Analysis of a 24-Year Photographic Record of Nisqually Glacier, Mount Rainier National Park, Washington

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Abstract

A systematic coverage of Nisqually Glacier by photographs taken from a network of stations on the ground was begun in 1942 to explore the value and limitations of such photographs as an aid in glacier study. Principles developed may be of value elsewhere, especially for the program "Measurement of Glacier Variations on a World-Wide Basis" of the International Hydrological Decade.

Nisqually Glacier in Mount Rainier National Park, Wash., covers 2.5 square miles (6.5 square kilometers) (1961) and extends from an altitude of about 14,300 feet (4,400 meters) near the top of Mount Rainier down to 4,700 feet (1,400 meters), in a horizontal distance of 4.1 miles (6.6 kilometers).

Analyses were made of the annual photographs taken by the writer for 24 years from about 20 stations. A number of pictures taken sporadically from 1884 to 1941 by others were also available for use in the study. Where possible, the results obtained from photographs were compared with those from the available engineering surveys. Such detailed analysis of an extensive photographic coverage of a single glacier may be unique.

Photographs illustrating the retreat and advance of the glacier's west ice margin in a reach extending for about a mile (1.6 kilometers) downstream from Wilson Glacier show that, by 1965, most of the ice thickness lost in that area between 1890 and 1944 had been recovered. Withering of the stagnant valley tongue down glacier from the nuntak is portrayed, as is its spectacular reactivation in the 1960's by a vigorous advance of fresh ice. Some of the visible characteristics of advancing and receding termini are noted.

Annual values of the glacier's surface slope (5 to 10 degrees) at a cross profile were measured on photographs with respect to a projected vertical line identifiable in each picture. The results were found to average about 2 degrees less than those obtained from the 5-year topographic maps, but they are thought to be a little more accurate owing to lack of a sufficiently small contour interval on the maps for this special purpose.

Year-to-year variations in the surface slope and other characteristics from place to place along the glacier are portrayed by pictures to a degree not economically attainable by any other means.

Annual changes in the glacier's thickness at two locations were determined from photographs and found to agree well with the results of stadia surveys.

A summary of conclusions reached in regard to other data or features of the glacier that were illustrated by annual photographs follows:

1. Toward the end of the ablation season, position of the annual snowline ranged between altitudes of about 5,800 and 7,300 feet (1,750 and 2,250 meters). The altitude limits within which firn was observed on the glacier were about 6,000 and 7,300 feet (1,850 and 2,250 meters).
2. Sources from which debris reaches the glacier are evident.
3. Medial moraines and other persistent patterns sometimes overlooked in the field are more noticeable in photographs. Ice-cored moraines and patterns of multiple lateral moraines are visible.
4. The extent, severity, and nature of crevassing in an area reflect the dynamic condition of the glacier at that location.
5. Erosion has caused certain bedrock areas or features on canyon walls to become unrecognizable within less than 15 years.
6. Effects of the 1932 and 1955 outburst floods on the stream channel and trees for a mile (1.6 kilometers) or so below the glacier are shown in comparison with ordinary, lesser floods. Visible effects include degradation, widening and changes in configuration of the channel, formation of small terraces, removal of vegetation from the flood plain, and the deposition of huge boulders on the stream banks and flood plain.

Some photographic procedures recommended for use in a program of this type are described in the section on "Recommended Photographic Procedures."

INTRODUCTION

PURPOSE AND SCOPE

Reasons for the program

Over the years, glaciers show marked changes. For their study and analysis a repetitive photographic program has obvious potential value because it is relatively quick and inexpensive and can include a wealth of information unobtainable by ordinary surveying techniques. Such a program graphically portrays the visible characteristics and changes inherent in a fluctuating glacier. Since this has long been recognized, systematic photographic programs have been undertaken on many glaciers in many parts of the world. However, no such program, to the knowledge of the writer, has combined a fairly detailed photographic coverage over nearly the full length of a single glacier, a long period of annual record, and an analysis of the potential of a program such as is described in this paper.

Published reports by Field (1932, 1937, 1947), Harrison (1954, 1956), LaChapelle (1962), Meier and Post (1962), and others have utilized glacier photographs, but the pictures for any one glacier did not include coverage or length of record as detailed as those available for Nisqually Glacier, nor did the reports indicate the many kinds of data obtainable from such photographs. Such an analysis is especially important now because a photographic record has been designated as a first, least costly step, in the new program "Measurements of Glacier Variations on a World-Wide Basis" of the Commission of Snow and Ice (International Association of Scientific Hydrology). This global-scale program is also part of the International Hydrological Decade. Thus, the findings and techniques described herein are thought to have possible application elsewhere.

The idea that worthwhile benefits might derive from a long-term program of annual photographs of Nisqually Glacier was conceived by the writer in collaboration with Arthur Johnson of the U.S. Geological Survey when Mr. Johnson was mapping the glacier in 1941.

Soon after the annual photographic records were begun, a marked thickening of the upper part of the glacier was noticed from the annual cross-profile surveys (Johnson, 1949). The thickening was followed over a period of two decades by one unusually large and several smaller kinematic (moving) waves of fresh ice advance. The effect of these was particularly impressive in the terminal area from 1963 to 1965. The waves probably resulted from the marked increases in precipitation on Mount Rainier as evidenced in the measurements at Paradise Ranger Station, situated less than a mile (1.6 km (kilometers)) from the glacier at an altitude of 5,430 feet (1,160 m (meters)).

The climatic change of the late 1940's, which subsequently was found to have caused the advance of glaciers in many parts of the world, apparently was first detected in 1946 and 1947 in glaciers on Mount Rainier. As a result, Nisqually Glacier became an object of considerable international scientific interest.

A program of this kind is less expensive than one based on aerial or phototheodolite photography because it does not require trained photogrammetrists or as costly equipment. Furthermore, since it consumes relatively little field time its success is more certain during brief periods of cloudless weather.

Purpose of the report

The primary purpose of this report is to describe, and domonstrate by means of examples, what kinds of data usable in analyzing glacier characteristics can be obtained from a simple program of long-term photographic coverage from stations on the ground. It is not intended to be a detailed or complete report on the glacier's physical characteristics.

Secondary purposes of the report are to describe to interested workers the photographs available here and to illustrate some of the spectacular changes that have occurred in this glacier. Examples are given of qualitative and quantitative data sought in regard to the glacier's growth, depletion, movement, slope, moraines, crevassing, snow and firn lines, and debris cover. Some objectives that developed as the photographic program progressed were the illustration of some geomorphological changes occurring in old moraines and the adjacent hills and valley, and the portrayal of erosion and other changes in the river channel below the glacier from outburst floods and other causes.

The report presents photographs taken by the writer for 24 years from about 20 stations and some older photographs taken by others. Only a hand-held amateur camera was used, without photogrammetric instruments of any nature. Office techniques used included the interpretation and marking of ice margins and slope crest lines on photographs, and the performance of simple scaling, scale-ratio computions, and angle measurements.

Selection of study area

Nisqually Glacier on Mount Rainier, Wash., was chosen for the project because of its variety of features for such an experiment, the availability of data from previous investigations, the many concurrent topographical and profile survey data which could be used for checking, the superior accessibility of this glacier, and the practical local interest in it as an important source of the water supply of the Nisqually River. The general location and access to the glacier are shown in figure 1.

Quantities of melt water coming from Nisqually Glacier vary with the amounts of snow and ice it contains and with external conditions such as air temperature and the amount of radiant energy received from the sun. Streamflow records show that the discharge of the Nisqually River is markedly affected by variations in the melting rates of headwater glaciers. Thus, because the river is used for the production of

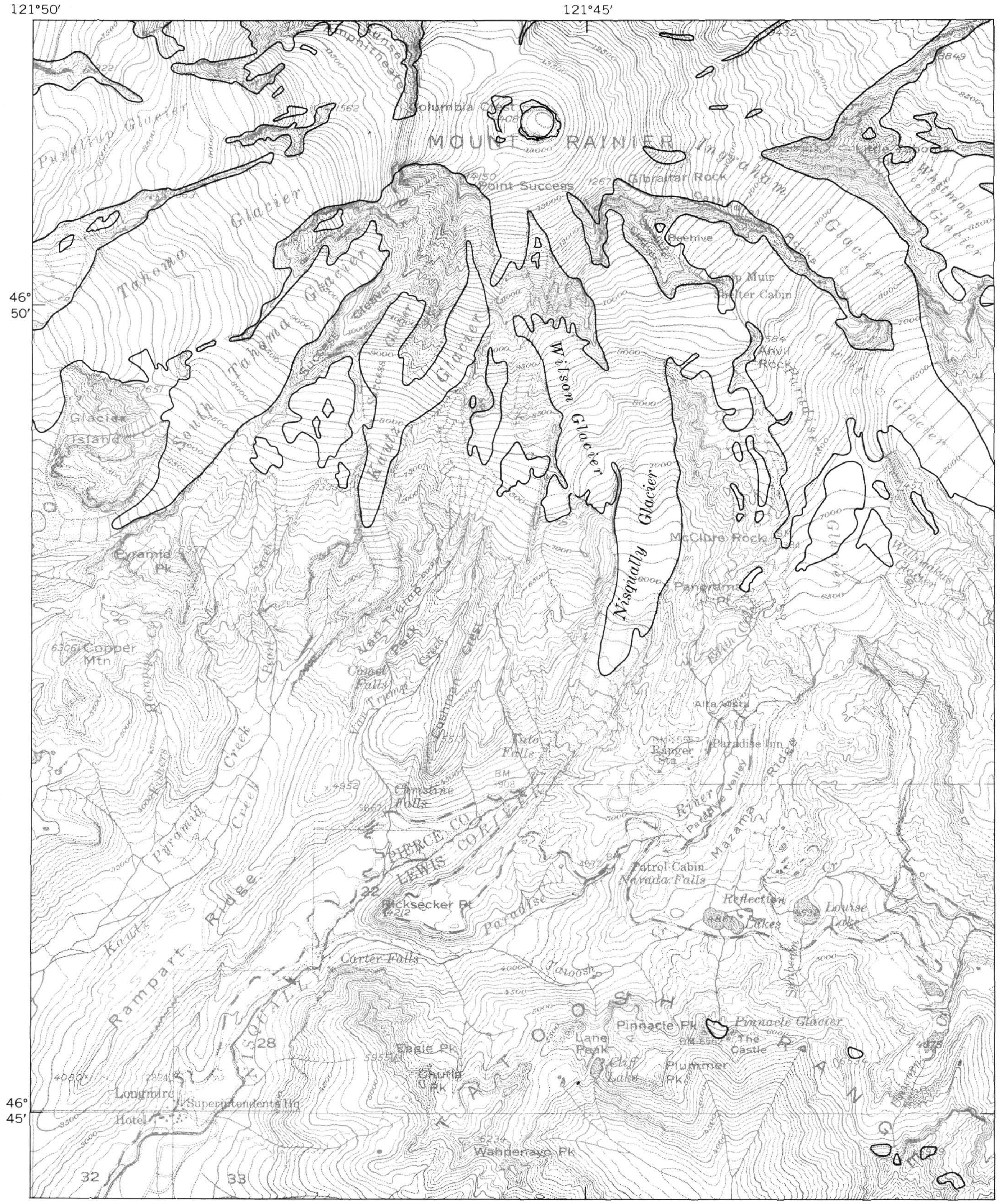

Figure 1.—South side of Mount Rainier and vicinity, showing location of Nisqually Glacier. Glacier margins and part of culture corrected to 1966. Scale 1 inch = 62,500 feet (approximately 1 inch = 1 mile).

power at hydroelectric plants downstream from Mount Rainier National Park, any study of glacier fluctuations and related climatic changes is of important economic interest in connection with the long-range planning of water resource use.

PREVIOUS INVESTIGATIONS

Photographs

Nisqually Glacier in Mount Rainier National Park long has been a favorite object of photographers, for it is a readily accessible subject for glacier research and is part of a high-altitude area of rare scenic grandeur. For many years (until 1936) its terminus remained less than half a mile (0.8 km) upstream from the former highway bridge on the road to Paradise Inn. The main body of Nisqually Glacier is visible from several vista points along its east side, accessible from the Paradise Inn area (pl. 1).

Numerous random photographs, mostly confined to the area of the terminus, were taken in association with surveying activities. The first known photograph of the glacier was a view of the snout taken by Allen C. Mason in 1884.

I. C. Russell (1898, p. 399–400), as a member of a U.S. Geological Survey group making a reconnaissance of Mount Rainier and its glaciers, recommended systematic photographic coverage and measurement of the position of the Nisqually Glacier terminus from permanent, marked locations. Russell also reported that Nisqually Glacier affords abundant opportunity for observation and study of the various features that glaciers possess, such as crevasses and moraines. No network of regularly scheduled photographs covering most of the glacier was established until 1942, nearly half a century later, when a program of annual photographs from about 20 stations was initiated by the writer, then district engineer, Water Resources Division, Geological Survey, Tacoma, Wash.

Surveys and maps

A definite location of the terminus of Nisqually Glacier was recorded first in 1857, by Lt. A. V. Kautz, and next in 1885, by James Longmire. Its approximate position in 1910 was determined on the small-scale planetable map of Mount Rainier National Park that was made in 1910–13 by the U.S. Geological Survey under the supervision of F. E. Matthes. Annual records of the position of the terminus, begun in 1918 by F. W. Shmoe, National Park Service, were obtained each year by that agency until 1961 and have been continued since then by the Conservation Division of the U.S. Geological Survey.

In 1930 and 1931, Llewellyn Evans, superintendent of the Light Division, Tacoma Department of Public Utilities, made cross-profile and other surveys and compared the results with data taken from Matthes' 1910 map. In 1931 a contour map was prepared cooperatively by the Tacoma [City] Light Division, the National Park Service, and the U.S. Geological Survey. A plan of contour mapping at 5-year intervals was then conceived by Llewellyn Evans, Owen A. Tomlinson, and Glenn L. Parker of those respective agencies. This has been done, beginning in 1936, first by planetable and later (covering a larger area) using photogrammetry from aerial photographs, by the U.S. Geological Survey in cooperation with the city of Tacoma and the National Park Service. At the request of the Tacoma Light Division a map of the same type was also made in 1940; it was not published but is on file in the office of the Conservation Division, U.S. Geological Survey, Tacoma, Wash.

Nisqually Glacier was also mapped by terrestrial photogrammetry in 1952 and 1956 by Walther Hofmann of the Technical Institute in Munich, Federal Republic of Germany (Hofmann, 1958).

Beginning in 1940, the Conservation Division of the U.S. Geological Survey, under the supervision of regional hydraulic engineers Arthur Johnson (to 1952), Fred A. Johnson (1953–62), and Gordon C. Giles (1963–), has made annual surveys by stadia techniques of three cross-profiles of the glacier (locations on pl. 1). The Conservation Division also has made surveys of glacier movement and has reported on recession and volume changes (Johnson, 1960). The surveys have been carried out with the assistance and cooperation of National Park Service personnel and, in some years, with the financial assistance of the Tacoma Department of Public Utilities.

The 1956 map used for showing locations of the photographic stations and cross profiles was prepared by the Topographic Division of the U.S. Geological Survey, which obtained the topography from aerial photographs by using a Wild A–8 plotter.

ACKNOWLEDGMENTS

This report was prepared under the general supervision of Mark F. Meier, geologist in charge of glacier research. The assistance of Austin Post and Donald Richardson was very helpful. Collaboration of several colleague reviewers, especially Arthur Johnson and Gordon C. Giles of the U.S. Geological Survey and W. O. Field of the American Geographical Society, is gratefully acknowledged. The Tacoma Department of Public Utilities furnished several photographs and assisted in the preparation of photographic illustrations for the report. Some photographs and the data on changes in ice-surface elevation at the cross profiles were supplied by the Conservation Division of the U.S. Geological

Survey. The cooperation of the National Park Service and the Washington State Historical Society in making their photographic files available is appreciated.

DESCRIPTION OF THE AREA

PHYSIOGRAPHY

Nisqually Glacier extends from an altitude of about 14,350 feet (4,370 m) near the summit of Mount Rainier southward 4.1 miles (6.6 km) to a terminus (in 1966) at an altitude of 4,640 feet (1,410 m) for a total drop in elevation of about 9,700 feet (2,960 m). It is divided by Nisqually Cleaver into two channels from altitudes of 13,100 to 9,500 feet (3,990 to 2,900 m) in a horizontal distance of about 3,200 feet (980 m). Ice flow in the east channel is discontinuous at the steep cliffs opposite the upper part of Cowlitz Cleaver, where the ice stream is discharged in the form of intermittent avalanches or falls. If the glacier thickened sufficiently, the flow at that point would be continuous.

The glacier is fed from the west between altitudes of 8,600 and 7,100 feet (2,620 and 2,160 m) by Wilson Glacier, as shown on the maps in figure 1 and plate 1 and in the photograph in figure 34. Wilson Glacier originates in a shallow cirque and occupies a short, wide basin on the south flank of the mountain. It is fed mainly by snowfall and snow avalanches, but it also receives a minor icefall or avalanche discharge from part of an upper lobe of Kautz Glacier.

Nisqually Glacier has a surface width of approximately half a mile (0.8 km) from the foot of Nisqually Cleaver to profile 2 (pl. 1). Below profile 2 it tapers to a width of 500 feet (152 m) near the terminus. Its total area, including Wilson Glacier, was measured on the 1961 map as about 2.5 square miles (6.5 km²).

The following tabulation augments the description of the glacier by providing basic data on the locations and altitudes of several features, as taken from the 1961 map, including rough approximations of the surface slope for the reaches between those features:

Feature	Distance above old highway bridge		Midglacier altitude in 1961		Slope (degrees)
	Feet	Meters	Feet	Meters	
Terminus in 1961 (crest of face)	5,830	1,780	4,800	1,460	
					25
Profile 1	6,870	2,100	5,290	1,610	
					17
Profile 2	9,380	2,860	6,050	1,840	
					13
Profile 3	12,850	3,920	6,840	2,080	
					16
Base of lower icefall and approximate firn limit [1]	14,460	4,410	7,300	2,220	
					30
Top of upper icefall (near top of Nisqually Cleaver)	24,400	7,440	13,100	3,990	
					27
Head	26,800	8,170	14,350	4,370	

[1] In this report, the term "snow" is restricted to that which fell during the most recent winter season, and "firn" designates granular snow that has survived one or more ablation seasons.

Nearly 8,000 feet (2,440 m) up valley from the site of the former highway bridge and 1,200 feet (370 m) above profile 1, the glacier flows past and sometimes over a nunatak [2] (fig. 27). The top of the nunatak is at an altitude of 5,670 feet (1,730 m). It currently diverts a major part of the east-half ice flow toward the west wall of the canyon; for more than 10 years, from the early 1940's to the mid-1950's, essentially all the ice flow was west of the nunatak.

CLIMATE

The Nisqually Glacier area receives most of its precipitation from moist, eastward-flowing cyclonic storms which form over the Pacific Ocean on the south edge of the winter Aleutian low-pressure area. More than 80 percent of this precipitation falls as snow during the period October to May. Since the low-level winds normally flow from the southwest during these winter storms, Nisqually Glacier, lying as it does on the south side of Mount Rainier, receives nearly the full effect of the storms. A precipitation shadow lies to the northeast of the mountain.

During the period 1920–59 the annual precipitation at Paradise Ranger Station (fig. 1), at an altitude of 5,430 feet (1,660 m), averaged 106 inches (269 mm) for the 24 complete but noncontinuous years of available record. On parts of the glacier, particularly at higher altitudes, the precipitation may have been greater. Snow depths at Paradise sometimes reach 30 feet (9 m). The range in annual precipitation recorded there during the 1920–59 period was from 64 to 138 inches (163 to 351 mm).

THE PHOTOGRAPHIC PROGRAM

NETWORK OF STATIONS

Several of the photographic stations were established at sites from which miscellaneous earlier photographs had been taken—for example, the 1890 view that was published in the 18th Annual Report of the U.S. Geological Survey. Additional stations were selected to improve the overall coverage and to collect some views illustrating geomorphological changes in the hills and valley. The objective was to provide fairly complete coverage of the glacier and valley below, with at least two angles of view available for every area insofar as feasible.

Along the east side of the glacier two "tiers" of stations were used—one as high as feasible and the other

[2] This rock hill was termed a nunatak by Giles (1960), is locally known by this name, and is so termed herein. However, this knob does not always project above the surface of the ice, nor is it always surrounded by ice, so it does not always fit the accepted glaciological definition of "nunatak."

not far above the glacier surface. The higher stations provide most of the information needed for study of the glacier, but the lower ones are especially useful in any analysis of longitudinal surface slope or in any photographic determinations of rates of surface movement (the latter subject was not studied in this report).

The selection of photographic stations, except near the highway bridge, was restricted to the more accessible east side of the glacier. An attempt was made to avoid hazardous areas, such as those too precipitous or subject to rolling rock, and sites where tree growth or rise of the glacier surface might later obstruct the view.

A brief description of each photographic station, including its period of record, is given in table 1; the locations are shown on plate 1. The approximate direction of every panoramic view photographed from each station is indicated on plate 1. Each view series is given a serial number corresponding to the number of the station, with direction of the view added when necessary for differentiation between series. Footnotes explain the changes that have been made in the location of each station.

PHOTOGRAPHIC SERIES NOT PUBLISHED

Several of the photographic series shown on the map and in the description list are not discussed in this report but are included to indicate their availability in the files of the U.S. Geological Survey, Tacoma, Wash., should they later become of interest. These are series Nos. 1–SW, 2–NE, 4, 5–W, 8–W, 8–N, 9, 10, 12, 14–N, 16, 17–S, 17–NW, 18–S, and 18–NW. Some have been discontinued.

TABLE 1.—*Descriptions of the photographic series, 1890–1965*

Series	Figures	Years of record	Altitude: Feet	Altitude: Meters	Geological Survey period of record	Direction of view relative to glacier	Place from which photographs were taken
1–NE	16–19	[1] 20	3, 900	1, 190	1942, 1947, 1949–	Up	Highway bridge on Nisqually River.
1–SW		20	3, 900	1, 190	1942, 1947–	Down	Do.
2–NE		20	4, 300	1, 310	1943–50, 1952, 1953, 1956–	Up	Stone monument on cliff.[2]
2–S	39	17	4, 300	1, 310	1943, 1947–50, 1952, 1953, 1956–	Down	Do.
3	36–38	14	4, 150	1, 260	1941, 1942, 1947, 1952, 1956–	do	Viewpoint ¼ mi (0.4 km) north of Ricksecker Point.
4		10	4, 250	1, 300	1944, 1955, 1958–	Up	Canyon Rim viewpoint.[3]
5	20–25	21	5, 240	1, 600	1940, 1942–45, 1949–52, 1954–	Up	Nisqually Vista, at trailside exhibit.
5–W		[5] 13	5, 240	1, 600	1943–46, 1949–57	Across	Do.[4]
6	27–31	24	5, 560	1, 690	1942–	Up	Point on cliff.[6]
7	2–5	16	5, 760	1, 760	1890, 1940–42, 1945, 1948, 1951, 1954, 1958–	Up	Bend in trail to glacier (1890 station).
8–W		21	5, 580	1, 700	1941–46, 1951–	Across	18 ft (5.5 m) west of B.M. 5587, on old moraine.
8–N		27	5, 580	1, 700	1931, 1936, 1941–	Up	Do.
9		10	6, 040	1, 840	1915, 1943, 1955, 1958–60, 1962–	Across	60 ft (18 m) west of old trail on ridge.[7]
10		19	5, 860	1, 790	1947–	do	Point on moraine trail.
11	35	16	6, 050	1, 840	1940, 1947, 1951–53, 1955–	Down	Do.[8]
12		13	6, 074	1, 850	1936, 1941, 1955–	Across [9]	B.M. 6074, on old moraine.
12–N	26	3	6, 074	1, 850	1940, 1955, 1956	Up	Do.
13	32–34	17	6, 325	1, 930	[10] 1949–	Across and up	Point on bedrock beside Skyline Trail.
14–W	7–10	18	6, 165	1, 880	1942–44, 1951	Across	B.M. 6165, on moraine.
14–N		20	6, 165	1, 880	1942–44, 1947, 1951–	Up	Do.
15	12	22	6, 293	1, 920	1943–46, 1948–	Up	B.M. 6293, on moraine.
16		17	6, 428	1, 960	1949–65	Across and up	B.M. 6428, on moraine.
17–S		2	6, 800	2, 070	1964–	Down	Large rock on a moraine.[11]
17–NW		2	6, 800	2, 070	1964–	Across and up	Do.[11]
18–S		17	6, 882	2, 100	1943–44, 1946, 1948–55, 1958–62, 1964	Down	B.M. 6882, on large imbedded rock.[12]
18–NW		17	6, 882	2, 100	1942–44, 1948–55, 1958–62, 1964	Across and up	Do.[12]

[1] Used old bridge through 1960 and new bridge several hundred feet downstream and a little higher in elevation, 1959–65. Numerous photographs looking up glacier from station 1 are available in the files of other agencies.

[2] Prior to 1964 this series was taken about 100 ft (30 m) farther up glacier, at old survey stake No. 1185.

[3] 1944 taken from road ¼ mile (0.4 km) south; 1955 and 1959 taken from bend in road 0.7 mile (1.1 km) south of Canyon Rim viewpoint.

[4] Prior to 1949 taken from bend in trail about 110 ft (30 m) northeast of Nisqually Vista.

[5] After 1957 the terminus was photographed in series 5.

[6] Prior to 1957 taken from site about 200 ft (60 m) west and 50 ft (15 m) lower in altitude.

[7] 1943 view taken from about 200 ft (60 m) north of 1915 site, and all views thereafter taken from new point about 400 ft (120 m) north of 1915 site.

[8] Taken from 3 points with a radius of 25 ft (8 m).

[9] Usually panoramas covering about 135° down, across, and up glacier.

[10] The 1949 photograph was taken at or near B.M. tablet 4–1940 situated about 500 ft (150 m) up glacier from the bedrock point used thereafter.

[11] This point established to supersede B.M. 6882 to obtain less hazardous access.

[12] In 1943, 1944, 1948, 1951, and 1953 the views were taken from B.M. 6853 which is about 50 ft (15 m) west and 30 ft (9 m) lower than B.M. 6882.

TIME OF YEAR AND WEATHER CONDITIONS

To obtain information on annual accretion, wastage, and movement of ice in Nisqually Glacier, the photographs have been taken as late in the ablation season as thought safe before a heavy, fresh snowfall might occur. Early in the program the photographs were taken in late August, but more recently they have been taken during the first 2 weeks of September. Although the minimum mass of glacier ice and snow normally occurs in late September, photographs are taken earlier to avoid risk of a snowfall which would conceal features such as the firn line.

The climate at Nisqually Glacier is characterized by rapid changes in weather which are difficult to predict owing to the paucity of weather data beyond the coastline. Such changes may seriously interrupt completion of the photography, and they sometimes necessitate a second trip to Mount Rainier. Weather variations make it much more difficult to schedule aerial photography or to spend a number of days in cumbersome (though more precise) phototheodolite procedure; this emphasizes the economy of using a hand camera in one quick trip that can take full advantage of a brief break in the weather.

CAMERA EQUIPMENT

Cameras used for taking the 1942–65 pictures mentioned in this report were: 1942–57—Kodak Model 3–A, film size 3¼ by 5½ inches, focal length 170 mm, equipped with cable shutter release; 1958–65—Kodak Tourist, film size 2¼ by 3¼ inches, focal length 105 mm. Exposures normally were for 1/200th second at f–11 or f–16, and were all made with the camera handheld.

In general, Kodak Super XX film (speed ASA 100) was used from 1942 to 1955 and Kodak Verichrome Pan (ASA 80) thereafter. The relatively low graininess of these films and their latitude to accommodate the contrasting lighting encountered in glacier scenes have been satisfactory.

In this program, the experimental use of lens filters, particularly the K–2 (yellow) one, have shown no advantage over the unfiltered lens.

LIGHT CONDITIONS

An effort was made to take the annual view at each station at the same hour of the day, as well as at the same time of year, so that similar light conditions would minimize illusory effects and possible misinterpretations. This was not always feasible, but analyses made during preparation of this report emphasize the importance of following such a procedure.

SCALE CORRECTIONS ON PRINTS

The selected enlargements or prints in each photographic series utilized in the quantitative analyses in this report were reduced to the same scale by developing and applying scale-ratio coefficients. These were obtained by scaling the linear distances between identical fixed points (features in bedrock) common to all the prints, and determining the ratio between the value for each print with respect to the comparable value on a selected base print. The resulting coefficients were applied to any analytical data measured on those prints to reduce all measurements to the scale of the base print.

QUANTITATIVE INTERPRETATIONS FROM THE PHOTOGRAPHS

CHANGES IN ICE THICKNESS

Annual photographs can readily be used for analyzing the approximate year-to-year changes in a glacier's thickness. Three examples are described below, using lateral ice margins, the crest of the ice as seen in lateral views, and the crest of an ice bulge as viewed from down glacier.

In the first example, on each annual photograph in series 7 (selected years of which are shown in figs. 2–5) a smoothed line was drawn for a few thousand feet along the west ice margin [3] downstream from Wilson Glacier. The positions of several points on each marginal line were then defined by measuring down to them, on the pictures, from a series of fixed points (bedrock features) along the canyon wall identifiable on all the photographs studied. Next, the distances so measured were adjusted to the scale of the August 23, 1951, view, which year was selected as the year of minimum ice in that area. The scale adjustment was done by means of scale-ratio measurements made between several fixed points identifiable on all the prints. Using the converted distances, the lines were transferred to the 1951 print (fig. 6).

Most of these ice-margin lines are believed to be accurate to ± 20 feet (6 m) vertically or horizontally. The greatest source of error is in the subjective determination of the location of the margin of the active ice for each year because the margin is obscured in many places by varying amounts of remnant ice, snow, or rock debris.

In the series 7 photographs, the valley wall is about 3,300 feet (1,000 m) away from the camera opposite the middle of the nunatak and 7,500 feet (2,300 m) away just below Wilson Glacier. The approximate

[3] The margin is the apparent edge of the moving ice, whether it is obscured by detritus or not.

Figure 2.—Nisqually Glacier, from confluence with Wilson Glacier to the nunatak, as seen from station 7 in 1890 (date uncertain). (Figures 2–5 were photographed from the same viewpoint as was used for the photograph published in the Geological Survey's Annual Report for 1896–97 (Russell, 1898).) Note some similarities to 1963 view in regard to extent of ice and patterns of crevassing; note also the absence of a large moraine near the west canyon wall. Photograph is believed to have been taken in 1890 by W. O. Amsden, but may have been taken in 1896 by a member of the I. C. Russell (U.S. Geological Survey) reconnaissance party.

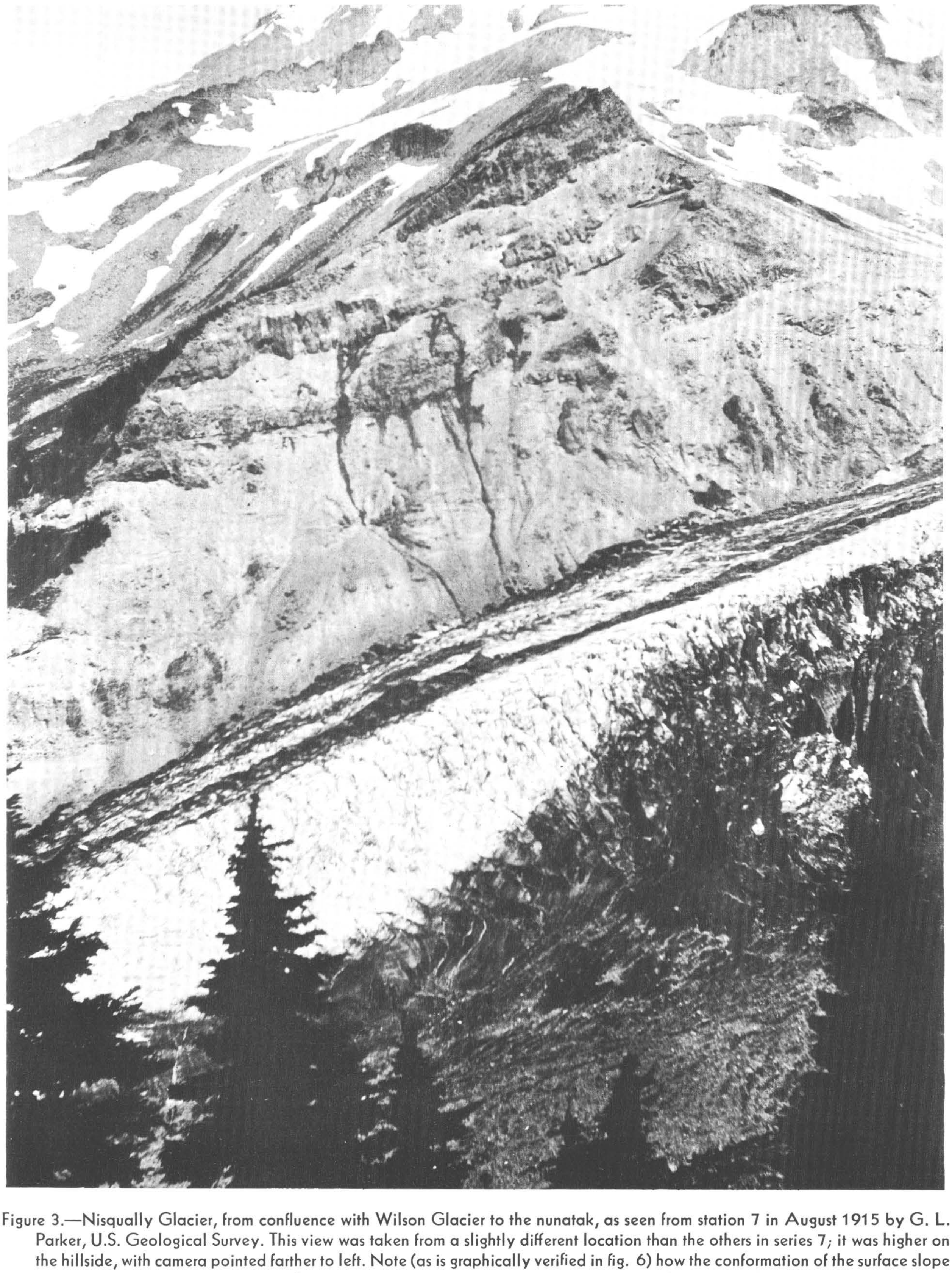

Figure 3.—Nisqually Glacier, from confluence with Wilson Glacier to the nunatak, as seen from station 7 in August 1915 by G. L. Parker, U.S. Geological Survey. This view was taken from a slightly different location than the others in series 7; it was higher on the hillside, with camera pointed farther to left. Note (as is graphically verified in fig. 6) how the conformation of the surface slope of the ice along the west canyon wall was different in 1915 than in 1963 or 1965, and how during the intervening half century many changes in exposure of the rock formations occurred. Note also the two moraines near far edge of glacier, marked by debris lines.

Figure 4.—Nisqually Glacier, from confluence with Wilson Glacier to the nunatak, as seen from station 7 on August 22, 1945. Upper part of glacier is at about its lowest known ice mass, as evidenced by the exposure of bedrock. There is almost no crevassing in middle reach. Slope at profile 2 (location in fig. 20) is very flat and broken below there. Note the light-colored medial moraine approaching nunatak from upper right. Sources of debris may be deduced. Note also large ice-cored moraine along west edge of glacier.

Figure 5.—Nisqually Glacier, from confluence with Wilson Glacier to the nunatak, as seen from station 7 on August 27, 1963. Note transverse crevasses developing in east part of glacier above nunatak indicating the direct down-valley movement of that ice. Ice-cored moraine seen in figure 4 is now subdued because of the rejuvenated movement. Note that since 1945 the glacier has recovered much of the volume evident in the 1890 view.

Figure 6.—Ice margins for selected years in period 1890–1965 are indicated on the series 7 photograph taken August 23, 1951. Note that by 1965 the glacier had recovered much of the ice thickness it had lost since 1890.

vertical scale of the valley wall on a photograph could readily be calculated from these distances and the camera's focal length.

In the second example of ice thickness analysis, data for the graphical plotting of the changes in ice-surface elevation at a single cross-profile axis were derived as follows. On each annual print of series 14–W (figs. 7–10) the distance was measured between a selected rock feature on the canyon wall directly opposite the photographic station and the ice margin directly below it. The results were converted to a common-scale basis with respect to the print for year of the lowest ice, 1951, as was described in the previous example, and the values were plotted graphically against time (fig. 11*A*) and compared with the thickness changes indicated by the annual cross-profile surveys. The graph of thickness changes measured on the photographs could not be given a vertical scale in feet (or meters) unless it were obtained by comparison with field survey results, as is this case, or by geometrical computation using map data and the camera lens focal length.

On the graph in figure 11*A* the scale of the photographic measurements was adjusted to closely fit the scale to which the field surveys were plotted. There are a few small inconsistencies between the field surveys and photographic measurements in figure 11*A*, probably due to the low vertical angle between the camera viewpoint and the distant ice margin which is not always clearly visible. Still, such a graph for a valley glacier lying between steep canyon walls is roughly indicative of the changes in ice thickness in the entire cross section of the glacier opposite the point of measurement.

A third example of a method of determining ice thickness variations from photographs utilizes the measurement reach indicated on the 1944 view in photographic series 15 (fig. 12) taken looking up glacier. In the annual photographs of series 15, distances were measured down from a bedrock feature to the crest, as seen from the photographic station, of a "standing" wave or bulge in the glacier surface nearly 4,000 feet (1,200 m) up glacier from profile 3 at an altitude of 8,400 ± 100 feet (2,560 ± 30 m). This bulge (fig. 12) occurs at the downstream end of a reach of relatively flat slope, and its crest is seen in profile when looking upstream from below. The distances so measured were plotted against time, using an estimated vertical scale, and thus their fluctuations were compared with the stadia surveys of profile 3 (fig. 11*B*). Though without a true vertical scale in feet (or meters), these results are indicative of the fluctuations in position of the ice surface at that site during glacier advance or recession. In this example the values are believed to be accurate to within plus or minus 25 feet (8 m).

It is most interesting that thickness changes were nearly synchronous at profile 3 and at the bulge 1.2 km above profile 3. The minor inconsistencies between the graphs in figure 11*B* may possibly be caused by differences in timing of the ice advances of Wilson Glacier with respect to those of Nisqually Glacier above Wilson Glacier. An attempt was made to check this timing, but the results were not satisfactory. The reason for this may be the small upward angle of view in the photographs of the top of any ice bulge on Wilson Glacier; they do not place the lip of the bulge sufficiently in outline or profile. Another source of inconsistency may be the irregular changing shape of the top of the ice bulge occurring from year to year.

CHANGES IN LATERAL ICE MARGINS

Some of the ice-thickness analyses in the preceding section also indicate changes in position of the lateral ice margins of the glacier. Such changes are further illustrated by lines around the nunatak as shown on an enlarged part of the August 22, 1951, view from series 6 (fig. 13). The ice margins for each of the selected years indicated were transferred by tracing from one single weight print to another, over a very bright light. All the annual prints used must be enlarged to the same scale.

The maximum error incurred in figure 13 is estimated to be ± 30 feet (9 m) measured along the surface of the ground rather than vertically or horizontally; the average distance from the camera is 2,500 feet (760 m), varying from about 2,100 to 2,900 feet (640 to 880 m).

It was found that the topographic maps and cross-profile survey results currently available for this glacier do not contain enough detail to permit the derivation of as accurate data on changes in the ice margins, in some areas, as can be determined from photographs.

LONGITUDINAL SLOPE OF THE ICE SURFACE

The photographs in series 14–W (figs. 7–10) were found suitable for obtaining measurements of longitudinal slope of the glacier surface at profile 2. On each annual print the angle of slope was measured by protractor with respect to a vertical line (figs. 7–10) projected on the canyon wall at far end of the profile. The position of this line was determined from a phototheodolite view that was taken by the Conservation Division of the U.S. Geological Survey and was checked from a photograph taken by the writer in which a plumb-bob line was suspended in front of the camera. It was interesting to find that the general slope of the glacier is deceiving to the eye; it is greater than it appears, and thus

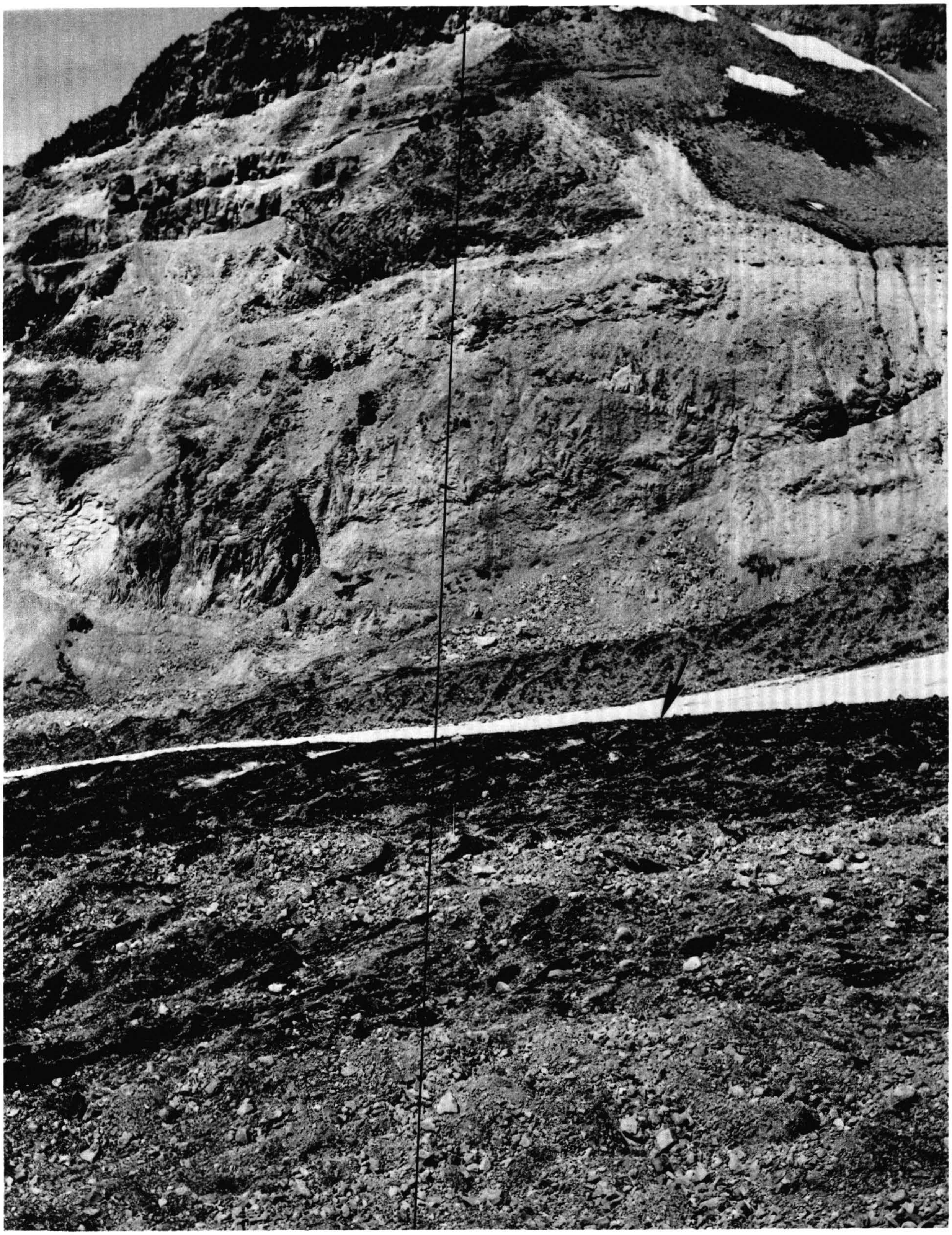

Figure 7.—View across glacier in series 14–W (profile 2) used to determine slope and changes in ice thickness; photographed on August 21, 1942. The vertical line used in measuring angle of slope of the ice surface is shown. Not indicated is the bedrock feature from which the changes in ice-surface elevation were measured. The apparent crest of the debris-covered ice (arrow), rather than the white ice, was averaged to compute slope and changes in thickness in this and all other views in this series. Note that the hand-held camera had been tilted, due to the deceptiveness of the true slope of the glacier.

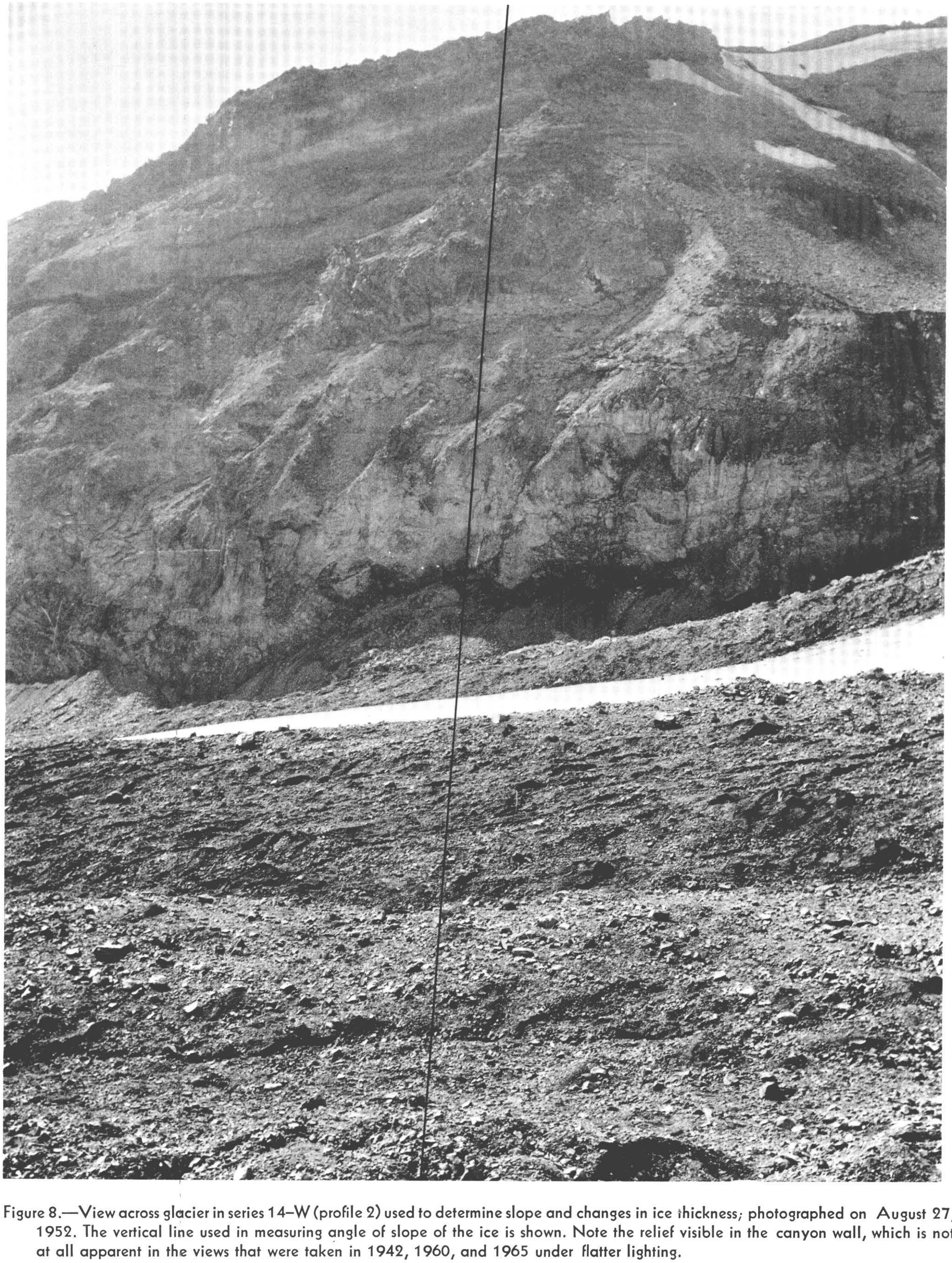

Figure 8.—View across glacier in series 14–W (profile 2) used to determine slope and changes in ice thickness; photographed on August 27, 1952. The vertical line used in measuring angle of slope of the ice is shown. Note the relief visible in the canyon wall, which is not at all apparent in the views that were taken in 1942, 1960, and 1965 under flatter lighting.

Figure 9.—View across glacier in series 14–W (profile 2) used to determine slope and changes in ice thickness; photographed on September 8, 1960. The vertical line used in measuring angle of slope of the ice is shown. Note that glacier surface in this area has become much rougher since 1952 (fig. 8), and the streak of white (clear) ice is now hidden behind the thickened zone of crevassed, debris-covered ice.

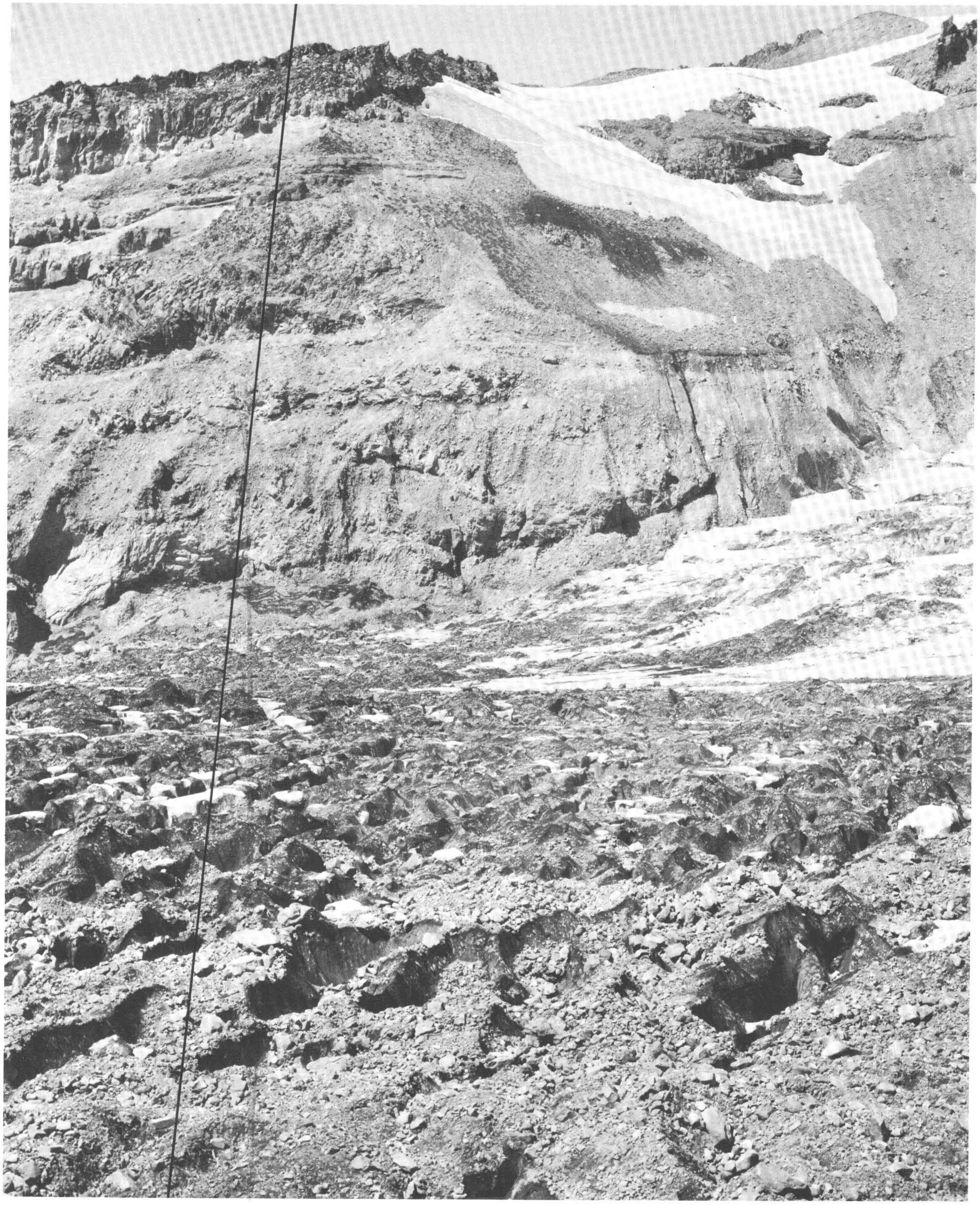

Figure 10.—View across glacier in series 14–W (profile 2) used to determine slope and changes in ice thickness; photographed on August 30, 1965. The vertical line used in measuring angle of slope of the ice is shown. Note that the crevassing is more pronounced than it was in the 1960 view (fig. 9), and there is less contrast between clear and debris-covered ice.

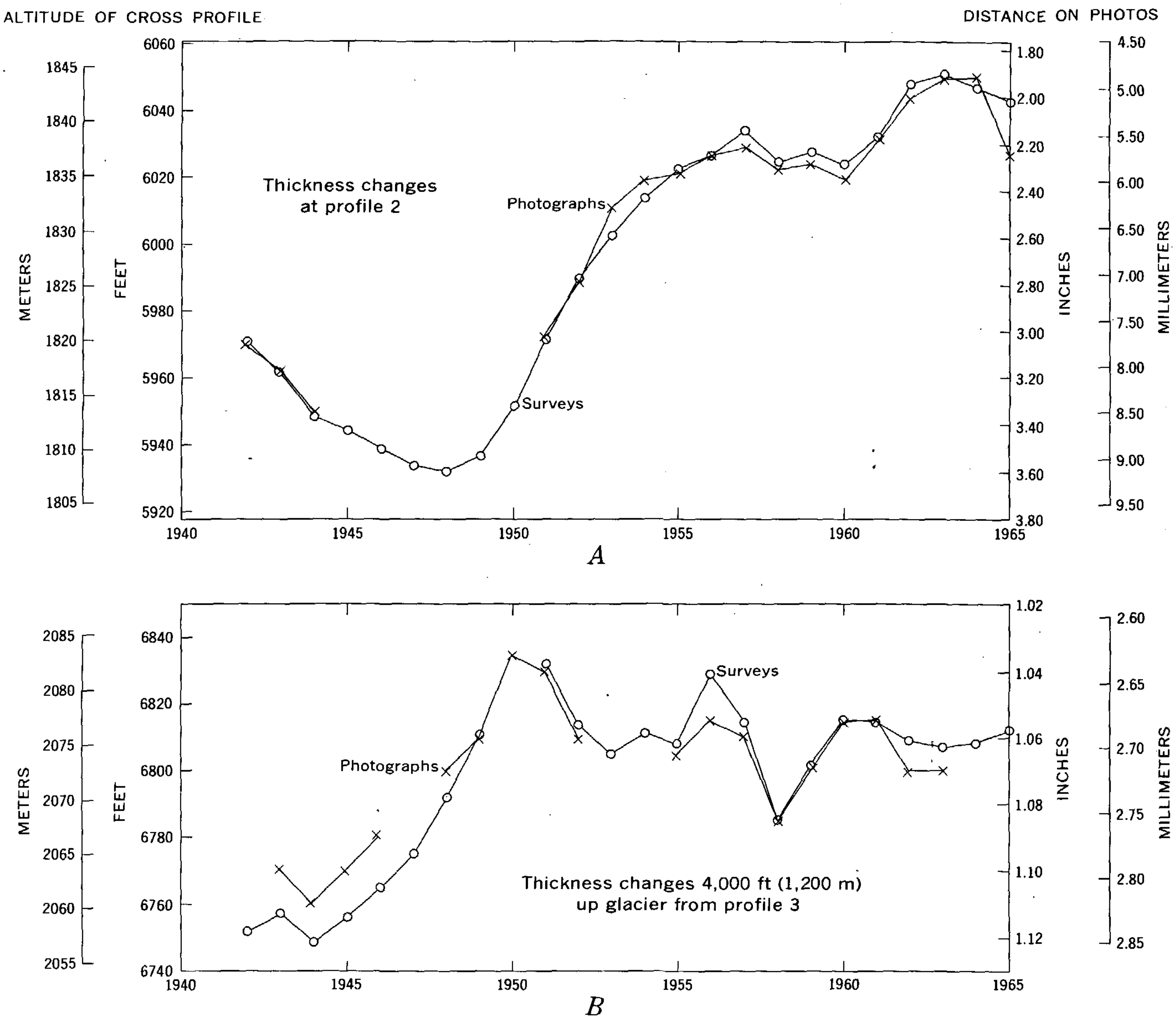

Figure 11.—Graphs showing changes in ice-surface elevation, or thickness, of the glacier. *A*, Changes in glacier thickness at cross profile 2 as measured on photographs are compared graphically with results of the annual stadia surveys. It should be noted that each stadia survey value used in the comparisons is the average ice-surface elevation along the cross profile, but each photographic measurement is made from a bedrock feature in the canyon wall down to only one point, selected in each photograph as either the apparent crest or a representative point useful for the purpose. *B*, Changes in ice-surface elevation as measured on photographs at an ice bulge nearly 4,000 feet (1,200 m) upglacier from profile 3 are compared graphically with the results of annual stadia surveys at profile 3. The values from photographs are obtained by measuring from a fixed point on bedrock down to the top of the ice bulge as it is seen in profile from down glacier at station 15 (fig. 12).

Figure 12.—Changes in ice thickness occurring about 4,000 feet (1,200 m) up glacier from profile 3, were measured on the photographs in series 15 in the reach indicated on this September 3, 1944, view from that series; upper end of measurement is the base of a lava flow and lower end is top of the ice. This 1944 view illustrates the general nature of the upper area after many years of recession had occurred, just preceding the ice advance of the late 1940's. The ice discharge from Wilson Glacier is low, and large areas of bedrock near its mouth are exposed. The falls at far left are relatively large compared with their condition in later years (1957–65). Note the opposite directions of cleavage in crevassing patterns which are visible in midglacier at lower left. It is evident that the debris load comes from sources along both sides of Nisqually Glacier and from Wilson Glacier. Bedrock areas marked by small X's were inundated by ice as the glacier thickened and expanded (compare with fig. 34 which shows this area in 1965).

Figure 13.—Ice margins around the nunatak for selected years in the period 1942–65 are indicated on the August 22, 1951, photograph taken from station 6. The down-glacier parts of the 1942, 1961, and 1965 lines are indeterminate because the ice is obscured by debris.

makes the photographer unconsciously tilt a hand-held camera a little in a down-glacier direction.

A protractor was placed along the apparent crest of the dark ice in each picture on a reach 100–200 feet (30–60 m) in length. On a few of the annual prints, the top of the white ice near the far margin of the glacier may have been better than the dark ice as an index of the slope, particularly on the print for 1952 (fig. 8), where the white ice surface is especially prominent and is about 2 degrees steeper than the dark ice. However, in the photographs for most other years, the white ice either is too obscured or could be confused with the glacier's margin, so it was not used.

For comparison with the photographic results obtained from 1942 to 1965, slope values in the same period were determined from topographic maps for 1941, 1946, 1951, 1956, and 1961. (See fig. 14.) On each map a 200-foot (60-m) reach was used, drawn along the same ice ridge as appeared in the corresponding photograph to be the crest of the ice. Elevations between contours were interpolated. The results for 1951, 1956, and 1961 probably are more accurate than those for 1941 and 1946 because of the more refined procedures used in making the later maps. The results were used (Meier, 1968) in a study of the flow and stress in Nisqually Glacier.

The slope values obtained from maps are somewhat greater, by about 2 degrees, than the corresponding values measured on photographs. This is believed due to a lack of sufficient detail in the maps for this kind of a study; they do not completely reflect the short reach of flattened slope that occurs in the immediate vicinity of profile 2 in the east half of the glacier, which is discernible in some photographs. (See fig. 4.) See also the generalized slope values for the glacier given in the tabulation on page 5.

One source of error in the measurement of glacier slopes on photographs, under conditions similar to those at profile 2, is the effect of varying vertical angles of camera view that result from the different stages of the glacier. During the 18 years covered by this analysis, the mean altitude of the glacier surface along profile 2 fluctuated below the camera viewpoint at station 14 by amounts ranging from 110 to 240 feet (34 to 73 m). Thus, because of the downward angle of camera view, the longitudinal ice-surface profile appearing on the prints to be the crest probably lies on the far side of the true crest. In addition, as the glacier surface rises and falls from year to year the crest seen on the photographs may shift laterally toward and away from the camera or, by chance, may lie at an angle to the main flow lines of the glacier.

The above factors create some relatively minor errors when glacier slopes measured on photographs are compared with those obtained from contour maps. However, the fact that the changes in slope obtained by the two methods are reasonably consistent with each other indicates that the photographic method, which is relatively low in cost, is accurate enough to be a useful and valuable accessory in a reconnaissance study of glacier slope.

Additional comments on the slope of the glacier are contained in the section "Crevassing and General Character of Glacier Surface."

SNOW LINES AND FIRN EDGES

Oblique photographs of a glacier taken from stations on the ground along only one side of a glacier were found to have but limited value for mapping and analyzing the boundaries of snow and firn. These photographs give fairly satisfactory coverage for that purpose on the full width of the glacier up to an altitude of about 5,800 feet (1,800 m), and on its eastern half up to about 6,700 feet (2,000 m). However, at higher

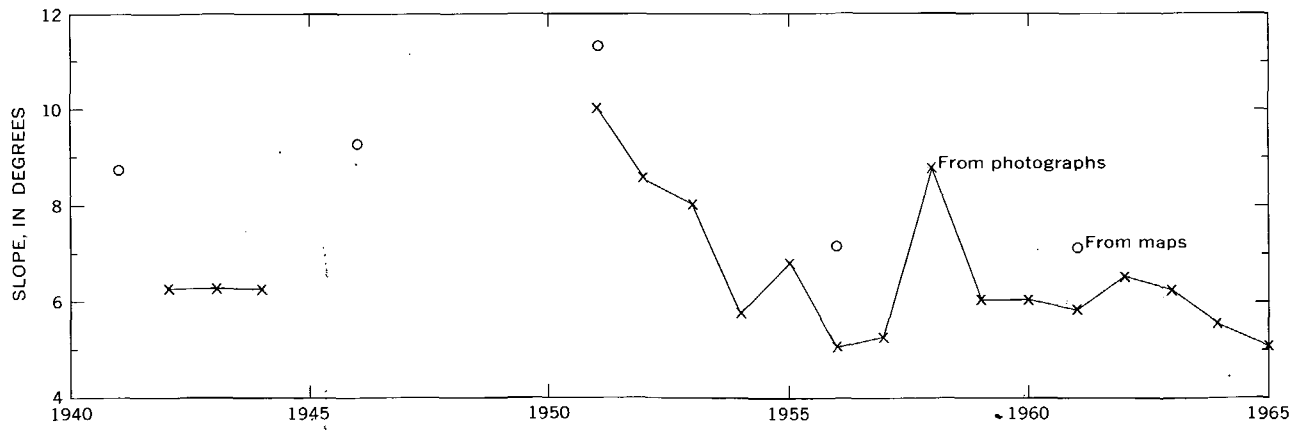

Figure 14.—Determinations of longitudinal slope of the glacier surface at profile 2, as measured on the annual photographs taken from station 14-W, are compared graphically with those measured on the 5-year series of topographic maps.

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altitudes some parts of the glacier surface are obscured by ice bulges or moraines or by slopes dipping away from the position of the camera. So, when these lines are to be mapped and it is not economical to have photographic stations at rather high altitudes on both sides of a glacier, it would be better to obtain aerial photographs.

In this report the lower edge of the snow is called the snow line, and the lower extremity or edge of the firn is called the firn edge. (See also footnote 1, p. 1.) The wide range in annual altitude of the snow line and firn edge on Nisqually Glacier from 1942 to 1965 and their extremely broken appearance are evident in the various photographs published herein. On a 1955 picture (fig. 15) taken from station 13 a few of the firn areas have been outlined to illustrate their scattered occurrence. Location of the firn edge ranged from about 6,000 to 7,300 feet (1,880 to 2,250 m) during the period covered by these photographs.

Position of the snow line in late summer of each year has been found to range between about 5,800 and 7,300 feet (1,750 and 2,250 m). An example of a well-defined snow line on this glacier is seen in the 1942 view in series 5 (fig. 20), where but little snow remained below 7,000 feet (2,100 m).

QUALITATIVE INTERPRETATIONS

CHARACTERISTICS OF THE TERMINUS

The terminus of Nisqually Glacier has been illustrated by photographs since 1884. These complement the field surveys by showing in more detail the irregularities of the terminal margin and by indicating its approximate position during periods when no surveys were made. For example, figures 16 and 17 show that the glacier terminus near the falls at left was in a more advanced position in 1908 than in 1903.

The dynamic condition of a glacier's snout also is revealed by photographs (Meier and Post, 1962). By its characteristic bulging, crevassed, "fat" appearance an advancing terminus (fig. 16) usually can be distinguished from a retreating terminus (figs. 17–19). If a glacier is receding or stagnant, the front has fewer crevasses and is more gently sloping; it may be segmented as is shown in the 1962 picture in series 5 (fig. 24) where the advance of fresh ice is visible upglacier but has not yet affected the dead-ice terminus. Ice hummocks on the glacier (fig. 17) also indicate a wasting condition. The "sliced-off" appearance of the terminal front shown in figure 18 has been typical of Nisqually Glacier's stagnant terminus during its long recession. For further illustration of changes in the glacier's terminus, see figures 20–25.

The photographs in this report, when viewed in the light of contemporaneous field survey results, show that the appearance of a glacier's terminus is roughly indicative of its dynamic state; however, the terminus does not reflect any condition upstream from the terminal area. Further, annual pictures of the snout do not necessarily reveal the presence or absence of movement of the terminus. For example, while photographs might illustrate the occurrence of a net recession of 30 feet (9 m) in a 12-month period, this could have resulted from 10 feet (3 m) of forward movement accompanied by 40 feet (12 m) of melting, or 70 feet (21 m) of forward movement offset by 100 feet (30 m) of melting.

DEBRIS COVER AND ITS DISTRIBUTION

Annual photographs are useful in a study of the changing patterns of debris carried on a glacier's surface. Examples of information about debris readily observable on the Nisqually Glacier photographs are as follows.

The 1945 view in figure 4 shows that the extensive load of debris carried on the east side of Nisqually Glacier between altitudes of 5,700 and 7,000 feet (1,740 and 2,130 m) originates from Nisqually Cleaver west of Gibraltar Rock, from the southwest slopes of Gibraltar Rock and Cowlitz Cleaver, and from the downglacier hillsides bordering the east side of the glacier. In years of above-average snowfall such as 1890 (fig. 2) and 1954 (fig. 22) this mantle of debris was obscured by snow as far down the glacier as about an altitude of 5,800 feet (1,800 m).

The photographs in figures 20–25 also indicate that the insulating effect of debris was responsible for development of the debris-covered, high, morainelike ridge of ice which was visible for many years near the west edge of Nisqually Glacier downstream from Wilson Glacier; and they show how this ridge later became obscured during the new ice advance.

Changes in debris conditions are also illustrated in figures 27–34, and described both in the picture captions and in the section "Crevassing and General Character of the Glacier Surface."

MORAINES

Photographs may bring out some detailed moraine and erosion patterns not noticed by an observer on the ground because film can emphasize color values and relief otherwise not very apparent. The pictures for different years can readily be examined and compared with respect to subtle features, which may easily be forgotten if observed only during occasional field inspections. An example of such a feature is the light-colored band in the large medial moraine near the east side

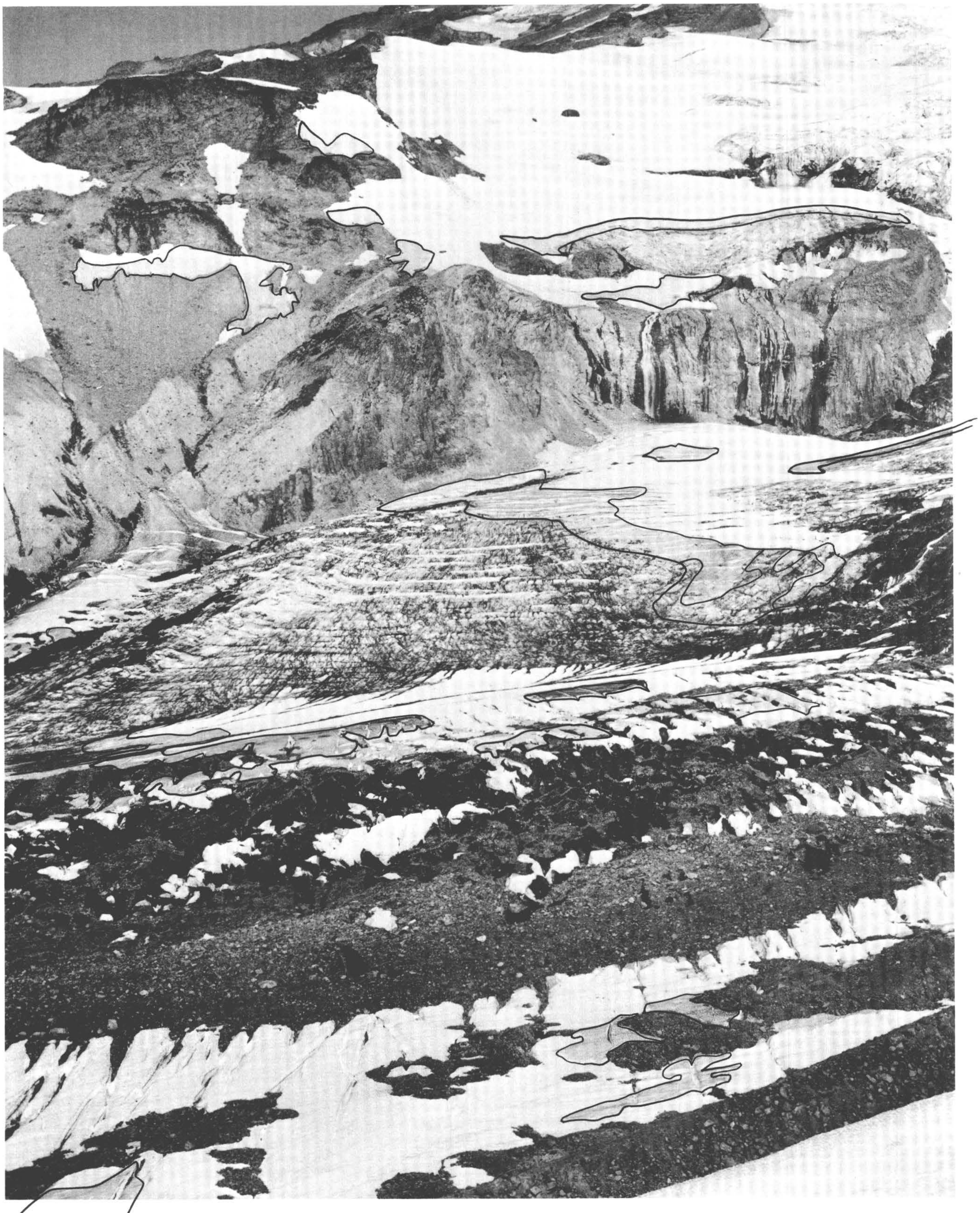

Figure 15.—Several areas of firn are outlined on this September 3, 1955, view taken from station 13. Note patchy, broken configuration of the firn edge.

Figure 16.—Photograph of the terminus selected from series 1–NE, taken from a point at or near the old highway bridge in 1903. Note bulging shape of terminus, steepness of downstream face, and the vertical crevassing pattern. These characteristics suggest that the terminus is, or has very recently been, advancing. Photographed by Eugene Ricksecker; furnished by the National Park Service.

Figure 17.—Photograph of the terminus selected from series 1–NE, taken from a point just below the old highway bridge in 1908. Note changes in terminus with respect to 1903 photograph. At upper left the bulging ice has been replaced by ice hummocks; the crevassing pattern on downstream face is no longer predominately vertical; ice surface now has the general appearance of being melted and eroded. These conditions suggest that the advance has ceased and the terminus has begun to recede. Photographed by Mr. Leftbetter of Seattle; furnished by Tacoma City Light.

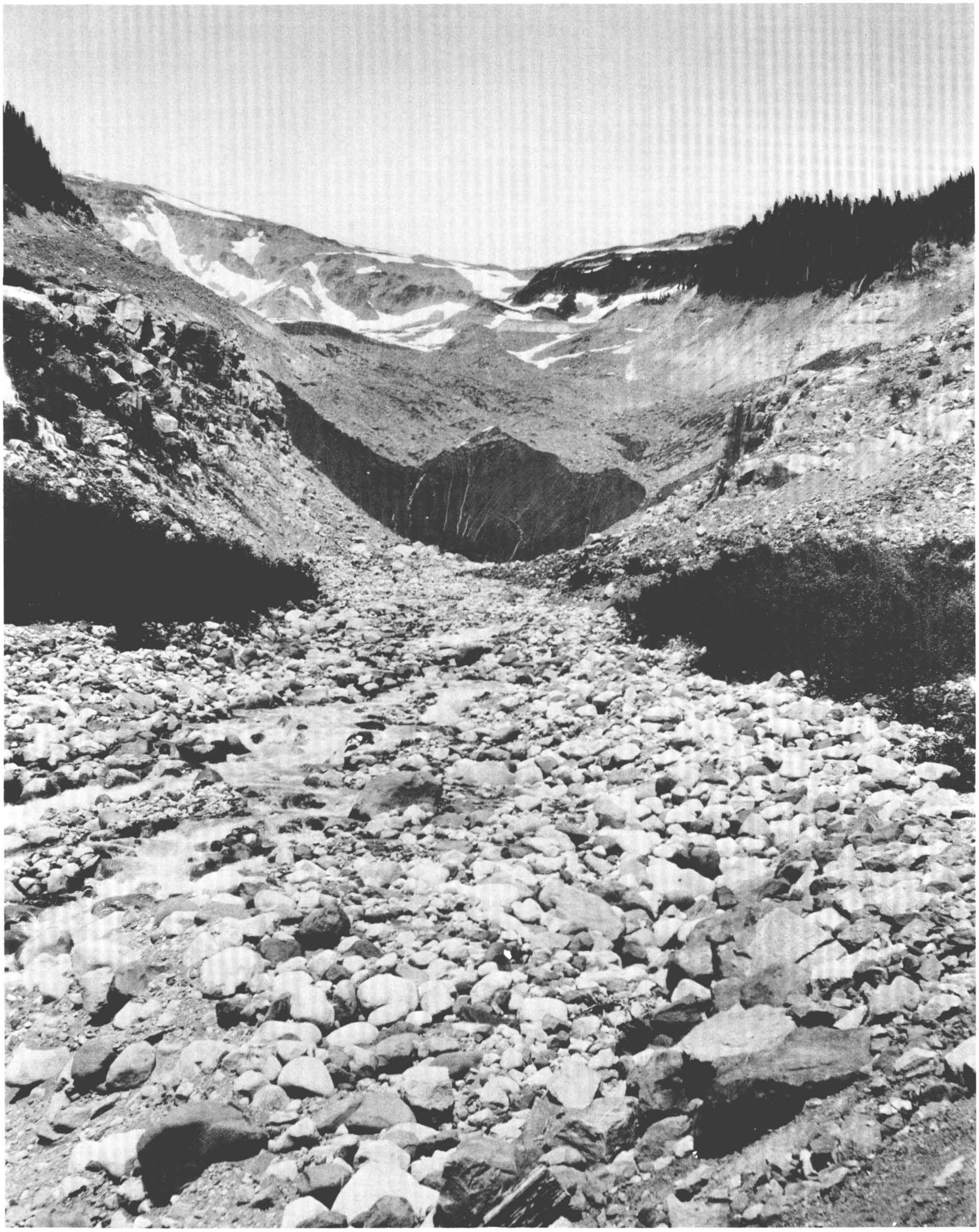

Figure 18.—Photograph of the terminus selected from series 1–NE, taken from a point at or near the old highway bridge on July 5, 1929. In marked contrast to the 1903 and 1908 appearances, the noncrevassed, "sliced-off"-looking terminal face and the generally concave, debris-covered condition of the surface above indicate that the terminus is now definitely receding and is approaching a stagnant condition.

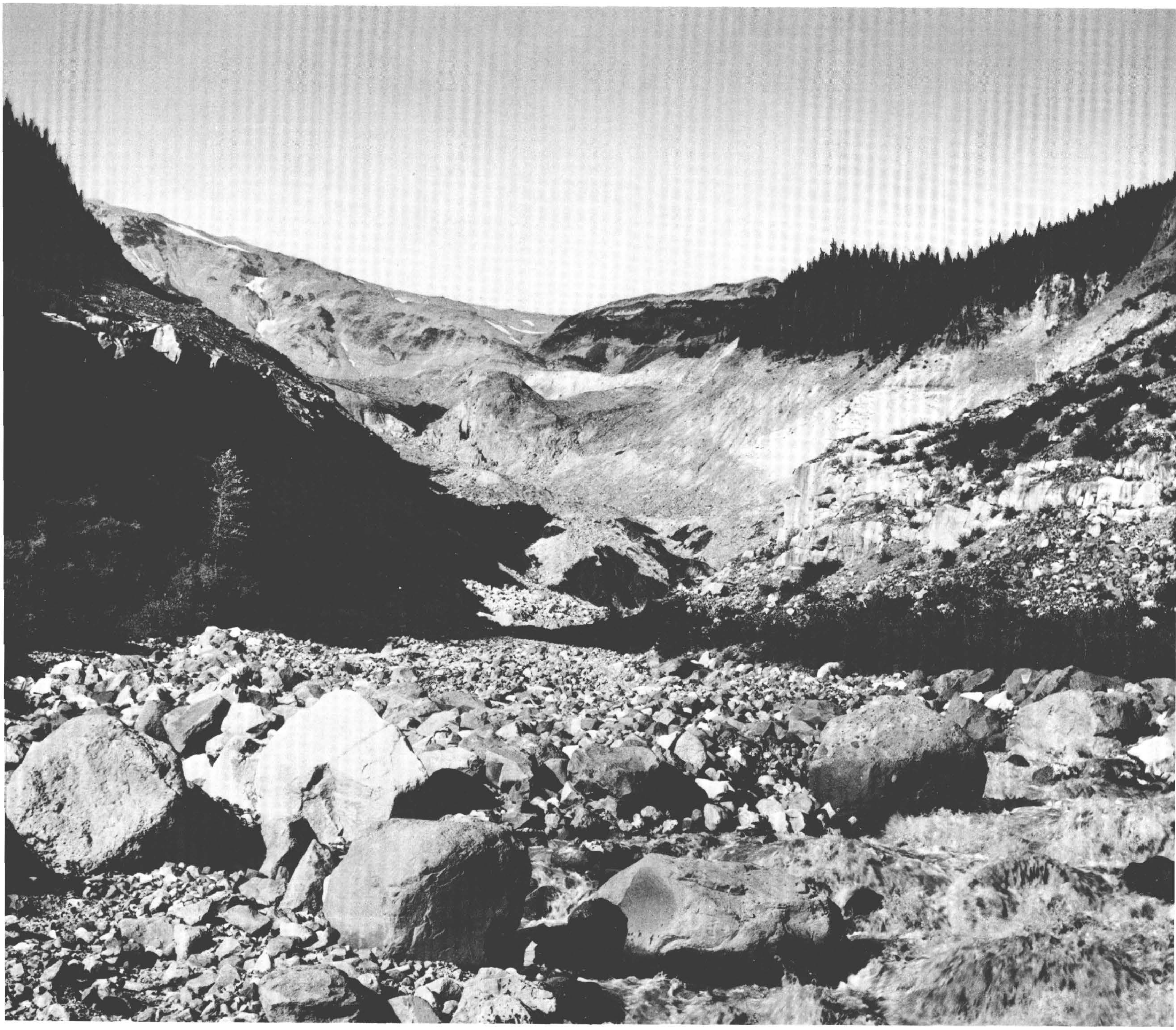

Figure 19.—Photograph of the terminus selected from series 1–NE, taken from a point at or near the old highway bridge on August 19, 1942. The terminus is now more irregular and segmented than in 1929. This suggests stagnation, as there is little evidence of ice flow to the terminus from above. The rate of melting is probably reduced because of the extensive debris cover.

Figure 20.—Lower part of Nisqually Glacier as seen from station 5 on August 31, 1942. Approximate locations of the surveyed cross profiles are shown. Entire glacier is receding. Area down glacier from profile 1 (lower end of the white ice) is stagnant, as indicated by hummocky, debris-covered, noncrevassed ice. Note the long morainelike ridge of debris-covered ice immediately to left of the white ice. The nunatak is bare. Note debris load on right half of the glacier from profile 3 downstream.

Figure 21.—Lower part of Nisqually Glacier as seen from station 5 on August 22, 1951. Since 1942 the glacier has thickened by about 80 feet (24 m) at profile 3 and 40 feet (12 m) at profile 2, but it still is thinning at profile 1. Note the lateral melting of ice ridge to left of the nunatak, as compared with the 1942 view, and the exposed river bed.

Figure 22.—Lower part of Nisqually Glacier as seen from station 5 on September 1, 1954. This is the year of minimum ice mass at profile 1 where, according to surveys, the glacier surface has dropped 13 feet (4 m) since 1951; at profile 3 it has dropped 21 feet (6 m), but at profile 2 the glacier is now 42 feet (13 m) thicker than in 1951. Note steep front of the vigorous advance of fresh ice which is passing to left of the nunatak. Downstream from there the ice is "dead" and melting away—slowly, however, owing to its insulation by a thick mantle of debris. Surveys show that 1954 is the first year when a segment of the ice surface near the west end of profile 1 began to rise.

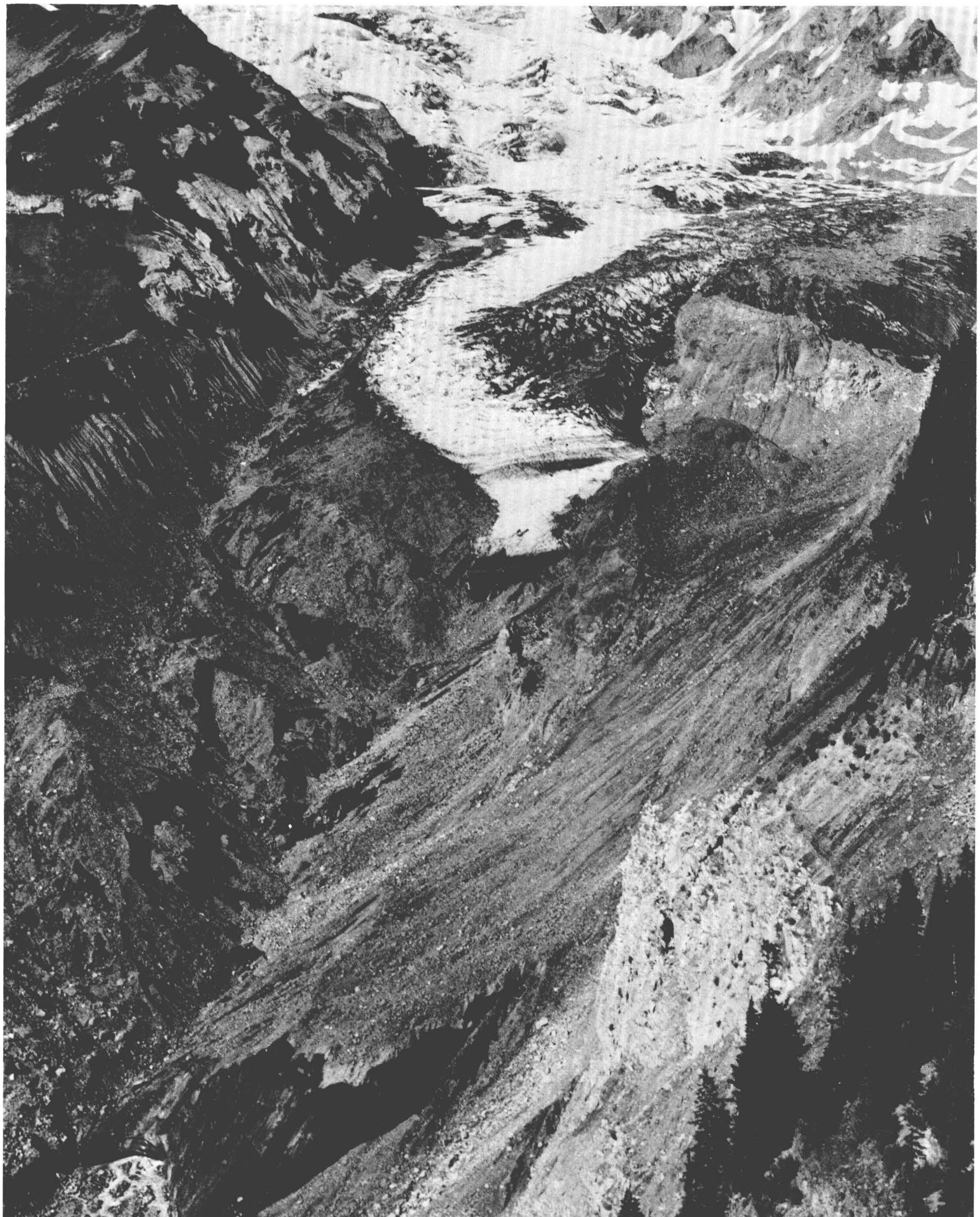

Figure 23.—Lower part of Nisqually Glacier as seen from station 5 on September 11, 1959. With respect to its 1954 condition the glacier now is 9 feet (3 m) thinner at profile 3, 12 feet (4 m) thicker at profile 2, and 70 feet (21 m) thicker at profile 1. The stagnant ice terminus now is visible at lower left. Fresh, white ice has nearly obscured the debris-covered ice ridge opposite the nunatak near the left (west) edge of the glacier.

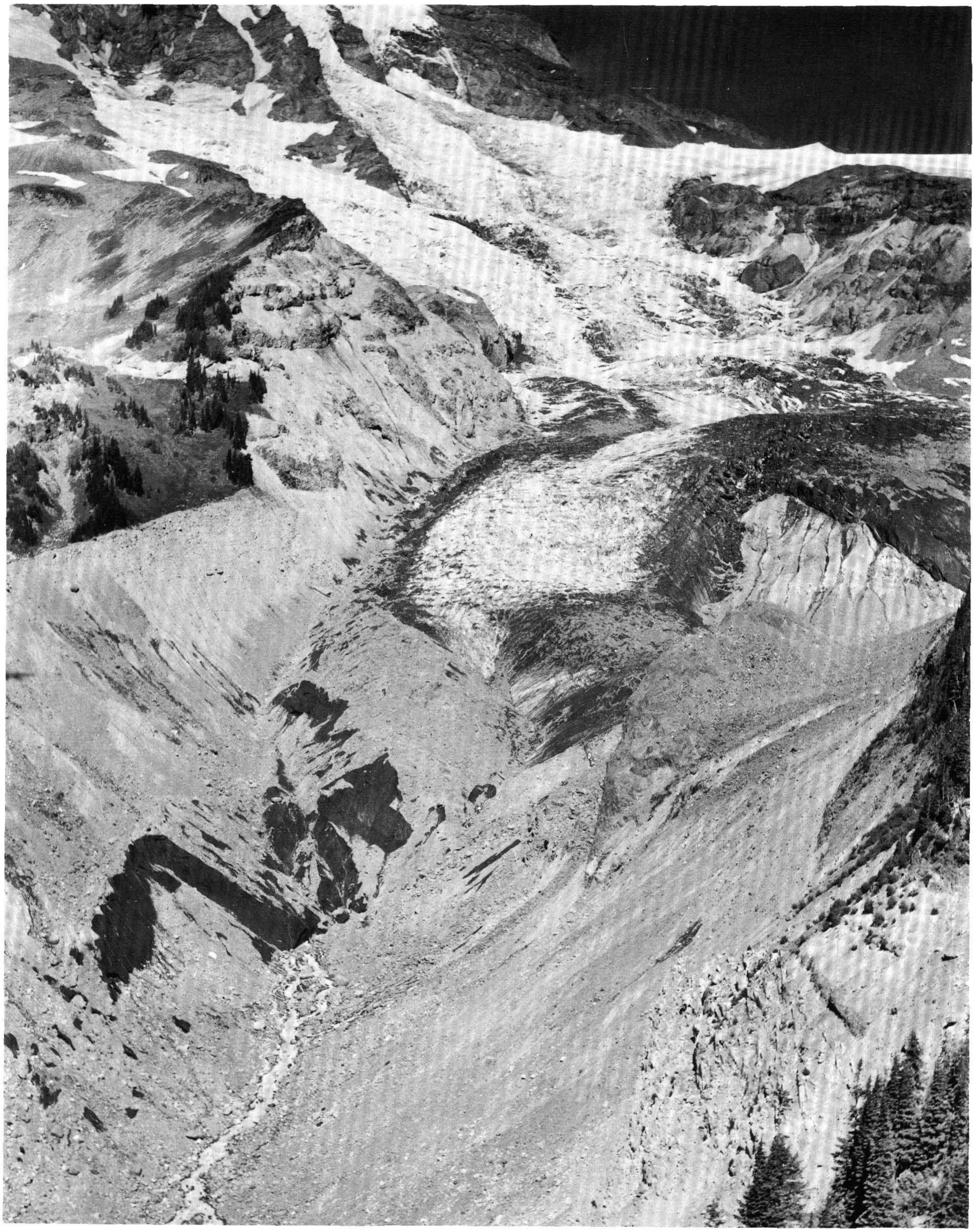

Figure 24.—Lower part of Nisqually Glacier as seen from station 5 on September 8, 1962. Profile 3 is 7 feet (2 m) higher than in 1959, and since then the glacier has thickened 22 feet (7 m) at profile 2 and 24 feet (7 m) at profile 1. The broad bulge of thickening is visible in midglacier in the vicinity of profile 2. The nunatak has been topped by flowing ice. Dead ice downstream has receded considerably since 1959, but now previously stagnant ice in midchannel is thickened and has been incorporated in the advancing terminus.

Figure 25.—Lower part of Nisqually Glacier as seen from station 5 on August 30, 1965. With respect to its 1962 condition the glacier has gained 3 feet (1 m) in thickness at profile 3 and lost 5 feet (2 m) at profile 2; however, at profile 1 the thickness has increased 34 feet (10 m). The preliminary result now available for the 1966 survey shows that 1965 was a peak year at profile 1. The vigorous terminal reach and snout of the glacier have completely covered or incorporated all vestiges of stagnant ice. The nunatak is almost entirely engulfed.

of the glacier in figure 4. Another example is shown in the 1940 photograph taken from station 12 (fig. 26), which illustrates several small lateral moraines that had been deposited along the east side of the glacier at an altitude of 6,400 feet (1,950 m), suggesting a discontinuous rate of recession of the glacier.

CREVASSING AND GENERAL CHARACTER OF THE GLACIER SURFACE

In addition to the data presented in the preceding sections, some further examples of what photographs can show about glaciers are given below on the following subjects (all of which have not been studied herein in detail):

1. Crevassing patterns, from which the nature of the subsurface structure, the direction of ice movement, and changes in rates of movement can be interpreted.
2. Information of changes in surface slope, or the shape of its longitudinal profile, in areas not covered by surveys and contour maps.
3. Some details about advance, recession, debris load, contour, movement, thickness, and surface erosion.

Terminus to profile 1

Photographic series 1–NE (figs. 16–19) and 5 (figs. 20–25) illustrate the gradual deterioration and shrinkage of the entire glacier downstream from the nunatak and profile 1, and its subsequent reactivation. This lower area was virtually stagnant from about 1944 to 1954, but a spectacular advance of fresh ice passed the nunatak in 1954–55 and reached the terminus in 1963. By 1965 it had given form to a new, vigorous-looking terminus.

Profile 1 to about 1,000 feet (300 m) above profile 2

Captions for the photographs in series 6 (figs. 27–31), 7 (figs. 2–5), and 14–W (figs. 7–10) contain miscellaneous descriptive comments for this reach of the glacier. Certain features can be seen more clearly in one series than in the others. The following comments about the photographs in series 6 and 7, arranged in chronological order for each series, include most of the descriptive material that is contained in the captions:

Photographic series 7 (figs. 2–5)

1890 The glacier above the nunatak is at the highest stage ever known to have been photographed.

1915 Note the debris-covered moraines along far side of glacier, which were not visible in 1890. The nunatak (at lower right) still is covered by ice.

1945 Nunatak is exposed. Slope at profile 2 is almost flat. Light-colored band of debris shows in medial moraine at right center; Wilson Glacier ice discharge is very low. There is almost no crevassing in middle reach.

1963 Crevassing in midglacier near profile 2 is extremely coarse or rough. Ice level at profile 2 is the highest in nearly 30 years. Direction of the crevassing pattern in east part of glacier above the nunatak, when compared with that in figure 27, indicates that as the nunatak becomes submerged a lesser proportion of the east-half discharge is diverted toward the west canyon wall.

Photographic series 6 (figs. 27–31)

1952 White-ice stream at left has much more uniform slope than in 1945. This is first year since the early 1940's when fresh crevasses have appeared in midglacier above the nunatak. Their direction, at a steep angle to the general direction of ice flow, indicates strong longitudinal shearing above the nunatak caused by more vigorous flow in the east half of the glacier.

1954 New ice front is passing the nunatak. Note severity of the crevassing upstream and its continued angling (since 1952) with respect to the valley axis.

1958 Ice level at profile 2 peaked in 1957; at profile 1 it remained constant for 4 years before again advancing in 1962. The slope at profile 1 appears rather steep. In this photograph there is a good portrayal of the ablation of crevasse walls.

1961 See large patch of debris at lower left which has greatly increased since 1958. A flat reach appears to be forming in white-ice slope above profile 2. Nunatak is being topped with ice.

1965 Profile 2 appears to be on a long reach of rather uniform slope, with flat slope occurring not far upstream from there. Nunatak is almost entirely engulfed with thick ice. This year the ice level at profile 1 is highest since about 1938.

1,000 feet (300 m) above profile 2 to above profile 3

For comments about this area, see captions of the photographs in series 15 (fig. 12) and 13 (figs. 32–34). Series 15 provides some coverage of upper part of glacier for the period prior to 1949, before series 13 was begun. A summary of the comments contained in the captions follows:

Series 15 (fig. 12)

1944 Glacier is nearing the end of a long period of recession, and at this stage there is very little crevassing. The inflow of ice from Wilson Glacier is low; note the large exposures of bedrock. A heavy load of debris is being carried, contributed from both banks of Nisqually Glacier.

Series 13 (figs. 32–34)

1949 This picture was taken from a point about 500 feet (150 m) upstream from the station where remainder of the series was taken. Crevassing pattern has expanded since 1944, especially in areas nearest the camera station. Bedrock outcrops at lower end of Wilson Glacier are nearly covered.

1957 Glacier surface at profile 3 is 10 ft (3 m) higher than in 1953; ice field at top of cliff at left is much thicker. Crevassing now extends to east edge of the glacier.

1965 Surface of glacier in general appears a little smoother and slopes less steep. Firn can be seen in several areas. Ice on cliff at left appears about the same as in 1962.

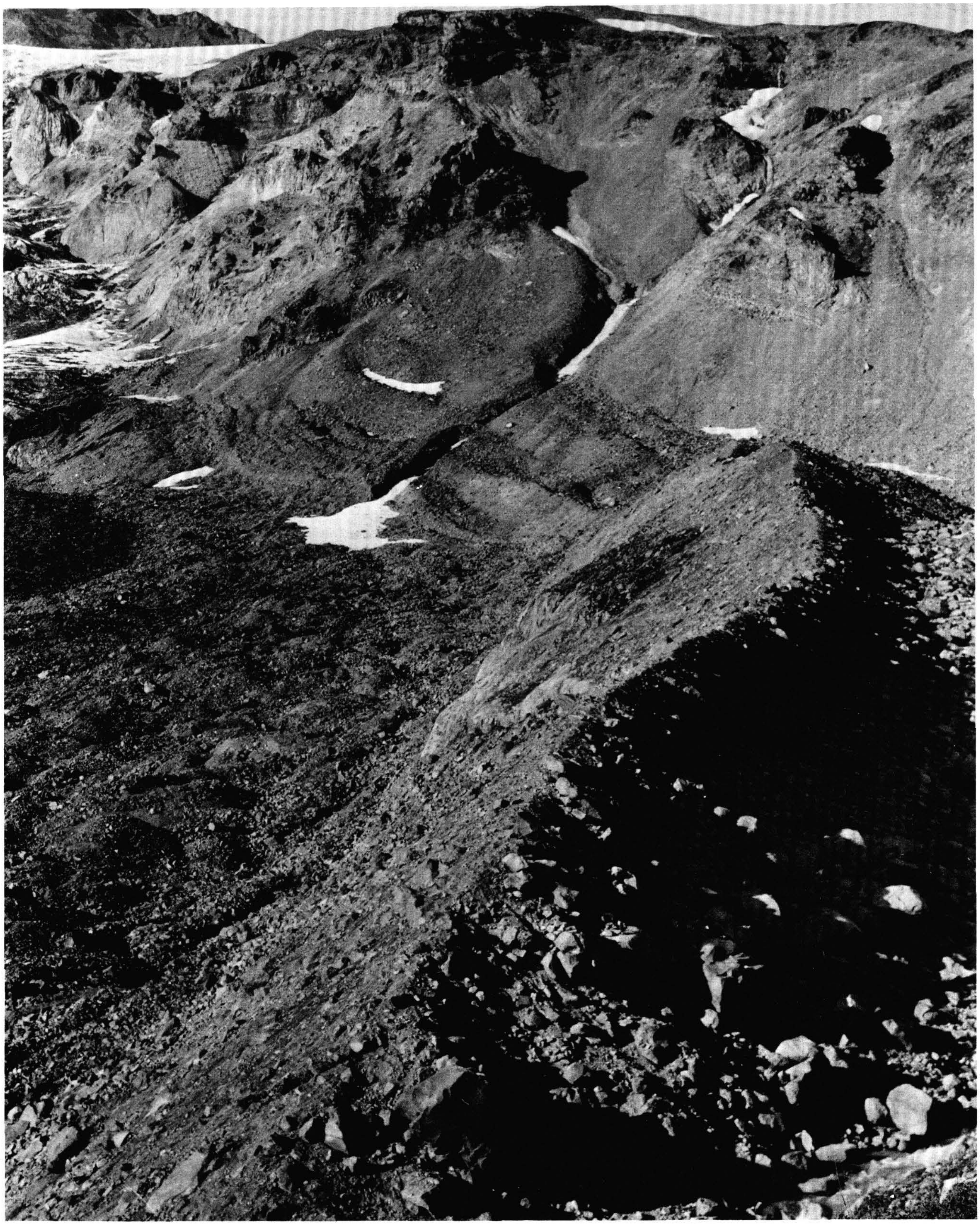

Figure 26.—Patterns of small recessional lateral moraines on east bank at an altitude of about 6,400 feet (1,950 m) are evident in this 1940 view taken looking up glacier from station 12. The patterns suggest that at times the recession progressed in a discontinuous manner, as in successive small steps interrupted by slight advances. Photograph by F. F. Lawrence, Conservation Division, U. S. Geological Survey, August 26, 1940.

Figure 27.—Nisqually Glacier near the nunatak, as seen from station 6 on August 27, 1952. Note long reach of smooth-appearing, convex-upward slope of the white ice, terminating in smooth black ice. Effect of advancing new ice now has nearly reached the nunatak, as evidenced in midglacier by the pronounced new (sharp-edged) crevassing. Stream bed shows both to left and right of nunatak.

Figure 28.—Nisqually Glacier near the nunatak, as seen from station 6 on September 1, 1954. Practically all the main ice flow from east half of glacier is being diverted to west side of the nunatak. Note steep front of the fresh ice advance.

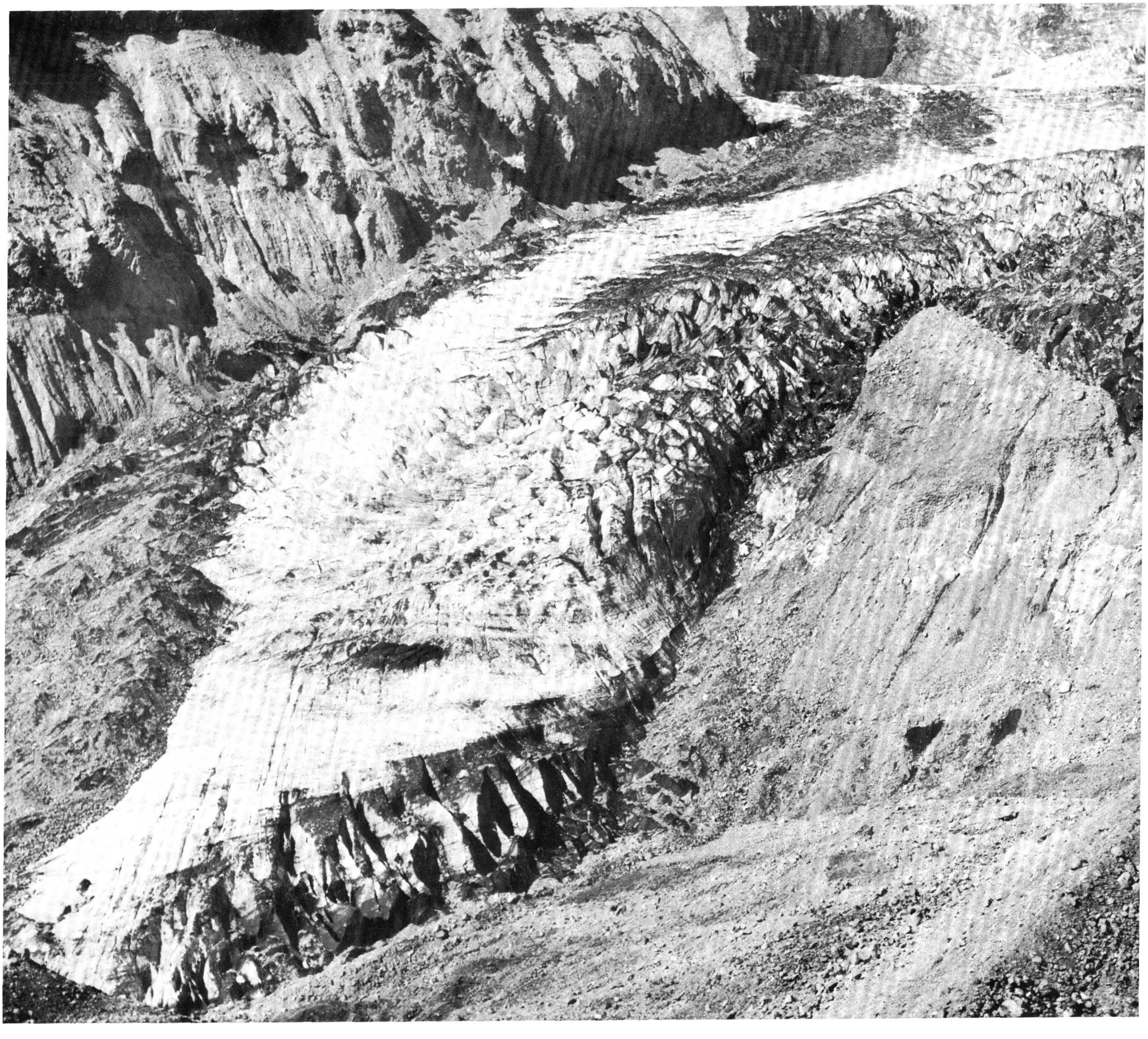

Figure 29.—Nisqually Glacier near the nunatak, as seen from station 6 on September 5, 1958. Note growth and movement of ice over peak of nunatak and along its east side which have occurred since 1954. Crevassing in midglacier in the vicinity of the nunatak has a very coarse pattern, and this photograph is a good portrayal of the ablation of crevassed walls. This was a summer of abnormally high ablation. The ice-cored, morainelike ridge noted at left in the 1942 view in series 5 (fig. 20) has nearly disappeared.

Figure 30.—Nisqually Glacier near the nunatak, as seen from station 6 on September 6, 1961. Note finer pattern of the crevassing in comparison with 1958, and the large patch of debris on ice at lower left. Slope at profile 2 appears reduced. This is the fourth consecutive year, beginning with 1958 (fig. 29), in which surveys show that the elevation and slope of the glacier surface from profile 2 to profile 1 have remained nearly constant.

Figure 31.—Nisqually Glacier near the nunatak, as seen from station 6 on August 30, 1965. Crevassing patterns this year are generally coarser than in 1961. This wave of ice advance which is engulfing *much of the nunatak reached a peak at profile 2 in 1963 and at* profile 1 in 1965. Photographs show that a substantial part of the east-half discharge is now continuing straight down glacier parallel to the valley margins, in contrast to the 1952–54 conditions of nearly complete diversion to the west. See also figures 5 and 25. The large patch of debris visible in 1961 has gone, but debris still is surfacing *just to left of nunatak. Debris mantle again is continuous in reach* along west canyon wall where an ice ridge formerly existed.

Figure 32.—Upper reaches of Nisqually and Wilson Glaciers as seen from station 13 on August 28, 1949, taken several hundred feet (say 150 m) up glacier from station 13. Location of profile 3 is shown. Along profile 3 the surface of the ice is 62 feet (19 m) higher than in 1944 (fig. 12); 19 feet (6 m) of this was added since 1948. Crevassing is becoming more extensive. Bedrock outcrops at the mouth of Wilson Glacier are nearly covered. Many of the bedrock outcrops noted with X's in figure 12 (1944) are already covered by the expanding glacier.

Figure 33.—Upper reaches of Nisqually and Wilson Glaciers as seen from station 13 on August 30, 1957. Most of exposed bedrock areas marked in figure 12 (1944) are now covered by Wilson Glacier. Glacier surface at profile 3 is only 3 feet (1 m) higher than in 1949, but near left edge of picture it probably is about 60 feet (18 m) higher because at profile 2 the ice level rose 97 feet (30 m) from 1949 to 1957. The crevassing appears much coarser (rougher) now and extends to the east edge of the glacier. Exposed face of the ice field above the cliff is thicker. The falls at far left are nearly dry (compare with fig. 12). Note the different layers (ages) of firn exposed in the small area at lower right, which can be differentiated by various shades of gray.

Figure 34.—Upper reaches of Nisqually and Wilson Glaciers as seen from station 13 on August 30, 1965. The glacier from profile 3 downstream to where it leaves this view has now reached a steady-state condition, as determined by the annual surveys. In general the crevassing appears similar to that of 1957. Firn can be seen in many areas. Ice on cliff at left is much thicker than in 1957.

EROSION AND DEPOSITION

Banks and lateral moraines

Annual photographs reveal the progress of erosion along the banks of a valley glacier and along old lateral moraines. The 1947 and 1965 views in series 11 (fig. 35) illustrate 18 years of erosion of west side of the old east-bank lateral moraine. Along this part of the moraine the average lateral recession of its crest over the 18-year period has amounted to a total of 10–15 feet (3–5 m).

In regard to erosion of the banks of a glacier, the views in series 14–W (figs. 7–10) show how some of the bedrock areas on the steep hillside above the west end of profile 2 became unrecognizable within 20 years. Note changes in the lower rock formations seen in the 1942 and 1960 views, which were photographed under similar light conditions. Thus, on photographs of a canyon wall, it may be difficult to pick out bedrock features that will be usable as long-term landmarks for measurements in photographic studies. In the present study, a few usable points were found that could be identified on pictures throughout the 24-page period of record.

Outburst floods

Repetitive photographs also portray changes in topography and vegetation in the channel and valley below a glacier that result from outburst-type floods (jökulhlaups). Three such floods emanating from Nisqually Glacier are described briefly below.

Flood of October 14, 1932. This flood tore away the reinforced concrete arch bridge which had been constructed in 1926. A precipitation total of 6.90 inches (175 mm) fell at Paradise Ranger Station October 10–13, inclusive. It is interesting to note what apparently is the deck of that bridge clearly visible in the 1947 view (fig. 37) in series 3 (figs. 36–38), just below the tree-covered island near the center of the picture.

Flood of October 24–25, 1934. A series of outburst surges from the glacier, according to the monthly report of the Superintendent, Mount Rainier National Park, dated November 5, 1934, "completely plugged the bridge and piled rock and debris 15 feet deep on top of the arch. Approach roads on both sides of the bridge were washed out." Precipitation of 8.92 inches (227 mm) occurred at Paradise Ranger Station October 20–25, inclusive. This bridge, less than 2 years old and situated at the same site as the bridge it replaced after the 1932 flood, was reconditioned and used until its washout in 1955.

Flood of October 25, 1955. The flood occurred about noon and destroyed bridges and other property downstream. It was preceded by heavy rainfall (a total of 5.51 inches (140 mm) was measured on the 24th and 25th at Paradise Ranger Station) and was observed by a Park Ranger to flow in several large surges. The frontal wave of the first surge was estimated to be 20 feet (6 m) high, and the water carried many large rocks and chunks of ice that were visible at the surface. The first surge tore from its abutments the heavily reinforced 80-foot (24-m) span, concrete highway bridge.

Natural changes below glacier from floods and other causes

The 1934,[4] 1947, and 1965 pictures in series 3 (figs. 36–38) illustrate the removal of vegetation, channel widening, and subsequent killing of trees that occurred for a few thousand feet (500–1,000 m) below the bridge as a result of glacier floods of the early 1930's and 1955.

The flood channel in the vicinity of the highway bridge was widened by the 1955 flood, and some vegetation was removed, as illustrated by the 1949 and 1956 views in series 2–S (figs. 39*A*, *C*). Margins of the flood plain and vegetation as they existed a month before the flood are indicated by white lines in figure 39*C* (1956). Note also the automobile-size boulders that were cast up onto the parking area just to left of and above the bridge, and the much larger boulder deposited upstream. Many large trees downstream from the bridge were washed away.

The annual photographs in series 2–S (only a few of which are shown in this report) show some interesting variations in the configuration of the low-flow channel between the glacier terminus and the highway bridge. They reveal how within one season the channel would change from meandering to straight, or vice versa, then retain one form for several consecutive years. An example is evident from a comparison of the photographs shown as figures 39*A* and 39*B*, for 1949 and 1950. Note also the new terraces visible in 1950 along the flood plain. Each subsequent annual view showed that the channel remained straight from 1950 until after 1953 (which was the last view taken until 1956).

A tributary alluvial fan, first visible in 1960, was deposited on right-bank flood plain above the bridge; by 1965 (fig. 39*D*) it had become a little larger.

The 1932–36 photographs taken by the National Park Service looking upstream from the bridge, which are not published here, indicate that the flood of October 1934 was very substantial and erosive above the bridge as well as in the vicinity of the island 1,000 feet (300 m) downstream.

[4] This "1934" undated photograph closely matches the appearance of the glacier terminus in a National Park Service photograph dated September 5, 1934. The match is fair, but less perfect, with their 1933 photograph; it is clearly poor with their October 1, 1932 photograph. Thus it seems likely that this "1934" picture, upon which the large amount of downstream flood plain vegetation is visible, was taken after the 1932 glacier outburst flood and before the October 1934 flood, when denudation of that vegetation probably took place.

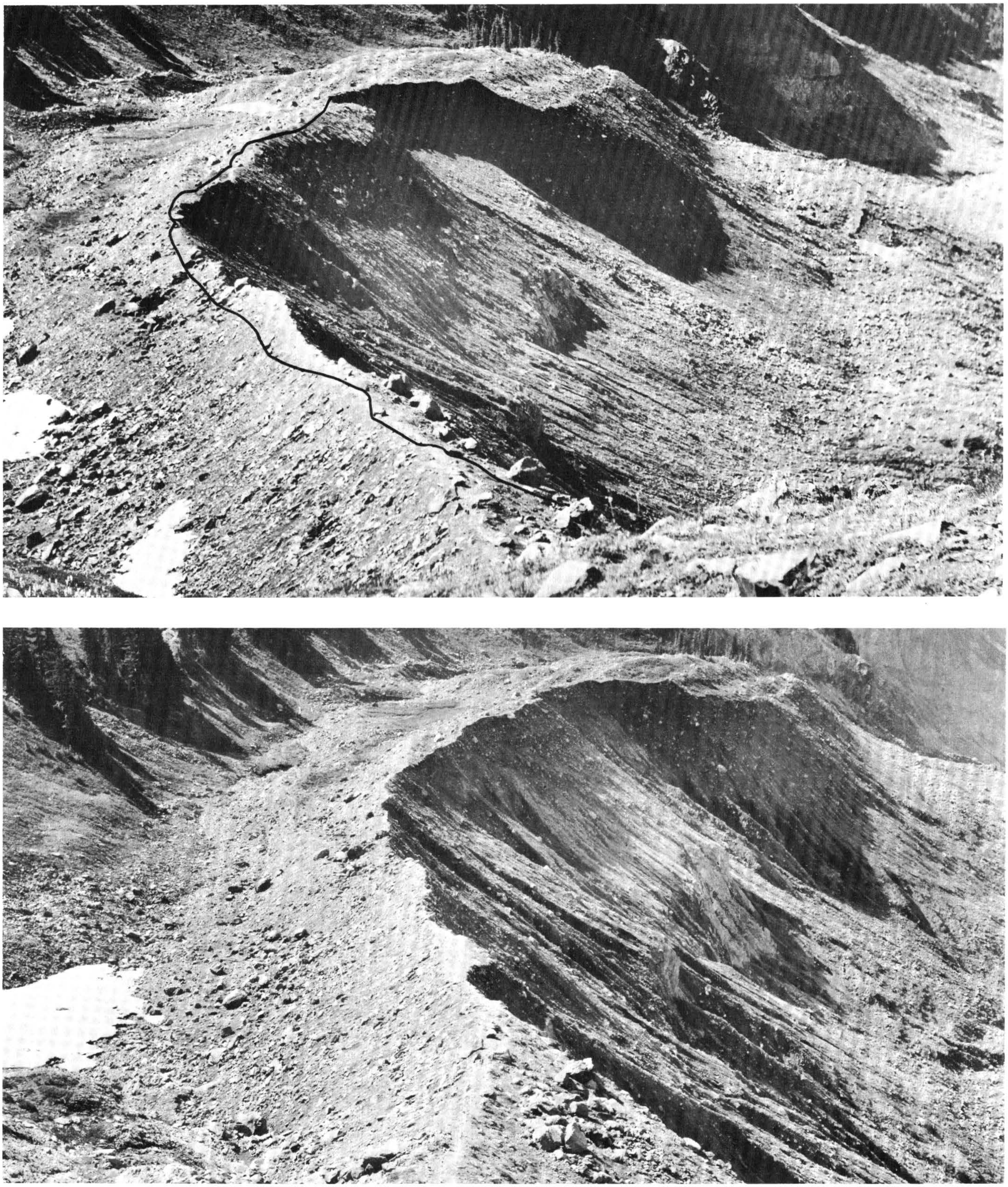

Figure 35.—Erosion of old (pre-1840) lateral moraine on east side of the glacier is shown by the series 11 photographs of August 25, 1947 (upper), and September 4, 1965 (lower). The total erosion during the period 1947–65, indicated by black line on the 1947 view, appears to have averaged between 10 and 15 feet (3 and 4 .5 m) horizontally.

Figure 36.—Nisqually valley below the glacier, as seen from station 3 in 1934 prior to October flood (date estimated; see footnote 4, page 44). Photograph furnished by Conservation Division, U.S. Geological Survey. Note substantial stand of trees and brush on west part of flood plain, and river on east side of flood plain.

Figure 37.—Nisqually valley below the glacier, as seen from station 3 on August 25, 1947. West of the island of trees, most of the vegetation present in 1934 view is gone, due to glacier outburst flood of October 1934. The river now flows west of this island of trees. The deck of the concrete highway bridge used prior to the October 13, 1932, flood is visible on flood plain just below island of trees (arrow).

Figure 38.—Nisqually valley below the glacier, as seen from station 3 on August 31, 1965. Aggradation on the flood plain, caused by the outburst flood of October 25, 1955, is evidenced by altered topography and dead trees. A new bridge was constructed high above the flood-affected channels.

CONCLUSIONS

The information and data on glacier characteristics and changes contained in this report are believed typical of what can be derived from a long-term record of annual photographs. A summary of the findings follows:

1. Data on changes in ice margins are readily obtainable from photographs. Likewise, changes in glacier thickness can be derived either from the positions of the ice margins along a canyon wall or from measurements made on the photographs of distances from a bedrock feature down to a bulge in the ice surface, with the latter photographed as a profile or "silhouette" from below. Both methods check well with the results of stadia surveys; values from the second method probably are accurate in this area to within plus or minus 25 feet (8 m).
2. Annual values of the surface slope at profile 2 were measured on photographs and are believed to be at least as accurate as those determined from the contour maps. Absolute values of the slope ranged from 5 to 10 degrees. A photographic analysis of slope can be made rather accurately from annual pictures provided there is established by field surveys the projection of a reference vertical line on the canyon wall directly opposite the picture station, identifiable on each print with respect to enduring landmarks. Also, the photographic station used must not be much higher than the glacier surface.
3. Position of the summer snow line on Nisqually Glacier was found to range between altitudes of about 5,800 and 7,300 feet (1,750 and 2,250 m), whereas the firn edges appeared to be between altitudes of about 6,000 and 7,300 feet (1,850 and 2,250 m). However, the snow lines and firn edges on this glacier usually are very irregular. Aerial photographs or a more complete coverage of ground photographs than is available for this project would be needed for an analysis of the snow and firn limits in relation to climatic fluctuations.
4. Photographs are helpful in analyzing the rates of retreat and advance of a glacier's terminus and in distinguishing an advancing terminus from a retreating one, through illustration of the characteristic appearance of each. If advancing, the front of the terminus is steep, bulging, and crevassed; if receding or stagnant, it usually has a noncrevassed, more gently sloping appearance or it may become hummocky or segmented.
5. The pictures portray the appearance of a wasting glacier, including its stagnant lower reaches, during the latter part of a long period of recession. Later, they illustrate waves of fresh ice advance which engulfed the nunatak and replaced the segmented, stagnant terminus by a bulging, crevassed "fat" looking front.
6. Photographs illustrate the occurrence, nature, and changes in moraines and debris-covered ice ridges. They also show the sources, distribution, and general nature of the debris carried on a glacier's surface.
7. The dynamic condition of a glacier is indicated quite well by the nature and pattern of the crevassing as well as by the general character of the glacier surface. During ice advances, the crevasses are larger and coarser in pattern than during a recession. A hummocky surface reflects the wasting and ablating condition of stationary or receding ice, as is shown on the photographs.
8. Information about the progress of erosion on the banks and lateral moraines of a glacier can be determined from annual photographs. Canyon wall bedrock features change more rapidly than might be supposed.
9. Some of the effects of glacier outburst floods, often more damaging than is realized, are illustrated by the photographs in this report. The removal or killing of many large trees and the deposition of enormous boulders are shown.

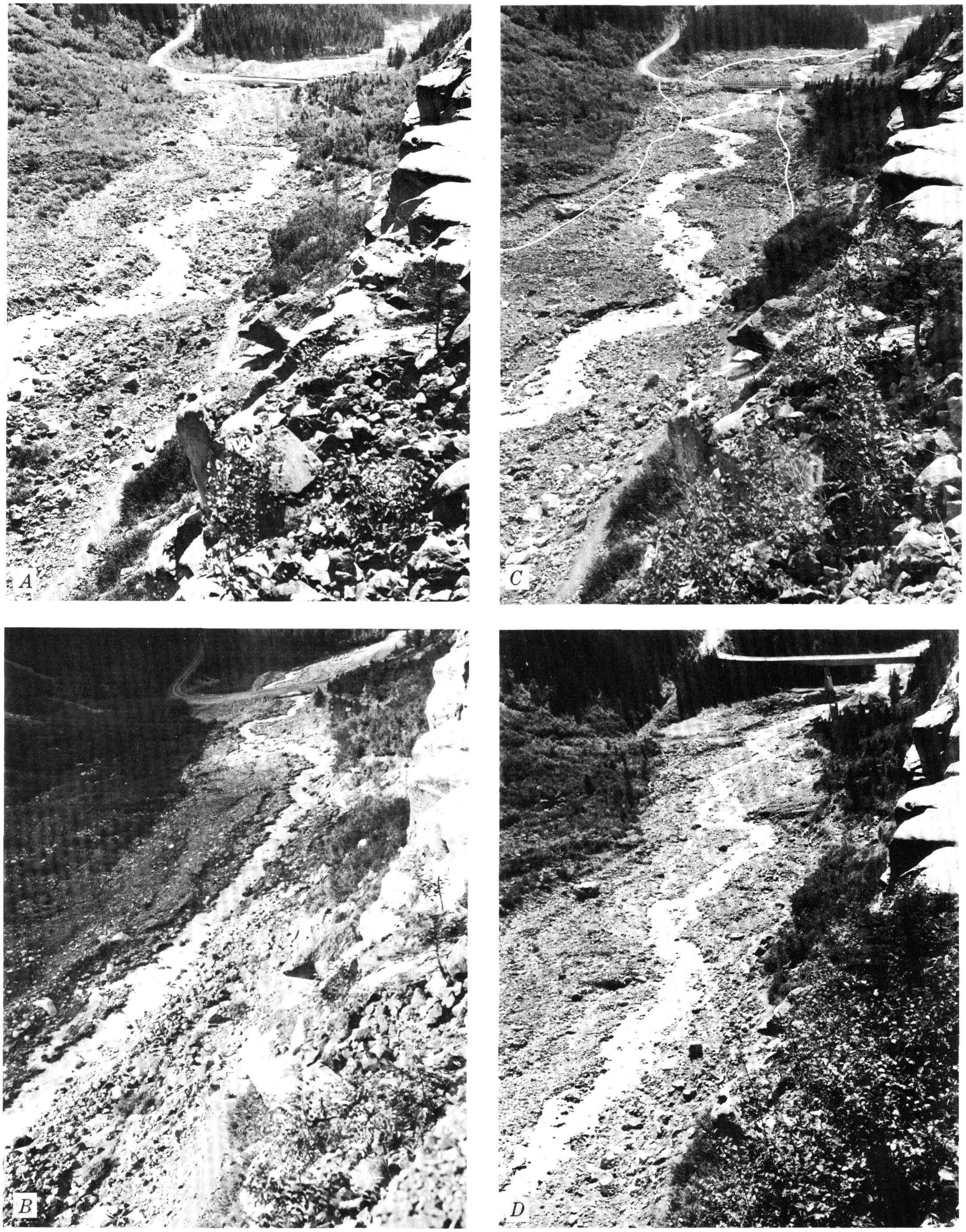
A
C
B
D

Figure 39.—River channel just above the highway bridge, as viewed downstream from station 2 on cliff.

A, August 28, 1949. Channel conditions illustrated in this view are about the same as those shown in the unpublished 1943, 1947, and 1948 photographs. No major outburst floods occurred in this period. Scale in vicinity of bridge is indicated by cars on parking area at left.

B, August 27, 1950. The relatively minor channel changes occurring between 1949 and 1950 still are larger than noticed for any other 12-month period not having a large outburst-type flood. The low-flow channel has become straightened and slightly degraded since 1949, and a few terraces and bars have formed along the left flood plain.

C, August 28, 1956. The October 25, 1955, glacier outburst flood has caused easily recognizable changes in the channel: 1, large (13 by 19 by 25 ft, or 4 by 5.8 by 7.6 m) boulder deposited at left; 2, wider swath cut through vegetation (edges of vegetation before flood indicated by white lines); 3, terrace formed along left side of flood plain; 4, many large boulders (one was 8 by 8 by 15 ft, or 2.6 by 2.6 by 4.9 m) deposited high on left bank above and below highway. Compare with fig. 39 A.

D, August 31, 1965. In the 9-year interval since 1956 note the following: 1, exceptionally large boulder at left has not moved; 2, small terraces are visible at left, caused by moderate-sized floods; 3, an alluvial fan (first visible in 1960) has been deposited by a right-bank tributary this side of the bridge.

RECOMMENDED PHOTOGRAPHIC PROCEDURES

PHOTOGRAPHIC STATIONS

When photographic stations are being selected, possible changes in the glacier and in nearby vegetation should be anticipated. Enough stations should be selected so that, if some should be destroyed or obscured, good views of all study areas including the terminus will still be afforded from other sites as the glacier advances or recedes.

All parts of the glacier subject to analysis should be photographed from at least two different viewpoints, if feasible. Where a particular reach is subject to study, every part of each ice margin in that reach should be visible in at least one picture.

For a study of surface slope from photographs, the station should be about the same elevation as the glacier surface and, if possible, where permanent features such as bedrock strata or outcroppings can be recognized in the background. If an ice advance should block the view from such a station, photographs taken at a higher altitude on an extension of the same cross-profile axis should be satisfactory for continuing the record of slope measurements.

Where stations are not on bedrock, the possibility of encroachment by vegetation or destruction by erosion should be considered. The site should be located in reference to two or more witness rocks in the vicinity. Stations should be marked with monuments such as bronze tablets or steel stakes, which are easily recognized.

When setting up a program of this kind it is better to establish too many rather than too few photographic stations. Some stations can always be dropped, but once any photographic records are missed they are lost forever.

OPTIMUM LIGHT CONDITIONS

Ideally, glacier photography should be scheduled so that the same lighting conditions occur every year at each station. To accomplish this, the photographs should be taken at about the same time of day and on about the same date each year. Without such uniformity in lighting, the changes illustrated in a series of pictures are difficult to analyze, and interpretations may be misleading.

At stations where photographs are taken in several directions, there may be no entirely satisfactory time of day for all of the views. Furthermore, the scheduling of photographs at a series of stations must be adjusted to fit the practicable time of travel from place to place, thus requiring some compromise with the desired light conditions.

When a particular view is found to be blocked or shaded by fog or clouds, it still is advisable to take a picture even though another photograph might be obtained later under better conditions. The first picture may be of poor quality, but perhaps it could be used for study if none other should become available.

SELECTING THE VIEW

The best direction of view at a station should be selected the first year, taking into account the probable movements of the glacier, and then repeated each year without change. The exact site over which the camera is placed should be identifiable by a permanent marker, and the camera should be positioned within a foot of the same location each year. When pointing the camera, it is helpful to refer to an earlier photograph that shows the desired view at the station.

Panoramic views should overlap 20 to 30 percent so that the photographs when trimmed will match satisfactorily. The transverse axis of the camera should be held in a level position, adjusting the view as necessary by raising or lowering the camera's front but without tilting it sideways.

EQUIPMENT

The camera should be sturdy and equipped with a lens that permits high resolution over the entire image and a minimum of optical distortion toward the corners of the picture. It is understood that, as a general guide, the best results from a good lens will be obtained when its aperture is closed two to four stops from its maximum opening. Therefore, under a condition of intense light such as is available at a glacier, a rather slow film is preferable so the middle range of lens openings can be utilized.

A film with wide exposure latitude is needed for satisfactorily reproducing all the shades of contrast that are present in most glacier scenes. Color photography is superior to black and white in recording vegetation, which in the case of many receding glaciers is a very important change to be recorded. For this purpose 35 mm film should be satisfactory. If the photographic party is equipped with two cameras, it is believed worthwhile that the views at all the photographic stations be taken both in black and white and in color.

A desirable format for the photographic image is 4 by 5 because of its ready adaptation to ordinary 8- by 10-inch (20- by 25-cm) enlargements. With any other proportion, part of the negative must be masked when an 8 by 10 print is made; selecting the part or parts of each picture to be masked out and placing the guide marks on each negative for use of the enlarger operator is a time-consuming and relatively unrewarding process.

The rapid shutter speeds normally usable in this work make hand-held camera exposures generally satisfactory from the standpoint of negative sharpness. However, consistently better results, both as to sharpness and proper positioning and levelling of the camera, can be obtained with a tripod if enough time is available.

As mentioned earlier, no advantage has been found in this program in the use of a lens filter—such as a K-2 (yellow) one. A haze filter for reducing the effect of ultraviolet rays on film at high altitudes is helpful in color photography.

RECORDING THE PHOTOGRAPHIC DATA

When the annual photographs of Nisqually Glacier are taken, data are entered on a looseleaf "Index to Photographs" form prepared for recording the following:

Column heading	*Information indicated*
Negative No	Serial file number, entered later in the office.
Film No	Manufacturer's exposure number, which is given on each film of a film pack.
Cam. and F.L	Model and size of camera, and focal length of its lens.
Film and Speed	Name of film, and its ASA speed.
By	Initials or names of each member of the party.
Date	Month, day, and year.
Station No	Number of the photographic station.
Direction	With respect to points of the compass or to the glacier's valley, like "up" or "across".
Hor. or Vert	Enter H or V for position in which the film is held when exposed.
Std. Time	(Inadvisable to use Daylight Time.)
Exposure 1/	For example, enter "200" to indicate 1/200th of a second.
f	Lens opening.
Filter	
Remarks	

A print of each form sheet that has been filled out with the data on a season's pictures is carried in the field for possible reference in succeeding years.

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