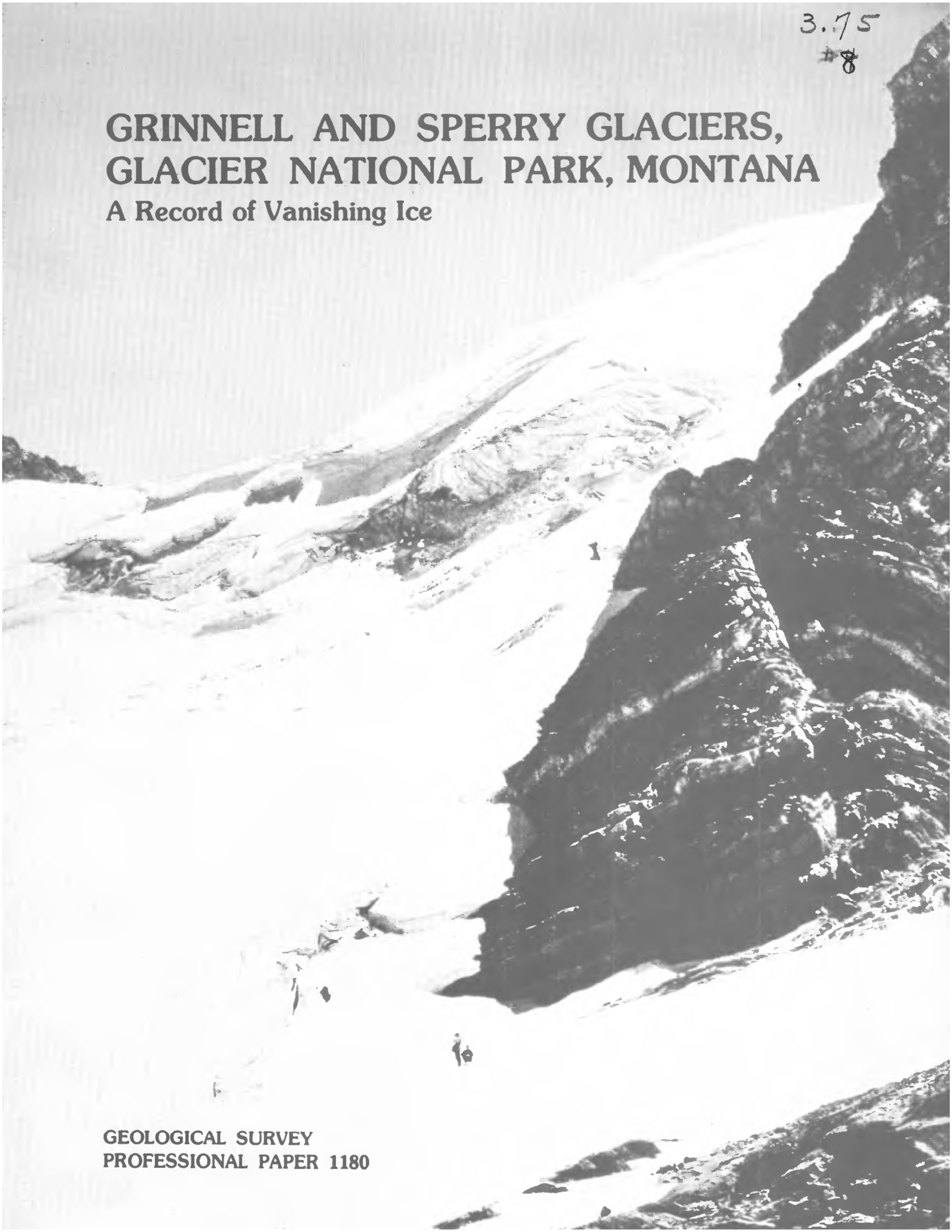
GRINNELL AND SPERRY GLACIERS, GLACIER NATIONAL PARK, MONTANA

A Record of Vanishing Ice



GEOLOGICAL SURVEY
PROFESSIONAL PAPER 1180

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Aerial view, southeastward, of the upper part of Sperry Glacier, July 27, 1969. Part of Gunsight Mountain is visible at the right. Photography by Mel Ruder, Hungry Horse News, Columbia Falls, Montana. Published through the courtesy of the photographer.

Grinnell and Sperry Glaciers, Glacier National Park, Montana—A Record of Vanishing Ice

By ARTHUR JOHNSON

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Recorded observations, during approximately 80 years, of the shrinkage of the two largest glaciers in Glacier National Park

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CONVERSION FACTORS FOR METRIC EQUIVALENTS

English unit		Metric unit
To convert	Multiply by	To obtain
Inch	2.54	Centimeter
Foot	.3048	Meter
Mile	1.609	Kilometer
Acre	.4047	Hectare
Acre-foot	1,233.00	Cubic meter
Square mile	2.590	Square kilometer
°Fahrenheit	Subtract 32 and divide by 1.8	°Celsius

GRINNELL AND SPERRY GLACIERS, GLACIER NATIONAL PARK, MONTANA—A RECORD OF VANISHING ICE

By ARTHUR JOHNSON

ABSTRACT

Grinnell and Sperry Glaciers, in Glacier National Park, Mont., have both shrunk considerably since their discovery in 1887 and 1895, respectively. This shrinkage, a reflection of climatic conditions, is evident when photographs taken at the time of discovery are compared with later photographs. Annual precipitation and terminus-recession measurements, together with detailed systematic topographic mapping since 1900, clearly record the changes in the character and size of these glaciers.

Grinnell Glacier decreased in area from 530 acres in 1900 to 315 acres in 1960 and to 298 acres in 1966. Between 1937 and 1969 the terminus receded nearly 1,200 feet. Periodic profile measurements indicate that in 1969 the surface over the main part of the glacier was 25-30 feet lower than in 1950. Observations from 1947 to 1969 indicate annual northeastward movement ranging from 32 to 52 feet and generally averaging 35-45 feet. The annual runoff at the glacier is estimated to be 150 inches, of which approximately 6 inches represents reduction in glacier volume. The average annual runoff at a gaging station on Grinnell Creek 1.5 miles downvalley from the glacier for the 20-year period, 1949-69, was 100 inches. The average annual precipitation over the glacier was probably 120-150 inches.

Sperry Glacier occupied 800 acres in 1901; by 1960 it covered only 287 acres, much of its upper part having disappeared from the enclosing cirque. From 1938 to 1969 certain segments of the terminus receded more than 1,000 feet. Profile measurements dating from 1949 indicate a lowering of the glacier surface below an altitude of 7,500 feet, but a fairly constant or slightly increased elevation of the surface above an altitude of 7,500 feet. Along one segment of the 1969 terminus the ice had been more than 100 feet thick in 1950. According to observations during 1949-69, average annual downslope movement was less than 15 feet per year in the central part of the glacier and slightly more rapid toward the edges and at higher parts on the glacier.

INTRODUCTION

This report summarizes information resulting from observations and surveys relating to Grinnell and Sperry Glaciers, in Glacier National Park, Mont. (fig. 1), during 1887-1969. The assembled information records the changes in these glaciers since their discoveries, and provides a basis for future studies. Descriptions of the glaciers by the area's earliest explorers and visitors contrast with observations made in recent years.

SUMMARY OF INVESTIGATIONS

The first measurable data relating to the glaciers resulted from the U.S. Geological Survey's topographic mapping in 1900 and 1901 of the Chief Mountain 30-minute quadrangle (scale 1:125,000, contour interval 100 feet).

William C. Alden (1914) described the glaciers and discussed the glacial phenomena he observed there in the summers of 1911-13.

George C. Ruhle, Park Naturalist, started terminal-recession measurements of Grinnell, Sperry, and other glaciers in 1931. Annual measurements were made by the National Park Service through 1944, and measurements for Grinnell and Sperry have been made since 1945 by the U.S. Geological Survey in cooperation with the Park Service.

James L. Dyson, former Ranger-Naturalist, topographically mapped Grinnell Glacier in 1937 and Sperry Glacier in 1938. He remapped in 1946 the entire Grinnell Glacier and the terminal (lower) part of Sperry Glacier.

Aerial photographs of most glaciers in the Park were made in 1950 and 1952 through the cooperative efforts of the National Park Service, the Glacier Natural History Association, and the American Geographical Society. From the 1950 photographs, the U.S. Forest Service mapped Jackson Glacier (southeast of Sperry Glacier), and the U.S. Geological Survey mapped Grinnell and Sperry Glaciers at a scale of 1:4,800.

From 1950 and 1960 aerial photographs of both Grinnell and Sperry Glaciers, the U.S. Geological Survey prepared 1:6,000-scale comparison topographic maps. The slight change during the intervening 10 years suggests that such frequent remapping is unnecessary.

The U.S. Geological Survey published in 1968 7½-minute quadrangle maps, scale 1:24,000, of the quadrangles in Glacier National Park. Grinnell Glacier is in the Many Glacier and Logan Pass

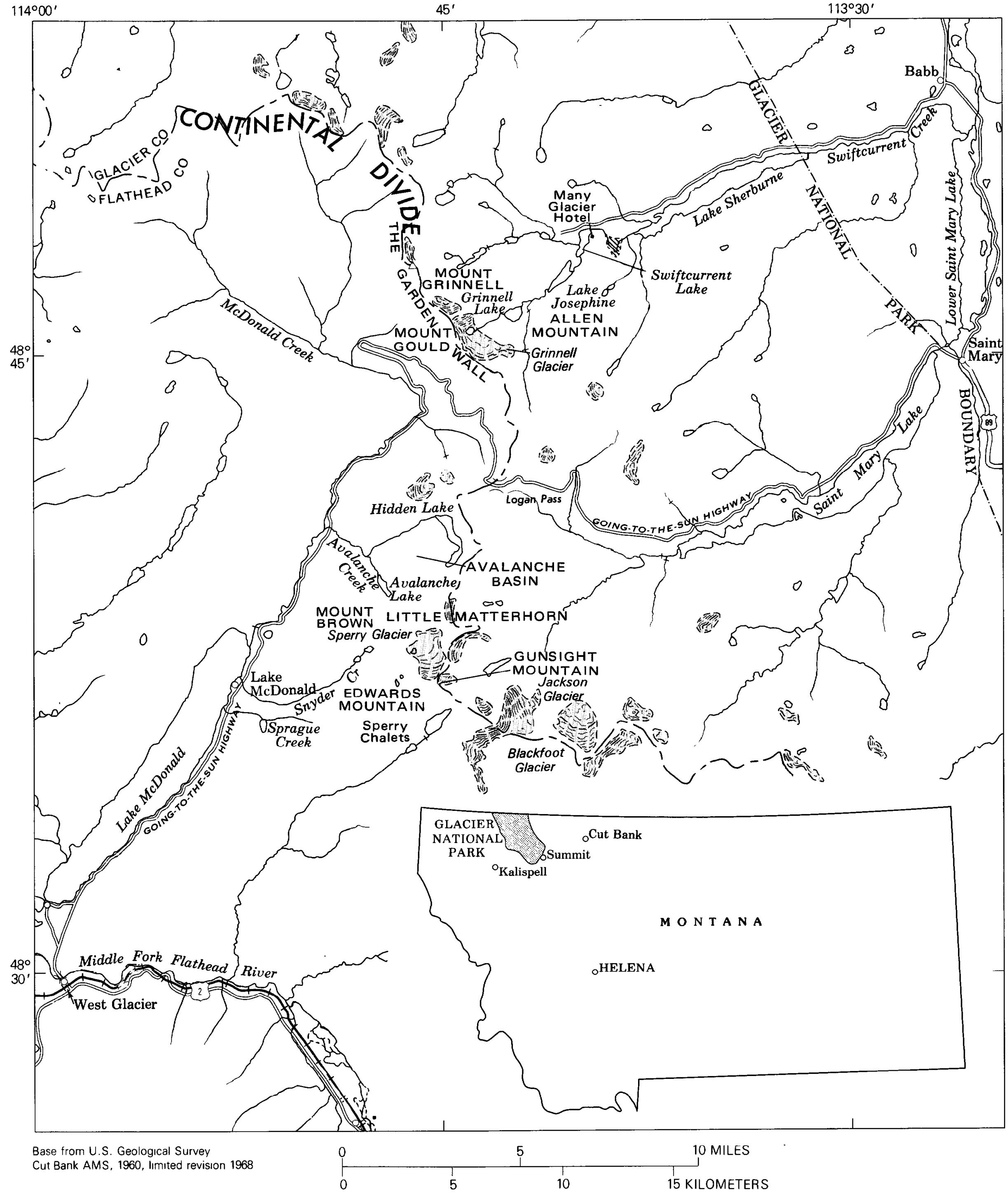

FIGURE 1.—Index map of the central part of Glacier National Park, Mont., showing location of Grinnell and Sperry Glaciers. Base from U.S. Geological Survey Cut Bank 1° x 2° quadrangle map, 1960–68.

quadrangles; Sperry Glacier is in the Mount Cannon, Lake McDonald East, and Logan Pass quadrangles.

A series of terrestrial photographs of the two glaciers taken with a phototheodolite during 1956-68, provide a good comparative record.

With few exceptions, changes in surface elevations of the two glaciers have been determined annually during late August or early September by measuring profiles of their surfaces along established lines. Data on surface movement have been obtained for Grinnell and Sperry Glaciers since 1947 and 1949, respectively.

Annual precipitation in the Grinnell Glacier area has been measured at two storage-precipitation gages installed in August 1949 and August 1955 by the U.S. Weather Bureau in cooperation with the National Park Service.

A gaging station installed by the U.S. Geological Survey in August 1949 on Grinnell Creek just below the outlet of Grinnell Lake (east of area shown on plate 1) provides continuous record of runoff from the glacier and its enclosing cirque and some records of precipitation and temperature. An auxiliary gaging station (pl. 1), installed in 1959 on the outflowing stream within about 1,000 feet of the glacier, operates during the summer and early fall; freezing conditions make it inoperative by October or November, and trail conditions make it not readily accessible until the following late June or early July.

ACKNOWLEDGMENTS

The National Park Service staff in Glacier National Park cooperated fully and assisted in the surveys and investigations. Matthew E. Beatty, Park Naturalist 1944-55, and his successors, H.B. Robinson, 1956-57, and Francis Elmore, 1958-70, by their interest and enthusiasm contributed greatly to the program. Donald H. Robinson, Assistant Park Naturalist, actively assisted in 1947-56. The National Park Service furnished saddle and pack animals for transporting personnel and equipment and gave me invaluable access to office files of historical information.

R.A. Dightman, then State Climatologist for Montana, furnished data from the two storage-precipitation gages in the Grinnell Glacier area.

Gerald M. Baden, of Fullerton Junior College, California, and former seasonal Ranger-Naturalist in the park, furnished data on the specific ages of trees that have grown in areas from which the glaciers have receded.

CLIMATE

The climate of Glacier National Park was studied in considerable detail by Dightman (1956, 1967). He noted the pronounced differences in precipitation which reflect the extremely rugged mountain terrain. For example, annual precipitation at Babb (fig. 1), the northeast entrance to the park, is now about 20 inches, whereas precipitation over Grinnell Glacier is estimated to be about 150 inches; this 130-inch increase occurs within a lateral distance of 15 miles and an altitude rise of 1,700 feet. Prior to discovery of Grinnell Glacier in 1887 and Sperry Glacier in 1897—when both glaciers were considerably larger than they are now—precipitation undoubtedly was even greater and temperatures were lower.

The earliest recorded climatic observations near Glacier National Park were in 1897 at Kalispell. Shown in figure 2 are values for annual precipitation, mean annual temperatures, and cumulative departures from the mean for Kalispell, West Glacier, and Summit. Precipitation and temperature data for certain pairs of years from 1915 to 1953 (table 1) were selected to illustrate the pronounced variations in successive years. Recording of precipitation, temperature, and streamflow in the Grinnell Glacier basin began in 1949 (discussed under precipitation and runoff of Grinnell Glacier). Precipitation

TABLE 1.—*Selected precipitation and temperature records for Summit, West Glacier, and Kalispell illustrating variations for successive years.*

Precipitation (in.)		Temperature (°F)	
Summit		**Summit**	
1952	26.15	1951	32.5
1953	55.51	1952	37.1
West Glacier		**West Glacier**	
1927	34.11	1934	45.6
1928	19.09	1935	40.9
1951	38.97	1951	38.8
1952	21.06	1952	42.6
		Kalispell	
		1915	43.7
		1916	39.2
		1934	47.6
		1935	42.1

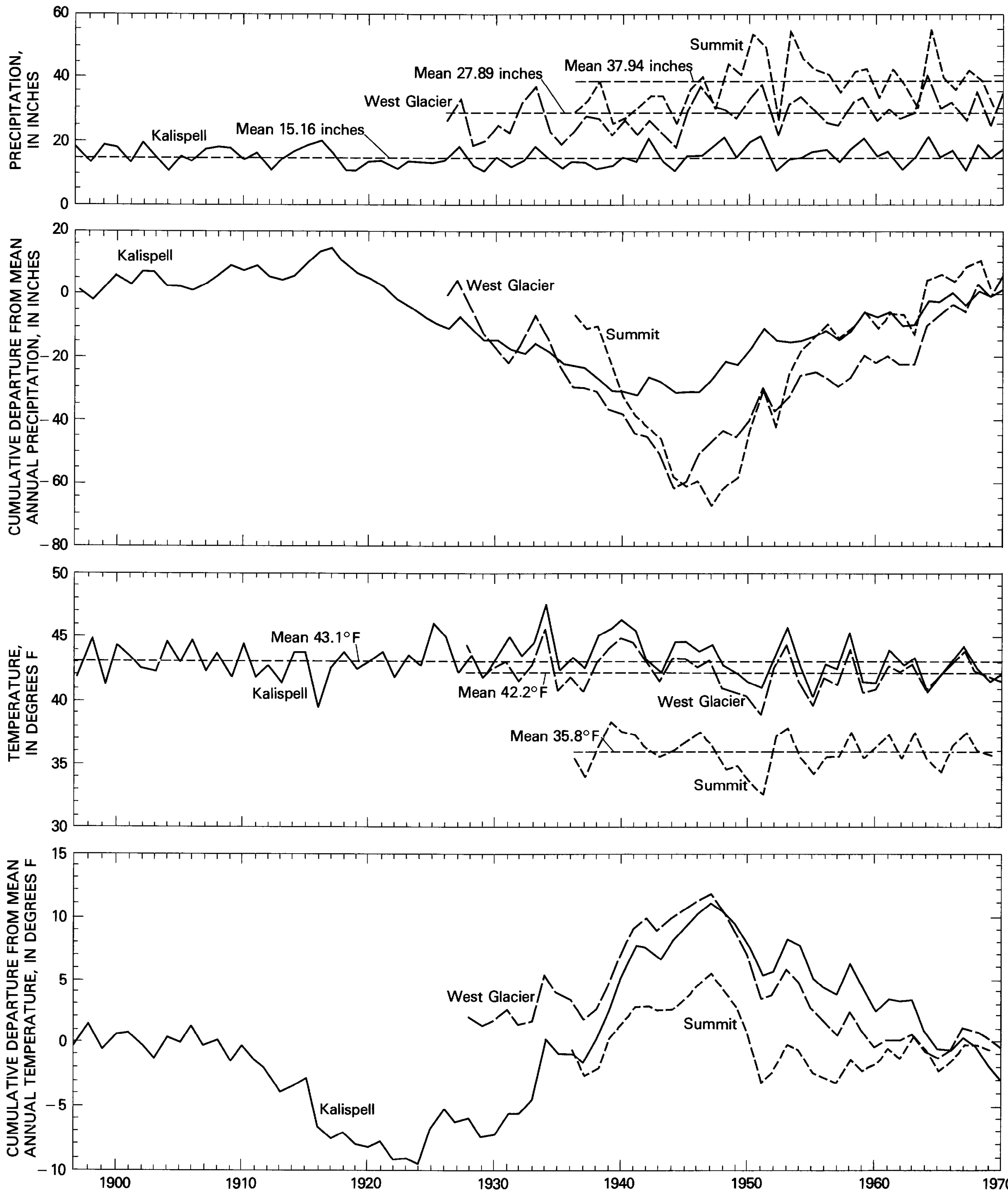

FIGURE 2.—Annual and mean precipitation and temperatures, and cumulative departures from the means, for three recording stations in the Glacier National Park area, Montana. Dashed line indicates mean. Kalispell, elevation 2,971 feet; 1897–70. West Glacier, elevation 3,154 feet; 1926–1970. Summit, elevation 5,213 feet; 1936–1969.

TABLE 2. — *July and August 1960-69 temperatures and precipitation at Sperry Chalets, Mont., elevation 6,500 feet*

[Data supplied by R.A. Dightman, U.S. Weather Bureau, Helena, Mont. July 1964 values based on observations from July 4 to July 31]

Year	Temperature (°F)						Precipitation (in.)	
	Mean		Maximum		Minimum			
	July	August	July	August	July	August	July	August
1960----	62.7	50.7	84	76	39	30	0.15	3.82
1961----	58	61.9	75	90	37	36	3.27	3.30
1962----	52.9	51	74	82	32	31	.76	2.41
1963----	53.5	56.6	76	81	35	36	2.30	1.60
1964----	56.1	45.5	79	76	37	33	2.69	3.52
1965----	53.4	53.1	74	77	34	29	1.98	6.44
1966----	55.8	52.3	76	81	32	32	2.03	2.60
1967----	57.9	62	81	77	39	42	.34	.20
1968----	56.5	54.5	78	79	37	40	2.18	5.21
1969----	54.8	56.6	72	87	36	33	1.95	.50
Mean--	56.2	54.4	77	81	36	34	1.76	2.86

and temperature data for Sperry Chalets, July and August, 1960-69, are given in table 2.

The station at Summit, highest of the three stations and on the Continental Divide at the south edge of the park, is 1,000 feet lower than and 35 miles south-southeast of Grinnell Glacier and 2,000 feet lower than and 30 miles southeast of Sperry Glacier. Nevertheless, the record from Summit closely reflects the climatic variations at the two glaciers.

The individual precipitation and temperature measurements for the three stations show no obvious similarity in pattern, but the curves for cumulative departure from means do show similar trends. The greatest negative departures from mean precipitation were in 1941, 1944, and 1947; a trend of increasing precipitation is evident for 1948 to 1969.

GRINNELL GLACIER

LOCATION AND ACCESSIBILITY

Grinnell Glacier, in Glacier National Park, is on the east slope of the Continental Divide, 17 miles south of the international boundary between the United States and Canada, at lat 48° 45′ N., and long 113° 44′ W.; it occupies a cirque formed by a sharp, narrow, serrated ridge connecting Mt. Gould (elev. 9,553 ft) and Mt. Grinnell (elev. 8,851 ft). The ridge is part of a spectacular feature known as The Garden Wall, which forms the Continental Divide in this area (fig. 1, pl. 1). The glacier is 6 miles southwest of Many Glacier Hotel.

DISCOVERY AND EARLY DESCRIPTIONS

George Bird Grinnell (fig. 3), after whom Grinnell Glacier is named, first visited the general area in 1885, while he was editor of Forest and Stream, a well-known outdoor magazine of the period. He was so impressed by his visit that he returned annually for several years and was among the early explorers to advocate the establishment of Glacier National Park (Grinnell, 1901). Available records indicate that the actual glacier was first visited in 1887, by Grinnell, James W. Schultz, and Lt. J.H. Beacon, U.S. Army. Schultz and Beacon each claimed to have named the glacier in honor of Grinnell, but Robinson

FIGURE 3.—George Bird Grinnell (1849-1938), editor, author, and explorer, was the discoverer of Grinnell Glacier. The exact date of the portrait is not known; it was made sometime before 1936, when it was given to the Glacier National Park museum by the Grinnell family. Photograph 7667 from the archives of Glacier National Park, courtesy of the National Park Service.

(1957) maintained that Beacon should have the credit. Glacier National Park was ultimately established in 1910.

In 1926, 16 years after establishment of the park, Grinnell revisited the glacier, accompanied by M.J. Elrod, Park Naturalist. Grinnell then described to Elrod the glacier in 1887, as he remembered it. Together with the 1887 photographs (now in the Park's historical files), these reminiscenses enable us to mentally reconstruct the Grinnell Glacier as it existed at time of discovery.

Francois Matthes topographically mapped the Chief Mountain 30-minute quadrangle, which encompasses Grinnell Glacier. He described (1904, p. 262) the glacier as he viewed it in 1900 from Mt. Grinnell:

> It covers a series of broad flat shelves with an aggregate surface of about one mile square, the ice descending in irregular cascades from the higher to the lower shelves. Around its upper end stretches a serrated comb-ridge, known as "the Garden Wall," connecting Mt. Grinnell on the north with Mt. Gould * * * on the south, and forming for several miles the crest of the Continental Divide. A short distance in front of the glacier its shelving site abruptly terminates in the precipitous, curving wall of a deep amphitheatre. A pretty green lake—Grinnell Lake—lies in its middle, surrounded by dense woods.

The lower, main body of the glacier is separated by a ledge-topped cliff from the glacier's upper, smaller part, called The Salamander (pl. 1). Visible in the 1887 and 1952 photographs (fig. 4) and labeled on the recent maps (Many Glacier 7½-minute quadrangle, 1950 and 1960 maps of Grinnell Glacier), The Salamander has scarcely changed since the glacier's discovery. In 1900 (when the Chief Mountain quadrangle was mapped) the terminus was slightly lower than 6,200 feet elevation, and the top of the glacier was at 7,500 feet elevation.

The next studies were in 1911 by Alden (1914, p. 19), who described the glacier as follows:

> This glacier has a width from the northwest to the southeast of about 1½ miles and a length from southwest to northeast of about 1 mile. Its area is a little over 1 square mile. It consists of a névé-covered upper part, lying on an upper bench in the western part of the cirque, and the main glacier, whose lowest part is not far from the crest of the cliff which rises abruptly nearly 1,000 feet from the valley floor above Grinnell Lake. Through most of its lateral extent the upper mass of ice [The Salamander] ends at the crest of the bare rock ledge below the upper bench. South of this, however, the ice cascades over the ledge with a much crevassed surface to the main glacier below. From the encircling cliffs the ice flow converges toward the lowest point in the lip of the cirque. A large part of the surface is crevassed, showing that the ice is moving down over an uneven bed, and nearly the whole surface is banded with the soiled zones which mark the outcropping of the ice strata. A morainal embankment, consisting of narrow sharp-crested ridges of drift 30 to 100 feet in height, closely borders the ice margin on the east and north. * * * This is in part [a] lateral and in part a terminal moraine.

PICTORIAL RECORD

Grinnell Glacier, like other glaciers in Glacier National Park and most glaciers in western North America, has significantly diminished in area and volume since it was first observed. Changes are well illustrated by selected photographs.

The earliest available photographs are those taken by the Grinnell party in 1887 (figs. 4*A* and 5*A*). Later photographs taken from the same locations (figs. 4*B* and 5*B*) and other comparative pairs of photographs illustrate the changes in the glacier's extent (figs. 5–8).

AREA

Grinnell Glacier, as shown on the Chief Mountain 30-minute quadrangle map, occupied 530 acres in 1900, a measurement probably accurate to within 5 percent. Periodic remapping has documented its diminishing area, as shown in the accompanying table. Of the two sections of the glacier that resulted from the disappearance of the previously connecting icefall in 1926 or 1927, Dyson (1948) considered only the lower part to be Grinnell Glacier.

Year of mapping	Source of data	Area of glacier (acres) Lower part	Upper part	Total
1900	Chief Mountain 30-minute map----------	480	50	530
1937	Mapping by J. L. Dyson----------------	328	---	---
1946	Mapping by J. L. Dyson----------------	280	---	---
1950	USGS 1:6,000 map (Grinnell Glacier)---	272	56	328
1960	USGS 1:6,000 map (Grinnell Glacier)---	259	56	315
1966	USGS 1:24,000 map (Many Glacier and Logan Pass 7½-minute quadrangles).	244	54	298

The upper part of the glacier, known as The Salamander because of its shape, is hemmed in by steep rock walls and so its area has scarcely changed since it was first mapped in 1900.

The lower, main part of the glacier, however, has steadily decreased in extent. The average annual decrease in area during successive periods was: 1900–37, 4.1 acres; 1937–46, 5.3 acres; 1946–50, 2 acres; 1950–60, 1.3 acres; and 1960–66, 2.5 acres. At the present lower edge of the ice the bedrock surface slopes rather gently and uniformly toward the glacier and so a measurable change in the surface elevation shifts the position of the ice front less than it would have in earlier years when the ice overrode the crest of the rock ledge. Gibson and Dyson (1939, p. 684) observed that the rock strata dipped 15° upvalley. The back, or top, of the glacier lies against the steep, almost vertical, cliffs of The Garden Wall.

A pond appeared at the north end of the glacier, probably in the early 1920's. The park naturalist (file report) reported in 1927 that "A lake of small size has formed on the north side of the glacier, between the ice front and the moraine. The face of the ice is a steep hill down which streams rush continuously." As the ice has retreated, this lake (shown on 1960 map as Grinnell Lake and on 1968 map of Many Glacier 7½-minute quadrangle as Upper Grinnell Lake) has spread from 3.4 acres in 1937 to 31.3 acres in 1968 (see table):

Date and source of data	Area of lake (acres)
1937 map by J. L. Dyson------------	3.4
1946 map by J. L. Dyson------------	14.8
1950 USGS map (Grinnell Glacier)---	20.8
1960 USGS map (Grinnell Glacier)---	22.4
1968 field surveys-----------------	31.3

The 1950–60 net increase of only 1.6 acres reflects mainly a sudden 8-foot drop of the lake level in August 1957, when some undetermined change in configuration of the glacier's underside shifted the direction of major melt-water drainage. After the sudden drop in lake level, there was no longer any direct drainage from the lake; major runoff of melt water bypassed the lake and followed the Grinnell Creek channel (pl. 1). The 17.4-acre increase in lake size between 1937 and 1950 represented about one-third of the glacier's concurrent areal shrinkage.

The apparent 1887 outline of the glacier as inferred from photographs was sketched on the 1950 USGS map; the size of the area was estimated to have been 565 acres at that time. In 1900 the glacier's area was only 530 acres. During roughly the same time, on Mount Rainier, Wash., both Nisqually Glacier (Johnson, 1960) and Carbon Glacier (Russell, 1898, p. 390) also receded.

RECESSION

Measurements of terminus changes generally are of limited value to short-term glacier studies because positions of the ice terminus are affected by both ice movement and ablation. Furthermore, as at Grinnell Glacier, local topography at the terminus may profoundly affect rates of recession or advance. Measurements to only one point on the terminus are even less meaningful because changes along the ice front are not uniform. Terminal recession does not necessarily indicate a shrinkage or lowering of the ice surface of the entire glacier. The surface elevation of the upper reaches of a glacier may be increasing even when the terminus is receding. This was demonstrated by investigations on Nisqually Glacier on Mount Rainier, Wash. (Johnson, 1960; Veatch, 1969).

The first known recorded observations of recession of Grinnell Glacier were made by M.J. Elrod, nature guide and ranger-naturalist, during the 1925, 1926, and 1927 summer seasons. He measured the location of the ice front by pacing to a large, conspicuous boulder near the present foot trail, shown as "Elrods Rock" on plate 1. Elrod's 1927 report stated "I am sure that the ice was around this rock in 1922 * * *." His measurements were as follows:

Date of observation		Distance (ft) from Elrods Rock to ice front	Recession (ft) since previous date
1925	Aug. 1----	62	---
1926	July 11----	82	20
	Aug. 10----	107	25
	Sept. 4----	117	10
1927	Aug. 26----	125	8

The widely varying rate of recession—from 35 feet during the summer of 1926 to only 8 feet for the year between the last two observations—reflects differing weather conditions. According to Elrod, the park season, which is weather-controlled, opened very early in 1926 and was very warm, and the warm weather continued until late in the year. By early July the previous winter's light snowpack had disappeared from the main body of the glacier, and ablation of glacial ice was rapid for the remainder of the season. In contrast, the 1927 park season began late and was cool, cloudy, and rainy. The preceding winter's heavy snowfall did not melt from the glacier until late August.

Elrod's measurements related to a single point on the front of the glacier. This section of the front, when mapped by Dyson in 1937, was 440 feet from "Elrods Rock," or 315 feet beyond the last position recorded in 1927, an average annual recession of 31.5 feet for that 10 years.

From 1932 until 1937 recession was measured annually by the park naturalist, George C. Ruhle. The following measurements were reported to the Committee on Glaciers of the American Geophysical Union (Matthes, 1937, p. 298; 1938, p. 319):

FIGURE 4 (above and facing page).—Comparative views of Grinnell Glacier from the upper end of lake Josephine photographed by Lt. J.H. Beacon, U.S. Army, with the Grinnell party in 1887 (*A*) and by Gerald Baden in 1952 (*B*). The terminus in 1887 was near the top of the cliff encircling the upper end of Grinnell Lake and near the crest of the waterfall shown in the 1952 view. The dark area in the lower part of the glacier in the 1887 view appears to be a protruding rock but is probably scree, broken rock debris that originated

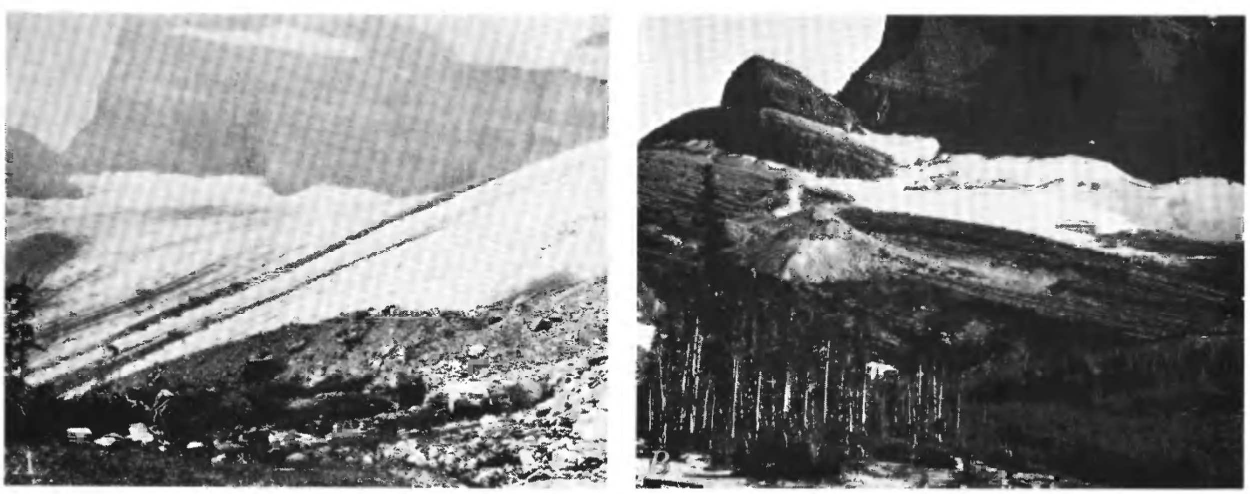

FIGURE 5.—Front of Grinnell Glacier as viewed (*A*) by the Grinnell party in 1887 and (*B*) by Arthur Johnson on August 28, 1969, from near the end of the present horse trail. Moraine, clearly shown in 1969 view, was partly covered by the glacier in 1887. Tall tree in 1969 view is probably the larger of the two trees shown in left side of 1887 view; in 1961 this tree had 260 rings (Gerald Baden, oral commun., 1969). Smaller trees in 1969 view have sprung up since 1887.

from rockfalls at the head of the glacier. In 1887 the north edge (at right in photograph) of the glacier nearly reached the top of the narrow, sharp-crested moraine, which is conspicuous in later photographs. The upper and lower parts of the glacier (*A*) became separated into two distinct parts in 1926 or 1927. The lower, larger part is barely visible in the 1952 view (*B*). *A*, Photograph 4383 from the museum of Glacier National Park, courtesy of the National Park Service.

Date measured	Recession (ft)	Cumulative recession (ft) since 1932
1932 Oct. 6----	0	0
1933 Sept. 14----	0	0
1934 Oct. 5----	54	54
1935 Sept. 22----	43	97
1936 Sept. 22----	64	161
1937 Oct. 25----	4	165

Measurements since 1937 have been based on mapping and are more accurate.

A comparison of the 1937 and 1946 maps by Dyson (1948, p. 101) shows a total average recession of 318 feet along the glacier front during the 9 years, an average annual recession of 35 feet.

In 1945 park naturalist M.E. Beatty and I selected and permanently marked several points that have served as convenient instrument stations for mapping the ice front. These points are shown on the 1960 map (pl. 1) as planetable bench marks 6459, 6425, 6413, and 6454.

Changes measured along a 2,000-foot section of the front of the glacier extending southeastward from Upper Grinnell Lake (pl. 1) are tabulated below. The ice front along the lake was not measured, inasmuch as changes there caused by ice breaking into the lake would not necessarily indicate a true recession.

The positions of the ice front in the years indicated were determined as follows: 1937, from map by

Period	Recession (ft) during the period	Average annual recession (ft)	Cumulative recession (ft) 1937–68
1937–45---	243	30.4	243
1945–50---	61	12.2	304
1950–60---	87	8.7	391
1960–68---	19	2.4	410

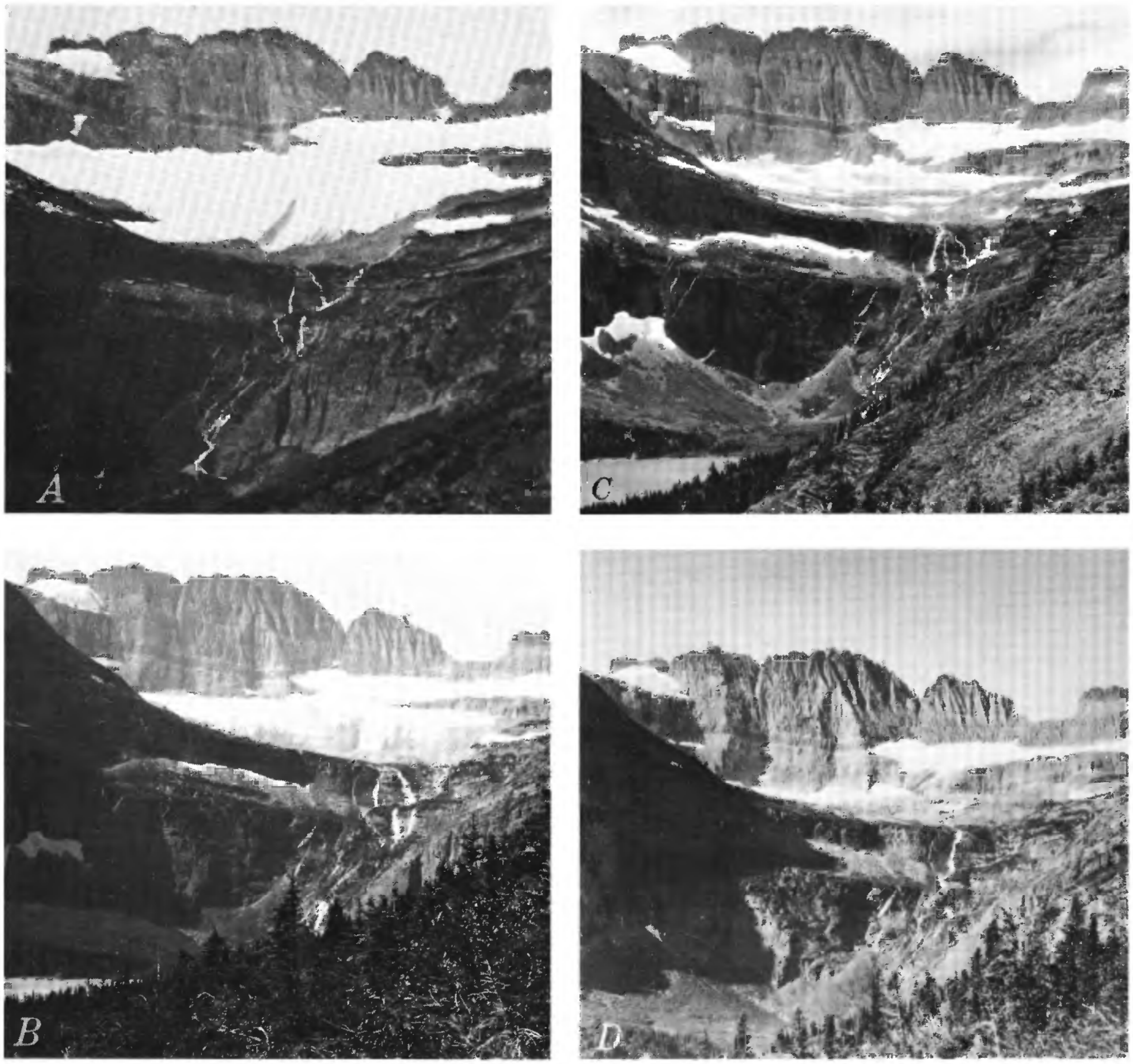

FIGURE 6.—Comparative views of Grinnell Glacier from locations on or near the trail along the south side of Mt. Grinnell: *A*, August 27, 1900 (Francois Matthes, photograph 33–A); *B*, August 1911 (T.W. Stanton, photograph 704); *C*, 1935 (Grant); *D*, September 1, 1956 (H.B. Robinson). Gem Glacier, the small ice mass visible in the upper left of all four views, has appeared much the same over the years; it occupies about 7 acres, and fills a shallow rock-rimmed basin.

A, Earliest available general view of Grinnell Glacier and surroundings; though viewpoint not identical to the 1887 views (figs. 4*A* and 5*A*), the photograph suggests that no appreciable recession or shrinkage occurred between 1887 and 1900.

B, 1911 view indicates some recession and shrinkage since 1900. The upper part of the glacier, particularly the part extending up toward the col (saddle) in The Garden Wall, was noticeably lower than in 1900 and the front seemingly has receded somewhat.

C, The glacier has separated into upper and lower parts, and has receded and shrunk considerably during the 24 years since 1911.

D, 1956 view shows further recession of the lower part since 1935. The upper part appears virtually identical in the 1935 and 1956 views and in views as late as 1969.

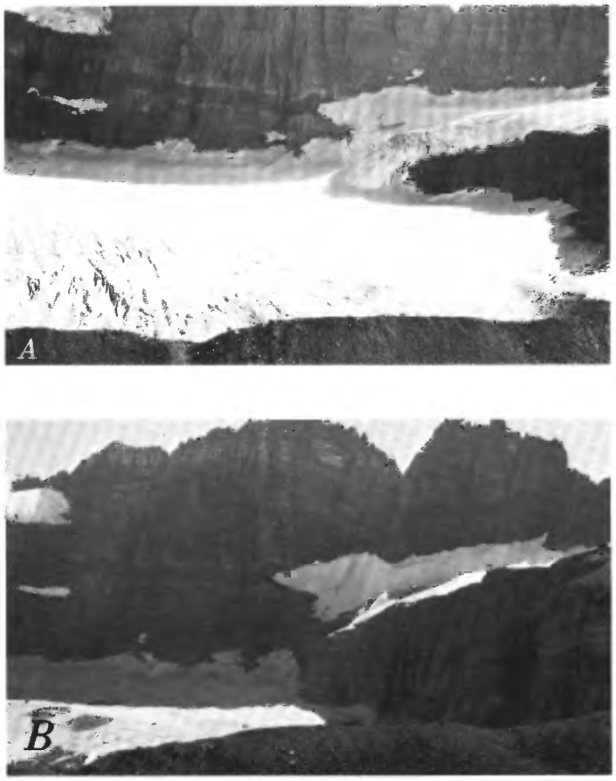

FIGURE 7. —Grinnell Glacier as it appeared in 1911 and 1966 from viewpoint north of the lateral moraine (foreground). *A*, photograph 711 by T.W. Stanton; *B*, photograph by Arthur Johnson.

A, By August 1911 the glacier had already retreated from its extent in 1887 (fig. 5*A*).

B, By August 1966 the glacier had retreated even farther and separated into an upper part (The Salamander) and a lower part. Upper Grinnell Lake (not visible in this view) had formed between the moraine and the glacier.

Dyson; 1945 and 1968, from field surveys; 1950 and 1960 from USGS maps.

The changes along the 2,000-foot section were not uniform, mainly because of the irregular steplike topography of the bedrock at the glacier's edge. The increase in annual precipitation and the decrease in annual temperature since the mid-1940's (fig. 2) would account for the decreasing rate of recession.

These recession measurements record change in the position of the glacier's edge rather than the recession of the true terminus. At a much earlier stage in the history of the glacier this edge was, no doubt, essentially the terminus. Now, however, it seems logical to consider the actual terminus as the south shore of Upper Grinnell Lake, which is consistent with the direction of movement shown on

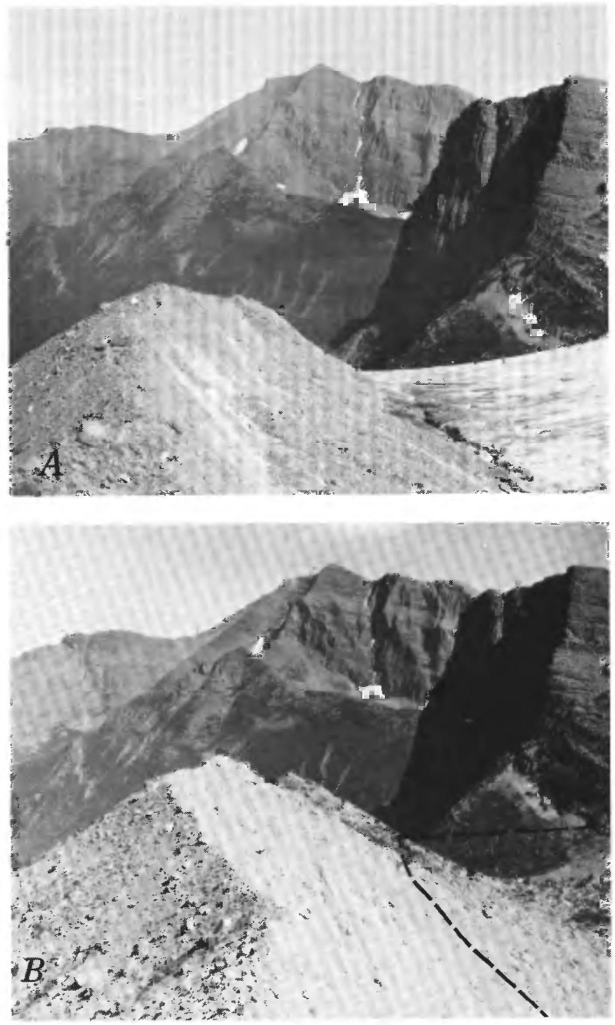

FIGURE 8.—Comparative 1911 and 1956 views eastward along crest of the lateral moraine north of Grinnell Glacier. *A*, August 1911 (T.W. Stanton, photograph 710); *B*, August 31, 1956 (H.B. Robinson). In 1911 edge of glacier extended well up on side of moraine (photograph *A* and line on *B*). In the 1956 photograph from the same position, none of the glacier is visible; its nearest edge is out of view to the right, more than 1,000 feet from the camera station.

plate 1. Accordingly, the recession figures were adjusted to the changing shoreline of the lake:

Year	Recession (ft) since previous date	Year	Recession (ft) since previous date
1937-------	0	1958-------	198
1946-------	400	1963-------	100
1950-------	248	1969-------	223

Recession, from 1946 to 1969, measured normal to a 1,125-foot base line, totaled 769 feet, an average of 33 feet annually during the 23 years.

MOVEMENT

The first recorded measurements of the glacier's surface movement were made by Alden (1923) for the period August 26-30, 1920. Four markers set on the glacier near its frontal edge moved 1 to 4¾ inches during the period. These measurements, characterized by Alden as "crude," indicated merely that the rate of movement during the brief period was rather slow.

Gibson and Dyson (1939, p. 689) estimated the rate of movement by considering the distance between stratification lines, which are the surface expression of boundary planes between successive annual accumulations of ice. Careful study of photographs identified 60 bands from the south cirque wall to a point 1,800 feet distant on the east front, which Gibson and Dyson interpreted to indicate an average movement of 30 feet. Probably because their measurements were at an angle to the direction of movement, this finding is less than from the subsequent 1947-69 measurements.

Movement since 1947 was determined by periodically plotting the location of prominent boulders on the ice surface. The boulders have been identified by year and sequence of marking; for example, 50-2 indicates the second boulder marked in 1950.

The 1947-69 data are summarized in table 3 and are plotted on plate 1. Movement has been generally northeastward. The movement was undoubtedly more to the east when the glacier was both larger and higher, for example, when it was discovered in 1887. As both area and surface elevation decreased, the direction of movement gradually changed from eastward to northeastward, as indicated by the 1947-69 observations.

TABLE 3.—*Movement of marked rocks on Grinnell Glacier, 1947-69*

[Vectors shown on plate 1]

Rock No.	Period	Movement (ft) Total	Movement (ft) Annual average	Rock No.	Period	Movement (ft) Total	Movement (ft) Annual average
47-1	1947-57	380	38	59-3	1959-69	355	36
47-2	1947-53	215	36	59-4	1959-65	275	46
50-1	1950-64	530	38	59-5	1959-66	320	46
50-2	1950-69	700	37	63-1	1963-66	110	37
52-1	1952-62	485	48	63-2	1963-69	190	32
52-2	1952-56	210	52	64-1	1964-69	185	37
52-3	1952-69	285	41	65-1	1965-69	170	42
58-1	1958-69	385	35	65-2	1965-69	180	45
59-1	1959-64	170	34	65-3	1965-69	185	46
59-2	1959-68	355	39	66-1	1966-68	80	40

The annual rate of movement observed since 1947 ranged from 32 to 52 feet, more than half the observed values being in the range of 35-45 feet. Measurement points with annual movement exceeding 45 feet were in a small area southwest from reference point bench mark 6454 feet, and that movement was toward the head of the outlet stream from the glacier. The glacier surface in the area of most rapid movement was steeper than in other areas where marked rocks were located.

Since 1947 the rate and direction of movement have continued virtually unchanged, even though the surface elevation of the glacier decreased 25-30 feet during the period. In general, decreasing surface elevation of a glacier would be expected to be accompanied by a slower rate of movement.

FLUCTUATIONS IN SURFACE ELEVATION

PROFILES

Changes in the surface elevation of Grinnell Glacier have been measured periodically, usually annually, since 1950. Periodic profiles, measured by planetable or transit and stadia along three lines of profile, are shown on plate 1; profiles *A-A′* and *B-B′* originate from planetable bench mark 6425 (1960 map) and profile *C-C′*, established in 1957, originates from planetable bench mark 6454. Also shown on plate 1 are profiles based on Dyson's 1937 and 1946 maps. Dyson's measurements, particularly for the higher parts of the glacier, should be considered as only approximate, owing to uncertainty of datum correlation between Dyson's maps and subsequent field surveys; Dyson's contouring on higher areas of glacier does not match later maps, profiles, and observations.

Profile *A-A′* is alined along the crest of the waterfall below The Salamander. The August 26, 1969, line shows a reversal in slope approximately at midpoint and a 25-foot drop in elevation at a point about 200 feet from the cliff, near the base of Salamander Falls. Mr. Grinnell, during his 1926 visit to the glacier, recalled that in 1887 a "well" or conical depression existed at the base of the falls. Dyson's 1937 map shows a depression, but with the lowering of the ice surface this depression disappeared. The general ice surface in 1968 sloped gently toward the lake, 800 feet from the base of the waterfall. The water from the waterfall does not appear as surface runoff, instead disappearing through or underneath the ice.

A comparison of the 1937 profile developed from Dyson's map with the 1969 profile shows a difference in surface elevation of about 100 feet to more than 120 feet. Even allowing for an error of as much as 20 feet (one contour interval on Dyson's map), the average decrease in the surface elevation was about 100 feet during the 32-year period. The 1946 elevations based on Dyson's map appear fairly reasonable except for the central part of profile *A–A′* where the 1946 and 1952 surfaces are shown as coincident. In view of later observations, the 1946 surface apparently should have been higher in that part of the profile.

Profile *B–B′* slopes rather uniformly to within a few hundred feet of the headwall, and then steepens abruptly. A comparison of the 1937 profile developed from Dyson's map with the 1969 profile shows a drop of more than 100 feet near the terminus and lesser differences higher up the glacier. A comparison of the 1946 profile (also from Dyson's map) with the 1969 profile shows a decrease in surface elevation of 50–60 feet.

Profile *C–C′* is much steeper than the other two profiles, particularly beyond 1,500 feet from the reference point, where the slope increases rapidly. The 1937-to-1969 decrease in surface elevation near the lower edge of the glacier was about 80 feet; the difference at midglacier was about 40–50 feet. The profile developed from Dyson's 1937 map indicates that beyond 1,800 feet from the reference point the ice surface was coincident with or below the 1969 surface, a condition considered unlikely. The developed 1946 profile conflicts with later observations and is therefore not included on plate 1.

As evident from profiles *B–B′* and *C–C′*, the glacier surface has dropped more near the northeast margin than near the headwall.

Changes in surface elevations from year to year (or, for earlier measurements, over a span of several years) for segments of each profile are listed in tables 4–6. The dates of measurement varied slightly from year to year, a fact which must be considered when

TABLE 4.—*Mean elevations, in feet, of segments of profile A–A′, Grinnell Glacier, on specific dates*

[Elevations are above assumed datum for glacier surveys (pl. 1). Distances measured from reference point, planetable bench mark 6425.---, no data]

Distance (ft)-----	100-500	500-1,000	1,000-1,500	1,500-2,000
Yr, mo, d(s)	Mean elevation (ft) of segment			
1950 Sept. 14-----	6,463.5	6,510.3	---	---
1952 Aug. 22-----	6,463.6	6,510.0	6,529.5	---
1953 Sept. 4-----	6,460.2	6,505.5	6,523.6	---
1954 Sept. 27-----	6,461.1	6,505.8	---	---
1955 Sept. 8-----	6,462.0	6,505.1	6,523.9	---
1956 Aug. 30-----	6,462.6	6,504.4	6,522.9	6,515.4
1957 Aug. 13-----	6,461.6	6,504.0	6,522.0	6.513.6
Sept. 10-----	6,458.1	6,500.7	6,518.3	6,508.3
1958 Aug. 12-----	6,454.8	6,497.0	6,513.2	6,503.2
Sept. 14-----	6,449.2	6,491.1	6,507.8	6,497.6
1959 Aug. 14-----	6,454.9	6,498.3	6,514.4	6,501.9
Sept. 12-----	6,452.2	6,495.7	6,512.2	6,500.3
1960 Sept. 2-----	6,453.0	6,495.9	6,511.1	6,502.3
1961 Sept. 19-----	6,447.0	6,489.2	---	---
1962 Sept. 1-----	6,446.6	6,488.4	6,505.0	6,496.1
1963 Sept. 12-----	6,440.6	6,484.2	6,499.9	6,492.4
1964 Aug. 28-29--	6,437.3	6,482.8	6.499.3	6,490.8
1965 Sept. 5-6---	6,438.8	6,482.7	6,498.8	6,490.2
1966 Aug. 16-----	6,439.9	6,483.9	6,500.7	6,492.4
1968 Aug. 27-----	6,433.5	6,478.7	6,496.4	6,483.7
1969 Aug. 26-----	6,428.1	6,474.8	6,492.7	6,483.3
Net decrease 1950-69-------	35.4	35.5	[1]36.8	[2]32.1

[1]For 1952-69. [2]For 1956-69.

TABLE 5.—*Mean elevations, in feet, of segments of profile B–B′, Grinnell Glacier, on specific dates*

[Elevations are above assumed datum for glacier surveys (pl. 1). Distances measured from reference point, planetable bench mark 6425. ---, no data]

Distance (ft)----	100-500	500-1,000	1,000-1,500	1,500-2,000	2,000-2,500
Yr, mo, d(s)	Mean elevation (ft) of segment				
1950 Sept. 14----	6,460.1	6,523.3	6,564.8	---	---
1952 Aug. 22----	6,460.3	6,522.6	6,563.8	6,604.8	---
1953 Sept. 4----	6,458.4	6,519.5	---	---	---
1954 Sept. 27----	6,459.5	6,522.0	6,564.4	---	---
1955 Sept. 6----	6,460.6	6,521.8	6,563.9	---	---
1956 Aug. 30----	6,461.7	6.521.6	6,563.8	6,604.6	6,659.9
1957 Aug. 13----	6,460.2	6,521.3	6,563.2	6,602.9	6,657.2
Sept. 10----	6,456.6	6,517.9	6,560.6	6,600.9	6,654.9
1958 Aug. 12----	6,452.5	6,515.2	6,557.1	6,596.4	6,649.6
Sept. 15----	6,446.4	6,509.8	6,551.6	6,591.2	6,642.7
1959 Aug. 14----	6,453.0	6,516.2	6,558.6	6,598.4	6,651.6
Sept. 12----	6,449.9	6,513.6	6,555.7	6,597.1	6,649.5
1960 Sept. 3-6--	6,449.9	6,514.1	6,555.5	6,594.7	6,646.7
1962 Sept. 1-2--	6,442.8	6,506.4	6,547.4	6,596.9	6,640.7
1963 Sept. 12----	6,437.5	6,499.2	6,541.8	6,582.4	6,634.4
1964 Sept. 15----	6,436.5	6,499.1	6,541.1	6,581.4	---
1965 Sept. 5-6--	6,436.4	6,499.6	6,540.9	6,580.2	6,635.0
1966 Aug. 17----	6,437.6	6,501.5	6,543.1	6,582.3	6,637.7
1968 Aug. 28----	6,432.1	6,498.8	6,539.5	6,578.8	6,633.9
1969 Aug. 27----	6,428.2	6,493.3	6,534.2	6,574.2	6,628.3
Net decrease 1950-69------	31.9	30.0	30.6	---	---
Net decrease 1956-69------	---	---	---	30.4	31.6

TABLE 6.—*Mean elevations, in feet, of segments of profile C–C′, Grinnell Glacier, on specific dates*

[Elevations are above assumed datum for glacier surveys (pl. 1). Distances measured from reference point, planetable bench mark 6454. ---, no data]

Distance (ft)------	500-1,000	1,000-1,500
Yr, mo, d(s)	Mean elevation (ft) of segment	
1957 Sept. 11----	6,592.7	6,670.8
1958 Aug. 13----	6,589.9	6,667.1
1959 Sept. 12----	6,587.3	6,666.8
1962 Sept. 3----	6,587.3	6,662.0
1963 Sept. 13----	6,583.5	6,655.6
1965 Sept. 7----	6,583.0	6,657.5
1966 Aug. 18----	6,585.0	6,660.5
1968 Aug. 28----	6,581.4	---
1969 Aug. 28----	6,579.3	6,653.1
Net decrease 1957-69----------	13.4	17.7

comparing results, but nearly all measurement dates fell between mid-August and mid-September. Composite changes during the 1-month period for 1957, 1958, and 1959 along profiles *A-A′* and *B-B′*, shown in the accompanying table, illustrate the direct relation between glacier melting and prevailing temperatures.

Period		Surface lowering (ft) Profile A-A'	Profile B-B'	Mean temperature at gaging station °F	°C
1957	Aug. 13-Sept. 10---	4.0	2.8	54.3	12.4
1958	Aug. 12-Sept. 14---	5.6	5.8	57.8	14.3
1959	Aug. 14-Sept. 12---	2.3	2.4	52.8	11.6

A graph of the mean annual elevations of selected segments of the three profiles (fig. 9) shows that from year to year elevations both increased and decreased; but the general trend was a decrease in elevation for these segments and for the entire glacier.

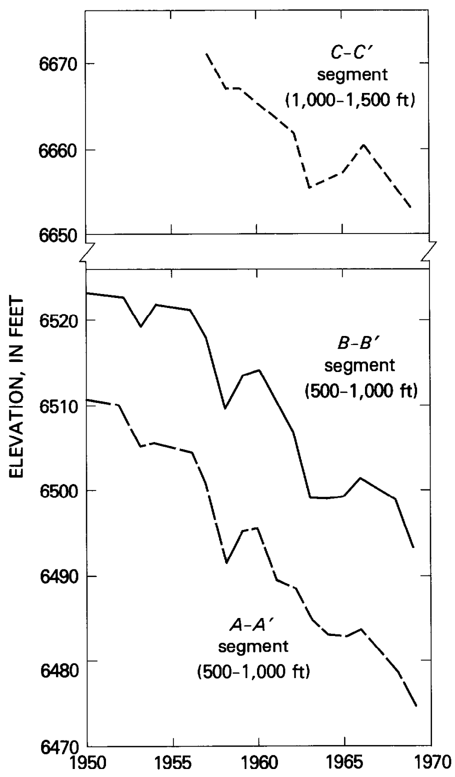

FIGURE 9.—Mean annual elevations of selected segments of profiles *A-A′*, *B-B′*, and *C-C′*, 1950-69, Grinnell Glacier. Segments measured from respective reference points shown on plate 1.

Rainfall does not significantly affect the glacier's melting rate. Theoretically, 1 inch of rain at 50°F (10°C) produces only one-eighth inch of melt water. From August 14 to September 12, 1959, for example, rainfall at the Grinnell Creek gaging station was 13.1 inches. If we assume that precipitation was uniform over the entire glacier and was at a temperature of 50°F, the depth of resulting melt-water runoff would have been only 1.6 inches. The equivalent loss of ice thickness—less than 2 inches—would be only a small fraction of the actual 2.4 feet of loss (profile *B-B′*) during that period.

The fluctuations in surface elevations of representative segments of the profiles are shown graphically in figure 9. The general trend has been a decrease in elevation, indicating a shrinkage of volume. From 1950 to 1969 the representative elevations on profiles *A-A′* and *B-B′* decreased 35 feet and 30 feet, respectively, approximately 1.7 feet per year. From 1957 to 1969 the elevation on profile *C-C′* decreased 18 feet, approximately 1.5 feet per year. The other segments of the profiles showed corresponding decreases.

ABLATION

To supplement information obtained from profile measurements, ablation (the amount of snow and ice removed from the glacier's surface by melting, evaporation, and wind erosion) was measured. Ablation was determined by drilling ¾-inch-diameter holes in the ice, with a specially designed ice-auger to depths as great as 20 feet, actual depths being governed by conditions of the ice. A wooden stake, ¾ inch by 6 feet, was placed in each hole, marked with an identifying location number and date of emplacement. For holes deeper than 6 feet, several stakes were emplaced, end to end, and numbered from bottom to top. The following example illustrates the procedure. On August 29, 1964, a hole was drilled to a depth of 19.7 feet. Three stakes were placed in the hole, the top of the uppermost (No. 3) stake being 1.7 feet below the ice surface. On September 6, 1965, 3.3 feet of stake 3 was exposed, indicating an ablation of 5.0 feet (1.7 + 3.3) since August 1964. On August 16, 1966, stake 3 had fallen away and 0.2 foot of stake 2 was exposed, indicating an ablation of 2.9 feet (2.7 + 0.2) since the 1965 observation. By August 27, 1968, the ice had melted so much that the hole was no longer evident and the remaining two stakes were lying on the ice, indicating an ablation of at least 11.8 feet since the 1966 observation. The results of ablation movements are recorded in tables 7 and 8.

TABLE 7.—*Seasonal measurements of ablation at Grinnell Glacier, 1960-65*

[Location of stakes shown on plate 1. ---, no data]

Stake No.	Period of measurements	Elapsed days	Ablation (ft)	Period of measurement	Elapsed days	Ablation (ft)
	1960			1961		
1	July 21-Oct. 4	75	11.9	July 17-Aug. 24	38	11.6
2	--do----------	75	14.1	--do-----------	38	11.1
3	--do----------	75	11.7	--do-----------	38	9.7
4	--do----------	75	10.8	July 19-Aug. 24	36	8.7
5	--do----------	75	11.0	--do-----------	36	8.8
6	July 22-Oct. 4	74	9.7	July 17-Aug. 24	38	8.9
7	--do----------	74	11.6	July 20-Aug. 24	35	8.8
8	--do----------	74	10.2	--do-----------	35	9.1
8A	--------------	--	----	---------------	--	----
9	July 22-Oct. 4	74	11.5	---------------	--	----
	1962			1963		
1	July 15-Oct. 3	80	12.7	July 26-Oct. 15	81	13.0
2	--do----------	80	12.9	July 27-Oct. 15	80	12.8
3	July 16-Oct. 3	79	10.7	--do------------	80	11.9
4	July 17-Oct. 3	78	10.8	July 9-Sept. 12	65	13.1+
5	July 16-Oct. 3	79	11.1	--do------------	65	11.2
6	--do----------	79	10.4	July 27-Oct. 15	80	11.9
7	July 17-Oct. 3	78	12.0	July 28-Oct. 15	79	12.3
8	--do----------	78	11.0	--do------------	79	11.9
8A	July 18-Oct. 3	77	10.3	July 28-Sept. 26	60	10.5
9	--do----------	77	11.7	--do------------	60	12.2
	1964			1965		
1	July 21-Aug. 29	39	8.7	---------------	--	---
2	----------------	--	---	Aug. 12-Sept. 6	25	5.2
3	July 21-Sept. 15	56	8.4	---------------	--	---
4	--do------------	56	9.7	Aug. 12-Sept. 6	25	6.2
5	----------------	--	---	--do-----------	25	3.1
6	----------------	--	---	---------------	--	---
7	July 21-Sept. 13	54	7.4	Aug. 11-Sept. 7	27	4.0
8	July 21-Sept. 17	58	8.5	---------------	--	---
8A	----------------	--	---	---------------	--	---
9	----------------	--	---	Aug. 11-Sept. 7	27	4.9

For 1960, 1962, and 1963 (table 7) during periods of 75-80 days from about mid-July to early or mid-October, ablation averaged about 11.5 feet. According to observations on intermediate dates, ablation was most rapid in July and August.

Usually some snow from the previous winter was on the glacier at the time the stakes were placed. At stakes 4 and 7, from 1961 to 1965, the snow from the previous winter either was entirely melted away or was less than 1 foot deep. At those two locations the observed ablation was essentially the actual loss from the main ice body.

PRECIPITATION AND RUNOFF

Studies of the relation between precipitation, runoff, and glacier variations at Grinnell Glacier have included measurement of precipitation at two storage gages near the glacier and measurement of runoff at two gaging stations on Grinnell Creek.

In 1949 the U.S. Weather Bureau, in cooperation with the National Park Service, installed a storage-precipitation gage (precipitation gage No. 1 on 1960 plan of Grinnell Glacier, plate 1) near the end of the horse trail. The gage, within half a mile of the glacier, is at an elevation of 6,227 feet, 200 feet lower than the terminus. Precipitation gage No. 2 was installed in 1955 by the Weather Bureau and the National Park Service 2,100 feet south-southeast of the first installation, at an elevation of 6,113 feet. The gages are designated as Grinnell 1 and Grinnell 2 in Weather Bureau records.

TABLE 8.—*Cumulative annual ablation measurements of Grinnell Glacier*

Stake No.	Period of measurement	Elapsed days	Ablation (ft)
1----	Aug. 29, 1964-Sept. 6, 1965	[1] 374	5.0
	Sept. 6, 1965-Aug. 16, 1966	344	2.9
	Aug. 16, 1966-Aug. 27, 1968	744	[2] 11.8+
2----	Oct. 4, 1960-Aug. 24, 1961	324	4.4
	Oct. 15, 1963-Aug. 29, 1964	319	1.5
3----	Oct. 4, 1960-Aug. 24, 1961	324	2.1
	Sept. 15, 1964-Sept. 6, 1965	358	1.9
4----	Oct. 4, 1960-July 19, 1961	288	0
	July 19, 1961-July 16, 1962	363	10.0
	July 23, 1964-Aug. 11, 1965	385	[3] 9.9+
	Sept. 6, 1965-Aug. 17, 1966	345	6.8
	Aug. 17, 1966-Sept. 7, 1967	387	13.1
	Sept. 7, 1967-Aug. 28, 1968	356	8.4
	Aug. 29, 1968-Aug. 27, 1969	364	12.5
5----	July 16, 1962-Aug. 28, 1968	2,236	6.8
	Aug. 29, 1968-Aug. 27, 1969	364	8.4
6----	Oct. 4, 1960-Aug. 24, 1961	324	1.3
	July 16, 1962-Aug. 28, 1968	2,236	15.0
	Aug. 29, 1968-Aug. 27, 1969	364	8.4
7----	Oct. 4, 1960-July 19, 1961	288	1.2
	Oct. 15, 1963-July 21, 1964	280	.3
	July 23, 1964-Aug. 11, 1965	385	[3] 9.9+
	Aug. 11, 1965-Aug. 18, 1966	373	11.0
	Aug. 18, 1966-Aug. 28, 1968	742	[4] 19.6+
8----	Oct. 4, 1960-July 19, 1961	288	[5] -1.4
	July 20, 1961-Aug. 11, 1965	1,484	12.5
9----	Oct. 4, 1960-July 19, 1961	288	[5] -1.5
	Oct. 15, 1963-Sept. 17, 1964	338	.1
	Sept. 17, 1964-Sept. 7, 1965	356	2.7

[1] Drilled hole 19.7 ft deep on Aug. 29, 1964.

[2] At end of period on Aug. 27, 1968, stakes emplaced Aug. 29, 1964, were no longer present. Ablation since Aug. 16, 1966, therefore was at least 11.8 ft.

[3] Drilled hole 9.9 ft deep on July 23, 1964. At end of period, stakes no longer in hole. Ablation somewhat greater than amount shown.

[4] Drilled hole 19.6 ft deep on Aug. 18, 1966. No stakes found at end of period; all out of hole and presumably washed downglacier into a crevasse. Ablation somewhat greater than amount shown.

[5] Glacier surface higher in 1961 than in 1960.

The gages are maintained by the Weather Bureau and the National Park Service and are read and serviced yearly in July or August. The periods between observations have ranged from 327 to 383 days. Precipitation in this area during July and August is usually light; consequently, the exact dates of observations generally are not critical to measurements of annual totals. The precipitation measurements that have been obtained and the Grinnell Creek runoff measurements for the corresponding periods are recorded in table 9. The catch at Grinnell 2 has always been greater than at Grinnell 1, the ratio between the two ranging from 1.34 to 1.81. The mean ratio for the 13 years of concurrent records, 1955-66 and 1967-69, was 1.55. The difference in the observed values at the two gages illustrates the pronounced effect of the wind patterns and air currents in this rugged mountain terrain, which causes the average measured catch to be greater at the lower gage.

In 1949 the USGS installed a gaging station on Grinnell Creek just below the outlet of Grinnell Lake

TABLE 9.—*Precipitation and runoff in vicinity of Grinnell Glacier, 1949-69*

[Gage locations shown on plate 1. Runoff measured at gaging station on Grinnell Creek below outlet of Upper Grinnell Lake. Runoff in inches: the depth to which the drainage area would be covered if all the runoff during the period were uniformly distributed on it]

Period of measurement	Elapsed days	Precipitation (in.)		Ratio Grinnell 2: Grinnell 1	Runoff (in.)
		Gage 1	Gage 2		
Aug. 27, 1949-July 20, 1950---	327	125.1	---	---	87.0
July 21, 1950-July 24, 1951---	369	117.5	---	---	109.8
July 25, 1951-July 15, 1952---	357	108.3	---	---	90.4
July 16, 1952-July 31, 1953---	381	106.9	---	---	101.9
Aug. 1, 1953-Aug. 5, 1954---	370	138.2	---	---	107.3
Aug. 6, 1954-Aug. 10, 1955---	370	109.2	---	---	105.2
Aug. 11, 1955-Aug. 7, 1956---	363	100.7	[1] 152.8	1.52	98.5
Aug. 8, 1956-July 16, 1957---	343	88.7	137.2	1.55	81.4
July 17, 1957-July 17, 1958---	366	78.9	115.8	1.47	84.0
July 18, 1958-Aug. 4, 1959---	383	111.6	184.6	1.65	108.8
Aug. 5, 1959-July 21, 1960---	352	107.7	166.6	1.55	91.6
July 22, 1960-Aug. 8, 1961---	383	98.3	131.8	1.34	106.1
Aug. 9, 1961-July 26, 1962---	352	87.1	121.4	1.39	73.3
July 27, 1962-July 18, 1963---	356	101.1	157.6	1.56	90.7
July 19, 1963-July 30, 1964---	378	95.5	144.4	1.51	108.1
July 31, 1964-Aug. 12, 1965---	378	102.0	164.0	1.61	107.6
Aug. 13, 1965-Aug. 12, 1966---	365	89.3	140.4	1.57	97.3
Aug. 13, 1966-Aug. 10, 1967---	363	[2] 104.0	147.4	1.42	92.6
Aug. 11, 1967-July 25, 1968---	350	87.7	159.1	1.81	98.3
July 26, 1968-July 31, 1969---	371	93.6	163.8	1.75	110.4

[1] August 15, 1955-August 7, 1956. [2] Estimated.

TABLE 10.—*Monthly and annual runoff at Grinnell Creek near Many Glacier, Mont.*

[Gage installed in July 1949. Lat 48°46.2′N., long 113°41.9′W.; elevation 4,925 feet; drainage area 2,221 acres (3.47 mi²). Water year begins previous Oct. 1 and ends Sept. 30. Acre-foot: the quantity of water required to cover an acre to the depth of 1 foot, equivalent to 43,560 cubic feet; runoff in inches: the depth to which the drainage area would be covered if all the runoff during the period were uniformly distributed on it. Source of data (U.S. Geological Survey, 1959, 1964, 1971, 1976), by water year: 1950, Water-Supply Paper 1308, p. 34; 1951-60, Water-Supply Paper 1728, p. 17; 1961-1965, Water-Supply Paper 1913, p. 35-38; 1966-69, Water-Supply Paper 2113, p. 25-27]

Water year	Runoff (acre-feet) during month												Total runoff	
	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Acre-ft	Inches
1950-------	687	758	261	61	56	83	373	1,890	5,820	5,390	2,750	1,210	19,340	104.4
1951-------	1,940	770	516	128	113	76	803	2,950	3,500	4,410	2,160	1,650	19,020	102.6
1952-------	1,650	252	162	45	45	48	1,130	3,030	3,700	3,000	2,170	998	16,230	87.7
1953-------	348	57	54	457	273	155	487	2,350	5,260	4,810	2,570	1,150	17,970	97.2
1954-------	369	425	310	160	140	149	473	3,090	4,740	5,730	3,090	1,810	20,490	110.7
1955-------	1,100	661	256	153	42	52	248	1,320	5,550	4,710	2,320	1,040	17,450	94.3
1956-------	1,860	512	302	139	36	78	543	3,260	4,900	3,740	2,390	1,180	18,940	102.4
1957-------	942	239	161	106	42	145	381	4,400	4,110	2,720	1,860	974	16,080	86.9
1958-------	577	258	107	75	127	122	319	4,540	3,910	2,720	2,270	1,470	16,500	89.2
1959-------	858	486	285	314	145	113	774	1,990	5,510	4,310	2,260	2,280	19,320	104.4
1960-------	1,500	399	115	83	104	268	591	1,770	4,910	4,180	2,080	1,190	17,190	92.8
1961-------	599	336	103	58	67	66	525	3,120	6,280	3,500	2,360	944	17,960	97.0
1962-------	2,530	403	110	81	97	40	1,060	2,660	3,800	2,820	2,170	935	16,630	89.9
1963-------	1,050	664	403	118	294	120	460	2,570	4,950	3,650	2,170	1,530	17,980	97.1
1964-------	696	345	111	38	79	75	181	2,090	7,270	4,420	2,000	1,300	18,600	100.5
1965-------	1,250	327	199	154	143	82	577	2,470	5,990	4,130	2,560	987	18,870	101.9
1966-------	724	523	277	149	112	160	612	3,660	4,510	4,010	1,940	1,300	17,980	97.2
1967-------	648	479	363	289	256	178	160	3,170	6,390	5,350	2,640	1,460	21,380	115.5
1968-------	928	869	261	374	274	488	403	3,360	7,140	4,740	2,340	2,930	24,100	130.2
1969-------	985	643	331	124	105	66	1,100	3,310	4,730	3,120	1,860	1,200	17,580	95.0
Maximum--	2,530	869	516	457	294	488	1,130	4,540	7,140	5,730	3,090	2,930	24,100	130.2
Minimum--	348	57	54	38	36	40	160	1,320	3,500	2,720	1,860	935	16,080	86.9
Mean-----	1,062	470	234	155	128	128	556	2,850	5,148	4,073	2,298	1,377	18,480	99.8
Percent of mean annual--	5.8	2.5	1.3	0.8	0.7	0.7	3.0	15.4	27.9	22.0	12.4	7.5	100.0	--

(Many Glacier 7½-min quadrangle). In Geological Survey publications its location is designated as Grinnell Creek near Many Glacier, Mont. The elevation at the gage is about 4,900 feet, and the drainage area is 3.47 square miles. Streamflow at this station includes the runoff from Grinnell Glacier, which covers about 14 percent of the drainage area. The mean annual runoff of 99.8 inches for 1950-69 closely reflects average precipitation in this area, although runoff is affected somewhat by evapotranspiration and by net changes in glacier volume.

Monthly and annual runoff at Grinnell Creek gaging station for the 20-year period October 1, 1949-September 30, 1969, is shown in table 10; 85 percent of the annual runoff occurred during the 5 months May-September (the main snowmelt period), and only 15 percent during the 7 months October-April (the main snow accumulation period). Monthly runoff was greatest in June.

During the 20-year period of record on Grinnell Creek (table 10), the estimated loss in volume of Grinnell Glacier, determined from profile measurements, totaled 7,720 acre-feet or an average annual loss of 386 acre-feet. This annual loss is equivalent to 2.1 inches runoff from the area above the Grinnell Creek gaging station, or about 2 percent of the average annual runoff. The runoff contributed by melting of the glacier in recent years has, therefore, to some extent compensated for the loss due to evapotranspiration, and the recorded runoff has probably been only slightly less than the average precipitation over the Grinnell Creek basin. Snow accumulation occurs during October-April and snowmelt occurs during May-September.

In 1959 the USGS installed a second gaging station on Grinnell Creek about 1,000 feet from the glacier. The location is shown on the Grinnell Glacier 1960 map (pl. 1). This station is only operable during the summer and early fall. Trail conditions preclude access until late June or early July. The recording gage has continued to operate through October of most years, and in some years, through November. The runoff for the months of complete record is listed in table 11, along with the measurements for the corresponding months at the station on Grinnell Creek near Many Glacier, and a comparison of the percent of runoff of the two stations.

The unusually high runoff-percentage relation in some months, such as 96 percent in August 1961 and 97 percent in September 1966, may reflect late-summer glacial melting or localized heavy rainshowers over the glacier. In some years almost all the previous winter's snow over the basin has melted by September or possibly even by August, and nearly the entire late-summer runoff represents melting of the glacier. Occasionally, rainstorms occur in the upper elevations of the basin while Grinnell Lake and Lake Josephine below are in sunshine. From the lower valley heavy clouds which envelop the glacier are frequently seen above an elevation of about 6,000 feet.

A monthly record of precipitation was obtained at the gaging station on Grinnell Creek below Grinnell Lake for May-September of 1956-65 (table 12). The five mean monthly values for the period totaled 22.2 inches. Concurrent records at Summit showed May-September precipitation during these years was 30 percent of the annual total there. Assuming the two locations show a constant relationship between monthly values, we may infer that the mean annual precipitation in the Grinnell gaging station vicinity during 1956-65 was about 74 inches.

The mean annual runoff at Grinnell Creek gaging station for 1956-65 was 96 inches. To account for the observed runoff, precipitation in the upper part of the basin must have been appreciably greater than in the area of the gaging station. The precipitation near the glacier, upstream from the near-glacier gaging station, was estimated by extrapolating the July-November runoff values recorded at the low gaging station, as follows:

Runoff (inches) at Grinnell Creek gaging station at Grinnell Glacier, 1950-69

July-November, on basis of records	102
December-June:	
low estimate	45.5
high estimate	68.5
Mean annual runoff:	
low estimate	147
high estimate	171

The estimated mean annual runoff, 147-171 inches, includes about 6 inches per year from the reduction in volume of the glacier. Thus the annual precipitation over the area above the gaging station near the glacier must have been in the range 141-165 inches. A reasonable estimate for runoff would be about 150 inches per year.

Additional information on precipitation and runoff is provided by a record of snow surveys in Montana (Farnes and Shafer, 1975) and runoff at a gaging station on Swiftcurrent Creek at Many Glacier. Grinnell Creek is a tributary of Swiftcurrent Creek. The snow survey course on Allen Mountain, 1.5 miles southeast of Grinnell Glacier, and 800 feet lower than the glacier, has been measured annually on or about May 1 since 1922. A snow course at Marias Pass (near Summit, fig. 1) has been measured on or about April 1 and May 1 since 1936. The results obtained at these two courses are summarized in table 13.

At Marias Pass the April 1 water content for the two periods was 47 percent of the average precipitation, which was 38.2 and 40.9 inches. The April 1 water content of the snowpack therefore represents roughly half the annual precipitation in the Marias Pass area.

Snow at the Marias Pass snow course shows an appreciable decrease in average water content from April 1 to May 1, although May 1 values were equal or greater in 11 years of the 34-year record, 9 of these occurring during the 20 years 1950-69.

For the Allen Mountain snow course the less pronounced decrease in water content from April 1 to May 1 may reflect its higher elevation and probably lower temperature. The Allen Mountain record should reasonably indicate conditions at Grinnell Glacier at the end of the snow accumulation period and the beginning of the melting or runoff period. This should be particularly true for the 1950-69 period in which, at Marias Pass, nine May 1 values equaled or exceeded April 1 values.

Runoff at a gaging station on Swiftcurrent Creek at Many Glacier for May to September has been recorded annually since 1912 (fig. 10). Grinnell Creek is a tributary of Swiftcurrent Creek through Swiftcurrent Lake. In general, the May-September runoff comprises the melt from the previous winter's snow accumulation plus the May-September precipitation. The average May-September runoff for the 58 years 1912-69 was 48.9 inches, about 75 percent of the annual total of about 65 inches. The May-September average for the period 1950-69 was slightly higher, 51 inches.

TABLE 11.—*Runoff measured at two gaging stations on Grinnell Creek*

[A: installed 1959, "gaging station" on plate 1, drainage area 704 acres. B: installed 1949, location shown on map of Many Glacier 7½-min quadrangle, drainage area 2,221 acres]

	A Grinnell Creek at Grinnell Glacier		B Grinnell Creek near Many Glacier		A as percent of B
	Acre-feet	Inches	Acre-feet	Inches	
1959					
July-------	2,460	41.93	4,310	23.27	57
August-----	1,700	28.98	2,260	12.21	75
September--	1,230	20.97	2,280	12.29	54
October----	662	11.29	1,500	8.09	44
1960					
July-------	2,770	47.30	4,180	22.57	66
August-----	1,700	28.98	2,080	11.23	82
September--	975	16.62	1,190	6.44	82
October----	351	5.98	599	3.24	59
November---	115	1.96	336	1.81	34
1961					
July-------	2,570	43.88	3,500	18.90	73
August-----	2,260	38.51	2,360	12.75	96
September--	666	11.35	944	5.10	71
October----	1,190	20.20	2,530	13.65	47
November---	51	0.87	403	2.18	13
1962					
July-------	2,090	35.57	2,820	15.25	74
August-----	1,840	31.37	2,170	11.74	85
September--	729	12.42	935	5.05	78
October----	529	9.01	1,050	5.65	50
November---	329	5.60	664	3.59	50
December---	113	1.93	403	2.18	28
1963					
July-------	2,310	39.39	3,650	19.72	63
August-----	1,860	31.78	2,170	11.71	86
September--	1,350	23.09	1,530	8.25	88
October----	567	9.66	696	3.76	82
November---	213	3.63	345	1.86	62
1964					
July-------	2,790	47.56	4,420	23.88	63
August-----	1,550	26.42	2,000	10.80	78
September--	600	10.22	1,300	7.02	46
October	581	9.90	1,250	6.75	46
November---	220	3.75	327	1.77	67
1965					
July-------	2,450	41.69	4,130	22.29	59
August-----	2,040	34.72	2,560	13.85	80
September--	412	7.03	987	5.33	42
October----	333	5.68	724	3.91	46
1966					
July-------	2,490	42.43	4,010	21.68	62
August-----	1,640	27.96	1,940	10.50	84
September--	1,260	21.50	1,300	7.03	97
October----	297	5.06	648	3.50	46
1967					
July-------	2,890	49.23	5,350	28.91	54
August-----	2,050	34.94	2,640	14.26	78
September--	1,240	21.14	1,460	7.89	85
October----	456	7.77	928	5.02	49
1968					
July-------	2,360	40.30	4,740	25.60	50
August-----	1,710	29.18	2,340	12.66	73
September--	1,880	32.08	2,930	15.81	64
October----	358	6.11	985	5.33	36
November---	140	2.39	643	3.47	22
1969					
July-------	2,060	35.07	3,120	16.87	66
August-----	1,620	27.56	1,860	10.07	87
September--	912	15.55	1,200	6.50	76

TABLE 12.—*Monthly precipitation, May-September, 1956-65, recorded at Grinnell Creek gaging station near Many Glacier, Mont.*

[Precipitation in inches. Tr., trace]

	May	June	July	August	September	Total for period
1956----	3.2	5.2	2.6	5.1	6.7	22.8
1957----	4.3	7.2	2.0	1.2	2.0	16.7
1958----	1.6	7.1	2.9	3.5	6.8	21.9
1959----	5.8	2.5	.4	6.5	11.9	27.1
1960----	6.5	6.0	Tr.	4.6	3.3	20.4
1961----	4.0	1.1	4.0	2.4	6.6	18.1
1962----	5.4	1.9	2.9	3.8	5.1	19.1
1963----	3.8	11.7	3.2	1.5	3.8	24.0
1964----	7.2	6.4	4.0	5.1	8.4	31.1
1965----	4.3	6.8	1.5	2.7	5.1	20.4
Mean--	4.6	5.6	2.4	3.6	6.0	22.2

TABLE 13.—*Mean snow depth, water content, and density at Allen Mountain and Marias Pass snow courses*

[Allen Mountain on USGS maps; Mt. Allen in Weather Bureau records. From Farnes and Shafer (1975)]

Snow course---	Allen Mtn.		Marias Pass			
Elevation-----	5,700 ft		5,250 ft			
Period--------	1922-69	1950-69	1936-69	1936-69	1950-69	1950-69
Record date---	May 1	May 1	April 1	May 1	April 1	May 1
Mean snow depth (in.)----	94.3	108.9	48.8	34.3	53.3	44.7
Mean water content (in.)--	43.0	49.4	18.0	13.8	19.2	18.1
Density (percent)------	45.6	45.4	36.9	40.2	36.1	40.4

Cumulative annual departures from mean water content at the snow course on Allen Mountain for 1922–69 are shown in figure 10, with the mean May–September runoff for Swiftcurrent Creek at Many Glacier for 1912–69. These curves exhibit the same general trends shown by departure-from-mean precipitation curves in figure 2.

A study of the departure from mean annual flow of the Kootenai River at Libby, Mont., for 1911–69 showed the same general characteristics indicated by the above curves and for the departure-from-mean precipitation curves shown in figure 2: a downward trend in streamflow from 1920 to the mid-1940's and an upward trend thereafter.

VEGETATIVE SUCCESSION

The following account of the area's vegetation is excerpted from Park Naturalist M.J. Elrod's report for 1927 (National Park Service files).

A fine problem is presented to someone who has the time and inclination, to study the ascent of vegetation as the glacier retreats. A few observations were made this season which may stimulate someone to further study.

Just below the present ice, and not extending down as far as the end of the horse trail when it is completed, twenty-eight species of trees, shrubs, herbaceous plants, sedges, grasses, and mosses were observed, in larger or smaller numbers. Within a hundred yards or so from the ice, alpine beardtongue, milfoil, yellow paintbrush, mountain timothy, white phacelia, *Carex*, cottonwood, dock, a red-top grass, and low alpine willow had made a start. Along the numerous small streams, among the boulders, and in protected places other species, both alpine species and those with wide altitudinal distribution, were found. The grasses, sedges, alpine beardtongue, yellow monkey flower, and cottonwood make the closest approach [to the ice], and are the apparent forerunners of a rather complex vegetation, whose roots soon will hold the soil made by the disintegrating rocks. Less than a good quarter of a mile from the ice a willow, head high, has a good start. Wild currant has a footing at several places. Small spruce trees, a foot high, are in small numbers showing conspicuously here and there. One was determined as 15 years old.

The other species were moss, *Cystopteris* and shield ferns, milkvetch, carpet pink, a short-headed sedge, a chickweed, a northern anemone, a mustard, goldenrod, a vetch, nodding onion, purple vetch, and valerian.

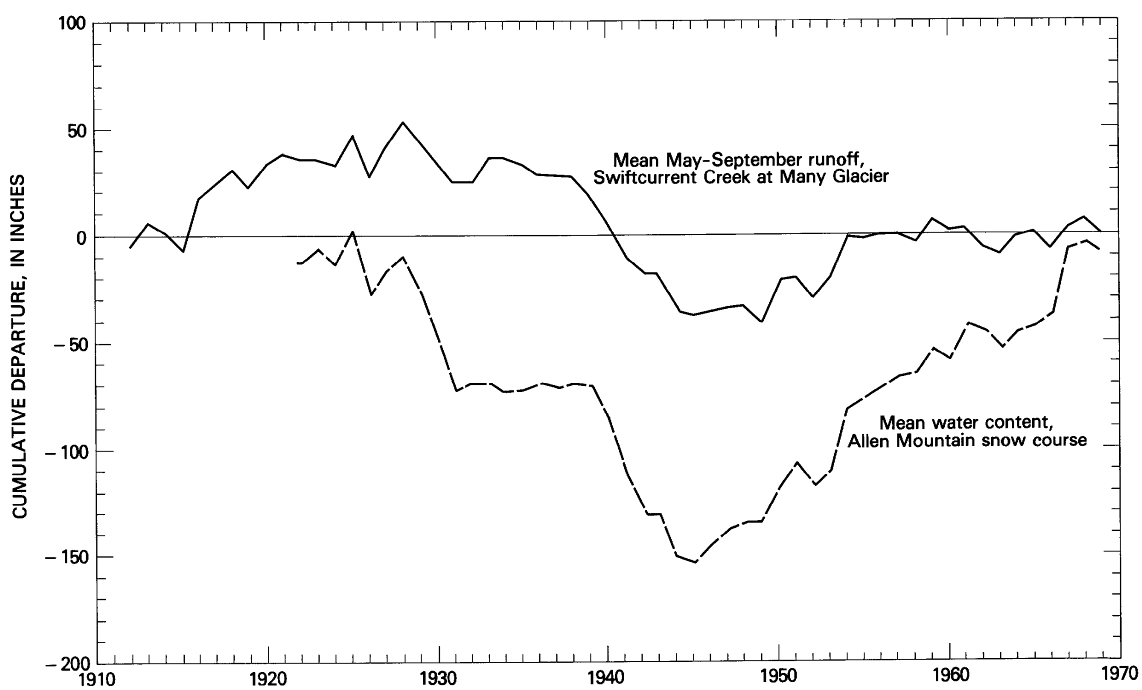

FIGURE 10.—Cumulative departures from mean water content at Allen Mountain snow course and from mean May–September runoff at Swiftcurrent Creek at Many Glacier

When Dr. George Bird Grinnell first saw the glacier in 1887 it is quite certain [that] ice covered all the space in which these twenty-eight species (perhaps others) are growing. This gives an idea of the change that has taken place in forty years. In another half-century visitors to the ice, which will be still higher on the mountainside, will pass through an open forest, ten to twenty feet high, with a floor carpeted with flowers.

The "problem" suggested by Elrod was taken up by Gerald Baden, seasonal Ranger-Naturalist, during 1952-61. His attention was directed primarily toward obtaining the age of trees from increment borings. Many of the trees sampled by Baden and me during the 1961 field season were located with a planetable. The tree locations are shown on plate 1. The identifying numbers are described in table 14. Several additional trees mentioned in the table are described with reference to known locations although they were not actually located in the field in 1961.

Additional information was provided by Mr. Baden (written commun., 1961): Borings were obtained in 1952 from some of the oldest-appearing trees in the stand on the bench west of the high moraine bordering the melt-water pond. A 9.5-foot-tall fir had 93 rings, a 15-foot white pine 52 rings, and a 10-foot spruce 38 rings. Also in 1952 a spruce with cones, located near the front of the upper part of the glacier (The Salamander) and near the edge of the cliff, was found to have a ring count of 46.

TABLE 14.—*Annual-growth-ring dating of trees near Grinnell Glacier, as determined from coring in 1959-61*

[Ring count was at boring height, several feet above ground level. Each tree, at time of count, was at least 5-10 years older than the age indicated by the stated number of rings]

Tree No.	Yr of coring	Description	Annual-growth-rings
1	1960	White bark pine	71
2	1960	Highest fir on vegetation-covered moraine, the second of three near precipitation gage 2.	182
3	1960	Fir	40
4	1960	Highest white bark pine near precipitation gage 2.	152
5	1960	Fir in dense thicket with roots sprawled over limestone boulders.	177
6	1960	Douglas fir	35
7	1960	White pine. Core did not reach center	130+
8	1960	White pine on well-defined older moraine	164+
9	1960	Fir, 5 ft from brink of cliff	43
10	1960	Fir, on brink of cliff	111+
11	1960	do	189
12	1960	White pine	184
13	1960	Fir	78
14	1960	White bark pine near brink of cliff	312
15	1961	Fir on brink of cliff, large trunk partially rotten.	177
16	1961	Fir on old moraine in dense stand of timber	158
17	1959	These six trees in a dense fir and alder thicket were not specifically located but are within 40 ft of a point which is 100-150 ft from top of waterfall.	
		Fir (topmost 4 ft a dense mat of dead branches)	119+
		Spruce, center rotten; several firs appear fused at base.	132±
		Fir, much branched about 4 ft above ground level, center rotten.	108+
		Fir	124
		do	146
		White pine	114
18	1960	White pine, prostrate, cracked	102
19	1960	White bark pine 15 ft northeast of stream from hitchrack.	185
20	1960	White bark pine on brink of cliff where stream from picnic area goes over cliff. Tree trunk in three parts with rotten core.	280
21	1960	White bark pine with cones; no center	172+
22	1960	Spruce, 200 ft northeast of stream referred to in No. 20, 13 ft west of a pine tree.	169
23	1960	Two firs 6 ft apart on a bench	99, 79
24	1960	Fir	74
25	1960	White bark pine; no center	169+
26	1960	Fir	104
27	1960	White pine on south side of trail near hitchrack, largest white pine in vicinity.	286
28	1960	Spruce near hitchrack and largest (height 40 ft, diameter 20 in.) in area. Cored 4 ft above ground level.	260
29	1960	Location on moraine that was entirely bare in 1887 (see fig. 5). Small stand of trees has grown on this moraine; the two cored appear to be oldest in stand.	
		Spruce	61
		Fir	53

SPERRY GLACIER

LOCATION AND ACCESSIBILITY

Sperry Glacier, in Glacier National Park, Mont., is 9 miles south and slightly west of Grinnell Glacier and 25 miles south of the international boundary between the United States and Canada, at lat 48°37'18"N., long 113°45'24"W. (fig. 1). It occupies a cirque on the northwest slope of Gunsight Mountain on the Pacific side of the Continental Divide, which follows the crest of Gunsight Mountain to its highest point and then bends sharply to the southeast.

The glacier is slightly less than 10 miles, by trail, from the McDonald Hotel near the upper end of Lake McDonald. It is accessible by horse travel for 9 miles, to an approximate elevation of 7,800 feet, and from this point by a well-marked foot trail. Sperry Chalets are 6.5 miles from the McDonald Hotel and 3 miles from the glacier, near the headwaters of Sprague Creek.

DISCOVERY AND EARLY DESCRIPTIONS

Sperry Glacier was named in honor of Lyman Beecher Sperry, M.D., of Oberlin College, Oberlin, Ohio. Sperry (fig. 11) camped with several others in the Avalanche Basin in 1894, and deduced from the milkiness of the water in Avalanche Lake that it came from a glacier. He, with several members of the party, succeeded in scaling the cliffs at the head of Avalanche Basin and reached a vantage point on the side of the Little Matterhorn, a small isolated peak in the saddle between Edwards Mountain and Mount Brown (fig. 1), from which the glacier was visible. Albert L. Sperry, a nephew of Dr. Sperry's, was a member of the party in 1894 and described the impression gained from their first view of the glacier as follows (Sperry, 1938, p. 51):

While standing upon that peak overlooking the terrain above the rim wall, we got the thrill of thrills, for there lay the glacier,

shriveled and shrunken from its former size, almost senile, with its back against the mountain walls to the east of it, putting up its last fight for life. It was still what seemed to be a lusty giant, but it was dying, dying, dying, every score of years and as it receded, it was spewing at its mouth the accumulations buried within its bosom for centuries.

Dr. Sperry, with a party including his nephew, returned to Avalanche Basin in 1895. They scaled the rim wall by following a ravine at its east end (figs. 12, 13), reached Mary Baker Lake and went on to the front of the glacier but did not go onto it.

The glacier was actually reached first by Dr. Sperry and his party in 1897. Their route was the same general route of the present trail. It took them near the present site of the Sperry Chalets and through the saddle between Gunsight Mountain and Edwards Mountain.

FIGURE 11.—Lyman Beecher Sperry (1841-1923), physician lecturer, and author, was the discoverer of Sperry Glacier. Sperry Glacier, Sperry Glacier Basin, and Sperry Chalets are named in his honor. During the summers 1894-1906, Dr. Sperry camped, climbed, and explored in the Montana Rockies, particularly in the area set aside by the Congress in 1910 as Glacier National Park. This photograph, taken in 1904 at some unspecified location in the Park area, was by George H. Dean, student of Dr. Sperry's, who accompanied him on the 1904 trip. Photograph 6274 from the archives of Glacier National Park, courtesy of the National Park Service.

PICTORIAL RECORD

The changes that have occurred on Sperry Glacier since its discovery can be visualized by reference to selected photographs. The earliest known photographs were published in the book, "Avalanche," by Albert L. Sperry (1938) (this report, figs. 12, 13).

The earliest available photograph showing nearly all the glacier was taken by Francois Matthes in 1901 during the mapping of the Chief Mountain quadrangle (fig. 14).

Comparative 1897 and 1969 views are shown in figure 15, and 1913 and 1956 views in figures 16 and 17.

AREA

In 1901 the area of Sperry Glacier, as shown on the Chief Mountain quadrangle map, was about 800 acres. Its western edge was almost in the saddle between Gunsight Mountain and Edwards Mountain (fig. 1). This edge is now two-thirds mile from the saddle. The lower extremity of the glacier at the western edge extended into the broad notch between Edwards Mountain and the Little Matterhorn, a small isolated peak in the saddle area between Edwards Mountain and Mount Brown (fig. 1). Drainage from this part of the glacier flowed through this notch into the head of Synder Creek as late as 1913 (Alden, 1914) but probably did not continue for many years thereafter.

In 1901 the terminus was defined by a series of moraines (pl. 2) extending across the valley. The east and upper edges were defined by the steep walls of the cirque.

The area of Sperry Glacier has decreased since it was first mapped in 1901:

Year	Source of data	Area	Reduction since previous measurement	
			Total	Average per year
1901	Chief Mountain quadrangle map---	800	---	---
1938	Sperry Glacier map (Dyson)------	390	410	11.1
1946	--do----------------------------	330	60	7.5
1950	Sperry Glacier map (USGS)-------	305	25	6.2
1960	--do----------------------------	287	18	1.8

Much of the decrease in area between 1901 and 1938 was due to the disappearance of 75-100 acres of ice from the western part of the cirque. Dyson's 1946 mapping covered only the terminal area. The difference between the 1938 and 1946 values, therefore, represents primarily the decrease in area as a result of terminal recession. Changes in area of the upper parts of the glacier were probably

FIGURE 12.—Sperry Glacier viewed from Avalanche Basin in 1894 or 1895 (Sperry, 1938, p. 42). Avalanche Lake is in lower foreground. Terminus of glacier is at head of central stream cascading down the cliff.

insignificant, owing to the steep walls of the cirque.

The rate of shrinkage slowed markedly after about the mid-1940's. The average annual decrease in area was 10.5 acres during the 45 years 1901–46, whereas it was only 3 acres from 1946 to 1960. The slower rate of loss in recent years can be attributable partly to a slight short-term warming, but, more significant, the remnant glacier is probably approaching hydrologic equilibrium with the long-term climatic trend.

Dyson (1948, p. 97) described the Sperry Glacier as being in 1938 "the largest in Glacier National Park and, with the possible exception of one or more of the Dinwoody Glaciers in Wyoming's Wind River Range, the largest in the Rocky Mountains south of the Canadian boundary." This may have been true in 1938, but owing to Sperry Glacier's more rapid rate of shrinkage, it has lost that distinction to Grinnell Glacier.

RECESSION

Dyson (1948, p. 97) estimated, by comparing 1913 photographs with his detailed mapping, that recession of the terminus from 1913 to 1938 totaled 1,533 feet measured along 5,700 feet of the front—an average annual recession of 61 feet.

Markers for recession measurements were set by the Park Naturalist in 1931 but no data were obtained during 1932–34. New markers were set in 1935 and the recession as reported by the Park Naturalist for the 10-year period 1935–45 was 641 feet, or an average of 64 feet per year. This matches closely Dyson's estimate of 61 feet annually for 1913–38. Dyson's 1938 mapping did not show the markers used for the recession measurements, so a correlation with the mapping was not possible. The 1938 mapping was, however, the first detailed mapping of the terminus since the 1901 mapping of the Chief Mountain quadrangle.

The method of determining terminal recession by planetable mapping, as described for the Grinnell Glacier, was begun for the Sperry Glacier in 1945. The terminus was remapped, in whole or in part, in 1947, 1949, 1950, 1952, 1956, 1961, 1966, and 1969. The total and average annual rates of recession for about the central half-mile section of the terminus for

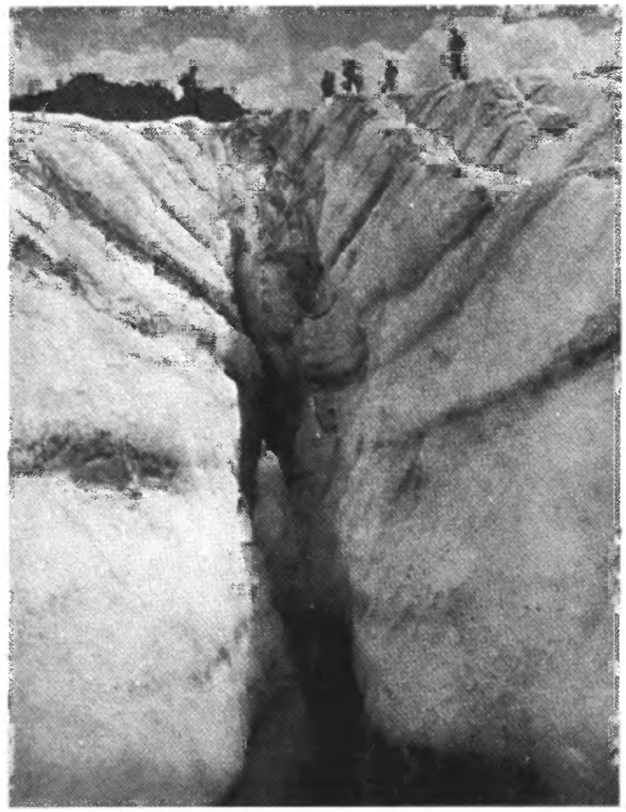

FIGURE 13.—Crevasses on Sperry Glacier, 1897 (Sperry, 1938, p. 130). Crevasses of this magnitude were not observed during the period covered by the present report.

FIGURE 15.—Comparative views of terminal area of Sperry Glacier, in 1897 and 1969. *A*, 1897 (Sperry, 1938, p. 132); *B*, August 23, 1969 (W.A. Blenkarm, USGS). In the earlier view the glacier extends to the moraines whereas in the later view no part of the glacier is visible. The position of the 1969 terminus is a considerable distance to the right of both views. ▷

FIGURE 14.—Sperry Glacier, October 18, 1901, by Francois Matthes. This earliest available photograph showing nearly the entire glacier was presumably taken from a point on the Continental Divide about 1 mile south of Hidden Lake. Surface details of the glacier are obscured by a light snowfall but its extent then is clearly evident. The end of the horse trail and the beginning of the foot trail to the glacier are just beyond the pass in the upper central part of the view. Lakes that are shown on recent maps did not exist at the time of this photograph; they formed as the glacier retreated. Photograph 7166 from Glacier National Park files, courtesy of the National Park Service.

FIGURE 16.—Panoramic views of Sperry Glacier from the side of the Little Matterhorn in 1913 and 1956, showing terminal recession and overall shrinkage during the 43-year interval. *A*, August 15, 1913, photographs by W.C. Alden (710, 711, 712); *B*, August 22, 1956, photographs by D.H. Robinson, National Park Service. The 1956 view also shows that the ridge extending downward from the high point of Gunsight Mountain was entirely bare. The snow-covered areas in the cirque to the right of this ridge are probably snowfields rather than glacier ice. The pronounced decrease in the glacier area on the side of Edwards Mountain is also apparent.

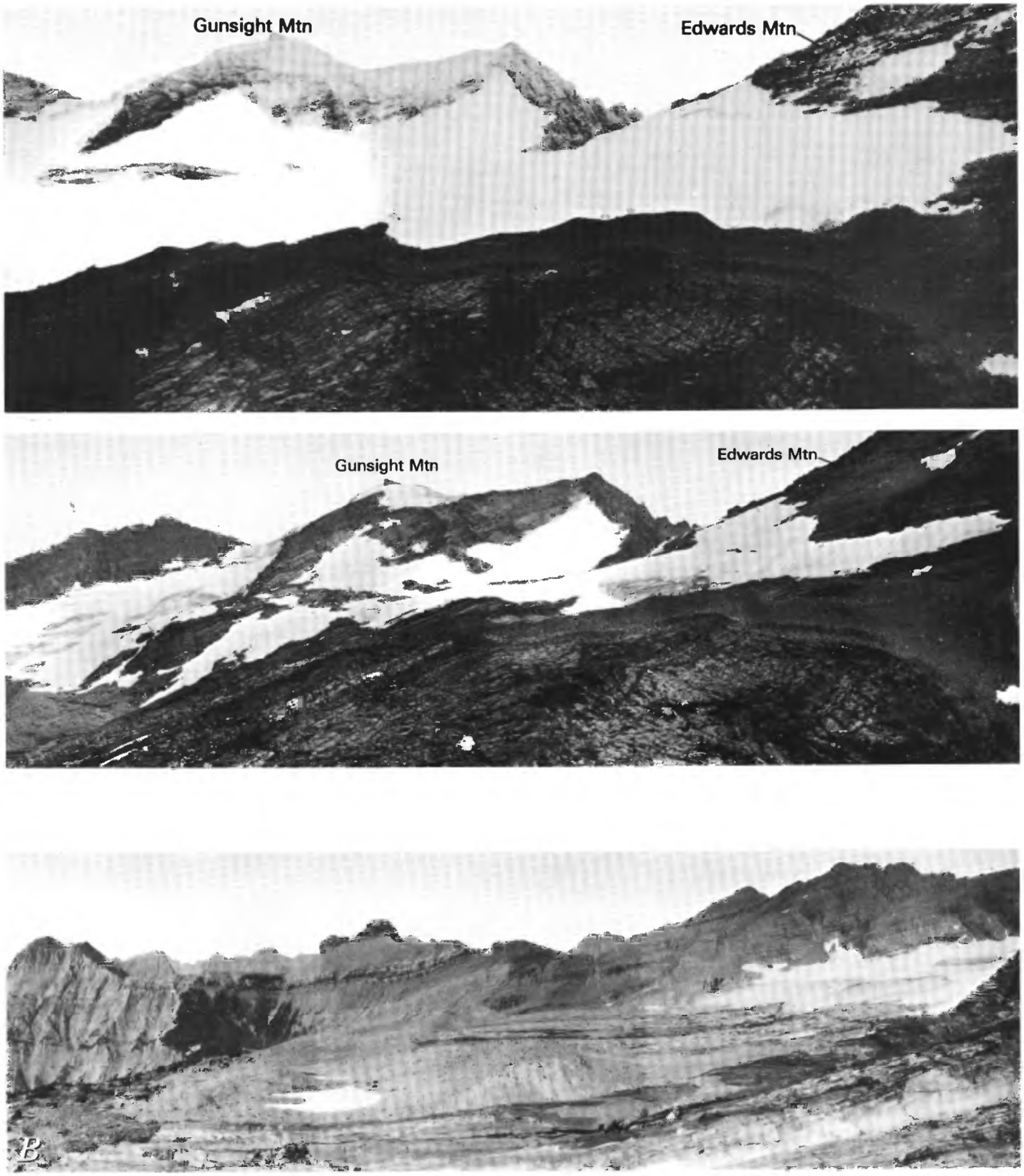

FIGURE 17 (above and facing page).—1913 and 1956 views of terminus and terminal moraines of Sperry Glacier. *A*, August 16, 1913, photographed by W.C. Alden (716); *B*, August 22, 1956, photographs by D.H. Robinson, National Park Service. Head of Avalanche Basin is in left center edge of views. Terminal recession during the 43-year interval is evident. Alden (1914, p. 16) noted that the pond in the lower foreground of the views was reddish in color, whereas Robinson reported in 1956 that it was milky white. The area now occupied by lakes shown on recent maps was concealed by the glacier in 1913.

selected periods are tabulated below.

	Recession (ft)		
	Total for period	Average annual	Cumulative total
1938–45----	351	50	351
1945–50----	177	35	528
1950–56----	85	14	613
1956–61----	196	39	809
1961–69----	185	23	994

Below an elevation of about 7,500 feet, the period of record was characterized by a continual recession of the terminus and a lowering of the surface; above this elevation, however, the surface elevation of the ice apparently increased.

Sperry Glacier has not, for several centuries, extended far beyond its present limits. This is evident from G.M. Baden's 1960 age determinations (written commun., 1961) on three old trees located north and west of the glacier. The locations and ages of the three trees are as follows:

From BM 7375 (fig. 18)		Approximate elevation (ft)	Age (yr) of tree, in 1960
Bearing	Distance (ft)		
N. 60° W.	2,850	7,120	350+
N. 22° W.	4,925	6,560	226
N. 23° W.	4,525	6,640	190

MOVEMENT

The advance of the glacier during a 24-hour period was measured by Alden (1914, p. 15) in August 1913 within four ice caves at the front of the glacier. Movement varied from ¼ to ¾ inch; the rate of movement apparently reflected the prevailing temperature that day—rapid on a sunny warm day, and slow on a cold blustery day.

So far as I can determine, further information on movement was not obtained until 1949 when M.E. Beatty, Park Naturalist, and I mapped the locations of 5 prominent rocks and marked 4 of them with identifying numbers 49-1 through 49-4. The fifth rock was marked in 1963. Their locations were periodically redetermined; and all five were redetermined in 1969, giving a 20-year record of movement from 5 points (pl. 2, table 15).

Movement in the central part of the glacier averaged about 13 feet per year, as recorded by rocks 49-1 through 49-4. Movement closer to the east edge of the glacier averaged 17 feet per year, as recorded from the unmarked rock. Rates of movement also increased toward the west edge of the glacier, as indicated by the 3-year record for rocks 66-1 and 66-2 and ablation stake 1-63, and by the annual results for stakes 1-61, 1-65, and 7-65. Stake 7-65 was the lower part of an ice auger lost in 1965 but exposed in 1966.

TABLE 15.—*Movement of marked rocks on Sperry Glacier*

[Locations shown on plate 2]

Location No.	Period	Movement (ft)	
		Total	Average annual
49-1---	1949-69	225	11
49-2---	1949-69	265	13
49-3---	1949-69	270	14
49-4---	1949-69	260	13
(*)	1949-69	340	17
66-1---	1966-69	85	28
66-2---	1966-69	50	17

*Unmarked.

Measurements of stakes 2-61 and 3-61, at higher elevations on the glacier, indicated considerably greater rates of movement there than at lower elevations. Even though appreciable errors may have been introduced by difficulties in field measurement, the measurements confirm the previous finding that movement was greater near the glacier's west edge than in the central part.

FLUCTUATIONS IN SURFACE ELEVATION

PROFILES

Changes in surface elevation of Sperry Glacier have been recorded by periodic measurements of four profiles (pl. 2). Profile *A–A′* extends across the entire glacier, approximately at right angles to the direction; profiles *B–B′*, *C–C′*, and *D–D′* are roughly parallel to the direction of flow. The mean elevations of segments of the transverse profile and profile *B–B′* were determined for comparative purposes (tables 16, 17). In comparing the observations, the reader should bear in mind the differing dates of measurement; for example, the 1958 and 1959 measurements were made in mid-August, whereas the 1957 and 1961 measurements were made later, in mid-September.

The transverse profile (*A–A′*) is slightly more than 3,100 feet long. The profile shows a fairly uniform

TABLE 16.—*Mean elevations, in feet, of segments of profile* A–A′, *Sperry Glacier, on specific dates*

[Elevations are above assumed datum for glacier surveys. Profile shown on plate 2. Distances measured from reference point, planetable bench mark 7699]

Distance (ft)-----	100–1,100	1,100–2,100	2,100–3,100	100–3,100
Yr, mo, d(s)	Mean elevation (ft) of segment			
1949 Aug. 30------	7,598.9	7,535.1	7,593.6	7,575.9
1950 Sept. 19------	7,597.9	7,534.5	7,594.3	7,575.5
1952 Aug. 19------	7,603.5	7,539.0	7,600.4	7,581.0
1956 Aug. 23------	7,607.0	7,539.9	7,603.5	7,583.4
1957 Sept. 14------	7,601.6	7,534.2	7,595.4	7,577.1
1958 Aug. 16------	7,596.7	7,528.8	7,590.6	7,572.0
1959 Aug. 18------	7,600.3	7,531.1	7,592.9	7,574.8
1961 Sept. 14------	7,596.0	7,525.0	7,587.8	7,569.6
1962 Aug. 30------	7,598.3	7,526.1	7,588.4	7,570.9
1963 Sept. 8------	7,599.5	7,525.8	7,588.0	7,571.1
1966 Aug. 24, 25--	7,608.1	7,531.5	7,592.0	7,577.2
1968 Sept. 1------	7,606.3	7,529.6	7,593.0	7,576.3
1969 Aug. 22------	7,607.5	7,530.6	7,584.4	7,574.2
Net change since 1949-----------	+8.6	-4.5	-9.2	-1.7

downward slope from the west edge for a distance of 1,700–1,800 feet, then a rise to the top of an ice ridge about 250 feet from the east edge. A depression occurs between the ridge and the east edge of the glacier.

Plate 2 shows that the 1969 ice surface was at a higher elevation than in 1949 for a distance of 800 feet from the west edge of the glacier, with a maximum difference of 20 feet. In most of the east half of the profile the 1969 ice surface was at a lower elevation than in 1949, with a maximum difference of 20 feet. Along the 3,000-foot section of the transverse profile (excluding a short distance at each end), the net change was a lowering of 1.7 feet (table 16). The fact that one section of the glacier showed an increase in surface elevation while another section showed a decrease does not necessarily indicate variation in amount of snowfall over the area. The differences in snow accumulation on various sections of the glacier probably reflect differences in wind patterns, which are influenced by the rugged terrain and the consequent drifting, rather than reflecting varying elevations.

TABLE 17.—*Mean elevations, in feet, of segments of profile* B–B′, *Sperry Glacier, on specific dates*

[Elevations are above assumed datum for glacier surveys. Distances measured upglacier and downglacier from intersection of profile *B–B′* with profile *A–A′* (pl. 2), 1,965 ft from reference point, planetable bench mark 7699. ---, no data]

	Downglacier from intersection				Upglacier from intersection		
Distance (ft)---	1,700–1,500	1,500–1,000	1,000–500	500–0	0–500	500–800	800–1,000
Yr, mo, d	Mean elevation (ft) of segment						
1949 Aug. 30---	---	---	7,449.2	7,492.4	7,569.9	---	---
1950 Sept. 19---	7,331.6	7,398.2	7,447.6	7,491.2	7,570.7	7,663.0	---
1952 Aug. 19---	7,324.3	7,397.0	7,452.6	7,493.5	7,576.0	7,671.8	---
1956 Aug. 23---	7,290.2	7,377.6	7,453.8	7,488.2	7,577.0	7,676.7	7,716.1
1957 Sept. 14---	7,279.4	7,368.6	7,445.8	7,481.0	7,572.3	7,673.8	7,714.0
1958 Aug. 17---	---	7,359.0	7,440.8	7,474.4	7,567.3	7,668.9	7,709.5
1959 Aug. 18---	---	---	---	7,474.3	7,570.2	7,672.9	7,713.2
1961 Sept. 14---	---	---	7,434.8	7,464.6	7,564.7	7,668.0	7,706.9
1962 Aug. 30---	---	---	7,435.8	7,465.9	7,568.0	7,672.9	7,713.1
1963 Sept. 8---	---	---	7,432.6	7,462.7	7,567.4	7,673.3	7,712.1
1966 Aug. 25---	---	---	7,432.8	7,463.0	7,574.6	7,680.5	7,723.2
1968 Sept. 1---	---	---	7,425.3	7,458.3	7,575.1	7,681.6	7,722.7
1969 Aug. 23---	---	---	7,417.5	7,453.9	7,571.1	7,674.0	---

Profile *B–B′* (pl. 2) is almost at right angles to the transverse profile, intersecting it at a point near mid-glacier. From the intersection, measurements extended upglacier 800-1,000 feet and downglacier to the terminus.

Along profile *B–B′* (table 17) upglacier from the intersection point both positive and negative changes in surface elevation have been measured. The surface was higher in 1969 than in 1950.

Downglacier from the intersection point the surface elevation has generally shown a continual lowering (table 17). During the 19-year period 1950–69 the terminus receded 725 feet along the profile alinement. In 1950, the ice at the location of the terminus in 1969 was 115 feet thick.

Profile *C–C′* (pl. 2) near the west edge of the glacier originates at bench mark 7375. It was first measured in 1947; then it crossed a prominent ice ridge that stood 40 feet higher than the depression or trough just upglacier. The successive profiles along this line (pl. 2) show a continual lowering of the ridge, which by 1969 had completely disappeared. The ridge crest in 1947 was 90 feet above the corresponding point in 1969. Upglacier (southeast) from the former trough or depression the ice surface has remained much the same since 1950.

Profile *D–D′*, originating at the same point as the transverse profile, bench mark 7699, was first measured in 1958. During the 11 years the terminal position advanced more than 200 feet and the mean surface elevation rose about 20 feet. The increase in surface elevation recorded at this profile corresponds with the increase at the transverse profile's southwest half, which was higher in 1969 than in 1950. The area crossed by profile *D–D′* has become more crevassed in recent years as a result of the renewed ice activity.

Along the transverse profile (*A–A′*) surface elevation fluctuated, whereas downglacier from it there was a continual shrinkage, as well as pronounced terminal recession. Upglacier there was some increase in surface elevation, as shown by the results at profile *B–B′* from 1950 to 1969 and at profile *D–D′* in 1958 and 1969. This increase in surface elevation—glacier thickening—is also indicated by a comparison of the 1950 and 1960 maps. The 7,700- to 8,100-foot contours were farther downglacier in 1960

FIGURE 18.— Moat at east side of Sperry Glacier, showing stratified ice wall, August 16, 1913 (Alden, 1914, fig. 3).

than in 1950. The 7,600- and the 8,300–8,600-foot contours were in virtually the same positions on the two maps.

The great thickness of glacier ice in 1913 is evident in Alden's photograph (fig. 18) and his related comments. In describing the structure of the glacier he (1914, p. 14) referred to the stratification as follows:

"The best view * * * of the bedded structure of the glacier is to be had where the east side of the glacier rounds a salient of the cirque wall at a point about two-fifths of a mile south-southeast of the front of the

TABLE 18.—*Seasonal measurements of ablation at Sperry Glacier for selected years*

[Location of stakes shown on plate 2. ---, no data. Stakes 7 and 9–12 emplaced in 1965. No measurements in 1964]

Stake No.	Period of measurement	Elapsed days	Ablation (ft)	Period of measurement	Elapsed days	Ablation (ft)
	1961			1962		
1	July 24-Sept. 14	52	10.1	July 21-Aug. 26	36	7.3
2	--do------------	52	7.6	--do-----------	36	6.2
3	--do------------	52	7.6	--do-----------	36	7.6
3A	---	---	---	--do-----------	36	7.0
3B	---	---	---	---	---	---
4	July 24-Sept. 14	52	8.9	July 21-Aug. 26	36	7.6
5	--do------------	52	9.2	---	---	---
6	--do------------	52	10.8	---	---	---
	1963			1965		
1	July 31-Sept. 8	39	7.5	Aug. 7-Oct. 13	67	5.3
2	--do------------	39	6.8	---	---	---
3	Aug. 1-Oct. 18	78	9.8	---	---	---
3A	Aug. 2-Oct. 18	77	6.5	---	---	---
3B	--do------------	77	8.4	---	---	---
4	--do------------	77	10.2	---	---	---
5	Aug. 4-Oct. 18	75	11.7	---	---	---
6	--do------------	75	10.4	---	---	---
7	---	---	---	Aug. 7-Oct. 13	67	5.5+
9	---	---	---	--do-----------	67	5.6
10	---	---	---	--do-----------	67	4.6
11	---	---	---	--do-----------	67	4.5
12	---	---	---	--do-----------	67	4.2

TABLE 19.—*Annual ablation measurements at Sperry Glacier*

[Location of stakes shown on plate 2]

Stake No.	Period of measurement	Elapsed days	Ablation (ft)
1---	Sept. 14, 1961-Aug. 8, 1962	328	1.7
	July 31, 1963-Aug. 24, 1966	1,120	12.6
	July 23, 1964-Aug. 24, 1966	762	5.8
	Aug. 6, 1965-Aug. 24, 1966	383	9.5
	Aug. 24, 1966-Sept. 8, 1967	380	8.7
2---	July 21, 1962-Sept. 8, 1967	1,875	4.0
3---	Aug. 7, 1965-Aug. 25, 1966	383	-1.9
	Aug. 25, 1966-Sept. 8, 1967	379	7.9
4---	Sept. 14, 1961-Aug. 26, 1962	346	.9
	July 31, 1963-Aug. 25, 1966	1,121	9.5
	Aug. 7, 1965-Sept. 8, 1967	762	-1.4
6---	July 23, 1964-Aug. 25, 1966	763	5.4
8---	Aug. 7, 1965-Aug. 26, 1966	384	8.1
9---	Aug. 7, 1965-Aug. 25, 1966	383	-1.9
	Aug. 25, 1966-Sept. 8, 1967	379	7.9
10---	Aug. 7, 1965-Sept. 8, 1967	762	6.9
11---	Aug. 7, 1965-Sept. 8, 1967	762	3.1

most easterly marginal lobe of the glacier. On the northwest side of the salient instead of the ice crowding against the rock slope there is a great chasm, or moat * * *, one side of which is formed by the rock wall. The other is a smooth, curving wall of stratified ice, 150 feet or more in height * * *."

The cirque-wall salient mentioned by Alden appears, on aerial photographs, to be roughly opposite the 1950 location of the terminus. The ice wall described and illustrated by Alden (1914) was no longer evident in 1944 when I first observed this glacier. From Alden's description, one can infer that the ice surface in 1944 was approximately 150 feet lower than in 1913. This would represent an average annual decrease in surface elevation of the glacier in this particular area of about 5 feet.

ABLATION

Ablation measurements on Sperry Glacier since first obtained in 1961 are summarized in tables 18 and 19. (The procedure for setting the stakes was the same as at Grinnell Glacier, see page 14.) The ablation stakes (pl. 2) were usually placed during the latter part of July or early August and readings were made in late August or early September, covering only a part of the ablation season. Ablation was considerable during May, June, and early July. The values in table 18 provide a basis for estimating total ablation during the melting season. Such estimates must, of course, take into consideration temperatures prevailing during the estimating period.

Table 1 shows July and August mean temperatures at Sperry Chalets, about 1,000-1,500 feet lower than the glacier. If the usual decrease in temperature with increasing elevation is applicable, temperatures over the glacier probably were about 5°F less than at Sperry Chalets.

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