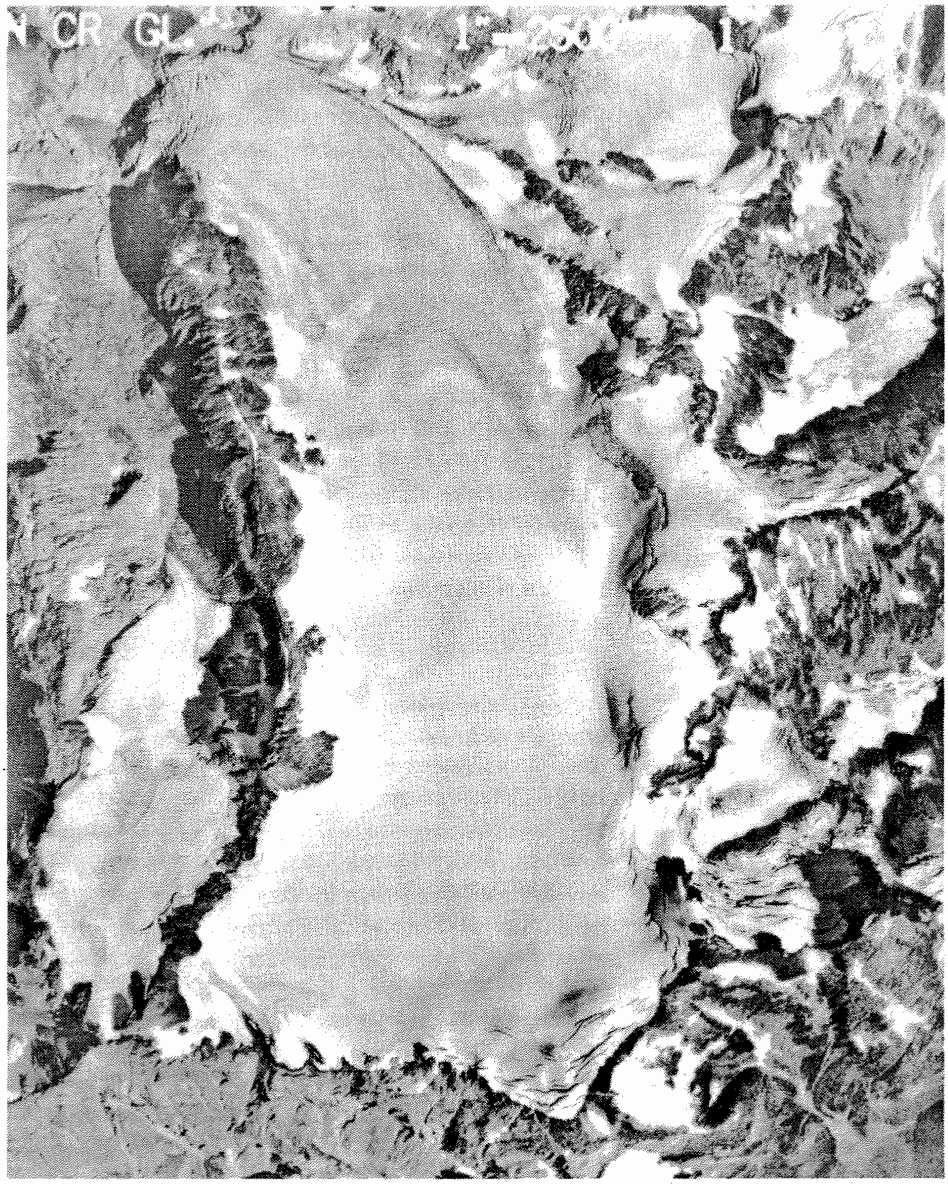

Fig. 4. 1989 aerial photo of Lemon Creek Glacier by Aeromap U.S., one of a stereopair used to plot the new map.

between 1957 and 1989. Figure 5 illustrates a schematic section of that method. Areas were calculated for both the main trunk glacier and the northeast feeder tributary (note glacier margins in Figures 2 and 3). Contour interval areas were measured by both digital and traditional hand planimetry; each area was measured twice. The two methods yield an area difference $<0.001 \times 10^6$ m^2.

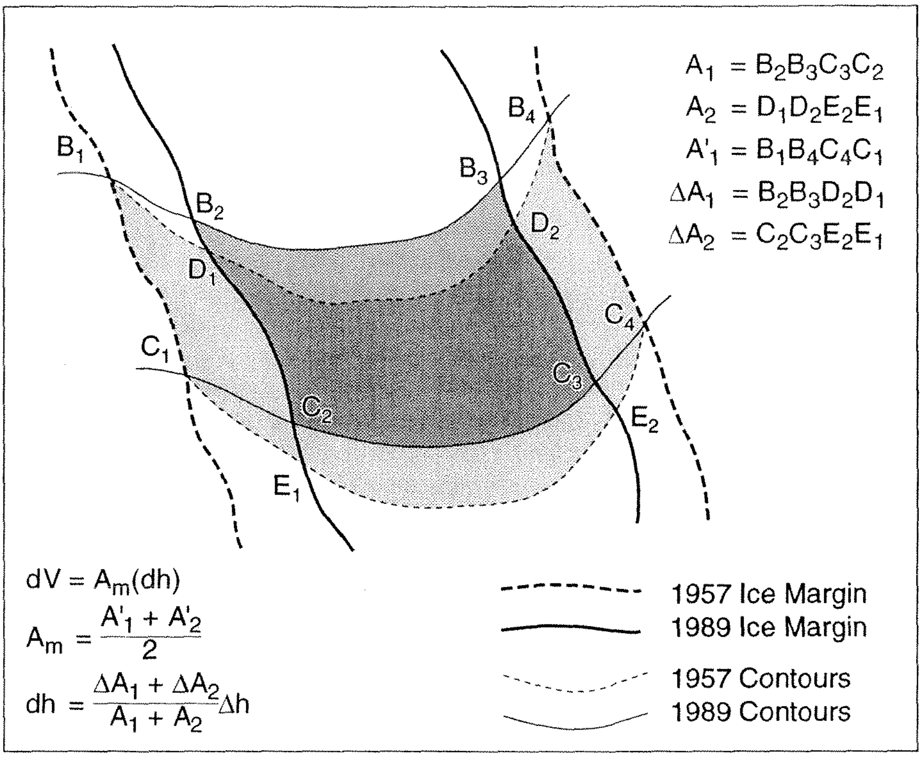

Fig. 5. Schematic representation of volume changes between successive contour line positions per the geodetic method of mass balance measurement.

Table 1. Mass Balance Data: Lemon Creek Glacier

	Change of surface area (10^6 m^2)	Change of ice volume (10^6 m^3)	Change of water volume (10^6 m^3)	Annual change ice volume (10^6 m^3)	Annual change water volume (10^6 m^3)
Full Glacier	-0.878	-131.90	-118.71	-4.12	-3.71
Northeast feeder	-0.090	-5.17	-4.65	-0.16	-0.15
Glacier less northeast feeder	-0.788	-126.73	-114.06	-3.96	-3.57

Mass balance changes for 1957–1989 are summarized in Table 1. Assuming a traditional mean glacier density of 0.90, the system experienced a water-equivalent loss of -118.71×10^6 m^3. During this period, the terminus retreated around 700 m (Fig. 6) and the surface area diminished by 0.878×10^6 m^2. Excluding the northeast feeder, the glacier lost 3.9% water and 10.3% area between 1957 and 1989.

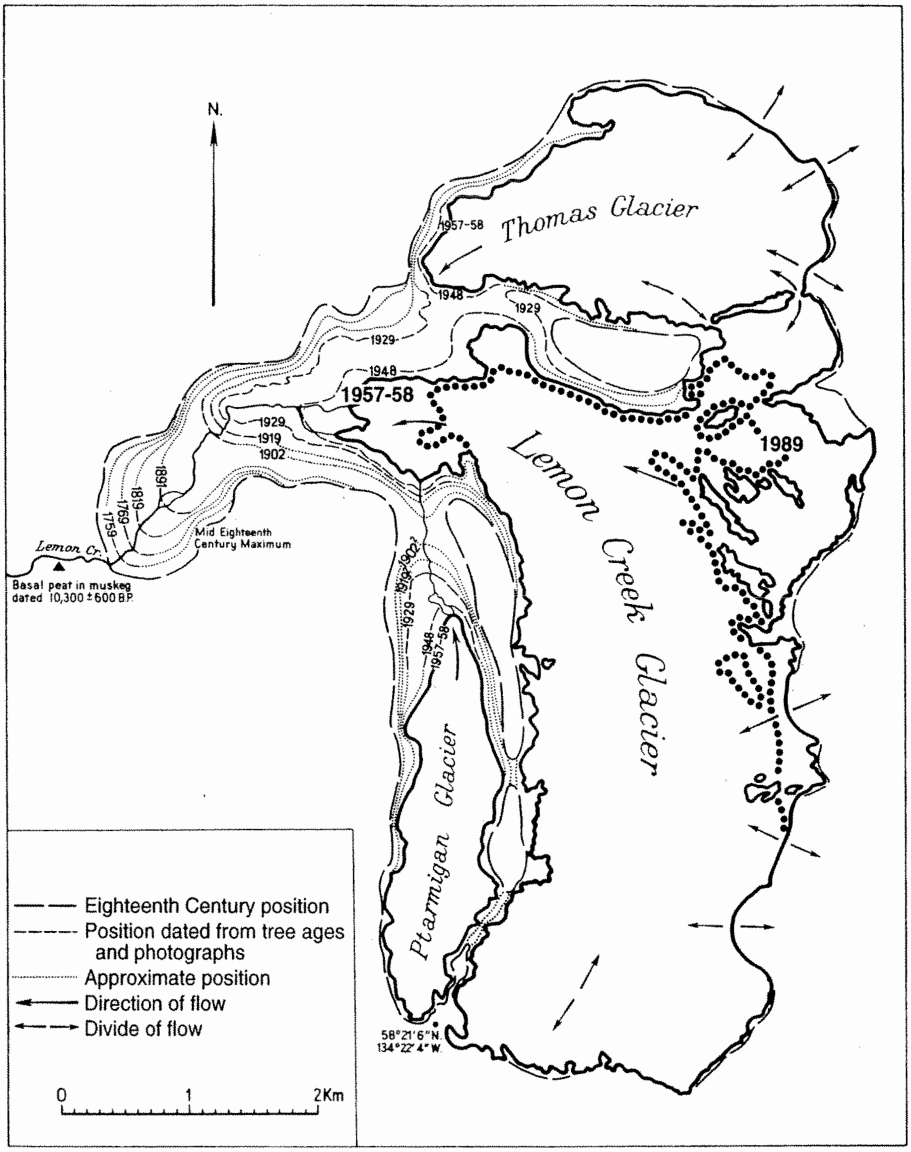

Fig. 6. Historical variations of Lemon Creek Glacier through 1989; 1958 base after Heusser and Marcus (1964).

Total change of glacier volume also was estimated. On the basis of respective gravimetric and seismic data from Thiel et al. (1957) and Prather (in Miller, 1975), the 1957 ice volume was estimated to be 901.72×10^6 m^3 (Table 2). Subtracting the 32-year ice loss (131.90×10^6 m^3) yields a glacial loss of roughly 14.6% of its volume between 1957 and 1989.

Table 2. Estimated Volume Change: Lemon Creek Glacier, 1957–1989

Year	Ice volume (10^6 m^3)	Water volume (10^6 m^3)	Ice volume change (10^6 m^3)	Water volume change (10^6 m^3)	Percentage change
1957	901.72	811.54	—	—	—
1989	769.82	692.84	-131.90	-118.71	14.6

Comparison to 1948–1957 Mass Balance

The 1948–1957 mass balance of Lemon Creek Glacier had been determined earlier (Marcus,1964). Water equivalent values from that study have been adjusted from an original density multiplier of 0.85 to 0.90. The nine-year water loss was 22.1×10^6 m^3.

Although annual average losses can be calculated, they can be a misleading statistic. For example, between 1948 and 1957 when annual mass balances were determined by either stratigraphic or ELA/AAR methods, actual yearly values ranged between -9.9×10^6 m^3 and $+13.3 \times 10^6$ m^3—dramatic departures from the annual mean change of -2.45×10^6 m^3 based on geodetic methods. In comparison, the 1957–1989 mean water loss was -3.71×10^6 m^3 yr^{-1}, an increase of 51% over 1948–1957. Thus, although these statistics do not reflect actual yearly conditions, they do demonstrate an overall increase in the rate of glacier wastage.

In areal terms, ice loss was almost entirely at or below 1100 m elevation during 1948–1957, with the greatest thickness changes occurring immediately above and below the lower glacier icefall. In later years, however, significant height and mass loss also occurred within 100–200 m of the glacier head.

Lastly, during 1948–1957, the terminus retreated an average 240 m along an irregular front. An additional retreat of roughly 700 m occurred during 1957–1989 (Fig. 6); thus, the decadal rate was roughly just under that of 1948–1957. This exemplifies problems in gauging glacier health by terminal position. Change of terminal position did not reflect the escalated rates of mass wastage.

SUMMARY

This paper has described the 1989 re-mapping of Lemon Creek Glacier, Alaska, and in conjunction with 1948 and 1957 maps of the glacier, identified 9-year and 32-year changes of glacier mass and terminal position. The four-decade period was one of overall glacier wastage, with a loss of about one-seventh of the glacier's total mass. These results correspond to negative mass balance trends for West Gulkana Glacier in the eastern Alaska Range (Chambers et al., 1991) and McCall Glacier in the Brooks Range during 1958–1971 (Dorrer and Wendler, 1976).

It is not the intent of this paper to address climatic implications of the IGY mass balance data. It should be noted, however, that the relationship of glacier behavior to climate change in northwestern North America cannot be defined solely from selected, "representative" IGY glaciers such as Lemon Creek. They provide valuable inputs to interpretation of the glacier-climate equation in lower elevations, but glaciers at higher elevations will have to be included to understand more fully these important interacting processes.

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