# OBSERVATIONS OF GLACIER TERMINI IN THE PRINCE WILLIAM SOUND AREA, ALASKA

by

Marion T. Millett, M. A.

A Thesis Submitted to the Faculty of
Graduate Studies and Research in Partial
Fulfillment of the Requirements for the
Degree of Doctor of Philosophy

Department of Geography
McGill University
Montreal

March, 1965

# PREFACE

This is a study of the fluctuations of glacier termini in the Prince William Sound area of Alaska. It is based primarily on field work done by expeditions during the summers of 1957 and 1961, and also summarizes and incorporates the work of previous investigators. The first part of the study draws heavily from the works of others; however, the data analysis and conclusions are original and the author bears full responsibility for them.

The author wishes to express his sincere thanks to Dr. William O. Field, Director of the Department of Exploration and Research of the American Geographical Society, for making the expeditions possible and for instilling in the author a deep interest in Alaskan glaciers. Thanks also go to the National Science Foundation and to Brigham Young University for sponsoring the expedition of 1961, of which the author was the principal investigator.

Special thanks are due to Professor Fritz Müller, of McGill University, for his thoughtful and careful direction of the author's research and writing.

## TABLE OF CONTENTS

Chapter | Page

## LIST OF FIGURES

| Figure | | Page |
|---|---|---|

| Figure | | Page |
|---|---|---|

Figure | Page

| Figure | | Page |
|---|---|---|

| Figure | | Page |
|---|---|---|

| Figure | | Page |
|---|---|---|

# CHAPTER I

# INTRODUCTION

Since Captain James Cook's historic voyage in 1778, Alaskan glaciers have been described, mapped, and studied many times. Several expeditions have gone to Alaska for the sole purpose of studying glaciers. Of these field studies the most important were the Harriman Alaska Expedition of 1899 (Gilbert, 1903), the National Geographic Society's Alaskan Expeditions 1909, 1910 (Tarr and Martin, 1914), and the work of William O. Field in 1931 and 1935 (Field, 1932 and 1937).

In the summers of 1957 and 1961, the author accompanied expeditions to the Prince William Sound area to study its glaciers. The 1957 expedition was led by William O. Field, and was part of the International Geophysical Year. The 1961 expedition was led by the author, and was sponsored by the National Science Foundation and Brigham Young University. These two expeditions reoccupied many fixed survey and photo stations from earlier expeditions in an attempt to determine glacial activity in the Prince William Sound area through the study of the fluctuations in the position and the condition of glacier termini.

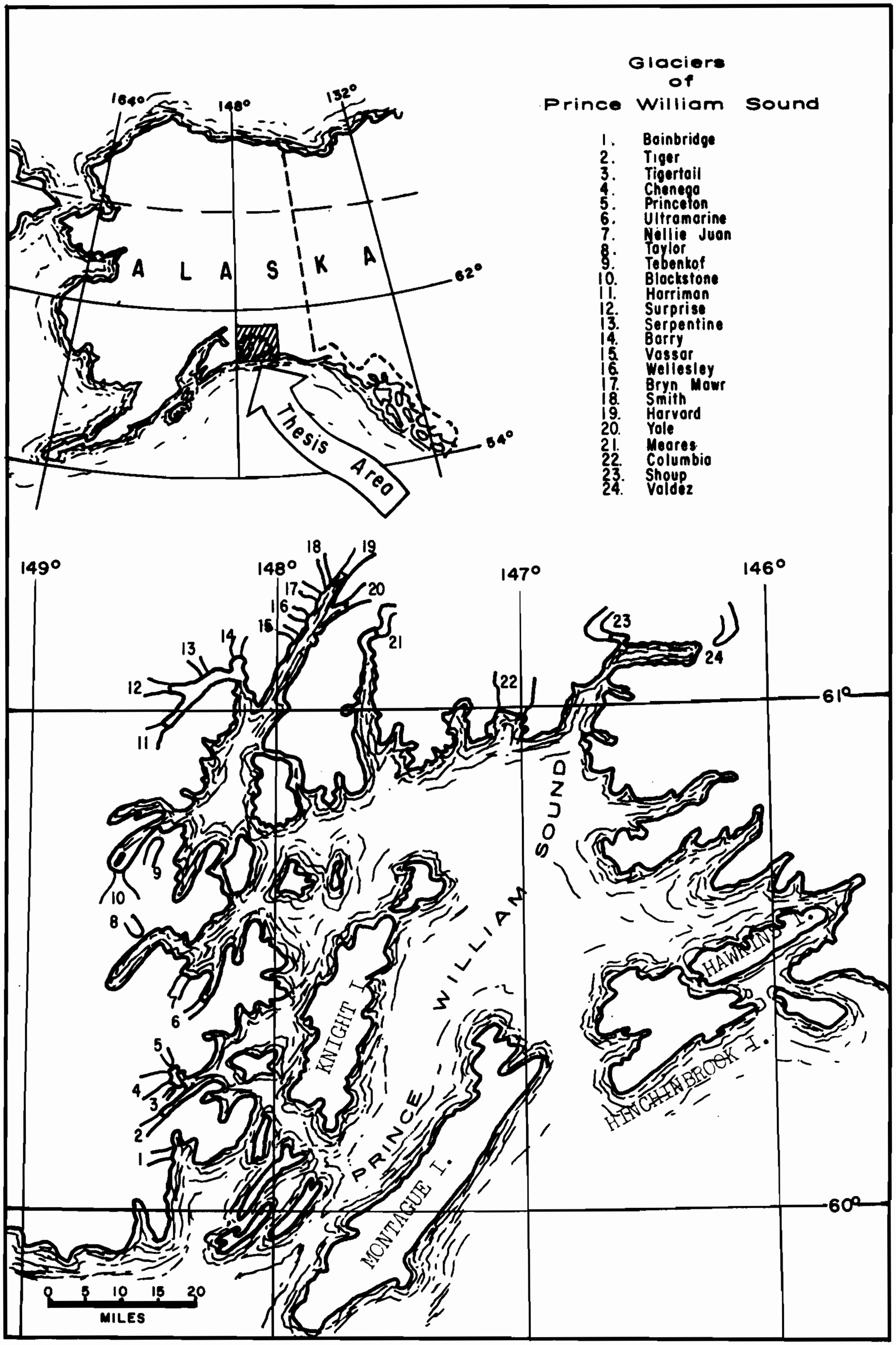
## Statement of Problem

This study, based in part on historical research and in part on the field work done by the 1957 and 1961 expeditions, attempts to discover the trends of glacier terminus expansion and recession in the Prince William Sound area since about the beginning of the century, and to determine whether these trends are related to known physiographic, climatic, and climatically-related factors.

## Description of the Area

Prince William Sound is a large, irregular embayment indenting the south-central coast of Alaska, and lying just north of latitude 60°, and west of longitude 146° (Figure 1). It is roughly square with nearly equal dimensions of 100 miles north-south, east-west, and is separated from the Gulf of Alaska by three large islands: Montague, Hinchinbrook, and Hawkins. Within this barrier is another large island, Knight Island, and several smaller ones. There are no large glaciers known to exist on these islands. Along the coast of the sound, land and sea interfinger in numerous complex fiords. Many fiords in the northern and western parts of the sound contain one or more tidewater glaciers. In the western and south-western part, glaciers flow from the eastern mountains of the Kenai Peninsula. The Sargent Icefield is found here and many of its tongues enter the sound. There are no large glaciers in the eastern part of the sound.

The mountains surrounding Prince William Sound rise abruptly from the base of the fiords and islands, and extensive areas of level or moderately sloping ground are uncommon. In most of




LOCATION of STUDY AREA

Figure #1

the eastern and western parts of the area, the mountain peaks seldom exceed a height of 4,000 feet, and the local relief is generally low. On the northern side, however, in the Chugach Mountains, the elevations are considerably higher, reaching 13,250 feet at Mt. Marcus Baker, with considerable local relief.

The major streams entering Prince William Sound are nearly all fed by glaciers; none of the streams exceeds 30 miles in length or is of more than local interest.

Climatically this area of Alaska is much like central Norway in that it has a large annual precipitation that varies greatly with the locality. This is demonstrated by the weather records kept at two communities in the area, Cordova and Valdez. Cordova, near the sea, receives nearly 150 inches annually, while deep in the protected fiords Valdez receives only 60 inches. Temperatures also vary from the open coast to the protected inlets. At Cordova the summers are cooler than at Valdez, but winters are milder. Winter snow accumulates at all altitudes, with some of it lingering until late summer, even below the line of perpetual snow.

In Prince William Sound there are two settlements serving as coast terminals of travel routes, mine enterprises, and canneries. There are also two Indian villages. The largest community in the area is Cordova, a town that was built as the coast terminal of the Copper River and Northwestern Railway. This railway was constructed to carry copper ore from the Kennecott mines to the steamship lines, and was in operation from 1911 until mining was discontinued in 1938. Cordova is now an important fishing center and the site of several canneries. Port Valdez boasts the oldest permanent white settlement in Prince William Sound. The town of Valdez was established in 1897-98 as the port of entry for the Copper River Valley, and became the coast terminus of the Richardson Highway. Until recently, it was the headquarters of the Third Judicial District of Alaska. Tatitlek and Ellamar are two small Indian villages located in the northeastern part of the sound.

## Pre-Historic Glaciation

The pre-Pleistocene topography of the Prince William Sound area is unknown and the influence of the pre-glacial drainage pattern on the present land forms has not been determined. Tarr and Martin (1914) believed that there was no pre-glacial arm of the sea in the present site of Prince William Sound, and felt that by the end of Wisconsin glaciation the entire area was covered by a great piedmont ice mass. Capps (1931, p. 6) held that a wide barrier of ice bordering the southern coast of Alaska "pushed out to sea some 60 miles" opposite Prince William Sound.

Work by more recent investigators (Moffit, 1954; Murray, 1945) suggests that the great depths (479 fathoms) found in the sound are very old and are not caused solely by Pleistocene glaciation. Also, the discovery of botanical refugia on some of the islands in the sound (Heuser, 1958; Moffit, 1954) suggests that the ice coverage was neither as extensive nor as deep as previously thought. Little is known of the details of post-Wisconsin glacial history. However, after a visit to the area with W. O. Field in 1935, W. S. Cooper (1942) suggested that ecological evidence indicated "A major period of ice contraction in middle post-Pleistocene time, followed by moderate expansion, is maintained in the Prince William Sound region, up to the present."

Early Exploration and Previous Work in the Area

The topography, geology, geography, and glaciation of Prince William Sound have been described by many persons (Gilbert, 1903; Davidson, 1904; Grant and Higgins, 1911; Tarr and Martin, 1914; Field, 1932, 1937; Cooper, 1942). It was first partially explored by Captain James Cook on his third voyage to the Pacific in May 1778 (1784). Subsequently, Russians carried on explorations in 1781, 1788, and 1793 (Petrof, 1900). In 1786, an Englishman, Meares, spent the winter in the eastern part of Prince William Sound; but there is little useful geographical information in his narrative (Meares, 1790). In 1787, the southern and southeastern parts of the sound were visited by the English fur hunters, Portlock and Dixon (Davidson, 1904); and while no mention is made of any visit of their boat to the northwestern part, their outline chart identifies the mouths of two large fiords in that locality. In 1790, Lt. Dn. Salvador Fidalgo (Davidson, 1904) sailed the Philippino into Prince William Sound, but reached no farther northwest than the harbor of Revilla Gigedo, the Unakwik Bay of the latest charts. Malispina, in 1791, and La Perouse, in 1786 (Davidson, 1904), did not reach this far west. By 1790, the Russians had already established sea otter stations in the sound and were rapidly depleting this valuable resource (Davidson, 1904). Vancouver, who arrived in 1794, in obedience to the specific order he had been given to make a survey of the continental shore, made so thorough a reconnaisance of the sound that his map was used by Tebenkof in his atlas of 1849. Vancouver's map continued as an authority until the beginning of the 20th century, long after Alaska had become a territory of the United States, and his early narrative (Vancouver, 1801) was the best authority until 1905.

In considering the descriptions made by the explorers named above, one should remember that only two of these early navigators had men of scientific qualifications with their expeditions to describe the natural history, botany, or geology of the places visited. These navigators were La Perouse and Malispina. Unfortunately, neither of these reached Prince William Sound, but confined their studies to the southeastern shore line of Alaska.

The region of Prince William Sound became better known through the expeditions of Abercrombie and Applegate in 1884 and 1887. In 1884, Lt. W. R. Abercrombie (1899), of the United States Army, tried to ascend the Copper River from its mouth and then tried to reach the interior from Valdez Fiord through the break in the intervening mountains. After the energetic but unsuccessful attempts of Lt. Abercrombie, quite a thorough exploration was made by a civilian, S. Applegate (Davidson, 1904), in the schooner-yacht Nellie Juan in May and June, 1887. Although Applegate's narrative was never published, it was carefully studied and summarized by George Davidson. After interviewing Applegate, Davidson wrote a very interesting description of the features seen by Applegate in the western part of the sound, and published this along with Applegate's map. This map (Davidson, 1904) is the earliest reference for many Prince William Sound glaciers. However, because Applegate was not always close to the features he mapped, data derived from the map are of uneven value.

In 1899, the Harriman expedition (Gilbert, 1903) visited Prince William Sound to study the glaciers. This expedition was perhaps the "grandest" ever to study Alaskan glaciers, having with it some of the finest naturalists and scientists of the time: John Muir, Grove Karl Gilbert, Henry Gannett, C. Hart Merriam, Charles Palache, Frederick Coville, and others. In Prince William Sound the expedition was mainly interested in Columbia Glacier, the glaciers of College Fiord, and the glaciers of Harriman Fiord, the latter taking its name from the expedition. The work of these men was very accurate and deliberate, and many of the stations they established are still useful. They surveyed many glaciers for the first time, established fixed points for surveying and photography, and described in careful detail the geology, botany, and wildlife of the area. The account, written by Gilbert, gives an excellent description of the trip and includes two maps and many photographs and drawings.

In 1905, 1908, and 1909, shortly after the Harriman expedition, U. S. Grant and D. F. Higgins (1910, 1911), of the United States Geological Survey, studied the geology of Prince William Sound. They were the first to discover and to study many of the glaciers. Their work included eleven excellent maps and many photographs.

The next important work was done during 1909, 1910, and 1911 by Tarr and Martin (1914) for the National Geographic Society. This expedition spent more time in the field than any previous party, and their written account has become a "Bible" for students of Alaskan glaciation. Their treatment of the glaciers of Prince William Sound is very comprehensive and several of their maps are still the best available. Tarr and Martin occupied many of the survey and photo stations established by the two earlier investigators, and the resultant comparisons were the first to show trends in glacier activity.

Beginning with his first visit in 1931, W. O. Field (1932) has kept an almost continuous record of many of the glaciers in this area. After his initial visit, he returned in 1935, 1957, and 1961. In 1935, W. S. Cooper accompanied Field, and Cooper's work (1942) of botanical dating of ice positions has been very useful to subsequent investigators. In 1957 and 1961, William O. Field was accompanied by the author, and some of the ground control for the maps of the present study is taken from Field's work of 1931 and 1935 (Field, 1932, 1937).

Other studies which concerned only one or two glaciers have been made, including the following: B. L. Johnson (1917) made observations of the retreat of the Barry Glacier between 1910 and 1914. Dora Keen (1915) gave an excellent description of the Harvard Glacier, among others, while her group was in the area in 1914. A series of valuable observations of the Valdez Glacier was made by L. S. Camicia (Gilbert, 1903), a Valdez optician and watchmaker, who visited the glacier and measured its retreat six times between 1901 and 1911. In 1931, C. K. Wentworth and L. L. Ray (1936) made a study of many Alaskan glaciers. The only glacier in Prince William Sound they visited was the Valdez Glacier, but, because of a faulty instrument, their map (1936) is somewhat incorrect and does not agree with the map made by Field the same year. In 1949, D. N. Brown (1952) was in Prince William Sound and took several photographs from established stations.

All of these early studies have been similar, consisting of a brief written description of general conditions at the foot of a glacier, accompanied by simple maps of glacier termini, or comparative photos from established stations. In 1953, Lawrence Nielsen (1963) led a scientific party on the Columbia Glacier. This is the only expedition that has tried to deal with the more serious problem of glacial budget. Due to very poor weather and an unusually heavy snowfall, the party produced meager results.

## Methods

### I. Data Gathering

Data have been gathered from maps and charts, surveys, photographs, narrative descriptions, botanical studies, earthquake reports, and climatological records. This material is presented in Chapter II.

A. Maps and Charts. Positions of glacier termini, from the earliest map (Vancouver, 1801) down to those made by the author in 1961, have been studied and summarized, and the various positions of glacier snouts are shown on a single map for each glacier. Early maps of the area, such as those by Tebenkof and Vancouver, while not accurate by modern standards, were still useful in later exploration of the area and its glaciers. Later maps of the area, especially

United States Geological Survey maps made from airphotos, represent the very best that can be produced by modern technology. Where possible, these latter maps have been used in this study as base maps for compiling all data from other maps.

B. Surveys. Most of the photographic stations around glacier termini also served as survey stations. In most cases, distances have been measured from the stations to the ice by using a steel tape, or angles have been measured to various points on the snout for determining distances by triangulation. In a few instances, distances from stations to ice have been measured only by pacing. These survey data are on file at the I. G. Y. World Data Center A: Glaciology, New York.

The results of these surveys, together with data from previous surveys, are incorporated into the maps to show positions of the present and former ice fronts.

C. Photographs. The Harriman Alaska Expedition in 1899 (Gilbert, 1903) and many subsequent investigators (Grant and Higgins, 1910; Tarr and Martin, 1914; Field, 1932, 1937; Wentworth and Ray, 1936; Brown, 1952) established fixed photographic stations for taking comparative photographs of glacier termini. Most previously established stations were occupied in 1957 and again in 1961, and many of the photographs taken then are used with earlier ones in this study to show changes in glacier snout positions. It is apparent that the photographs used in these comparisons have been taken in different months of the summer seasons. Unfortunately, exact dates for the earlier photographs are unknown and, therefore, these data have been omitted from all the captions. However, the resulting errors in comparability are minor, as changes in the position of termini over a summer season are slight compared with the longer period fluctuations considered in this work. The index numbers on the photographs refer to the photographic files at the I. G. Y. World Data Center A: Glaciology, New York.

Airphotos for mapping purposes have been taken at various times by the United States Government. It has been possible to use many of these airphotos for determining firn line elevations as well as glacier snout location. Most of these airphotos were taken in early August. While this is not at the end of the ablation season, it is approximately the same time of year that other firn line determinations have been made, and the photographs have, therefore, been considered valid for comparative purposes in this study.

D. Narrative Description. Many previous studies (Vancouver, 1801; Abercrombie, 1900; Davidson, 1904; Gilbert, 1903; Grant and Higgins, 1910; Tarr and Martin, 1914; Keen, 1915; Johnson, 1917; Field, 1932, 1937; Wentworth and Ray, 1936) include written descriptions of the condition of glacier termini as well as their locations. When neither photographs nor surveys were available, these descriptions have been used to estimate the former positions of the ice fronts.

E. Botanical Studies. Vegetation trimlines found in many parts of Prince William Sound mark the formerly expanded limits of glaciers. By studying the ages of vegetation inside and outside of these trimlines, it has been possible to date the period of glacier growth. Dating of the vegetation has been by counting annual growth rings of cores, by simple plant succession observations, and by noting the size and density of various plants.

F. Earthquake Reports. Although there are no seismic stations in Prince William Sound, some data on earthquake activity in the general area were found in the U. S. Department of Commerce publication, Earthquake History of the United States, Part 1, Continental United States and Alaska 1895-1958.

G. Climatological Records. The communities of Valdez and Cordova have served as official United States Weather Bureau stations since about 1900. Climatic data from these two stations published by the United States Weather Bureau are found in the Annual Summary of Climatic Data, Alaska. Climatic data used in this study have been taken from this publication. Precipitation and temperature for Valdez and Cordova have been plotted and compared to determine trends and means.

II. Data Analysis

Data gathered from all of the above sources have been analyzed by comparing traditionally accepted views of glacier behavior with actual measurements. These data are shown in the tables and graphs of this study and include individual glacier characteristics, climatic data, records of glacier termini fluctuations, earthquake data, a consideration of radiation and glacier fluctuations, and glacier ranking. This material is presented in Chapter III.

# CHAPTER II

# THE GLACIERS OF PRINCE WILLIAM SOUND

In this chapter all of the individual glaciers are identified and described; historical accounts are reviewed; and the data from 1957 and 1961 are used to present an overall picture of each glacier and its activity. Beginning in the southwestern corner with Bainbridge Glacier and proceeding clockwise around Prince William Sound, the glaciers in the various ports and fiords are discussed and analyzed. Passage Canal in the northwestern corner of Prince William Sound is a military reservation and has been omitted from this study.

Each of the major ports or fiords is briefly described before the individual glaciers are considered.

## Port Bainbridge

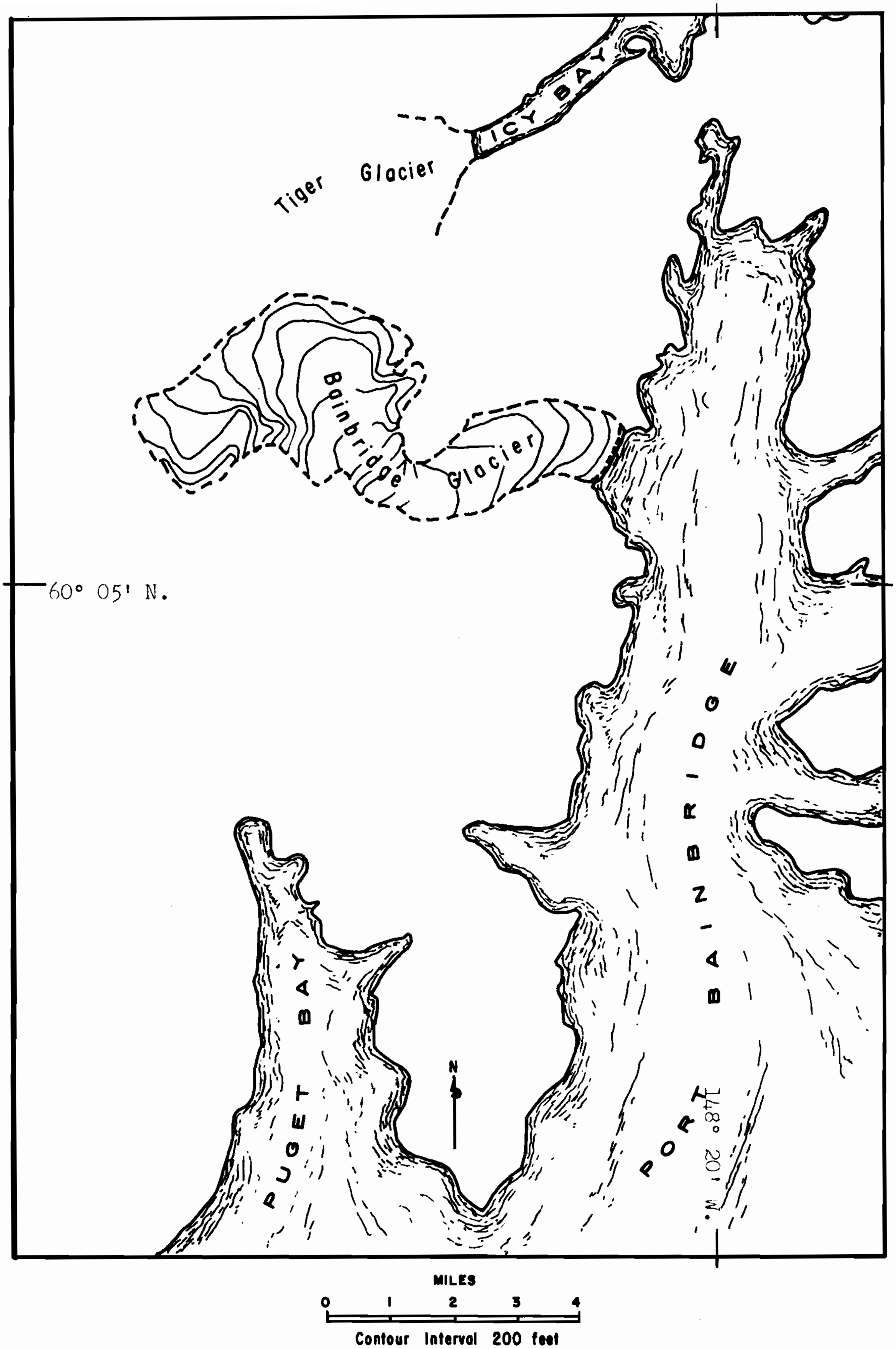
Port Bainbridge is located in the southwestern corner of Prince William Sound. It is about 3 miles wide and 12 miles long, nearly straight, and runs north-south. The head of the port is a low saddle, about a mile wide, leading to Icy Bay. Although shallow at the head, most of the port is deeper than 600 feet. There are no known moraines in the bay, and the bottom drops off rapidly along the shores. Opposite Bainbridge Glacier, the only glacier in the bay, the 600 foot depth is reached within a few hundred yards.

## Bainbridge Glacier

Bainbridge Glacier is located in the southeastern corner of Prince William Sound, 5 miles from the head of Port Bainbridge on the western side (Figure 2). It originates in the Sargent Ice Field, and its accumulation area is contiguous to that of Tiger Glacier of Icy Bay to the north, and that of Excelsior Glacier to the southeast. In plan, Bainbridge Glacier is shaped roughly like a reversed letter "S"; in profile it has a very gentle, regular surface gradient, dropping from 4,500 feet to sea level in just over nine miles (Figure 3). Airphotos dated August, 1950, show the firn line at about 2,300 feet elevation, which means that the accumulation area ratio (AAR) was 0.714 (Figure 3). A large part of the front of the glacier is bathed with sea water at high tide, while at low tide a beach up to 20 feet wide is exposed almost across the entire front. Undercutting by high tides causes small ice falls from time to time. The front of the ice is steep, with vertical faces in the center. Large glacial boulders just in front of the terminus suggest a terminal moraine. Vegetation trimlines and lateral moraines are found along both margins, and along the northern margin immediately outside the outer lateral moraine is a thick stand of dead spruce trees. An inner lateral push moraine is found three to ten feet from the present edge of the ice. Vegetation between these lateral moraines is sparse.

The earliest account of Bainbridge Glacier was written by Grant and Higgins (1911, p. 417). They relate:

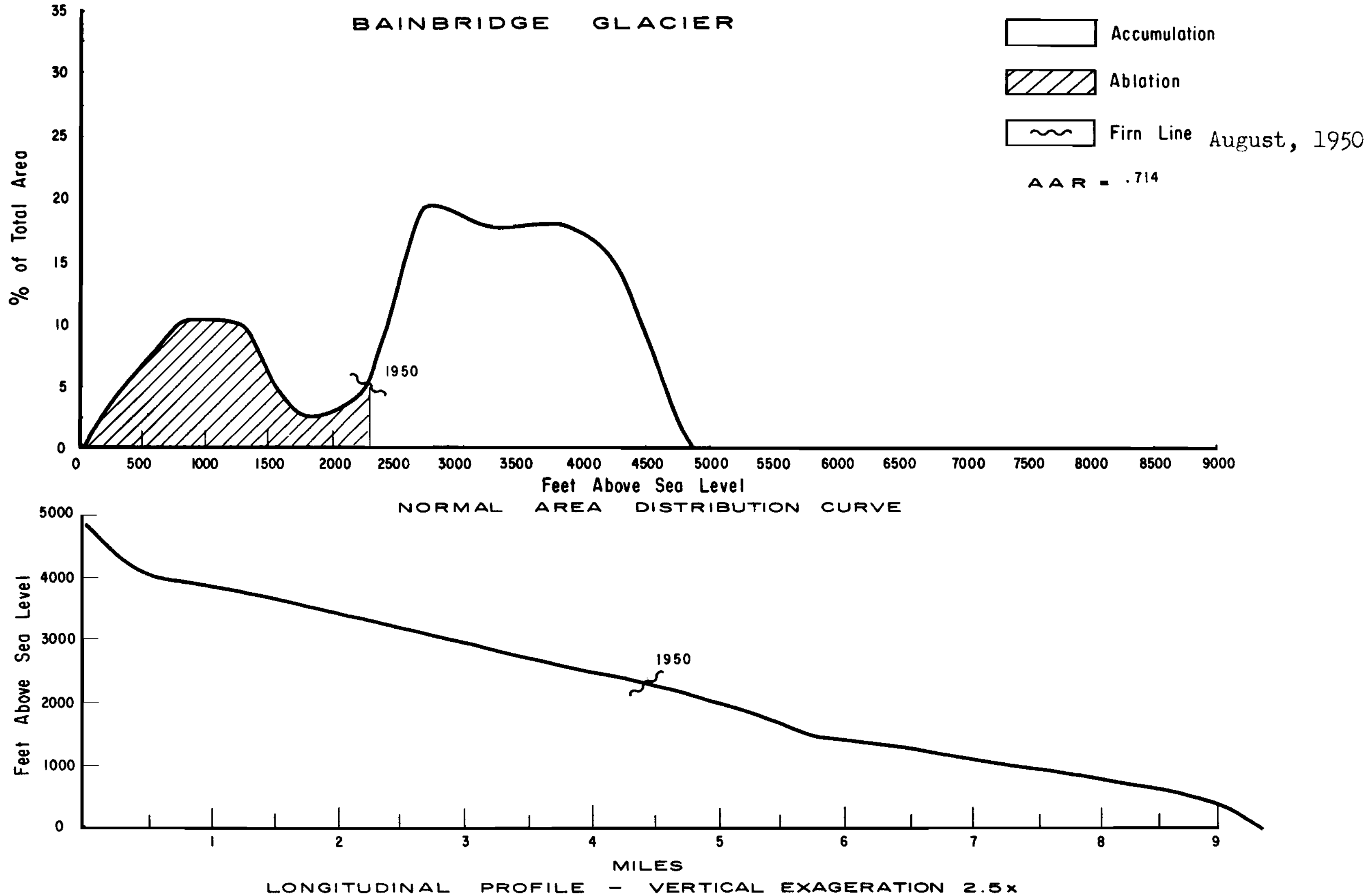
> We saw the glacier from a distance in 1905, and on August 3, 1908, visited it and mapped its front.




BAINBRIDGE GLACIER

Figure #2

Figure #3



BAINBRIDGE GLACIER
Accumulation
Ablation
Firn Line
August, 1950
AAR = .714
% of Total Area
35
30
25
20
15
10
5
0
1950
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
5500
6000
6500
7000
7500
8000
8500
9000
Feet Above Sea Level
NORMAL AREA DISTRIBUTION CURVE
Feet Above Sea Level
5000
4000
3000
2000
1000
0
1950
1
2
3
4
5
6
7
8
9
MILES
LONGITUDINAL PROFILE - VERTICAL EXAGERATION 2.5x

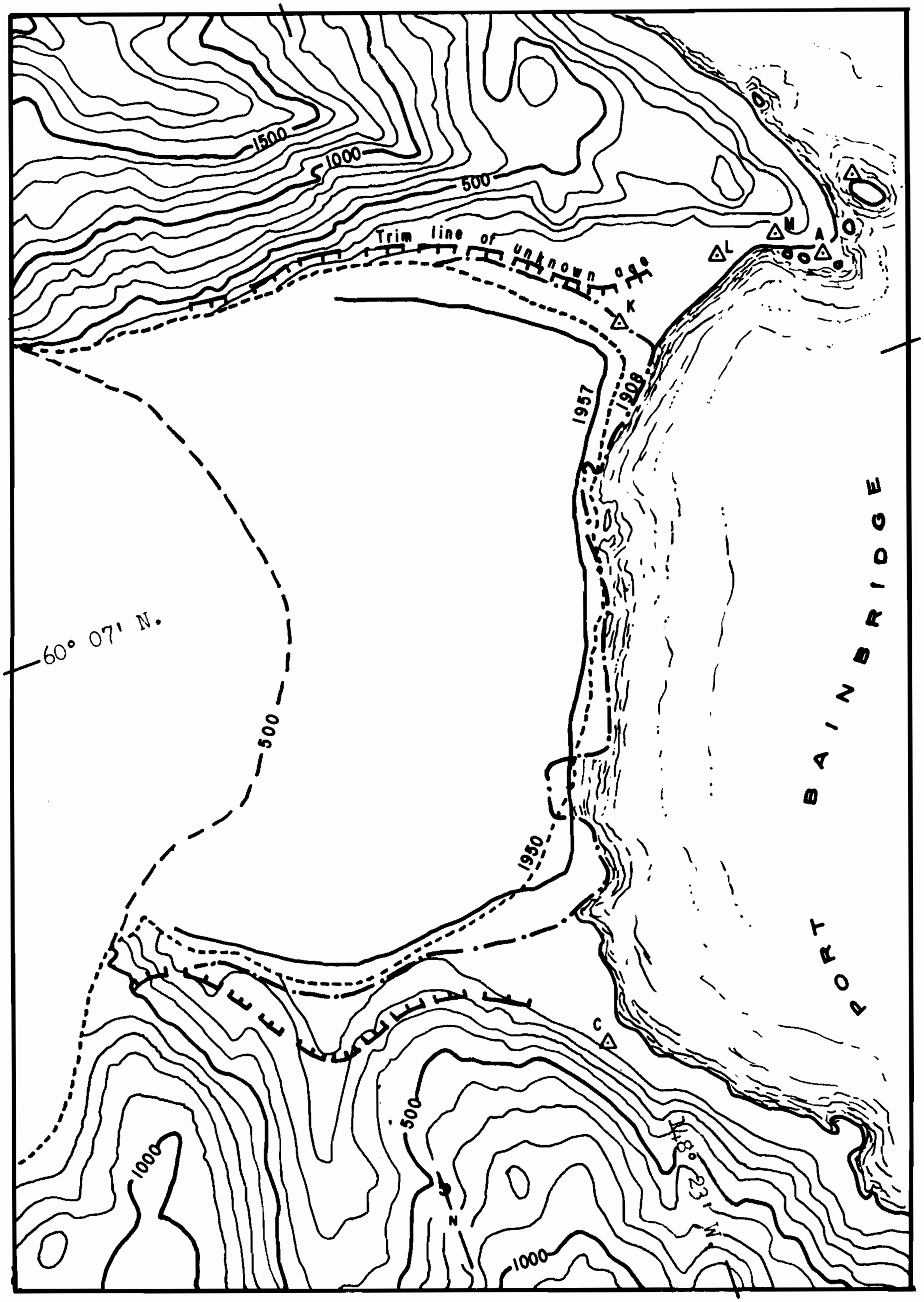
The Bainbridge Glacier ends on a glacial flat, and the central part of the front is reached by the usual high tide, and thus an ice cliff is developed along this portion of the front. This cliff is approximately 100 feet in height and its top is composed of ragged ice pinnacles, singularly free from debris and showing in the sunlight a beautiful play of greenish blue colors. Near the northern part of the ice front is a push moraine, 10 feet high, in places directly at the edge of the ice and in other places as much as 60 feet from the ice. The moraine is very fresh, and probably was formed during the summer of 1908. The moraine includes fragments of trees, and towards the north encroaches upon a spruce forest, many of whose trees have been killed recently by being partially buried in glacial outwash. On the south side of the front there is a small irregular bare zone of rock between the ice and the forest.

The photographs (Figure 5) here reproduced will mark the position of the front of the Bainbridge Glacier on August 3, 1908. The ice was practically, if not absolutely, at its maximum advance since the growth of the present forest.

Airphotos were taken in August, 1950, and from them a map was prepared by the U. S. Geological Survey (Seward A-4). This map was used as a base map for Figure 4. On it, the 1950 position of the terminus was very nearly the same as the 1908 position (Figure 4). The large boulders seen in front of the terminus in 1908 are still there and are shown on the Seward A-4 map.

No further recorded visits to Bainbridge Glacier were made until 1957, when the I. G. Y. party spent one day, August 15, studying the terminus. Photographs were taken from the same stations used by Grant and Higgins (Figure 5), and the glacier was resurveyed. A base line was measured and four survey-photo stations were established. Leslie Viereck, expedition botanist, dated the vegetation on the moraines and studied the trimline.

The expedition found that the ice position had changed very little since 1908 or 1950. The ice had moved back 200 to 300 feet from the lateral moraines of 1908, and a new small moraine was found



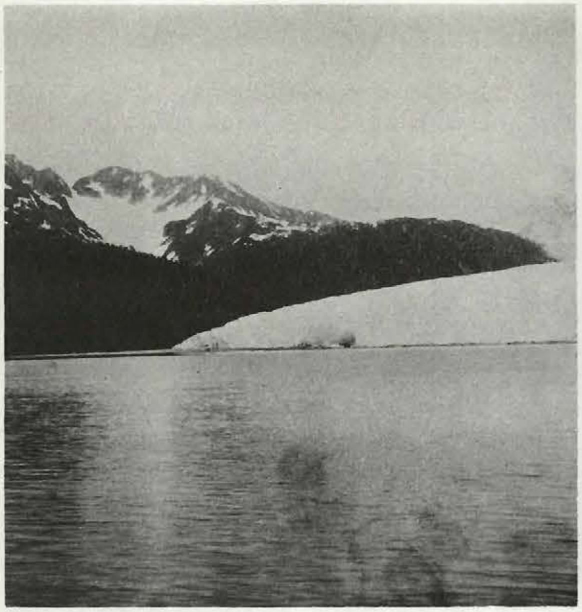

Based on U. S. Geological Survey Map, Seward A-4

MILE
0 1/2 1

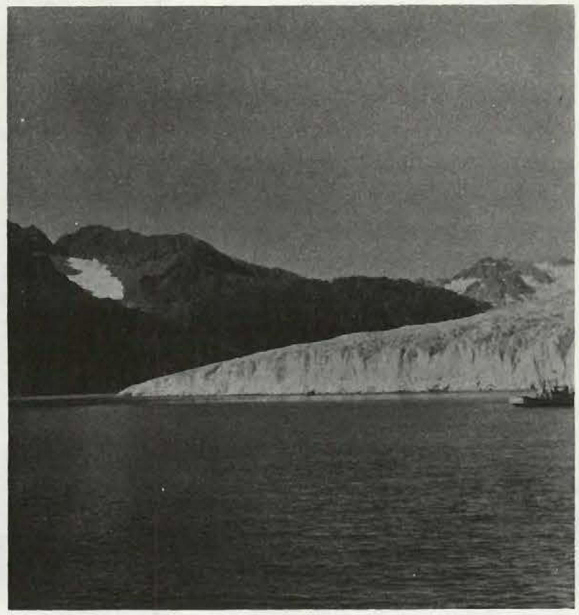
Contour Interval 100 feet

BAINBRIDGE GLACIER TERMINUS

Figure #4

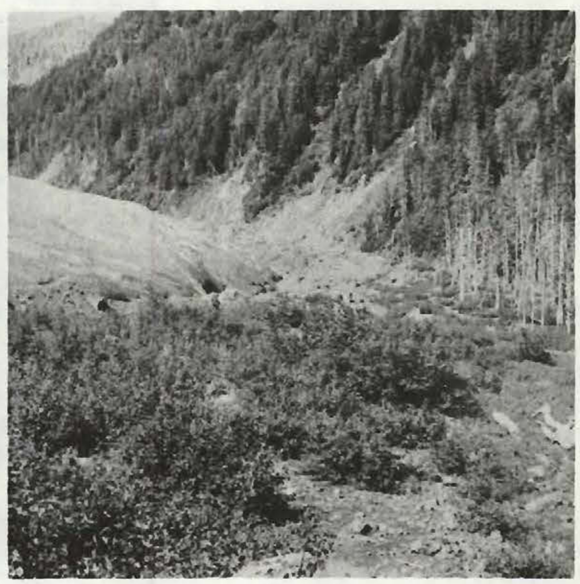


Bainbridge Glacier
1908, from Station A
Photo #40 by U.S. Grant



Bainbridge Glacier
1957, from Station A
Photo SG-2-57 by M.T. Millett

North margin, Bainbridge
Glacier, 1908
Photo #41 by U.S. Grant



North margin, Bainbridge
Glacier, 1957
Photo G57-R147 Robert Goodwin

Figure #5

near the ice. The position of the front in relation to the large boulders appeared to be very nearly the same. Vegetation on the 1908 moraine was only about 20 years old, and the zone between this moraine and the inner one, near the ice, had only non-woody plants growing in it. The dead trees along the northern margin, seen in 1908 by Grant and Higgins (1911) were very well preserved and gave the appearance of having been killed only within the last few years. Living trees, just beyond the dead ones, were cored and found to be about 300 years old. The estimate of Grant and Higgins (1911) that the ice was near its recent maximum in 1908 was confirmed by the age of vegetation along the trimline.

<u>Summary</u>

Bainbridge Glacier reached its post-glacial maximum around 1900. The relatively young age of vegetation growing on the outermost moraine in 1961 suggests that the ice either remained in this position for nearly 30 years or that it receded, then re-advanced, destroying the vegetation. Retreat from the hochstand has been slow, and vegetation inside the outermost moraine is only a few years old. The oldest tree on the moraine is about 20 years old, suggesting that the ice was very near its maximum position until the mid 1930's.

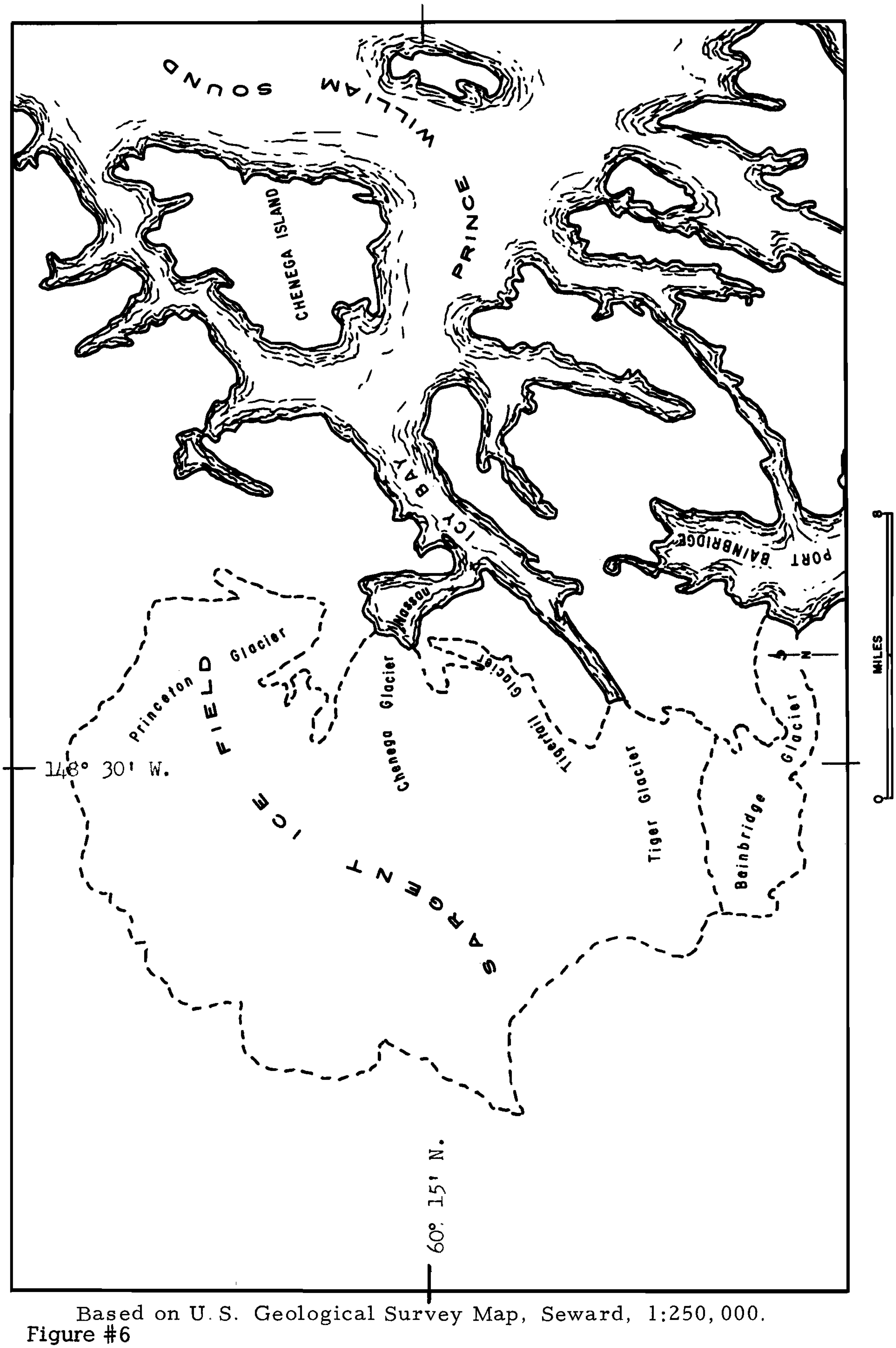
The small moraine near the 1957 ice position indicates an advance within the last few years and then a recession to the 1957 position. Lack of vegetation on this moraine suggests that it is only a year or two old.

Total recession, since the post-glacial maximum is only 200 to 300 feet along the margins, and 50 to 100 feet from the large boulders in front of the terminus. This remarkable stability indicates near-equilibrium conditions in the glacier. Figure 3 indicates that a lowering of the firn line would not increase the ablation area very rapidly. If the firn line has risen recently from a lower position, this has not affected the accumulation area very much. However, any further upward movement of the firn line will affect the accumulation area quite seriously. Thus if the slow upward movement of the firn line continues, as suggested by the retreating terminus, it will affect frontal behavior considerably.

## Icy Bay

Icy Bay is in the southwestern part of Prince William Sound opposite Chenega Island (Figure 6). The Bay is about 12 miles long and tapers from a width of 2 miles at the mouth to less than half a mile at the head. Icy Bay is terminated by a tidal ice tongue named Tiger Glacier. There is a large embayment over 3 miles in length and from three quarters of a mile to 2 miles wide on the northern side of Icy Bay, about halfway between the head and the mouth. This embayment is known as Nassau Fiord, and here the Chenega, Princeton, and Tigertail Glaciers terminate. Chenega Glacier, second largest tidal glacier in Prince William Sound, discharges a tremendous quantity of ice into the bay and is considered by Field (1937) to be one of the most active glaciers in Alaska. Princeton and Tigertail Glaciers do not reach tidewater.

All of the glaciers of Icy Bay are tongues of Sargent Ice Field. The two tidal tongues, Chenega and Tiger, are very steep near their termini and heavily crevassed. Calving of ice occurs regularly from these glaciers, frequently restricting passage in the bay. Both glaciers appear to be in deep water, although their steep gradients suggest that they may be near the heads of their bays. No moraines are visible and the ice is very clean. Grant and Higgins (1911) saw high rocks stretching nearly one-third of the distance across the front of Tiger Glacier in 1908, but this condition has not been observed since. Other than the coverage of these rocks on Tiger Glacier, the positions of these tidal tongues appear to have changed very little since first observed and mapped (Grant and Higgins, 1911).



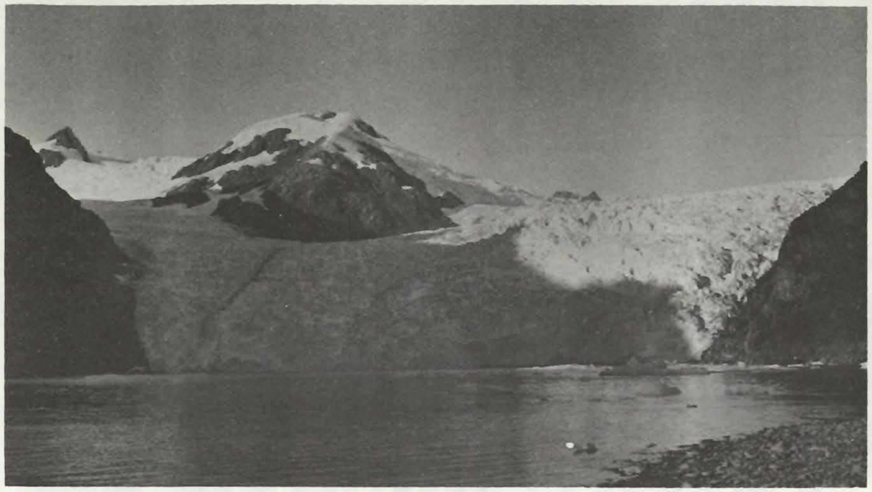

Based on U.S. Geological Survey Map, Seward, 1:250,000.

Figure #6

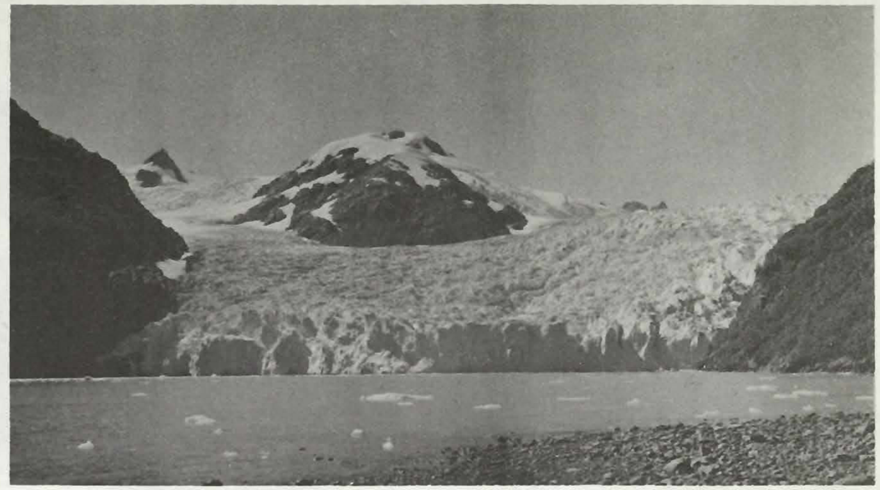
The two tongues on land, Princeton and Tigertail, are characterized by a thick, dirty layer of ice which is overlaid by clean ice (Figure 7). The termini, which have large ablation-opened crevasses, descend to about 100 feet above sea level. Tigertail Glacier is rather small with a very steep gradient (Figure 8). Princeton, on the other hand, is large (21 sq. miles) and has a very low gradient. Tigertail's terminus is only 200 to 300 feet from the shore, whereas Princeton's, with its low-angled slope, is just over a mile from the beach.

Earlier studies of Icy Bay showed the Bay almost filled by a single glacier, here termed the "Icy Bay Glacier." Later work, however, sketched the present picture of four smaller, separated tongues. The first indication of a glacier in Icy Bay is in Portlock's account (1789) of a 1787 visit to Prince William Sound. Although he did not actually see the glacier front because of fog, Portlock did encounter great quantities of drift ice and heard the great rumbling of calving ice. His map is indefinite, but the description of icebergs and noises indicates that an active tidal glacier was nearby in Icy Bay.

The first map and description of the "Icy Bay Glacier" were made in 1794 by Vancouver's lieutenant, Whidbey (Davidson, 1904, p. 23), who described Icy Bay as: "A bay on the western shore about a league wide, and about four and a half miles deep, terminated by a compact body of ice that descended from high perpendicular cliffs to the water side, and surrounded by a country composed of stupendous lofty mountains covered with snow." The map shows the ice front across Icy Bay near the entrance of Nassau Fiord.



Tiger Glacier from Station B., 1935
Photo f-35-842 by Wm. O. Field



Tiger Glacier from Station B, 1957
Photo M-57-SG19 by M.T. Millett

Chenega and Princeton Glaciers from Station C, 1908, Photo No. 48 by U.S. Grant

Chenega and Princeton Glaciers from Station C, 1957, Photo M-57-SG17 by M.T. Millett

Figure #7

The next observation was made almost a hundred years later, in 1886, by Seton Karr (1887), who visited the native village at Chenega Island near the mouth of Icy Bay. His description of Icy Bay was: "A broad bay covered with small icebergs... close at hand several glaciers descend into the sea from . . . low flat snowfields." His sketch of Icy Bay, as seen from Chenega Island, shows a glacier and snow fields in the background. Both his description and sketch indicate that the large glacier described by Whidbey was still far out near the mouth of Icy Bay. Applegate was in this area in 1887, but did not show an ice front on his map. He referred to an ice tongue, however, as "a fine glacier, coming down to the water" (Davidson, 1904, p. 23).

In 1898, an army expedition led by Captain Glenn (1899) visited this area, and their map shows the "Icy Bay Glacier" front in approximately the same position as that shown by Whidbey in 1794, changing only in shape. Since no "Icy Bay Glacier" is mentioned in Glenn's account, his map may be based on some earlier survey; however, the outlines of the glacier and bay are considerably different from those shown by Whidbey, and the roughly contoured fiord walls on Glenn's map also suggest a new survey.

In 1908, Grant was in Icy Bay, and his map, photos (Figure 7), and description show a vastly different condition from all the previous accounts. He said:

> The axis of Icy Bay runs northeast and southwest and the fiord is approximately 10 miles in length. This bay has been represented on the maps as about 4 miles in length with an east and west axis. It was not until after 1908 that the bay was delineated with approximate accuracy. The reason for this lies in the fact that the later maps followed Vancouver's representation of this bay, and he reported that the bay was "terminated by

> a compact body of ice that descended from high perpendicular cliffs to the water side." At that date (1794) it is very probable that the glaciers in Nassau Fiord, the large bay on the northwest side of Icy Bay, completely filled that fiord and extended out into, but not across, the main part of Icy Bay. This, together with the extensive discharge of ice from these glaciers (combined as one), probably prevented close inspection of the bay and the discovery of its upper part (Grant and Higgins, 1911, pp. 412-416).

Grant also named and described the ice tongues of Nassau Fiord and concluded that ice undoubtedly filled Nassau Fiord, covering the peninsula at the north side of the entrance, within the last 100 years and possibly within a much shorter time. Because of forest growth in Icy Bay, he concluded that ice had not recently filled this bay, and that an Indian tradition of an ice-filled bay referred to Nassau Fiord instead of Icy Bay.

In 1909, the Perkins party (Tarr and Martin, 1914) also photographed the glaciers of Icy Bay. The only difference from the conditions of the previous year was a short advance of Tiger Glacier, which now covered the rocks at the terminus. The other glaciers appeared unchanged.

In 1910, Tarr and Martin (1914) reported the positions of the ice fronts to be unchanged from those of the previous year, and their study of the vegetation in Icy Bay is interesting when compared with Whidbey's 1794 description, and the position of the glacier "terminus" shown on his map. Northeast of Nassau Fiord the forest was thick and mature, containing trees from 24 to 32 inches in diameter. The annual rings in a number of them were counted in 1910 and three trees about 24 inches in diameter were found to be 113, 120, and 122 years old. There were trees of about the same diameter, and about as thickly set, all along the coast up to and including the small island northeast of the entrance of Nassau Fiord. These were not stunted trees, even those nearest the glaciers being well-developed. As Whidbey's visit was 116 years before 1910, the presence of trees 120 to 122 years old proves clearly that the glacier could not have extended quite as far to the northeast in 1794 as the site of these trees. Along a sharply defined line near the entrance of Nassau Fiord, however, this mature forest ended; and the interior shores of Nassau Fiord, the mountain between Princeton and Chenega Glaciers, and the shores of Icy Bay from that point southwestward had only scattered trees, none of which was more than 20 years old. On the first prominent rock point inside of Nassau Fiord (near Photo Station D) the higher part of the barren zone had scattered willows, alders, young spruces, and hemlocks at an elevation of about 200 feet above sea level, the oldest one counted having 22 annual rings, though some of the others may have been even older. Nearer sea level the slopes were absolutely barren. This suggests that the ice front observed by Whidbey was maintained up to rather recent times. On and near the depression between Icy Bay and Port Bainbridge there were scattered conifers which from a distance appeared large. They did not ascertain whether these extended down to sea level or not, nor how old they were. However, the presence of these trees led them to conclude that the expanded ice tongue of 1787-1794 was supplied wholly by the Chenega and Princeton Glaciers which emerged from Nassau Fiord and filled the lower part of the inlet. They also said:

> One of the most interesting features in relation to forest growth in this region is the shape of the barren zone on the peninsula east of Nassau Fiord, between that indentation and

> Icy Bay. This shows clearly that while the expanded Chenega and Princeton Glaciers filled Nassau Fiord and extended over the narrow northeastern portion of the peninsula, the higher southeastern side of the peninsula and the low island there, which are thickly forested, were not covered by the glacier. The boundary of the barren zone indicates, therefore, that the expanded Chenega-Princeton Glacier was tidal in Icy Bay in the cove east of this peninsula as well as opposite the mouth of Nassau Fiord; but that the two tidal termini did not coalesce and transform the higher part of this peninsula into a nunatak, nor override it completely (Tarr and Martin, 1914, p. 380).

In 1935, W. O. Field (1937) visited Icy Bay and found that since 1908, the Chenega terminus had not changed position. He described it as being one of the most active ice fronts of the Alaskan coast, and compared its discharge of icebergs to the Muir and Columbia Glaciers. Field reported that from 1908 to 1925, Princeton Glacier had retreated and shrunk in volume. He felt that this shrinking continued at a still more rapid rate from 1925 to 1935. Tigertail Glacier was found to have shrunk in volume and to have ceased discharging icebergs. On the other hand, he noted that Tiger Glacier was slightly in advance of its 1910 position, and was adjacent to mature alders.

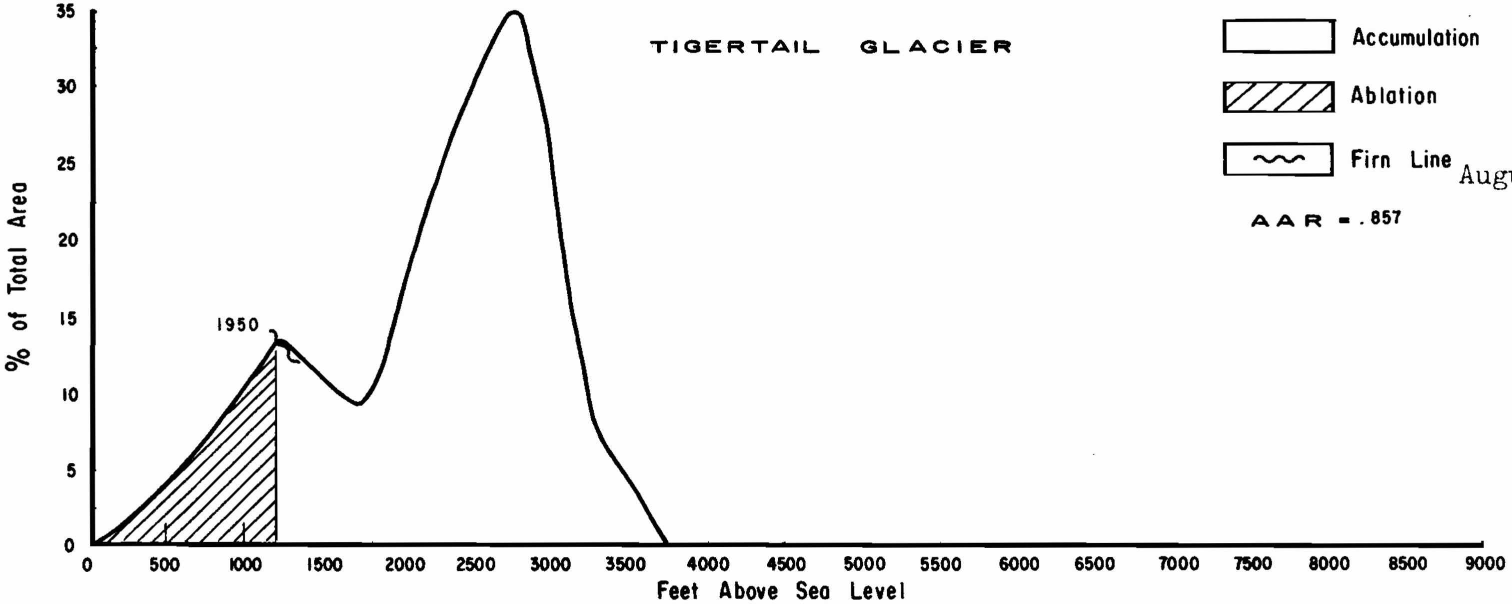
The International Geophysical Year party was in Icy Bay in 1957, when all of the old stations were occupied and comparative photographs were taken (Figure 7). Because there was little change in the position of the termini, the glacier fronts were not mapped. The only noticeable difference since 1935 was the downmelting and retreat of Princeton Glacier, a very short retreat of Tigertail, a small lowering of Chenega, and a slight thickening of the Tiger terminus. The positions of all except Princeton appeared to be within a few yards of their mapped positions of 1908. Botanists of the party made an interesting study of the vegetation near the mouth of Nassau Fiord and shed some additional light on the problem of the recent ice maximum. Trees on the low island just east of the mouth of Nassau Fiord were found to be up to 221 years old, while a stump on the nearby peninsula was 273 years old. As these trees were near sea level, there is sufficient reason to conclude that ice has not been farther down Icy Bay since at least 1675 and perhaps much longer. Other spruce trees found near the terminus of Tiger Glacier suggest that this ice stream has not been greater in many years, and the fact that it is encroaching on a mature alder thicket indicates that its present position may represent its post-glacial maximum. It was quite clear that the terminus did not extend another six miles down the bay in 1794, as shown by Whidbey, or in 1887, as shown by Karr.

## Tigertail Glacier

Tigertail Glacier is located in the northwestern part of Nassau Fiord just half a mile south of the Chenega Glacier terminus (Figure 6). It is a small glacier only 3-1/2 miles long, with an area of 2.7 square miles, and confined between the narrow walls of a steep valley. The August, 1950, firn line was at 1,100 feet elevation, providing an accumulation area ratio (AAR) of 0.857. The area distribution curve (Figure 8) shows the firn line at the top of a steep peak; any change up or down should affect glacial behavior rather quickly.

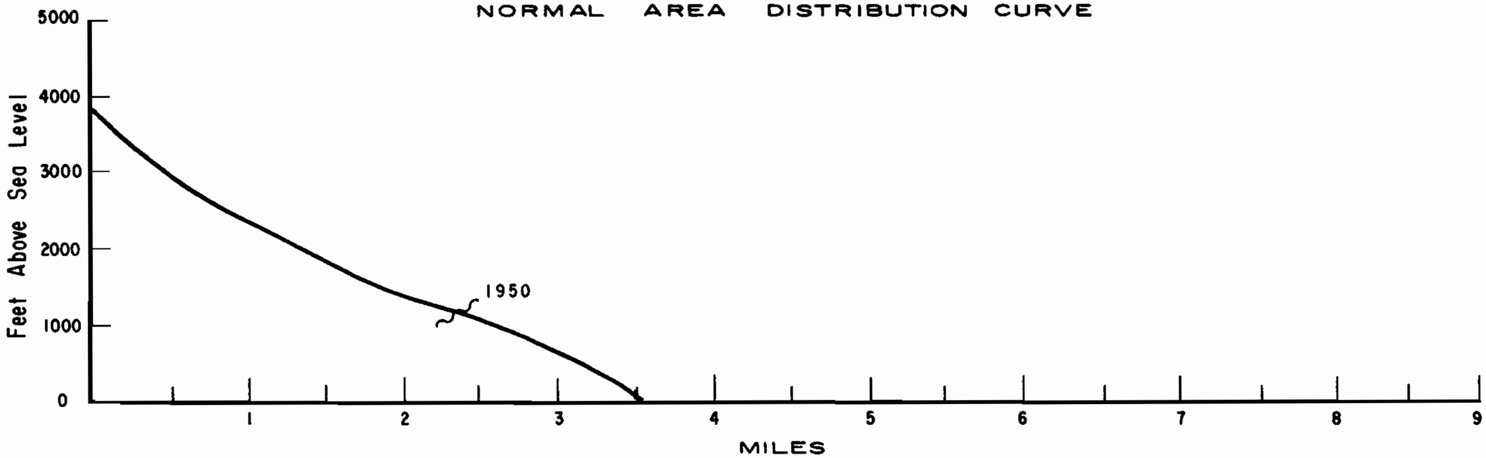
The stability of the terminus between 1908 and 1957 indicates near equilibrium conditions in the ice stream. Recession of less than 100 yards had reduced the total glacier size an immeasurably small amount.

Figure #8




August, 1950

NORMAL AREA DISTRIBUTION CURVE




LONGITUDINAL PROFILE – VERTICAL EXAGERATION 2.5x

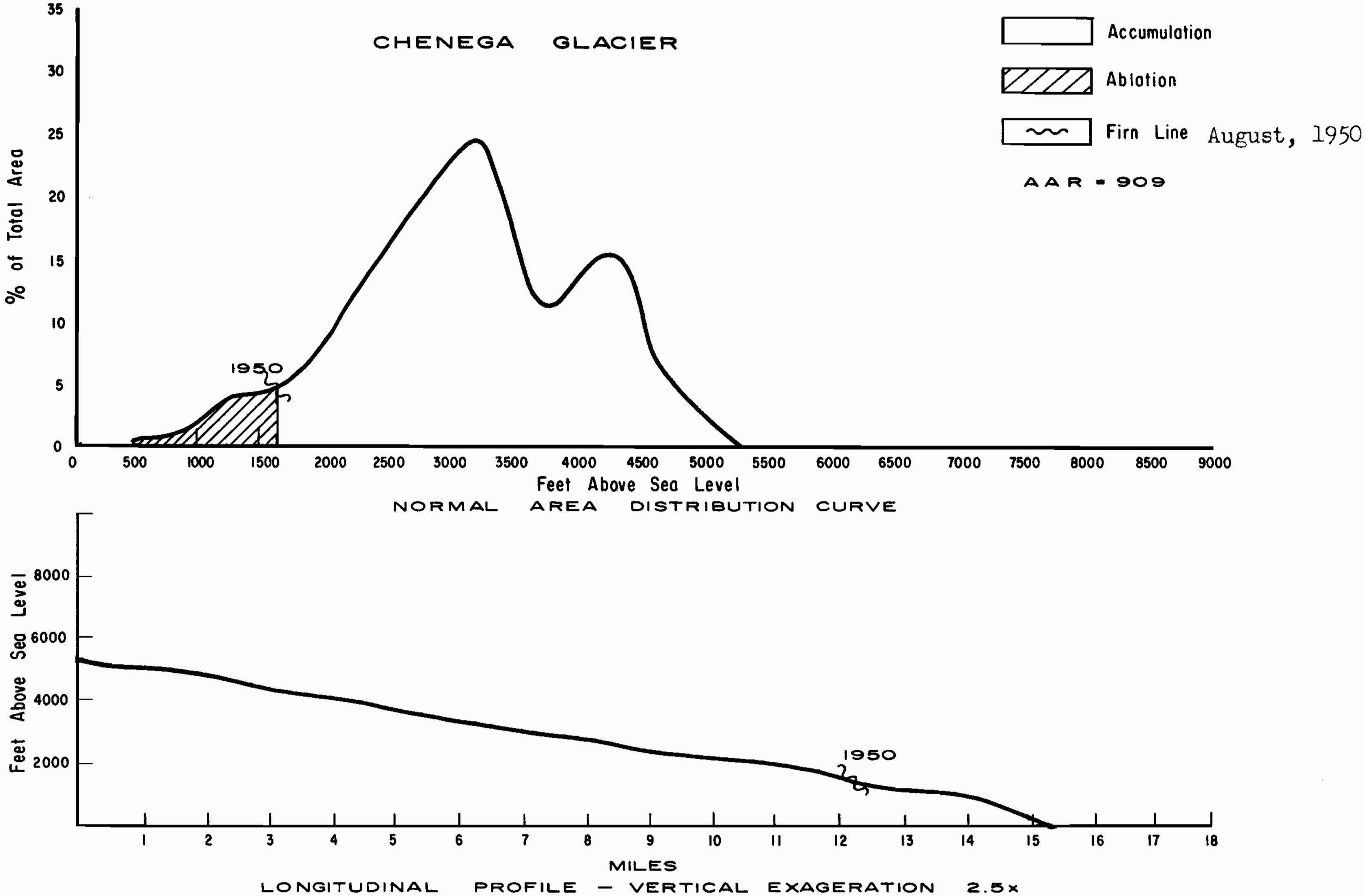
The accumulation area is contiguous to the Chenega Glacier on both the northwestern and southwestern sides. Most of the accumulation area is between 2,000 and 3,200 feet elevation. This low collecting basin is similar in altitude to that of the receding Princeton; however, the area distribution and profile are considerably different.

This tongue undoubtedly participated in the recent expansion and recession of the glaciers of Nassau Fiord.

## Chenega Glacier

Chenega Glacier is the largest glacier in Icy Bay, and is second only to the Columbia Glacier in Prince William Sound. Its width at the terminus is just over a mile and a quarter and its length is about 16 miles (Figure 6). It covers 136 square miles and drains most of the center of the Sargent Ice Field. The glacier is somewhat fan shaped, with the terminus at the apex. The area distribution curve (Figure 9) shows that only a small percentage of the total is below the firn line. Because of the overwhelming proportion of the glacier in the accumulation area, any minor change in the position of the firn line would not seriously affect glacier behavior; but, any climatic change responsible for firn line movement would affect the glacial budget. Ice loss due to iceberg calving is very high and although the glacier has only an overall moderate gradient, the flow must be very fast. The steep gradient near the terminus and the tremendous number of large crevasses (Figure 7) give the impression of a giant ice fall ending in the deep water of Nassau Fiord. This fractured condition undoubtedly facilitates break

Figure #9


CHENEGA GLACIER
Accumulation
Ablation
Firn Line
August, 1950
AAR = 909
% of Total Area
35
30
25
20
15
10
5
0
1950
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
5500
6000
6500
7000
7500
8000
8500
9000
Feet Above Sea Level
NORMAL AREA DISTRIBUTION CURVE
Feet Above Sea Level
8000
6000
4000
2000
1950
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
MILES
LONGITUDINAL PROFILE – VERTICAL EXAGERATION 2.5x

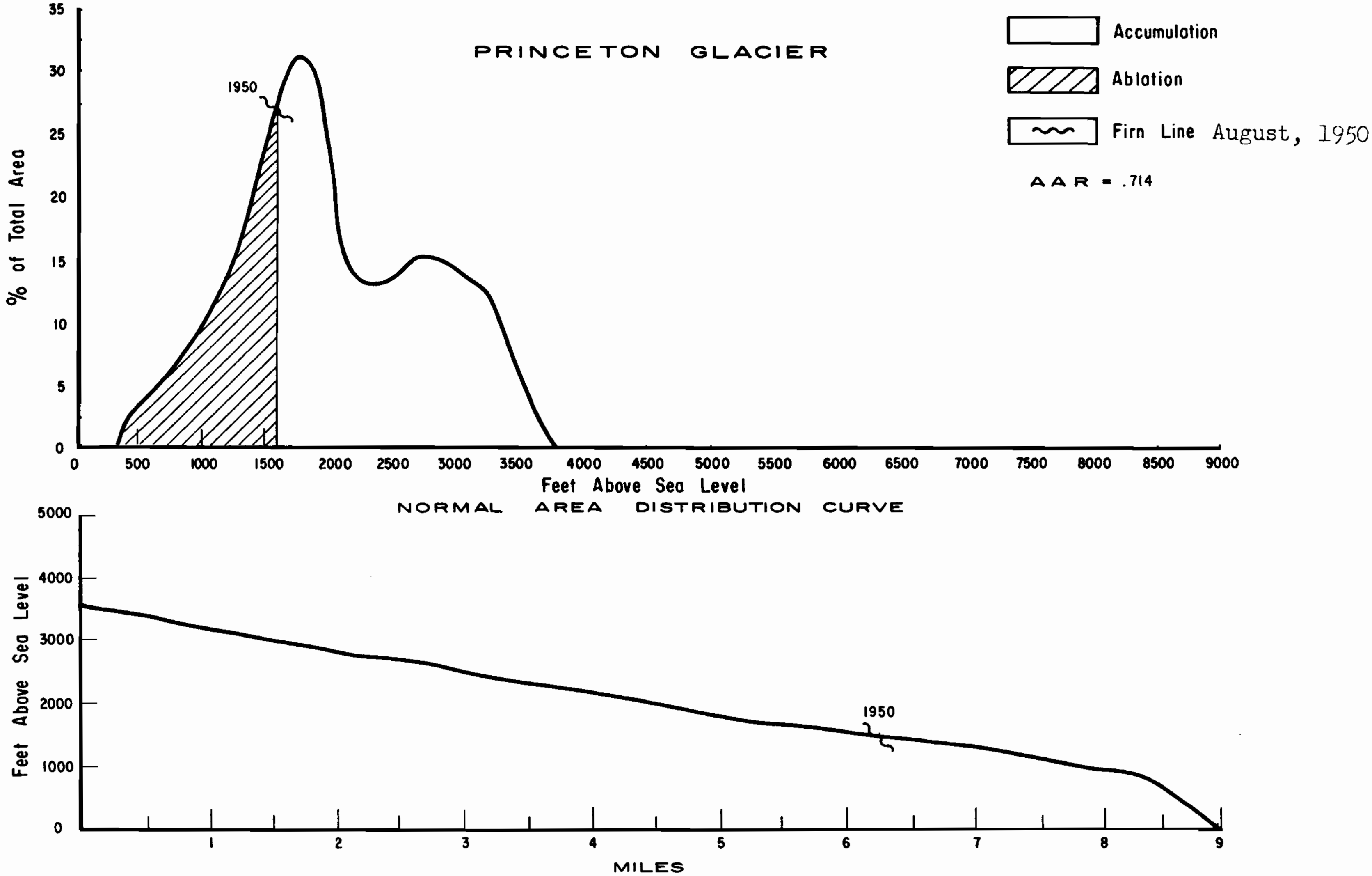
up and berg calving. The position of the terminus in 1957 did not appear to have changed since 1908.

## Princeton Glacier

Princeton Glacier is located in the northern part of Nassau Fiord, slightly more than a mile from Chenega Glacier (Figure 6). This ice tongue is more than a mile from tide water and terminates at about 100 feet above sea level. The glacier, which drains a low eastern part of the Sargent Ice Field, covers nearly 22 square miles and is 9 miles long. The 1950 firn line was near 1,600 feet elevation dividing the glacier with a 0.714 accumulation area ratio (Figure 10), one of the lowest ratios in Prince William Sound. The steepness of the area distribution curve (Figure 10) shows a high sensitivity to firn line movement. The glacier is roughly diamond shaped, and the present position of the firn line is very near the widest part. Any movement of the firn line would drastically affect the glacier budget. For example, if the firn line rose 500 feet, it would increase the ablation area by 17 per cent.

Between 1908 and 1950, the terminus receded about one mile and was even farther back in 1957. Downmelting is obvious in every photo comparison (Figure 7). The fact that most of the accumulation area is below 3,000 feet is probably the most important single factor in the glacial budget. Undoubtedly much of the spring and fall precipitation is rain at this low altitude, whereas in higher areas it is snow.

Figure #10




LONGITUDINAL PROFILE - VERTICAL EXAGERATION 2.5x

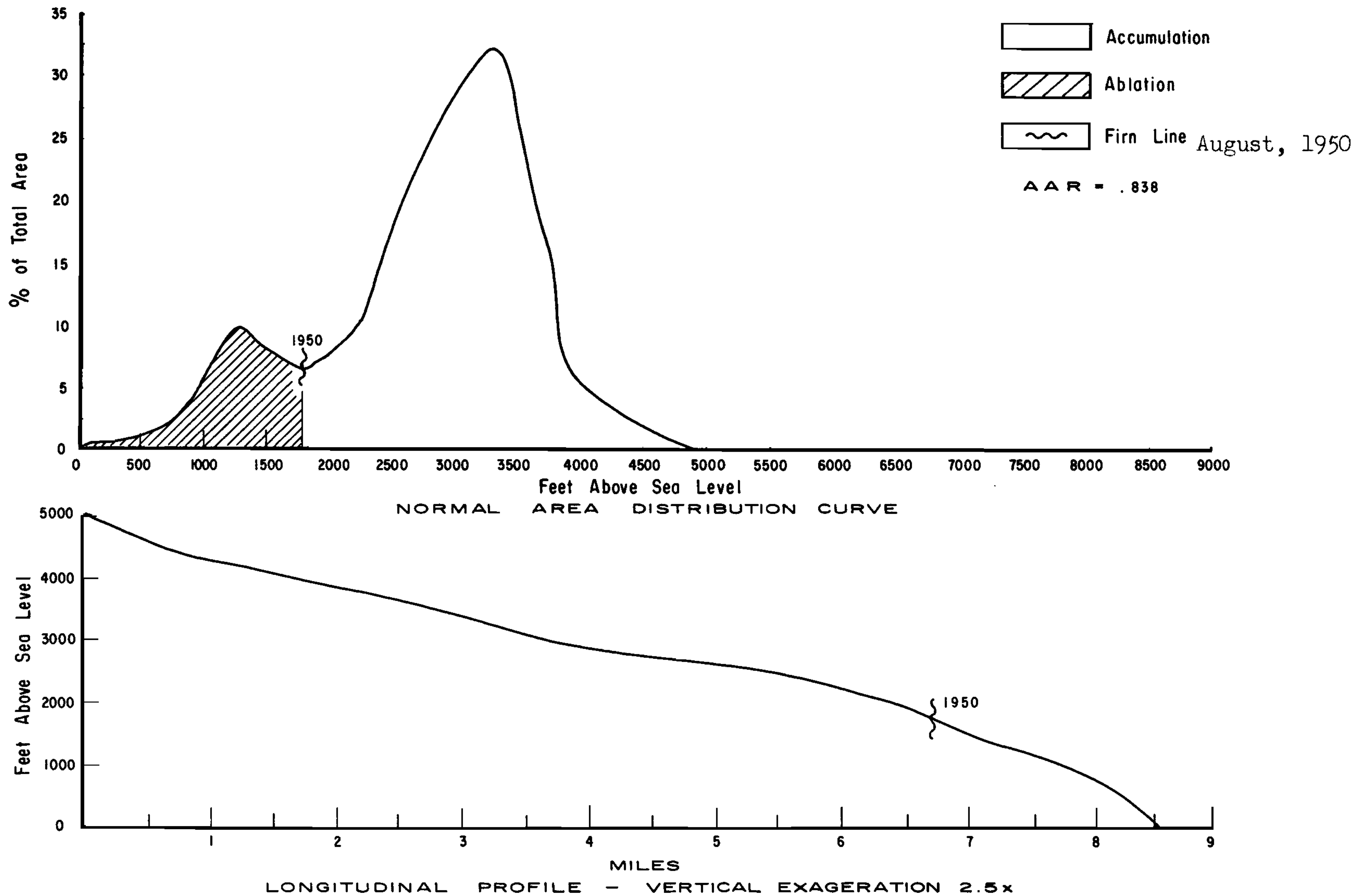
## Tiger Glacier

Tiger Glacier is located at the head of Icy Bay (Figure 6). At its terminus it is only half a mile wide and very steep. Much ice is lost through calving, and the steepness and crevassing of this terminus is similar to that of Chenega Glacier. The length of Tiger Glacier is 8-1/2 miles and it covers an area of 23-1/2 square miles. Its accumulation area is part of the Sargent Ice Field, and is contiguous to the drainage of Chenega Glacier on the north, to Excelsior Glacier on the west, and to Bainbridge Glacier on the south. Most of the accumulation occurs between 2, 500 and 4, 000 feet elevation (Figure 11). The 1950 firn line was at about 1, 750 feet elevation. On the area distribution curve (Figure 11) the firn line is in a shallow dip which suggests that the accumulation area ratio is relatively stable.

As has been mentioned earlier, Grant saw exposed rock in front of the glacier one-third of the way from the north margin in 1908. This rock was covered by a short advance during the next year, and has not been seen since. Although movement of the terminus has been slight, it has all been forward, and in 1935 and 1957 the ice margin was adjacent to mature alders. Mature spruce trees less than a mile from the terminus indicate that Tiger Glacier did not participate in the recent expansion and recession of the glaciers of Nassau Fiord. The mature alder thicket at the present ice front suggests that Tiger Glacier has not been larger in a great many years.

Figure #11

TIGER GLACIER



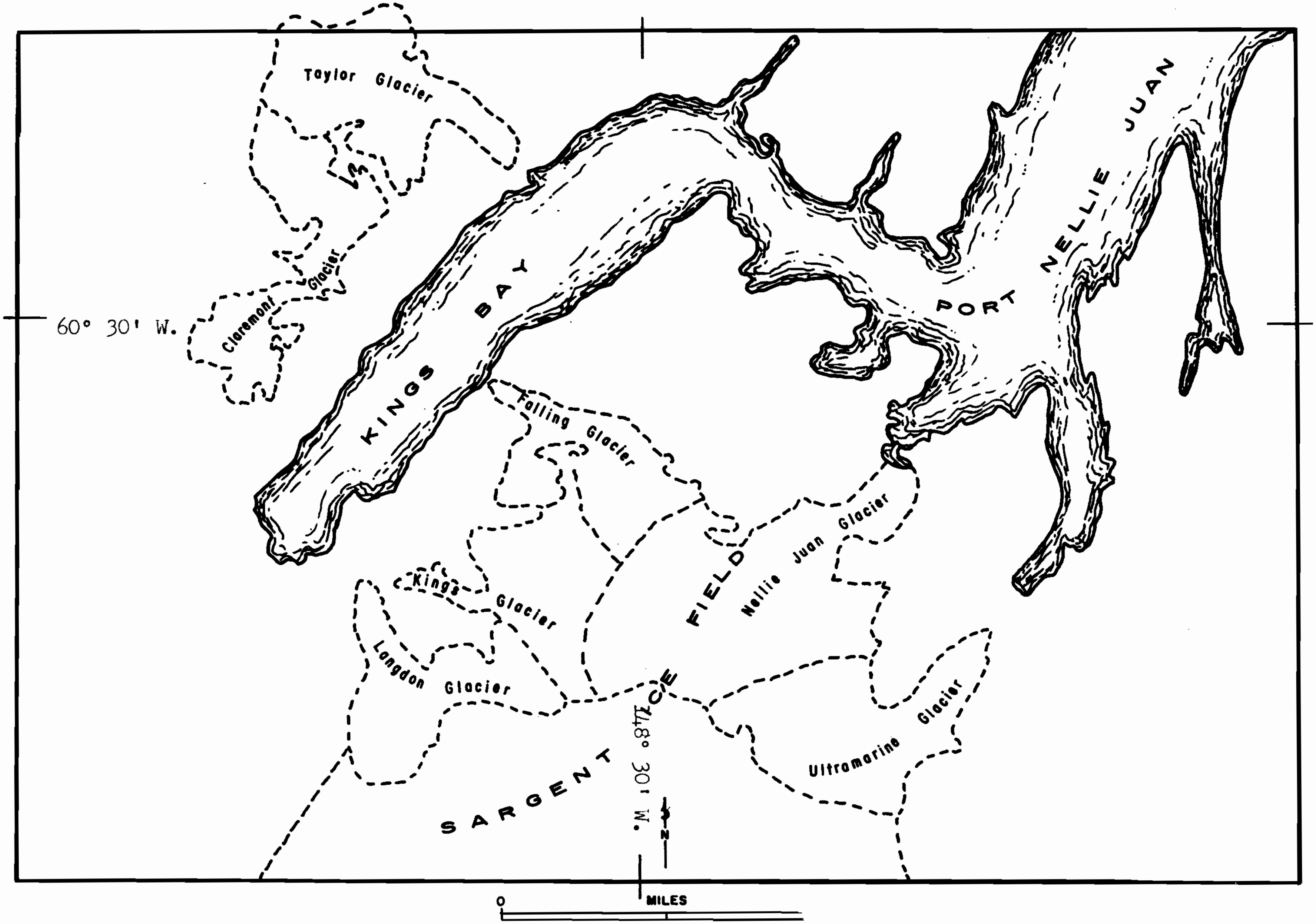
## Port Nellie Juan

Port Nellie Juan, located midway along the western shores of Prince William Sound, contains seven major glaciers, and drains the northern and northeastern parts of the Sargent Ice Field (Figure 12). The port, which is about 26 miles long and from 2 to 4 miles wide, is shaped roughly like the letter "Z." The inner part is named Kings Bay, and the southeastern embayment is known as Blue Fiord. Ultramarine Glacier is located at the head of Blue Fiord, with its terminus about one mile from tidewater and 150 feet above sea level Nellie Juan Glacier, the only tidal ice tongue in this port, is located near the middle of the port at the head of a short bay. All of the other glaciers are located in Kings Bay. They include Taylor, Falling, Langdon, Kings, and Claremont Glaciers.

### Nellie Juan Glacier

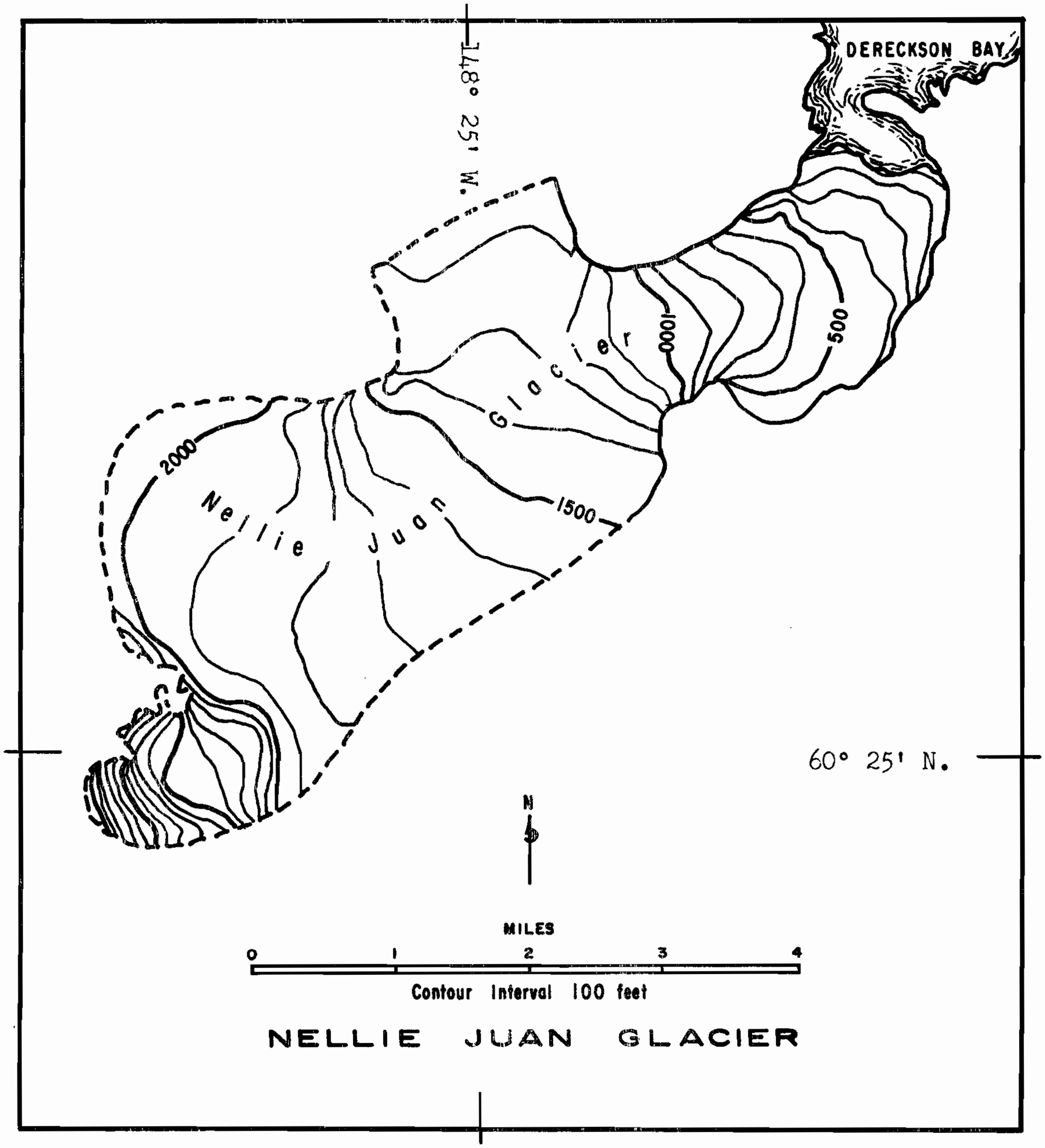
Nellie Juan Glacier, located at the head of Dereckson Bay, is a tongue of the Sargent Ice Field (Figure 13). It descends from a height of 3,600 feet to sea level, where it terminates in a tidal lake (Figure 13). The glacial front rises vertically from the lake to a height of 60 to 150 feet, and here icebergs are calved regularly into the lake and carried out into the sound at low tide. Although the ice stream has only a moderate gradient (Figure 14), all of the lower end is heavily crevassed. The upper part of the glacier is a segment of the Sargent Ice Field, and since it is only one of several glaciers draining radially from the eastern end of this ice field, its

Figure #12




**PORT NELLIE JUAN and KINGS BAY**

Based on U.S. Geological Survey Map, Seward, 1:250,000.




Based on U.S. Geological Survey Map, Seward B-4

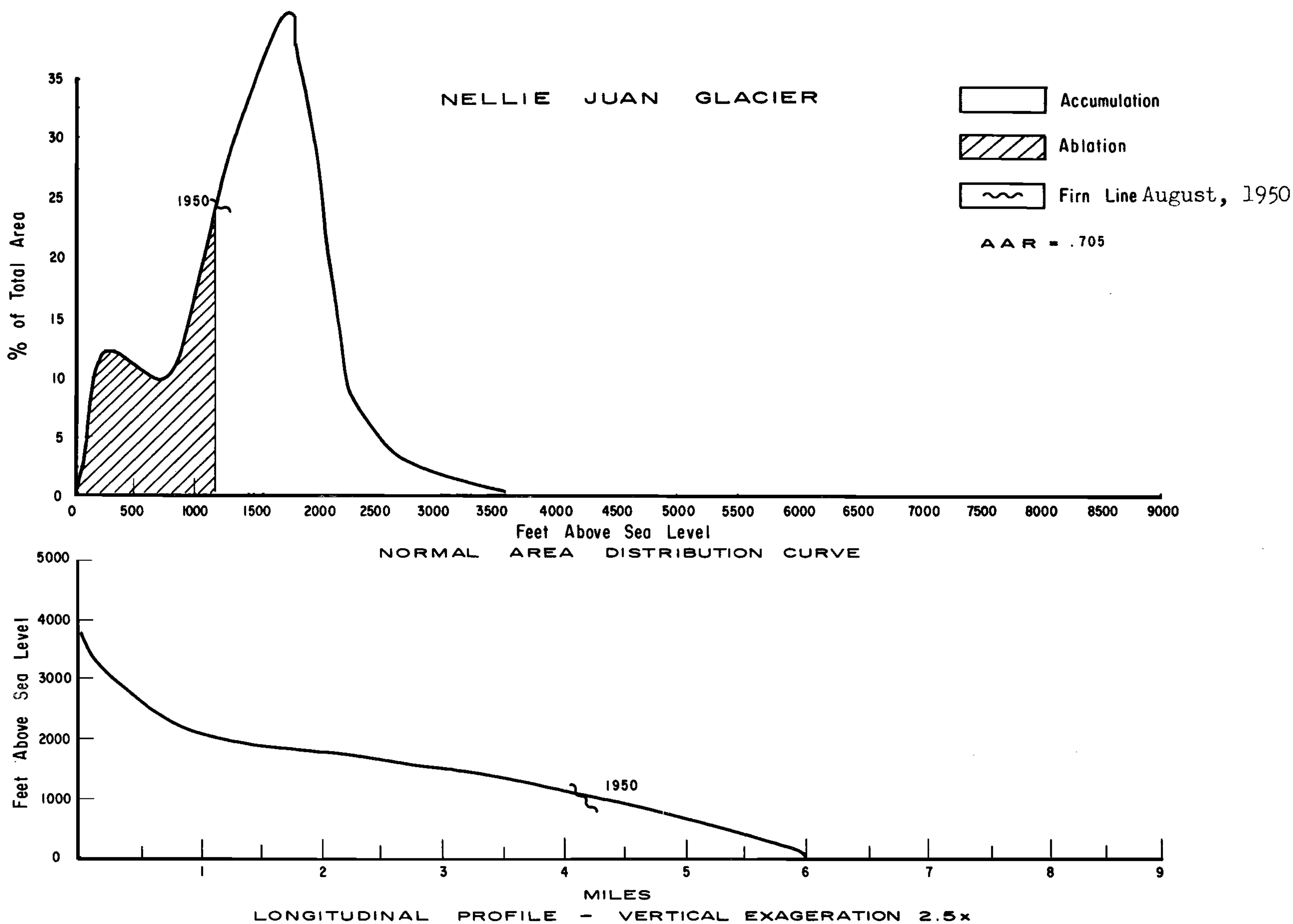
Figure #13

drainage area is difficult to define. However, contour lines on the 1953 U. S. Geological Survey map suggest a total size of 8.75 square miles and a length of just over six miles. Near the 1,000 foot contour line the glacier squeezes through a pass, then spreads out in the terminal area, giving the whole glacier an hourglass shape. The 1950 firn line was near the 1,200 foot contour line. This gives an accumulation area ratio of 0.705. Most of the collecting basin is between 1,200 and 2,300 feet elevation (Figure 14). That the glacier has recently been much larger is immediately apparent from well-defined trimlines and fragments of terminal moraines.

Nellie Juan Glacier, like the port, was named after the schooner Nellie Juan by the ship's captain, S. Applegate, who first mapped and described the area in 1887 (Davidson, 1904). The glacier is represented on his map as terminating in the sea; its ice cliff facing the northeast. Davidson (1904, p. 27) describes it as "a very broad glacier breaking boldly upon the water."

In 1908, Grant and Higgins (1911) spent a day at Nellie Juan Glacier and produced a very small scale map and some excellent photographs. They described the glacier as resting on a gravel beach, most of which was covered by high tide. Along the margins of the ice they found bare zones 100 to 150 feet in width. An especially bare zone was found on a granite knob near the western side of the glacier front. Crossing the top of this knob was a moraine 10 feet in height and 5 to 30 feet in width, and the distance from the summit of the knob to the ice front was 500 feet. They concluded that this moraine marked the farthest advance of the ice in at least a century and probably a few centuries. They dated this

Figure #14


NELLIE JUAN GLACIER
Accumulation
Ablation
Firn Line August, 1950
AAR = .705
% of Total Area
35
30
25
20
15
10
5
0
1950
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
5500
6000
6500
7000
7500
8000
8500
9000
Feet Above Sea Level
NORMAL AREA DISTRIBUTION CURVE
Feet Above Sea Level
5000
4000
3000
2000
1000
0
1950
1
2
3
4
5
6
7
8
9
MILES
LONGITUDINAL PROFILE - VERTICAL EXAGERATION 2.5x

advance and moraine as at least 20 years old and probably older.

The National Geographic Society's expedition (Tarr and Martin, 1914) visited Nellie Juan Glacier in 1910 and described it as reaching the sea only at high tide, except near the eastern margin. The ice front was steep, but not very high. By using photographs made by Grant and Higgins (1911), Tarr and Martin concluded that little change had occurred in the two intervening years and suggested that the ice was apparently still wasting, as a smaller portion of the ice front was bathed by low tide. They also noted:

> The marginal stream on the eastern side was of great size and was building a steeply sloping delta whose area increased greatly from 1908 to 1910. Grant's conclusion that the advance in association with the terminal moraine had taken place at least 20 years before 1908 would seem to associate the advance with the tidal condition of the glacier when mapped by Applegate in 1887. In connection with the long stand of the glacier terminus, with only about 500 feet of retreat in 23 years, there has accumulated an extensive terminal deposit of gravel, sand, and clay, laid down in large part below sea level. The weak terminal moraine on the land, the broader terminal deposit in the sea, and the barren zone are all conspicuous phenomena in connection with the history of Nellie Juan Glacier from 1887 to 1910 (Tarr and Martin, 1914, p. 372).

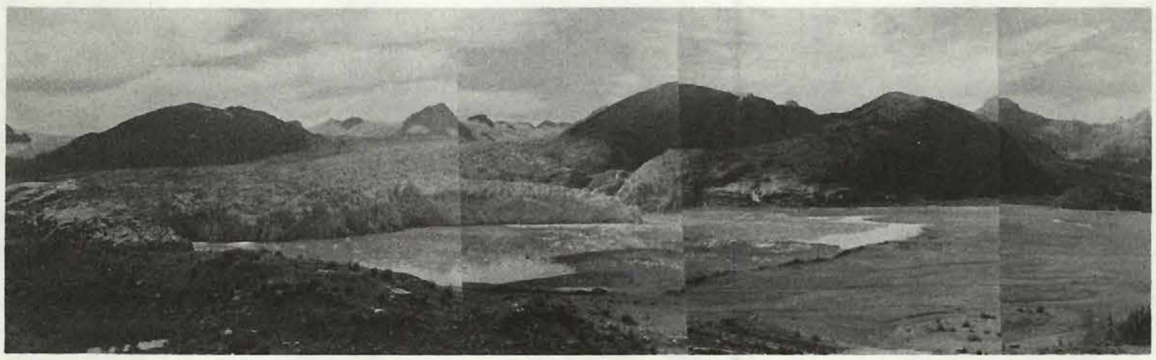
In 1925, F. H. Moffitt photographed the glacier, and his pictures indicated little change in the terminus since 1910.

Field (1937) visited Nellie Juan Glacier in 1935 and observed that since Moffitt's visit in 1925, a rapid retreat had taken place along the entire terminus. By surveying, Field was able to determine that from 1910 to 1935, the total recession at the west end of the ice front was 1,912 feet, while recession at the eastern end was 1,532 feet. He concluded that most of this recession had occurred in the last 10 years. Field's photo (Figure 15) of the terminus shows a small push moraine directly in front of the ice. This and the rather steep angle of the front suggested to him that an advance may have been occurring at that time.

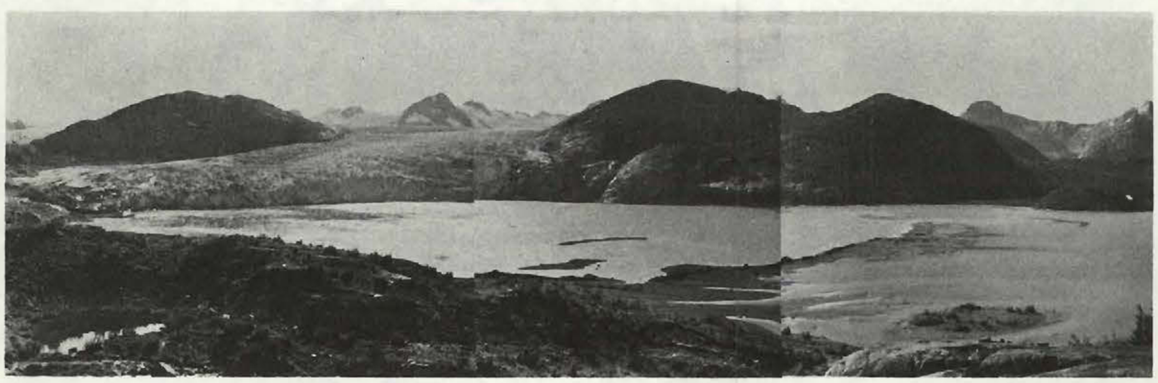
In 1957, the I. G. Y. party spent two days at Nellie Juan Glacier, re-occupying one station which had been established by Grant and Higgins in 1908 and occupied by Field in 1935. The party also occupied another station established in 1935 and established two new stations. In addition, it mapped the terminus and measured the distance to the ice front. The rapid recession reported by Field (1937) was still in progress (Figures 15 and 16), and continuing so rapidly that silting was no longer keeping pace with recession, and a large lake had formed at the terminus (Figures 15 and 16). The heavy calving of ice into this lake is undoubtedly responsible for part of the rapid recession. However, the grounded portion of the terminus on the eastern and southeastern portions is also melting very rapidly. A small lake shown dammed by the ice on the eastern side in 1950 (Seward C-4 map) had drained and had left only a small pond. Measurements and surveying indicated a recession of 3, 035 feet since the first map of 1908 (Grant and Higgins, 1911). Much of this has occurred since 1935 (approximately 1, 500 feet). A careful comparison of a push moraine shown in a 1935 photograph with the present moraine remnants showed that a small advance was culminating in 1935 (Figure 15).

Nellie Juan Glacier was again visited by the author on August 30, 1961, and terminus conditions were compared with those of the previous visit. Again old stations were occupied and some new ones established. Surveying and chaining showed that the retreat recorded since 1908 was going on at a greatly accelerated pace (Figures 15

Nellie Juan Glacier, south margin, 1935, from Station B (2)
Photos f-35-804, 805, 806 by Wm. O. Field



Nellie Juan Glacier, south margin, 1957, from Station B (2)
Photos M-57-SG46, 47,48, 49 by M.T. Millett



Nellie Juan Glacier, south margin, 1961, from Station B (2)
Photos M-61-SG 219, 220,221 by M.T. Millett

Figure #15

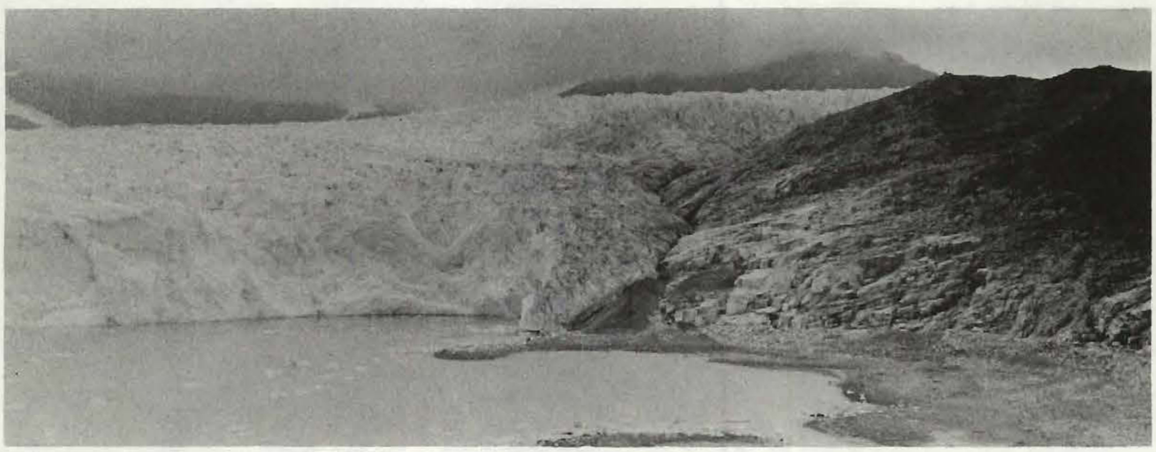
and 16). The tidal lake was very large, and it was no longer possible to walk to the western terminus, since the glacier there was against a steep rock cliff. Along the eastern side, recession had been so rapid that large bodies of ice had detached from the glacier appearing as low, sandy knolls along the shore. Large ice falls were observed, and, at times, the lake was nearly covered with icy debris.

Comparing the map of the terminus made by Grant and Higgins in 1908 (Figure 17) and their photographs (Figures 15 and 16) with the photo record of 1935, the Seward B-4 map based on the 1950 aerial photos, and the surveys of 1957 and 1961, the following changes in the glacier can be seen:

1. Recession of the terminus has not been at an even rate. During a period prior to 1935 a small advance occurred which left a well-defined terminal moraine. That this was not merely a still-stand in the retreat pattern is indicated by the moraine being a push moraine (Figure 15). From 1935 to 1950, the ice again retreated at a rate similar to that of pre-1935 years. After 1950, the melting increased rapidly, and by 1961 the total size of the glacier diminished by approximately 21 per cent from that of the 1880 hochstand.

2. Vertical shrinking of the glacier has also been obvious. A well-defined vegetation trimline formed during the 1880 hochstand (Figures 16 and 17) was more than 500 feet above the surface of the 1961 terminus. In addition, on the 1950 map (Seward C-4) the terminus is shown at the 100 foot contour position while investigation in 1961 showed it to be at the 400 foot contour position on the same map. The height of the terminus remained a constant 100

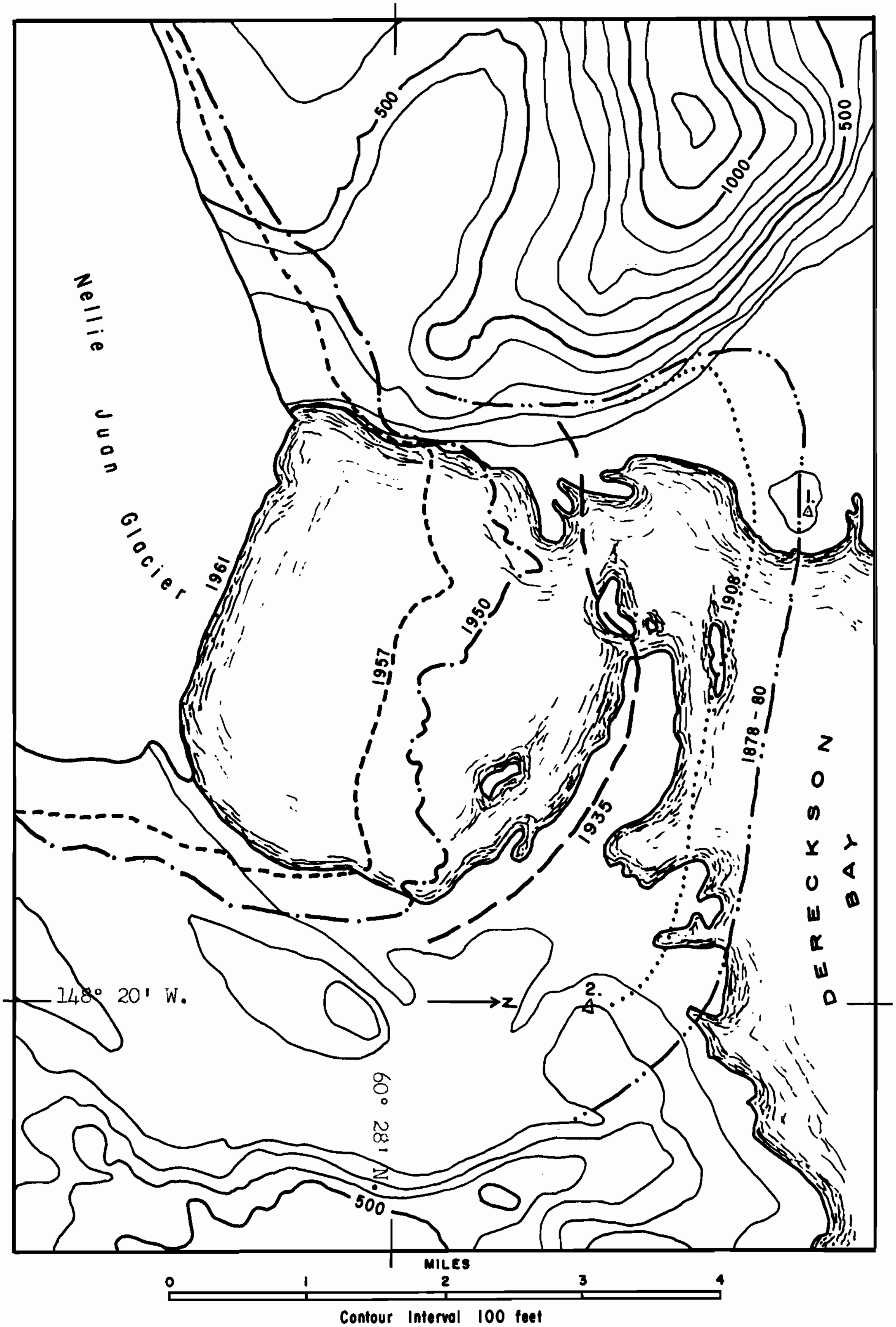
North margin, Nellie Juan Glacier, 1908, from Station A (1)
Photo No. 52 by U.S. Grant



North margin, Nellie Juan Glacier, 1935, from Station A (1)
Photo f-35-791 by Wm. O. Field

North Margin, Nellie Juan Glacier, 1961, from Station A (1)
Photos M-61-SG 214 by M.T. Millett

Figure #16




Based on U.S. Geological Survey Map, Seward B-4

Location of Terminus 1878 – 1961

**NELLIE JUAN GLACIER**

Figure #17

feet, suggesting not only retreat, but also downmelting of nearly 300 feet, in the 11 year period, a rate of about 27 feet per year.

3. Continued enlargement of the tidal lake at the terminus probably has accounted for much of the increasing rate of recession. During the 1961 visit almost the entire front appeared to be in deep water, and large ice falls occurred regularly. An increase in melting also resulted from the presence of the tidewater along the front. That melting and recession are greater in the water was evidenced by the large bodies of stagnant ice left behind along the shore of the eastern margin.

4. Silting in of the bay appears to be controlled by the rate of glacier recession. During slow recession, or stillstand, complete silting in occurs, producing bars, deltas, and changes in the shoreline, while during rapid recession these features are not produced, and the lake in front of the terminus expands and gets deeper.

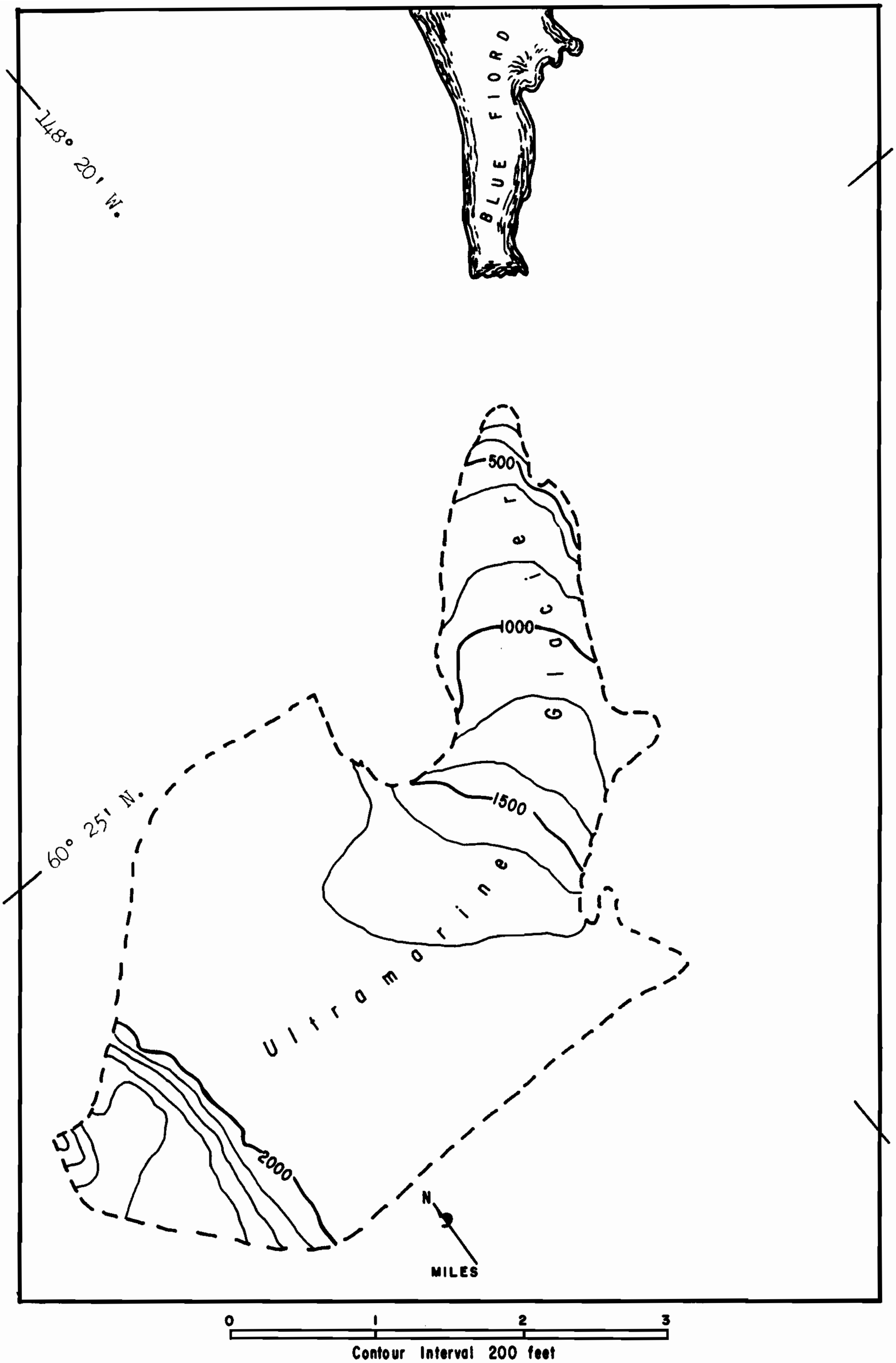
## Ultramarine Glacier

Ultramarine Glacier, named by Grant and Higgins (1911) because of its blue color, is located at the head of Blue Fiord in Port Nellie Juan (Figure 12). The ice front is about one mile from the beach and nearly 150 feet above sea level. The surface of the ice at the terminus is clean and moderately crevassed. This glacier is a narrow pointed tongue of ice draining from the Sargent Ice Field (Figure 18). Its upper margins in the ice field are somewhat difficult to define, but contour lines on the Seward B-4 map give a suggestion of its drainage basin. The total size is 11-1/2 square miles with a length of 6-1/2 miles. The gradient near the head is steep (Figure 19) while the middle part is very flat, dropping steeply near the terminus. The firn limit, as indicated on 1950 airphotos, is in the vicinity of the 1,400 foot contour which would give an accumulation area ratio of 0.800, most of the accumulation area being between 1,400 and 2,300 feet elevation (Figure 19). As seen from the area distribution curve (Figure 19) any movement of the firn line would critically alter the glacier budget.

Although easily accessible, this glacier has received little attention from investigators. It was first described by Davidson (1904, p. 27) in his discussion of Applegate's map of 1887: "Into the head of the southernmost arm he (Applegate) lays down a broad glacier coming down to the water front with a narrow moraine outside. He was close to the moraine." Consequently, Applegate's description and map can be assumed to be reasonably accurate.

The next account is from Grant and Higgins (1911, p. 411), who did not visit the glacier, but made their observations and maps from a considerable distance (Figure 20). The vagueness of their account is compounded by a misinterpretation of Applegate's map. They said:

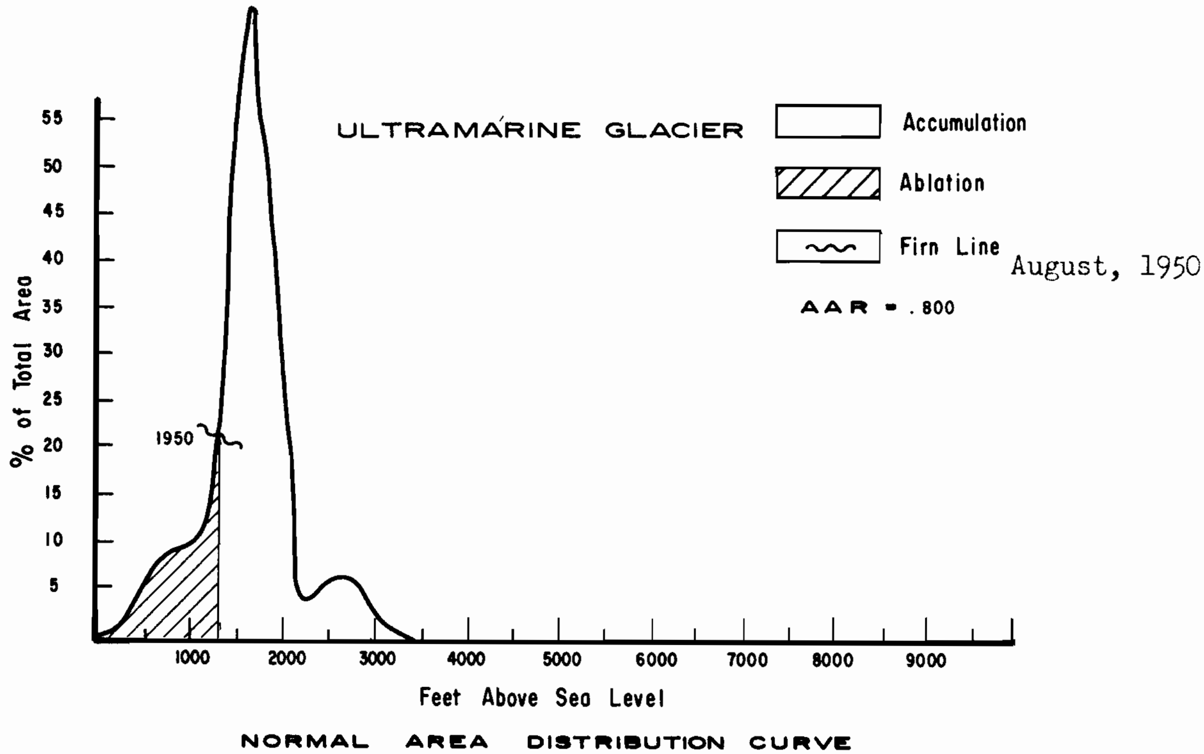
> The glacier comes within about a quarter of a mile of tidewater and the western part of the front extends farther forward than the eastern two-thirds and rests on a glacial flat. The eastern part of the front rests on a rock ridge about 300 feet above the sea. On this ridge there is a marked bare zone, and also one on the other side of the glacier. The front of the glacier was not visited, but at a distance this bare zone appeared as if the ice had retreated from it in the last two or three years. Applegate's map indicates that the glacier in 1887 reached to tidewater along its whole front. The forest in front of the eastern part of the glacier shows that this could not have been the case, although the western part may have reached tidewater at that time, but even this is doubtful. Our observations on this glacier were made at a distance of about a mile and a half.




**ULTRAMARINE GLACIER**

Based on U.S. Geological Survey Map, Seward B-4

**Figure #18**


ULTRAMARINE GLACIER
Accumulation
Ablation
Firn Line
August, 1950
AAR = .800
1950
% of Total Area
55
50
45
40
35
30
25
20
15
10
5
1000
2000
3000
4000
5000
6000
7000
8000
9000
Feet Above Sea Level
NORMAL AREA DISTRIBUTION CURVE

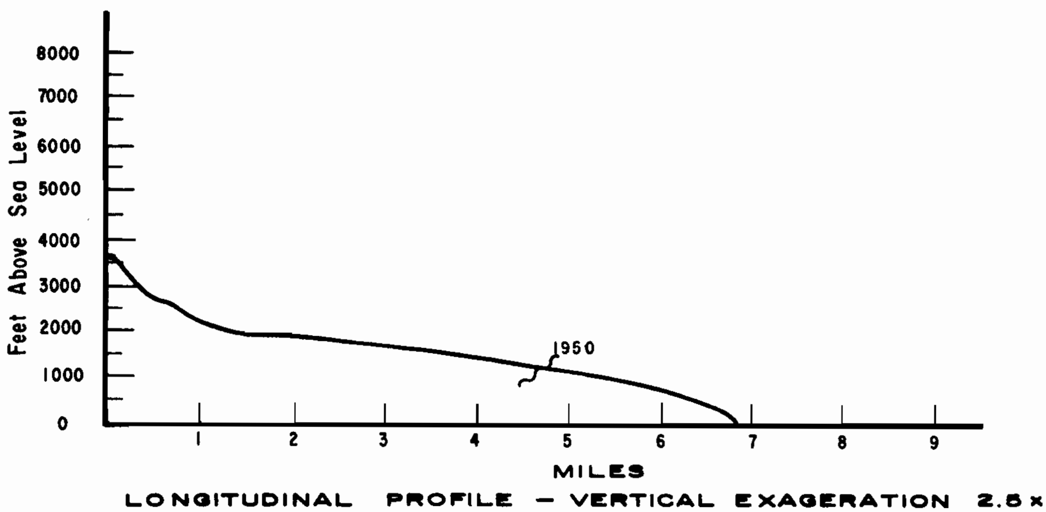
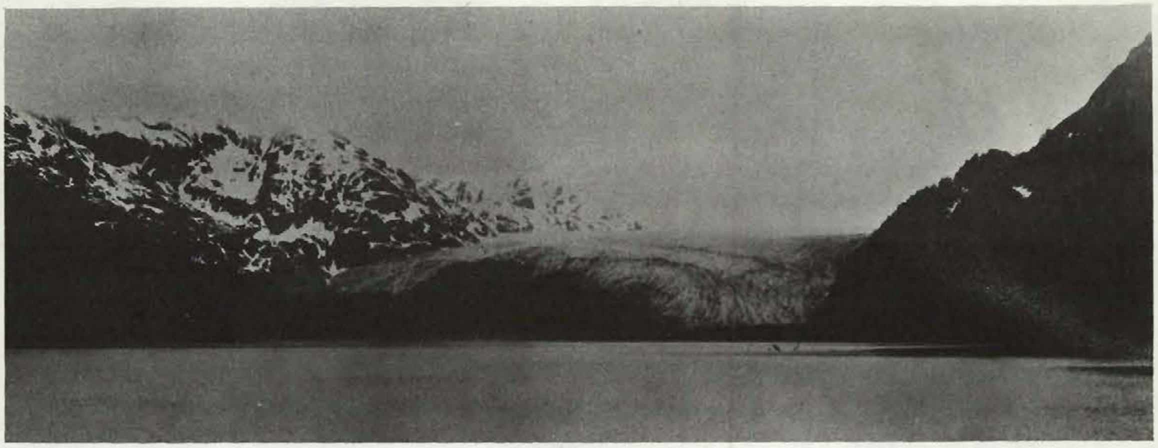
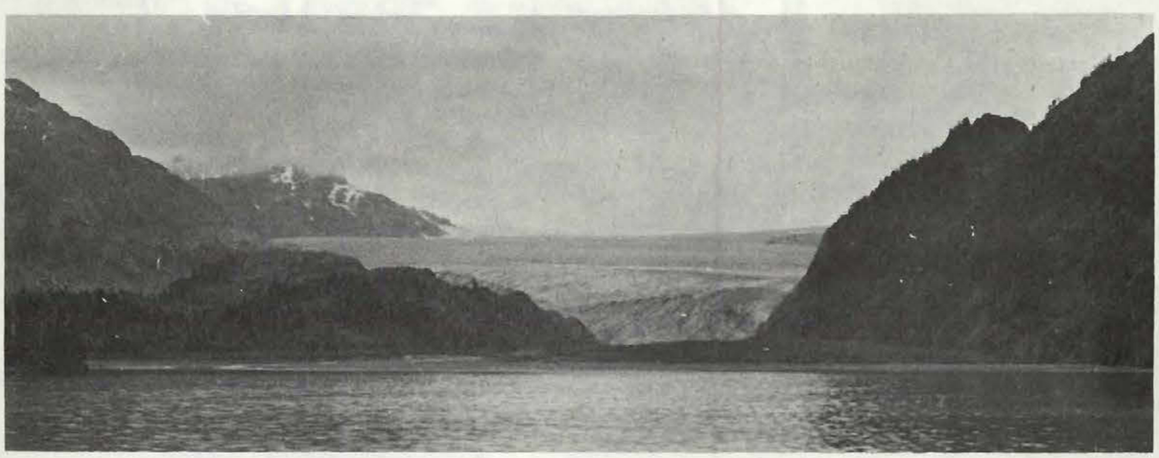

Feet Above Sea Level
8000
7000
6000
5000
4000
3000
2000
1000
0
1950
1
2
3
4
5
6
7
8
9
MILES
LONGITUDINAL PROFILE — VERTICAL EXAGERATION 2.5 x

Figure #19



Ultramarine Glacier, 1908, as seen from boat on Blue Fiord
Photo No. 50 U.S. Grant

Ultramarine Glacier, 1935, as seen from boat on Blue Fiord
Photo f-35-821 by Wm. O. Field



Ultramarine Glacier, 1957, as seen from boat on Blue Fiord
Photo G-57-V228 by Robt. Goodwin

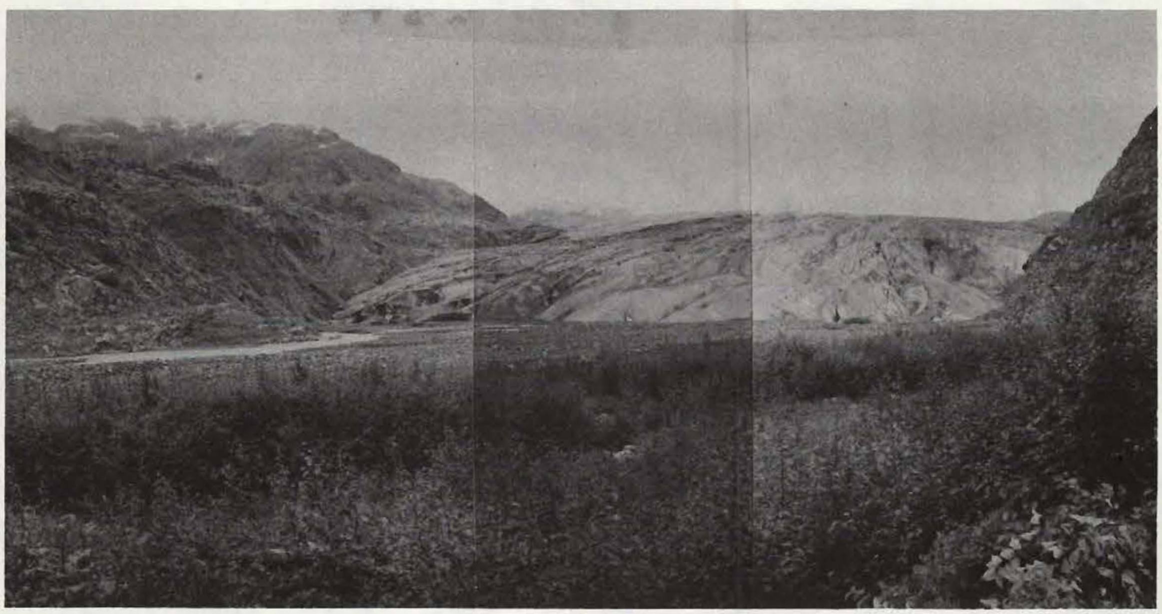
Figure #20

In 1935, Field (1937, p. 80) visited Ultramarine Glacier but did not go beyond the terminal moraine, where he took one photograph (Figure 21). He said: "Ultramarine Glacier, a nontidal glacier at the head of Blue Fiord, receded more than 1,000 feet between 1908 and 1935."

In 1950, the United States Air Force took vertical airphotos which were used by the United States Geological Survey to prepare a map (Seward B-4). Thus up to 1957 the glacier had not been seen from less than one-half of a mile away, although the 1950 position is carefully plotted on the Seward B-4 map.

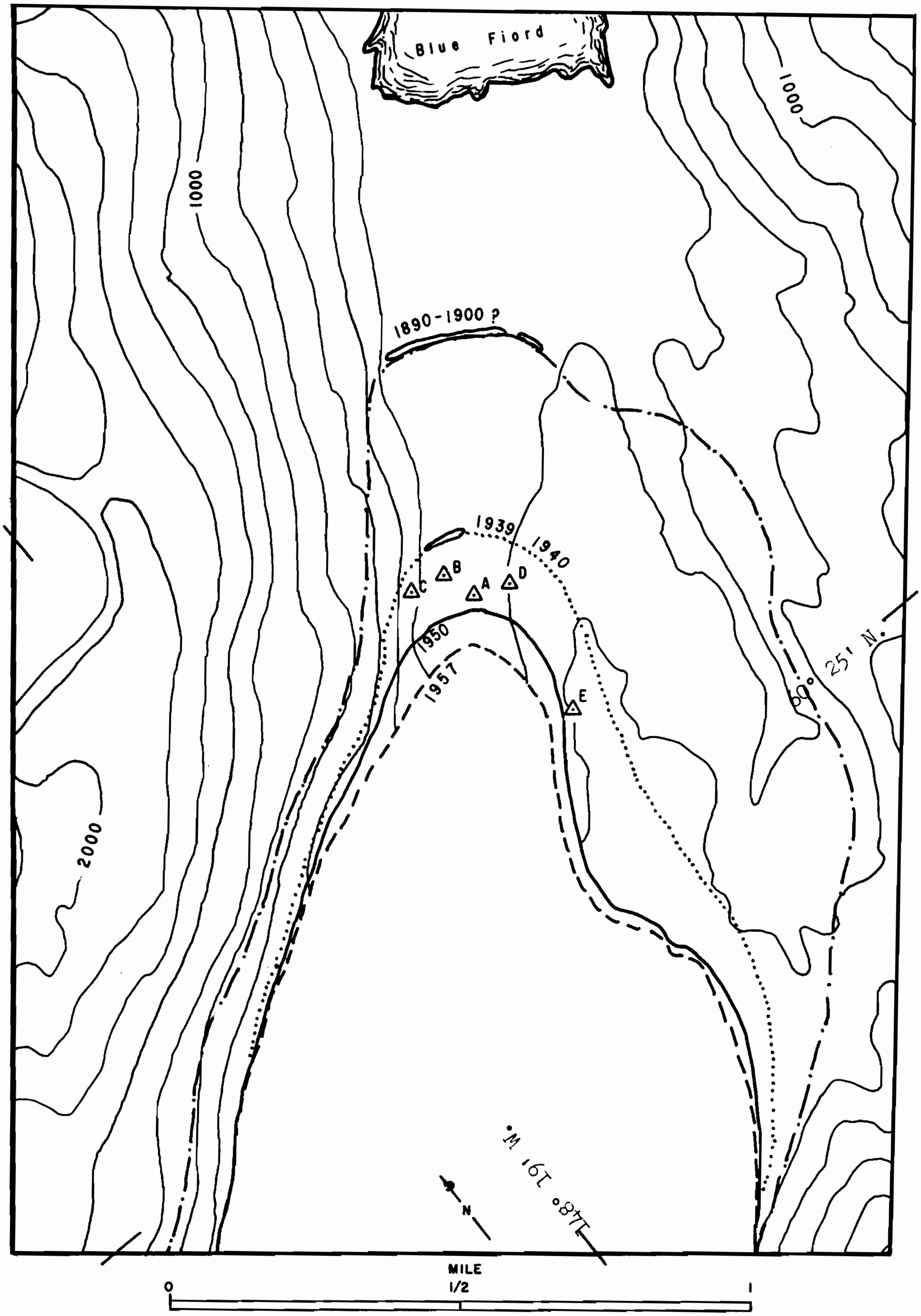
The 1957 I. G. Y. party spent a day at Ultramarine Glacier, and during the visit they prepared a map, established permanent survey and photo stations, and examined and dated moraines and trimlines by botanical methods. Along the western valley wall is a conspicuous vegetation trimline continuous with, and formed at the same time as, the prominent terminal moraine, which is half way between tidewater and the ice front and is nearly continuous across the valley (Figure 22). Since the oldest tree on this moraine was 46 years old, the botanists concluded that the moraine was formed between 1890 and 1900. Many old trees outside this moraine on the eastern side indicate that the ice has not been beyond the moraine in several hundred years. Ice recession from this hochstand was not even, as is indicated by many small recessional moraines stretching across the valley. One of these, about 1,000 feet from the 1957 ice front, had sufficient vegetation to date its formation time at about 1930. This advance, or stillstand, may have been contemporaneous with the 1935 advance of the Nellie Juan

Ultramarine Glacier, 1935, from terminal moraine
Photo f-35-822 by Wm. O. Field



Ultramarine Glacier, 1957, from terminal moraine
Photos LV-57-208, 209, 210 by Leslie Viereck

Figure #21




ULTRAMARINE GLACIER

Figure #22 Based on U.S. Geological Survey Map, B-4

Glacier, six miles to the north.

The Ultramarine Glacier was not visited in 1961.

## Summary

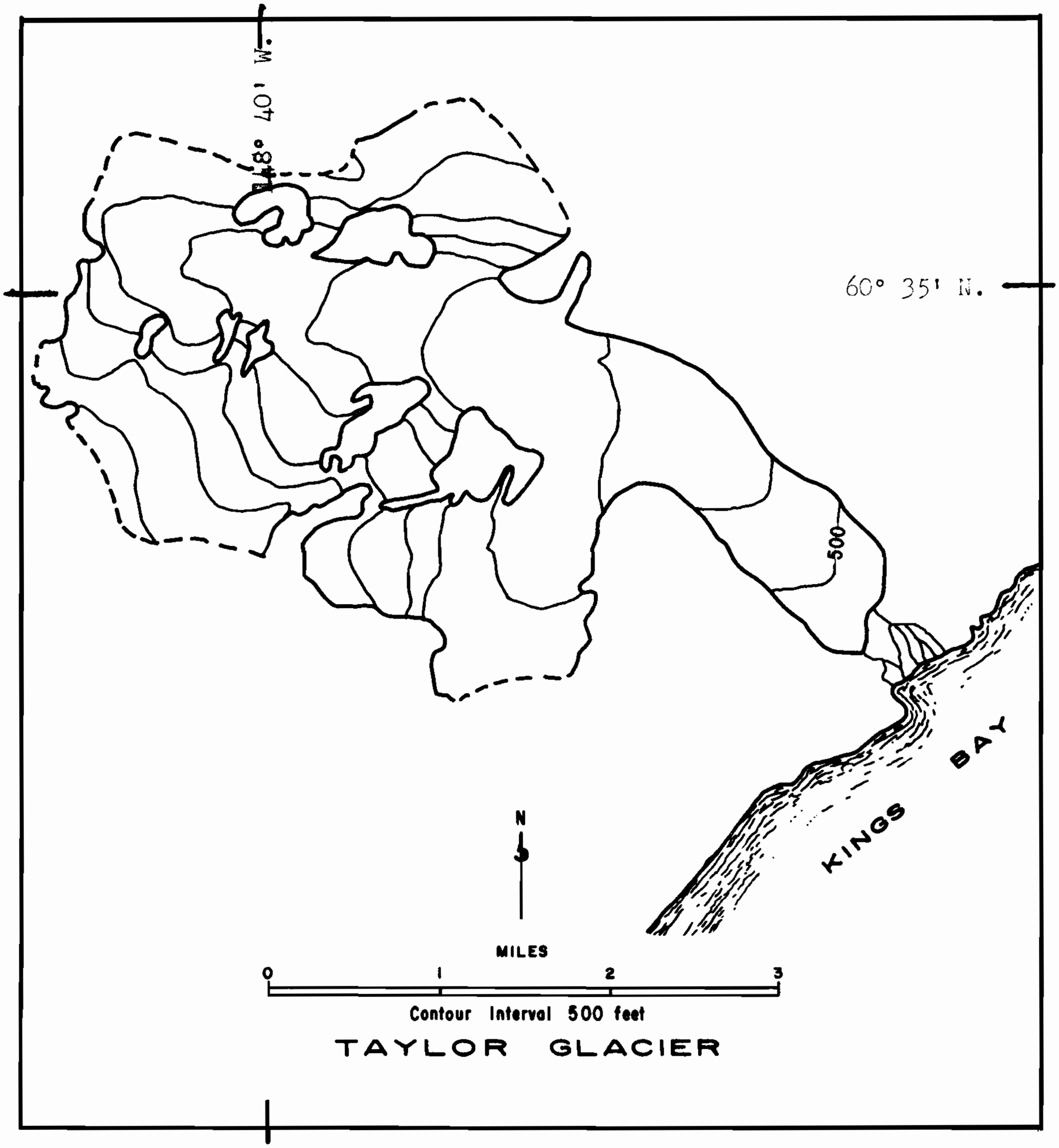
Although the terminus of Ultramarine Glacier is known to have been visited only once, a considerable amount of information is available and a fairly clear history may be pieced together from early maps and photos, and recent research. The information shown on Figure 22 is based on botanical dating, photography, and surveying, all done in 1957.

The mature forest mentioned by Grant and Higgins (1911) is on the eastern side of the valley and not on the outwash plain directly ahead of the present ice. It is therefore probable that when the ice was at its maximum extension, tidewater was much closer to the terminal moraine than at present. A long stillstand near this position could have silted in a considerable distance of the narrow fiord. This would account for the long distance (nearly one-half of a mile) between the terminal moraine and tidewater in 1957, and the relatively short distance suggested on the early maps. The rate of recession since the hochstand is unknown except from recessional moraines, one of which was formed around 1930. The distance between these moraines is about 1,800 feet, which would make the recession rate about 51 feet per year. After 1930, the terminus receded 800 feet to the position shown on the Seward B-4 map (1950), or at a rate of 40 feet per year. From 1950 to 1957, it receded about 350 feet, or at a rate of 50 feet per year. These rather uniform rates of retreat may hide any variations that may have occurred.

## Taylor Glacier

Taylor Glacier is located in Port Nellie Juan on the northeastern side of Kings Bay about nine miles from the head of the bay. The terminus is nearly half a mile from tidewater but only a few feet above sea level. The glacier is 6-1/2 miles long and covers an area slightly larger than 9 square miles (Figure 23). The accumulation area is adjacent to the Blackstone complex and drains from heights just over 5,500 feet above sea level southeast through a well-defined valley. The firn line in August, 1950, was between 2,000 and 2,200 feet elevation. However, most of the collecting area is between 2,500 and 4,200 feet. With the firn line at this elevation, the glacier has an accumulation area ratio of 0.714 (Figure 24). There are five large tributaries along the southwestern side and two along the northwest. The importance of these tributaries is not apparent in the longitudinal profile (Figure 24) where the firn line appears midway in the glacier. However, the area distribution curve (Figure 24) indicates that these tributaries are of high elevation and are an important source of accumulation. The ice is fairly clean (Figure 25), and medial moraines of the tributaries are small but obvious.

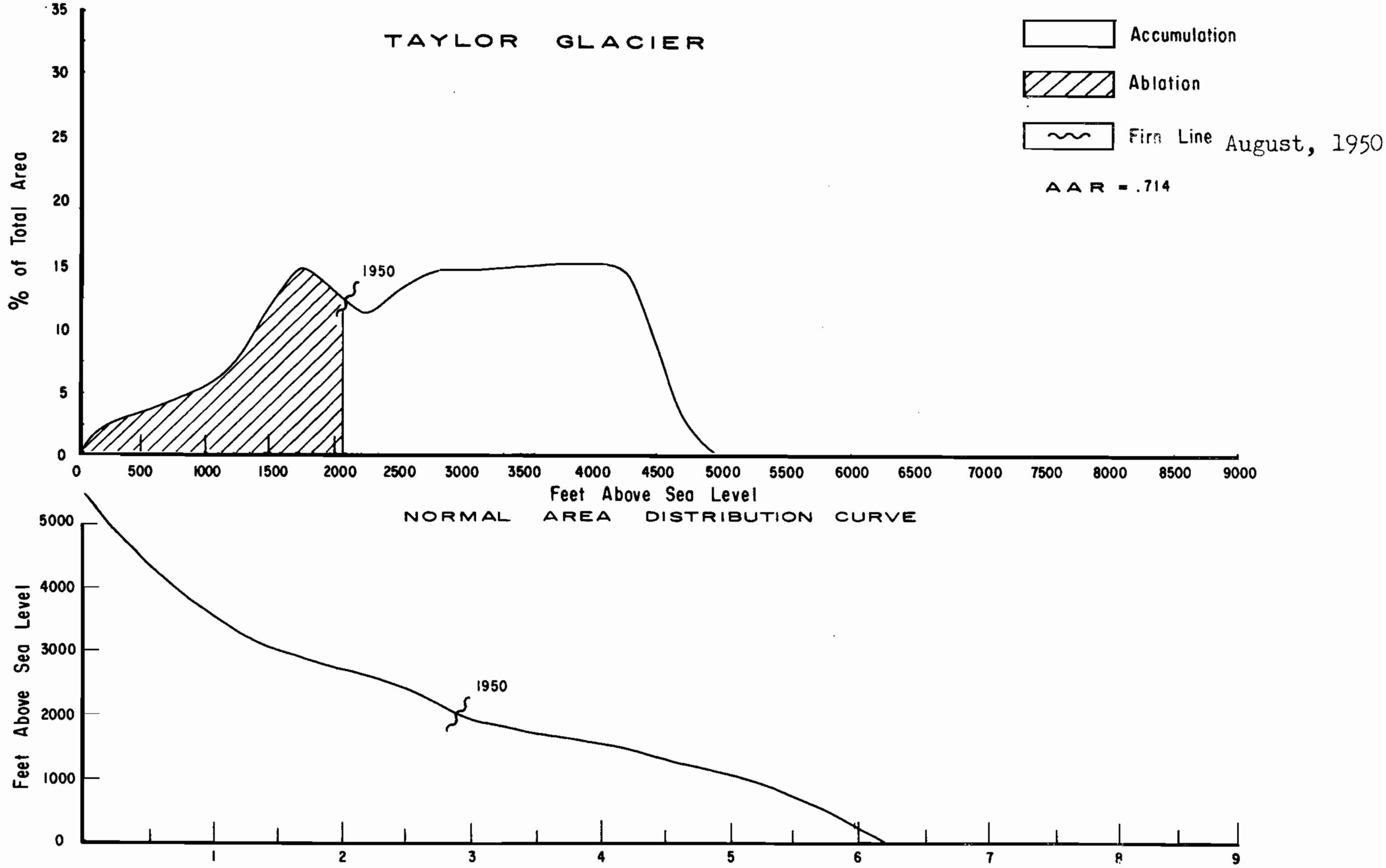
In front of the 1961 terminus a rock ridge extended from the northeastern valley wall across the valley, sloping down near the western wall until it was just higher than the outwash plain. Since the ice front is just behind this ridge, it cannot be seen from the bay. The ridge dams the melt water from the glacier, forming a small lake. From this rock ridge an unbroken outwash plain




Based on U.S. Geological Survey Map, Seward C-5

Figure #23

Figure #24




NORMAL AREA DISTRIBUTION CURVE

LONGITUDINAL PROFILE – VERTICAL EXAGERATION 2.5x

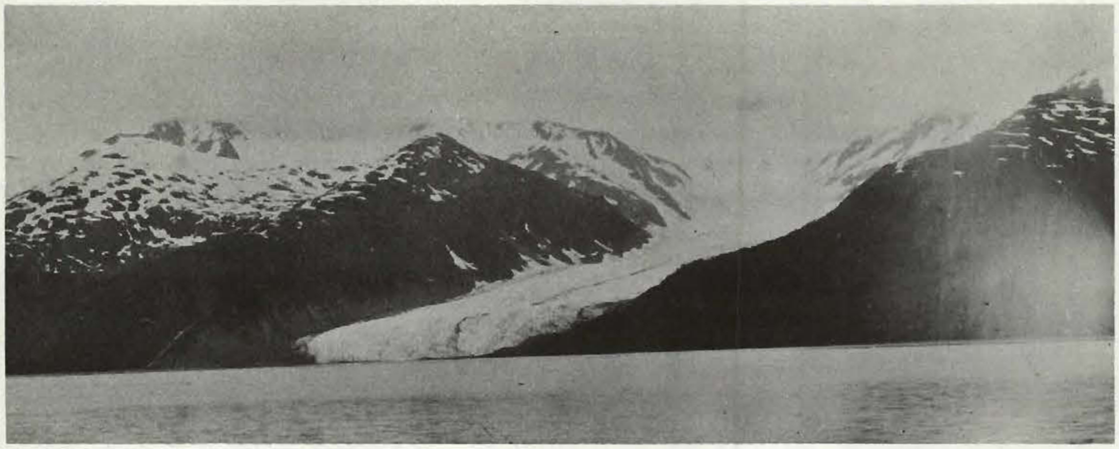
extends to tidewater. There is little or no vegetation on this outwash, and no moraines to indicate former positions of the ice front. Old vegetation trimlines are found along either valley wall. Data for Figure 26 are taken from photographs, trimlines, and a survey made in 1961.

The earliest reference to Kings Bay fails to show Taylor Glacier. Davidson (1904, p. 27), describing Applegate's voyage and map of 1887, said: "On the northwest shore. . . he lays down a steep ravine breaking upon the shore from the westward, with rocks in front of it. It suggests the line of a former glacier." This conclusion can only be an error, since the 1908 map of Grant and Higgins (1911) not only shows Taylor Glacier reaching the water, but also shows trimlines indicating a recent maximum. It is unreasonable to assume an advance of a mile or more, then a recession of several hundred feet, in just 20 years. Applegate's map was further proved incorrect by botanical dating done in 1957.

Grant and Higgins' (1911, p. 410) description is only one sentence: "On the west side of the southern part of the port are other glaciers, one of which, the Taylor, reaches sea level." The National Geographic Society's expedition (Tarr and Martin, 1914) visited Kings Bay in 1910 but did not see Taylor Glacier. Their account merely quotes the single sentence of Grant and Higgins.

In 1925, F. H. Moffitt of the U. S. Geological Survey took a photograph (Figure 25) of Taylor Glacier from a boat in Kings Bay. He gives no description other than a simple caption.

In 1935, W. O. Field (1937, p. 79) visited Kings Bay (Figure 25) and reported:



Taylor Glacier, 1908, as seen from boat
Photo No. 56 by U.S. Grant

Taylor Glacier, 1935, as seen from boat
Photo f-35-771 by Wm. O. Field

Taylor Glacier, 1961, as seen from boat
Photo M-61-229 by M.T. Millett

Figure #25

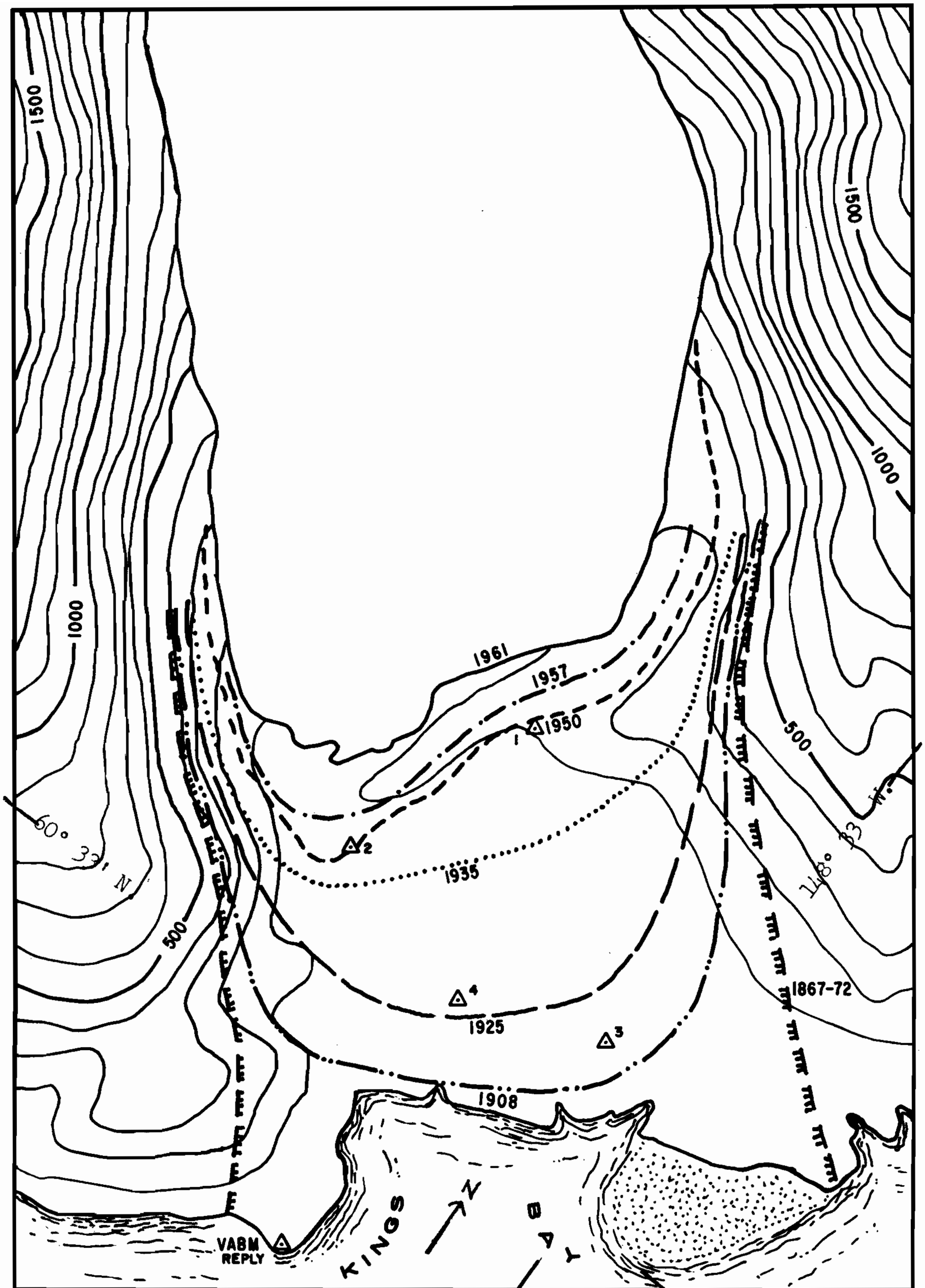
There are no precise measurements available for the fluctuations of the glaciers of Applegate arm [Kings Bay] of Port Nellie Juan. All the glaciers have receded fairly recently from a maximum position very near to mature vegetation. Comparison with early photographs shows that the two largest glaciers, Taylor and Falling, which practically reach tidewater, changed very little between 1908 and 1925 but that since then there has been considerable shrinking in their lower parts.

An excellent map was produced by the U. S. Geological Survey (Seward C-5) from airphotos taken in August 1950. All of the data of Figures 24 and 26 were taken from this map, which is also used as a base map for Figure 23.

The I. G. Y. party visited Taylor Glacier in 1957 and established two permanent photo stations along the rock ridge just in front of the terminus. Botanists of the party dated the trimline as being formed in the years 1867-72. This trimline extends almost to the water's edge; however, there were no moraine remnants visible near the shore to suggest the former limit of this hochstand.

In 1961, Taylor Glacier was surveyed and photographed from the 1957 stations (Figure 26). In addition, two more photo-survey stations were established. Recession of the glacier has involved both a retreat of the front and a considerable downmelting in the terminal area. The entire terminus is behind the rock ridge, and all drainage is around the west end through a single channel. A lake, ponded by the ridge, has become larger, but because of silting it has also become more shallow.

The age of the trimlines in mature forest indicates that the glacier reached its post-glacial maximum in the years 1867-1872. The slope of the trimlines and the deep water of Kings Bay suggest that the ice stream did not extend far out into the bay. No terminal




Based on U.S. Geological Survey Map, Seward C-5

FEET
0 1000 2000

Contour Interval 100 feet

TAYLOR GLACIER

Figure #26

moraine is visible, but a large mud flat (Figure 26) near the northeastern side of the valley may have been caused by silting in behind a submerged moraine. The well-defined trimline indicates that the ice at least extended down to this point. In 1908, (Grant and Higgins, 1911) the ice was tidal, but did not extend to the 1867 trimline. That the ice retreated from the 1868-72 hochstand by 1887 and then re-advanced to tidewater by 1908 is unlikely. The omission of Taylor Glacier from Applegate's map of 1887 was probably an oversight. This omission leaves a considerable hiatus in the evidence from which the above history was reconstructed.

Summary

The behavior of the terminus has been one of continuous retreat since 1908. Figures 25 and 26 show slow retreat up to 1925, then rapid retreat until the mid thirties, followed by slow retreat until the mid fifties, when melting again increased (Figure 26).

Most of the collecting area is between 2, 500 and 4, 200 feet elevation (Figure 24), well above the 1950 firn line, and suggests that Taylor Glacier is not very sensitive to small fluctuations in firn line position. However, its low gradient, below 2, 500 feet, provides a large ablation area. Its orientation to the south also exposes it to maximum sunshine.

Total loss in the terminal area since 1908 is one square mile, or 11 per cent of the total glacier area.

## Langdon and Kings Glaciers

These two glaciers are located near the head of Kings Bay on the southern side. They are both small and have, until recently, been joined at the terminus. No known studies have been made of these ice tongues, although they appear on the early maps of Applegate (Davidson, 1904), and Grant and Higgins (1913). On both maps the glaciers are shown curving toward each other and joining to form a giant "U." By 1935, the two tongues had separated. The bare zone that now lies between them was visible on an airphoto taken by W. O. Field in 1935. The 1950 airphotos show that they were separated by nearly 2,000 feet.

In 1957, an attempt was made to study these glaciers, but due to heavy fog and rain the attempt was abandoned, except for setting up cairns as future reference points.

Nothing is known of the history of these glaciers, and the early maps are not detailed enough to provide the exact position of the terminus in those years. What appears to be a trimline can be seen in airphotos extending in an arc about 3,000 feet from the 1950 terminus. Vegetation suggests this as a hochstand occurring in the last one or two hundred years. An inner trimline, about 1,000 feet from the 1950 ice, has little vegetation inside it and appears to be near the 1935 position. The 1935 airphoto also shows what may be a push moraine at the base of the central tongue of the terminus, indicating that a slight advance possibly took place in the early or mid 1930's.

## Claremont Glacier

The relatively small Claremont Glacier on the northwestern side of Kings Bay is made up of two branches. The north branch has a southerly flow and the western branch a northeasterly flow. Until recently, these branches joined above the terminus giving the glacier a "Y" shape.

Sofar as is known, no detailed observations have been made of this glacier, except for the indication of an end moraine on Grant and Higgins' 1908 map (1913). The only other data are photographs either taken from the air or from Kings Bay. Oblique airphotos were taken in 1935 by Field, and trimetrogon photos were taken by a U. S. Army flight in 1941. In addition, vertical airphotos, which form the basis of the Seward C-5 map, were taken in 1950.

A general history of terminus behavior may be determined from the above data and additional data obtained by the I. G. Y. party in 1957, and by the author in 1961. In 1908, according to Grant and Higgins' map, recession from the end moraine appeared to be a few hundred feet. By 1935, there was an additional retreat of about 2,000 feet. Between 1935 and 1941, the termini of the northern and western branches became separated at the snout, although they were still linked in their accumulation areas. Between 1935 and 1950, the terminus of the northern branch receded about 1,000 feet and the western branch nearly 3,000 feet. After 1950, but before 1957, the two branches completely separated, and by 1961 the terminus of the northern tongue receded an additional 1,000 feet and the western branch about 1, 500 feet. Total recession since 1908 is, therefore, about 3, 000 feet for the northern branch and over 7, 000 feet for the western branch.

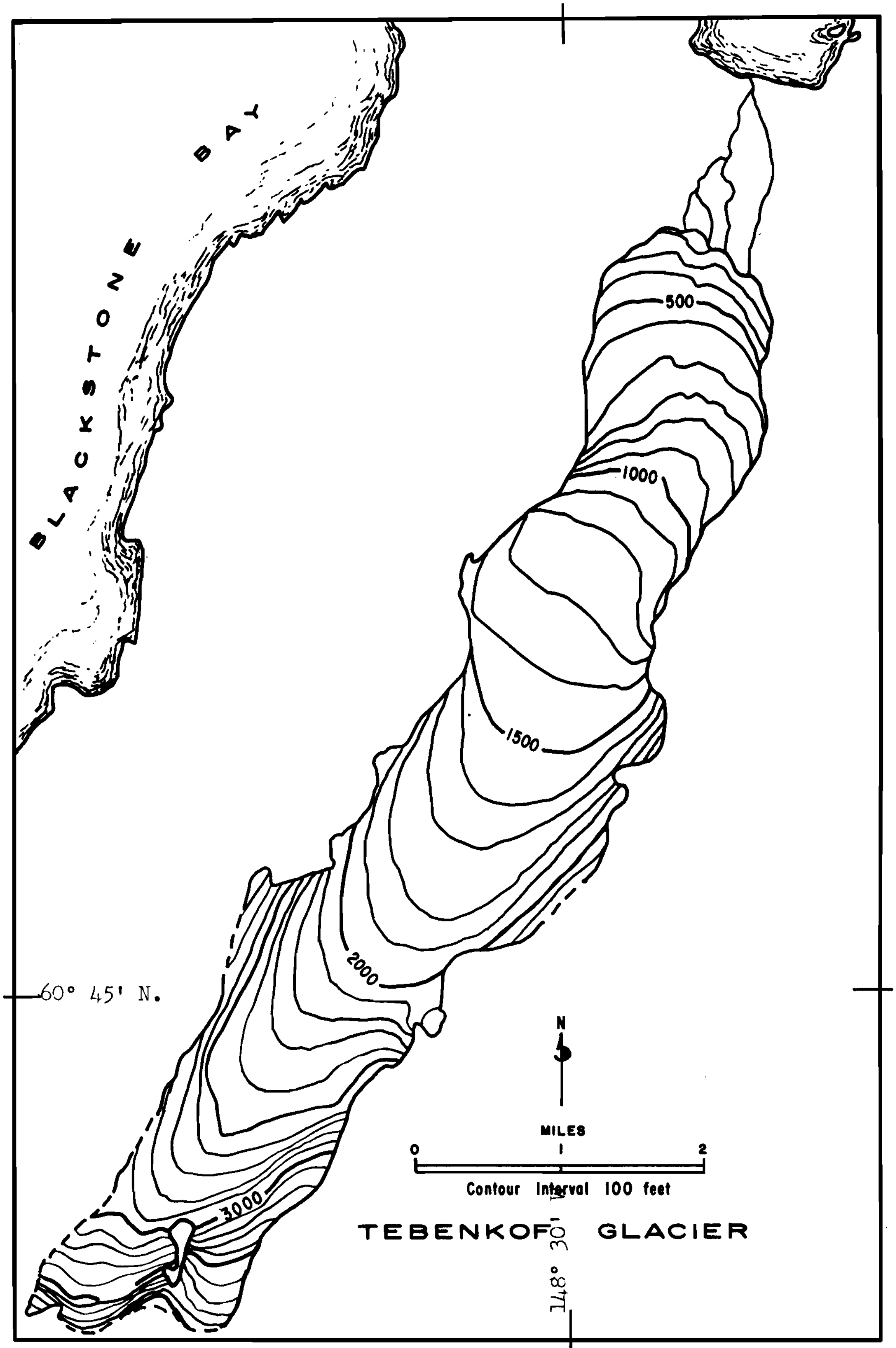
## Falling Glacier

Falling Glacier, located midway along the southern side of Kings Bay, is the only ice tongue in the bay to reach tidewater. However, only a small central part of the terminus actually touches the sea, and no icebergs are discharged. Falling Glacier is a small distributary tongue of the Sargent Ice Field and probably has, on a modified scale, a history of terminus fluctuation similar to that of Nellie Juan Glacier and Ultramarine Glacier.

Falling Glacier does not appear on Applegate's map (Davidson, 1904) of 1887. Since Taylor Glacier, directly opposite on the north side of Kings Bay, is also missing, Applegate was probably never in the bay; and the ommission of these two termini may not be considered a result of retreat. On Grant and Higgins' (1913) map of 1908, the terminus is clearly shown in roughly the same position as in 1961. Other photos taken between 1908 and 1961 also show a remarkable stability in the position of the ice front. A total recession of 300 feet or less in more than 50 years indicates a near-equilibrium in the ice stream.

## Tebenkof Glacier

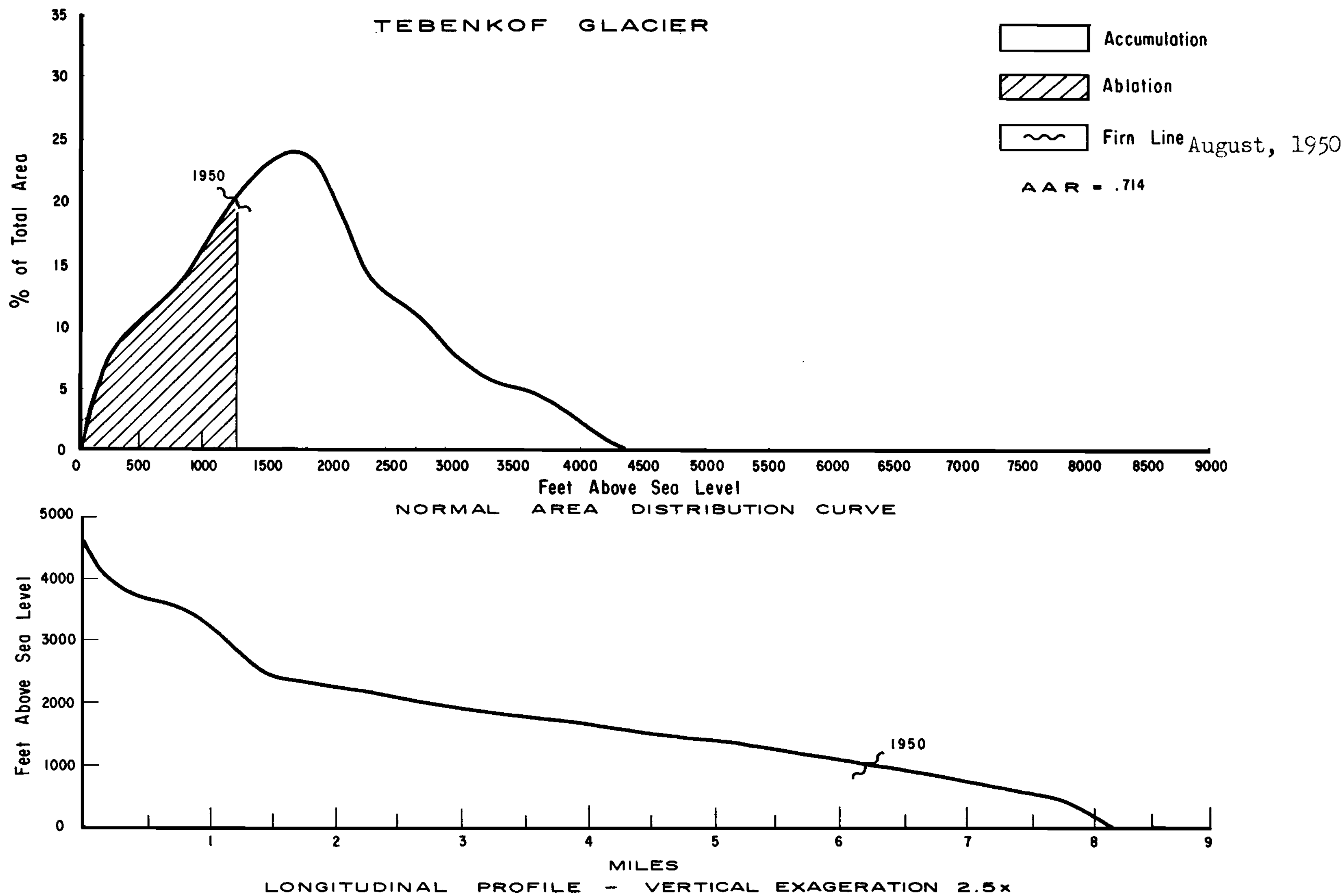
Tebenkof Glacier, named after a governor of Russian America in the period 1845 to 1850, is located near the mouth of Blackstone Bay. Its present terminus is about a mile inland from tidewater and the ice at the terminus is clean except at the very edge. There are several large, splaying crevasses in the terminal area, but access to and travel on the glacier is very easy. The glacier descends from 4,583 feet above sea level to 50 feet above sea level in about 8-1/2 miles, and the resulting average gradient of 520 feet per mile is fairly even and gentle except near the head where it drops rather abruptly from its highest point (Figure 28). The shape is unusual in that the glacier has neither tributaries nor arms. Tebenkof Glacier nearly fills an almost straight valley without flanking high mountains, a valley that is neither narrower than one mile, nor wider than 1-1/2 miles. It descends in a north-northeasterly direction from snowfields adjacent to those that feed the glaciers on Blackstone Bay on the north and Cotterell Glacier on the south. The névés of these three systems are nearly contiguous, being separated only by low divides. The glacier itself covers approximately 10-1/2 square miles (Figure 27). The firn line, determined from airphotos, was near the 1,300 foot contour in August, 1950. The accumulation area ratio was accordingly about 0.714, most of the accumulation occurring between the firn line and the 3,000 foot contour (Figure 28). Judging from the position of the firn line and the nature of the area distribution curve, the budget of this glacier is subject to easy upset.



Based on U.S. Geological Survey Maps, C-4, C-5

**Figure #27**

Figure #28



TEBENKOF GLACIER
Accumulation
Ablation
Firn Line August, 1950
A A R = .714
1950
% of Total Area
Feet Above Sea Level
NORMAL AREA DISTRIBUTION CURVE
Feet Above Sea Level
MILES
LONGITUDINAL PROFILE - VERTICAL EXAGERATION 2.5x

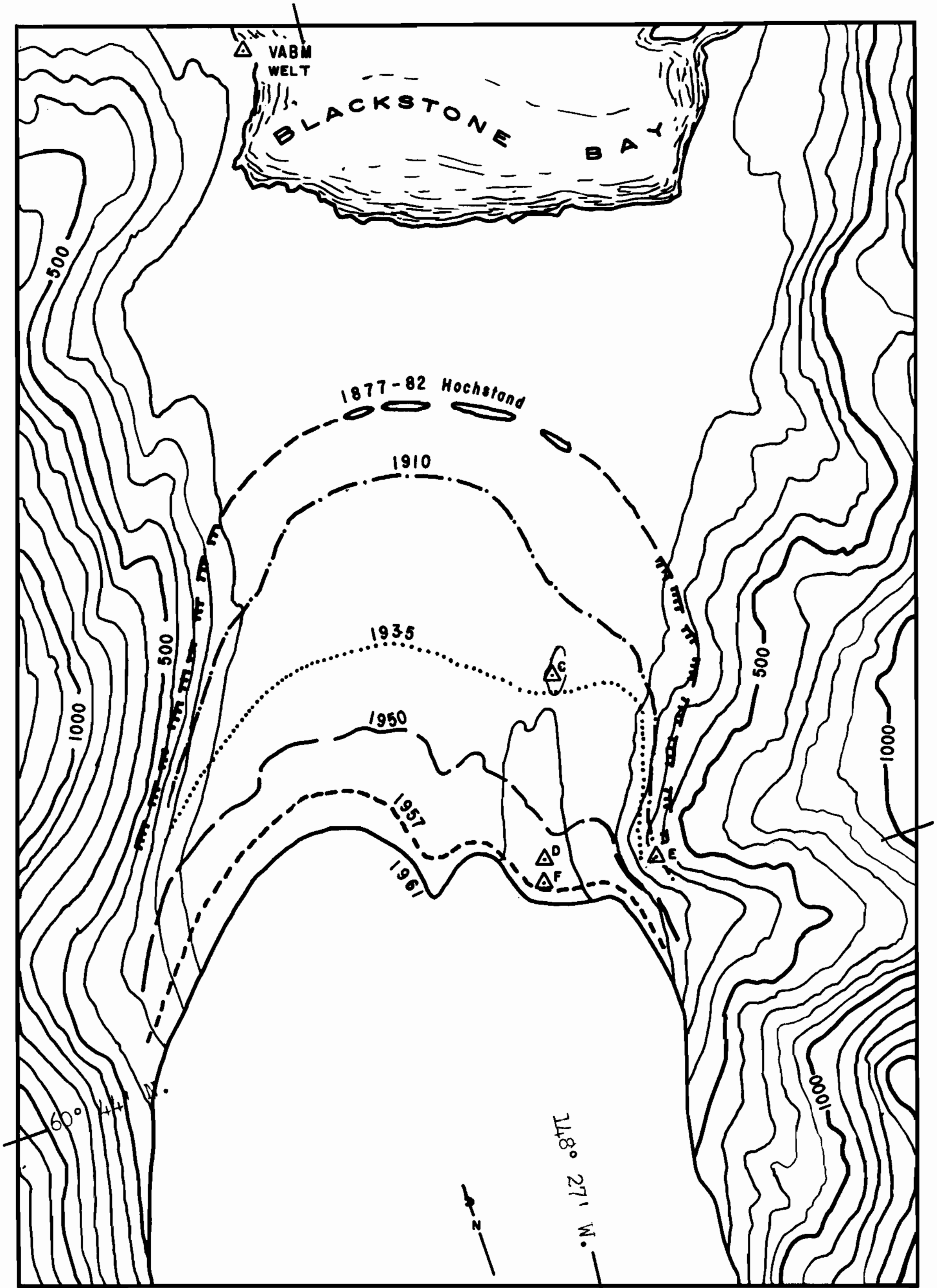
The earliest description of Tebenkof Glacier was Applegate's (Davidson, 1904, p. 27). Davidson recorded: "Three miles inside the entrance to this arm (Blackstone Bay) on the southeast shore, Applegate's chart has a small glacier facing northeastwardly, but it does not reach the water front." In their visit in 1909, Grant and Higgins (1911, pp. 406-407) confirmed this position of the glacier snout by their description of a forest growing in front of the ice. They said further that "The ice had not reached tidewater in the last century, and probably not in a considerably longer period." Although they did not visit the terminus, they were able to observe a bare zone adjacent to this forest and estimated the ice to have retreated about 500 feet in the previous 10 to 15 years. In the following year, Tarr and Martin (1914, pp. 352-354) visited Tebenkof Glacier and produced the first map of its terminus. They stated: "The terminus of the Tebenkof Glacier in 1910 was not very different from the conditions of 1909, and so far as information is available, in previous years. Applegate showed the glacier in 1887 in about the same position as in 1909 and 1910." Tarr and Martin also described two terminal moraines, the innermost being 600 to 800 feet from the ice front, and the older, outer moraine being only about 50 feet from the inner one. In contrast with the inner moraine, the outer one had a more vigorous growth of moss and shrubs. The largest willow growing in the moraine in 1910 displayed only eighteen annual growth rings. Vegetation on the inner moraine had growth rings indicating 8 to 12 years' growth. Outside the moraines, trees of three feet in diameter were found, and Tarr and Martin suggested an age of at least one century for the outer moraine. They also found a forest trimline on either side of the valley at a distance of from 200 to 400 feet from the ice. The area between was littered with dead trees. Alders growing in this zone had seven annual rings, and Tarr and Martin correlated the trimming along the sides with a recent expansion of the terminus to the inner moraine which they estimated to have occurred at least 12 years before the 1910 expedition.

In 1935, William O. Field (1937, p. 78) visited Tebenkof Glacier and described it as follows: "From 1910 to 1935 the terminus retreated fully 1,000 feet and the glacier shrank laterally. A comparison of photographs indicates that the surface of the ice for some miles along the terminus has been appreciably lowered." Between 1910 and 1935, recession exposed a ridge of bedrock running parallel to the glacier, the ridge having since served to separate the tongue into two parts. Field established photo station C on the first high point of this ridge. At that time this station provided an excellent view of the entire terminus. Field found remnants of an interstadial forest along the northern side of this ridge in 1935. These were the first such forest remains to be found in Prince William Sound, and Field (1937) suggested a correlation with the destroyed forests of Glacier Bay which had grown since the Wisconsin maximum. Cooper (1942), however, believed that destruction of this forest was a relatively recent event and not contemporaneous with early Glacier Bay forests.

On August 19, 1957, the I. G. Y. party spent most of the day at Tebenkof Glacier. They found that on the outwash plain at least four glacial streams joined, forming a single channel which entered the sea near the center of the fiord. The filling in of the fiord by the silt of this stream tends to exaggerate the retreat of the glacier, since the distance from the ice to the water is slowly increasing by sedimentation. The low gradient of this large outwash plain produces a wide tide flat. Dense vegetation began almost immediately above the high tide level. About 2,000 feet in from the beach, the party located the old moraine that marked the post-glacial maximum (Figure 29). This moraine was neither large nor continuous across the valley. The change of vegetation at the moraine was easily noticeable. Inside the moraine the alders were neither as large nor as dense as outside the moraine, and traveling was considerably easier.

Field's station C was located, and new photographs were taken (Figure 30). This station, however, had lost much of its value because higher points on the ridge had since emerged from the glacier and much of the center of the glacier terminus could no longer be seen from the station. Accordingly, three new stations were established at D, E, and F (Figure 29), and photographs and triangulation measurements were taken for the terminus.

Because no measurements of the position of the terminus had been made since the map produced in 1910, recession since this date could only be estimated by photographic comparisons. Photographs (Figure 31) taken from station C in 1935 and 1957 suggest a recession of nearly 900 feet in that period. In addition, airphotos taken in 1950 suggest that recession since 1910 had amounted to approximately 2,750 feet. In 1961, photographs were made from previous stations (Figure 32), and together with a new survey,



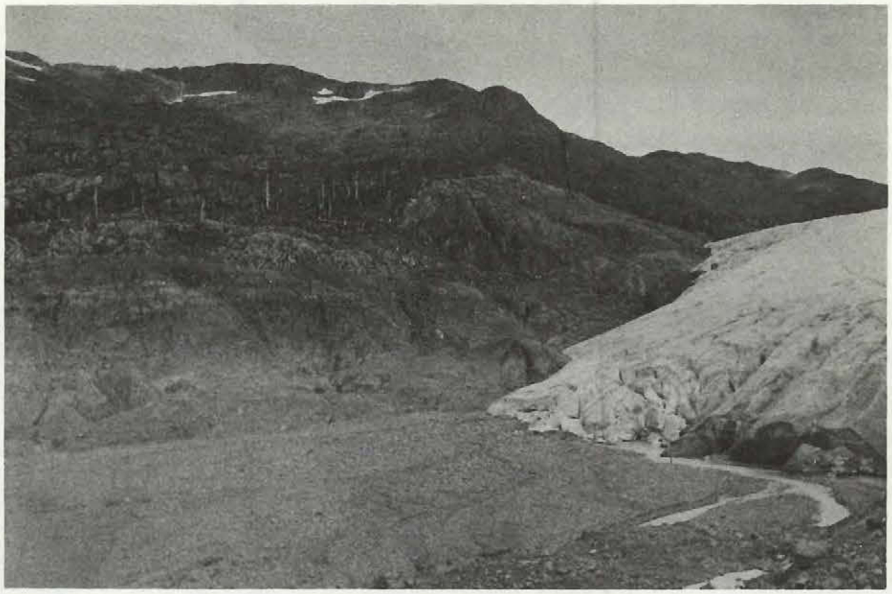

Based on U.S. Geological Survey Maps, Seward C-4, D-4

0 MILE 1

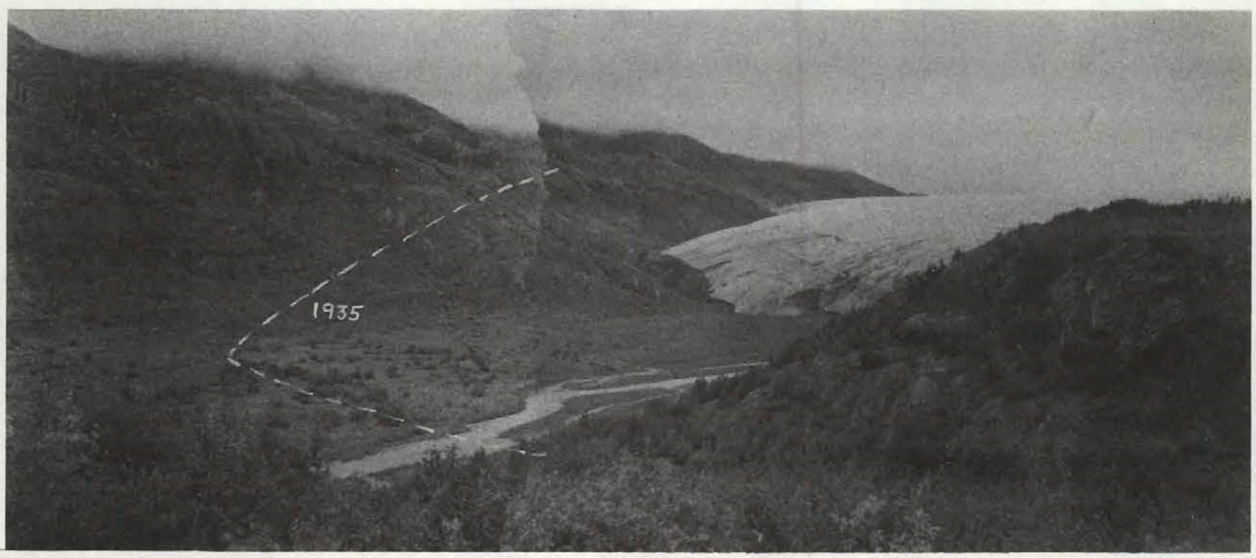
Contour Interval 100 feet

TEBENKOF GLACIER

Figure #29



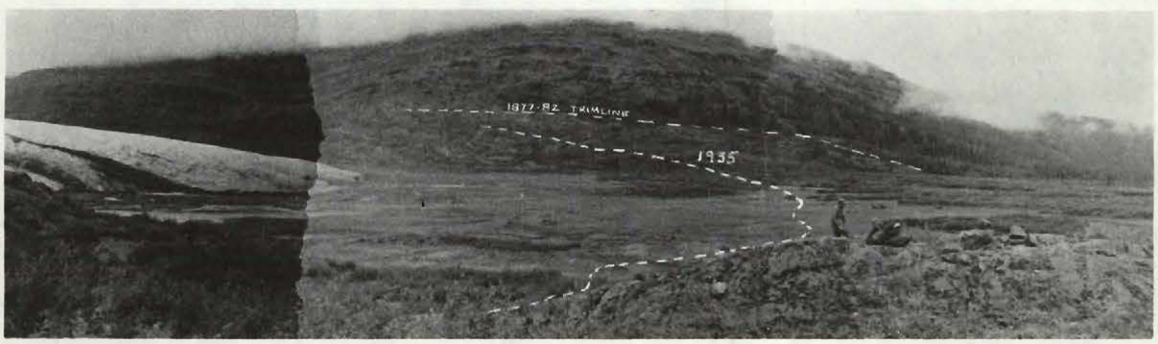
Tebenkof southern lobe from Station C, 1935
Photo f-35-756 by Wm. O. Field




Tebenkof southern lobe from Station C, 1957
Photos MM-57-SG91,92 by M.T. Millett

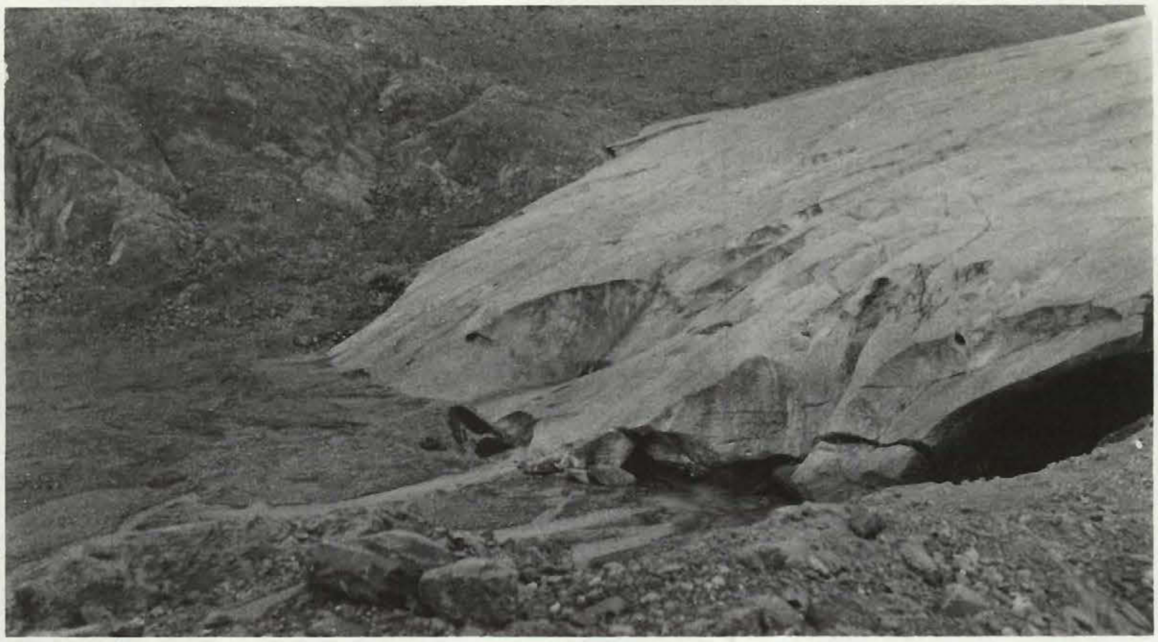
Figure #30

Tebenkof north lobe from Station C, 1935
Photo f-35-757 by W.O. Field




Tebenkof north lobe from Station C, 1957
Photos MM-57-SG87,88,89 by M.T. Millett

Figure #31



Tebenkof southern lobe from Station D, 1957
Photo #MM-57-SG90 by M.T. Millett

Tebenkof southern lobe from Station D, 1961
Photo #M-61-206 by M.T. Millett

Figure #32

showed an ice recession of nearly 250 feet since 1957 (Figure 29). The annual rate of retreat from 1957 to 1961 was about 62 feet per year. This is similar to the 1910-1950 rate of 70 feet per year and the 1950-1957 rate of about 60 feet per year.

The ridge which emerged with the wasting of the glacier between 1910 and 1935 is a prominent feature and still serves to split the tongue into two main lobes. The ridge in 1961 was over 1,700 feet long and rose about 100 feet above the outwash plain on either side. To the north of this ridge, another rock was barely showing in 1957. By 1961, this rock was a conspicuous feature of the terminus and split the main north lobe into two minor ones (Figure 29).

Botanists of the 1957 party studied the vegetation on the two moraines and concluded that the post-glacial maximum ice reached this point in the period of 1877-1882. This is roughly the same date estimated by Tarr and Martin earlier, and confirms their conclusions.

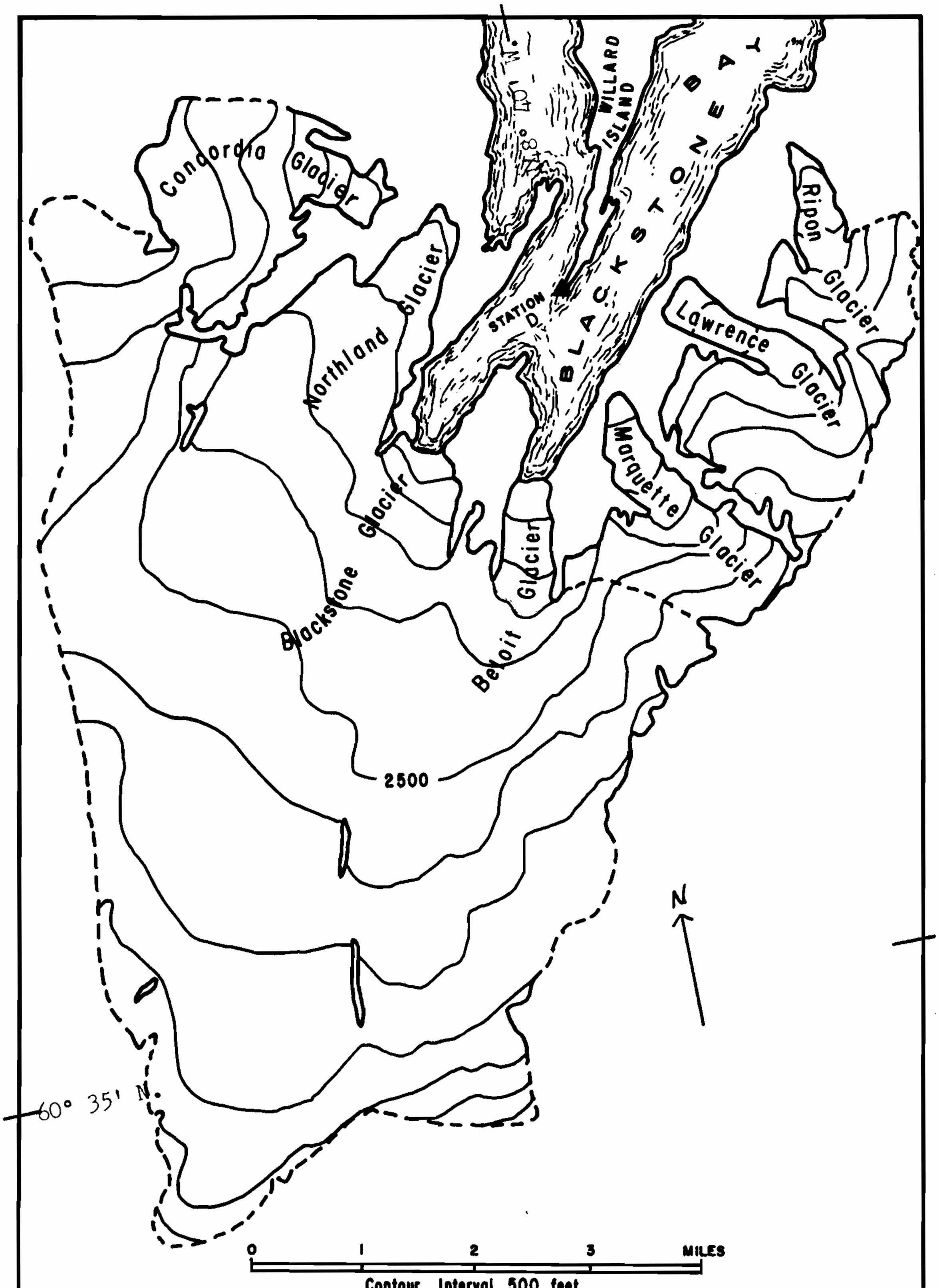
## Summary

Since first observed, Tebenkof Glacier has had a history of continual, steady retreat. Vegetation suggests that an advance culminated sometime between 1877 and 1882, and remnants of a terminal moraine mark the position of this hochstand. Vegetation outside of this moraine is very old, indicating that the glacier has not been more extensive in several hundred years. Vegetation trimlines along either side of the valley descend to the valley floor in the vicinity of the terminus moraine and appear to be associated with it.

## Blackstone Bay

Blackstone Bay, located in the northeast corner of Prince William Sound (Figure 33), has an amazing history of glacier termini stability. Near the head of this large bay are seven glaciers, two that have active tidal fronts, three that almost reach the water, and two that hang high on the valley walls. In the center of the bay is a long narrow island with elevated areas that provide excellent views of the surrounding glaciers (Figure 34). Three glaciers at the head of the bay, Northland, Blackstone, and Beloit, are tongues from a common icefield; but the others are separate valley glaciers whose accumulation areas coalesce on dividing ridges. Because of this contiguity of the upper areas, these ice streams were all called the Blackstone Glacier until 1910 when Tarr and Martin (1914) named the individual tongues after colleges in Wisconsin. The gradient of all these ice streams is steep; they have been described (Tarr and Martin, 1914, p. 355) as "cascading glaciers of varying steepness." Only one, the Marquette Glacier, has a medial moraine, and all of them are very clean and white. Without exception, the lower parts are so heavily crevassed that it is difficult to locate precisely the firn limit. Field (1956) estimated it to have been around 1,300 feet elevation in 1950. The lack of moraines near the termini, and the fact that there is little vegetation on the steep rock walls complicate the problem of dating any movement of these tongues by usual procedures.

The earliest map and description of this part of Prince William Sound was by Whidbey (Vancouver, 1801). His 1794 map shows

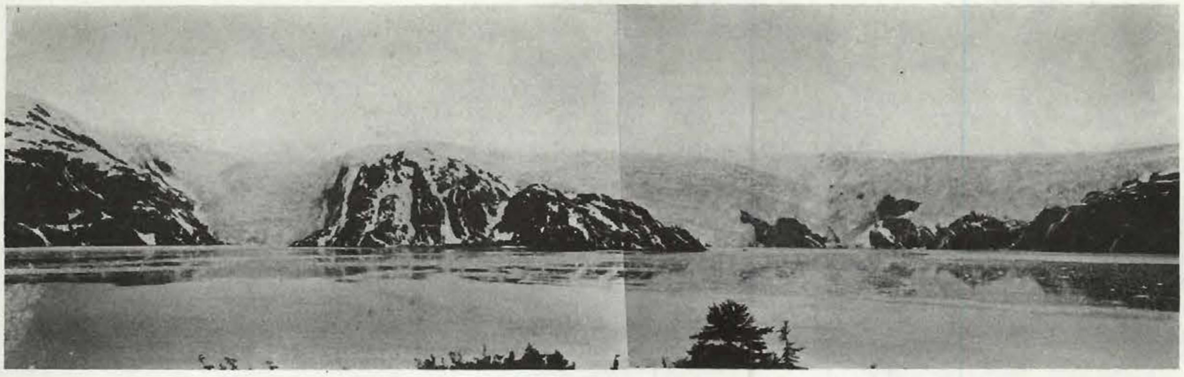



GLACIERS of BLACKSTONE BAY

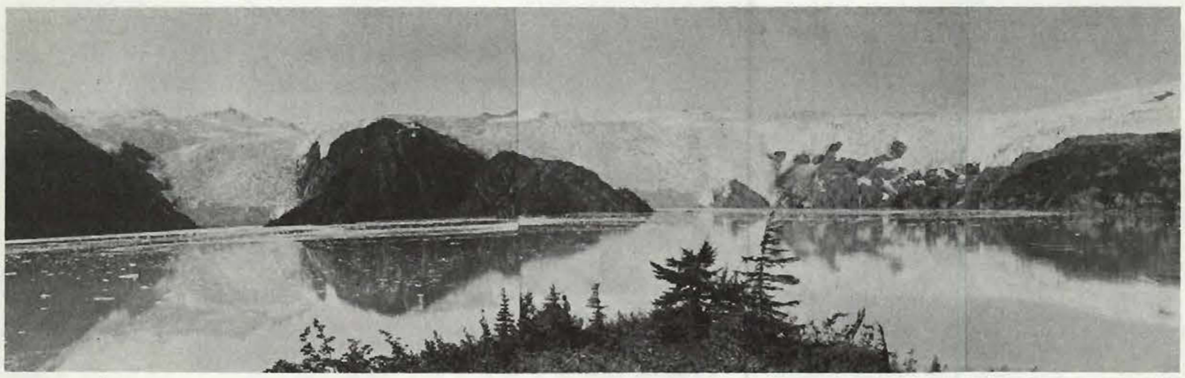
Figure 1

Based on U S. Geological Survey Map, Seward C-5

Figure #33



Panorama of Upper Blackstone Bay from Station D, 1905
Photo numbers 213,214 by U.S. Grant



Panorama of Upper Blackstone Bay from Station D, 1935
Photos f-35-708,709,710 by Wm. O. Field

Panorama of Upper Blackstone Bay from Station D, 1957
Photos M-57-SG114,115,116 by M.T. Millett

Figure #34

Blackstone Bay to be very short, and as is usual in Vancouver's maps, he shows no glaciers; even Willard Island is omitted. Because of the lack of detail, no conclusions as to the condition of the Blackstone Bay glaciers can be made.

In 1887, Applegate mapped the area (Davidson, 1904) and in describing Applegate's map, Davidson reported that Applegate found five large glaciers at the head of Blackstone Bay. The main glacier was divided by an island, and he suggested that this would offer an excellent mark for determining the movement of the faces. Since Applegate did not come closer than five miles to the glaciers, his map is not as accurate as is suggested by Davidson. Mendenhall's 1898 map (Mendenhall, 1900) is taken from Applegate and is similarly unreliable.

The first map to show the positions of the termini accurately was that of Grant and Higgins (1911) in 1909. According to them, "no information concerning the definite positions of the fronts of these glaciers at an earlier date is extant" (1911, p. 405). They also offer an explanation for the erroneous termini positions of the earlier maps which:

> . . . show the south end of Willard Island covered by ice, but as this seeming condition is very deceptive till one comes almost to the south end of the island, and as the size and density of the vegetation on the island indicates a number of decades growth, it is altogether probable that the ice has not been as far forward (north) as Willard Island within the time of which we have record, i. e., since 1794 (1911, pp. 407-408).

Their map shows a moraine extending east from Willard Island to the mainland. This moraine they labeled as the ancient front of the glacier. They found no evidence of this moraine west of the island. The moraine and an apparent vegetation trimline across Willard

Island led them to conclude that the ice of the combined tongues was at this point, "perhaps two centuries ago" (Grant and Higgins, 1911, p. 408).

In the following year, 1910, Tarr and Martin (1914) visited Blackstone Bay and named the individual tongues. They indicated that little change had taken place since the previous year. They sounded the bay, and recorded the submarine contours on their map. They very carefully showed the moraine east of Willard Island. Opposite this moraine, on the west side, they recorded depths between 300 and 400 feet. The abrupt change of vegetation of Willard Island adjacent to the moraine led Tarr and Martin (1914, p. 360) to conclude that:

> North of this line there is thick, mature forest, and it therefore seems clear that an advance of the former glacier of Blackstone Bay extended down to this line some scores of years ago and possibly over a century ago. The fact that the edge of this barren zone continues the line of the morainic bar just described, suggests the association of the moraine with this advance.

The next description of Blackstone Bay was by Field (1937) who was there in 1935. He found that changes in the principal glaciers since 1908 were very slight - not more than a few score feet. The discovery of a 450 year-old tree within 6,000 feet of Blackstone and Beloit Glaciers led him to conclude that the glaciers at the head of the bay had not coalesced within at least 500 years. Field also discovered a submerged terminal moraine in the channel on the west side of Willard Island. This he believed to be a continuation of the conspicuous moraine in the eastern channel.

W. S. Cooper (1942), who was with Field in 1935, decided that the apparent coincidence between the abrupt vegetation (Tarr and Martin, 1914, p. 360) change on Willard Island and the two bars in the east and west inlets was not the result of glacial activity, but rather of climatic factors. He substantiated his conclusions from the location of very old trees in protected areas throughout the bay and within the bare zone.

Photographs taken by Brown (1952) in 1949 indicated that only a very small recession had occurred since 1935 and that the fronts were still very near the 1908 position.

Airphotos in 1950 and the subsequent map, Seward C-5, show the glacier fronts in almost exactly the same position as on the Grant and Higgins map of 1909 (1911), the Tarr and Martin map of 1910 (1914), and the Field map of 1935 (1937).

In 1957, the I. G. Y. party spent August 22 at Blackstone Bay. Most of the old photo stations were reoccupied and comparative photographs were taken. A comparison of these photos with older ones (Figure 34) substantiates the remarkable stability of these ice tongues. The large ice streams have receded very little, although the small hanging glaciers show measurable retreat. Because of the minor changes in the termini positions since 1935, the area was not remapped.

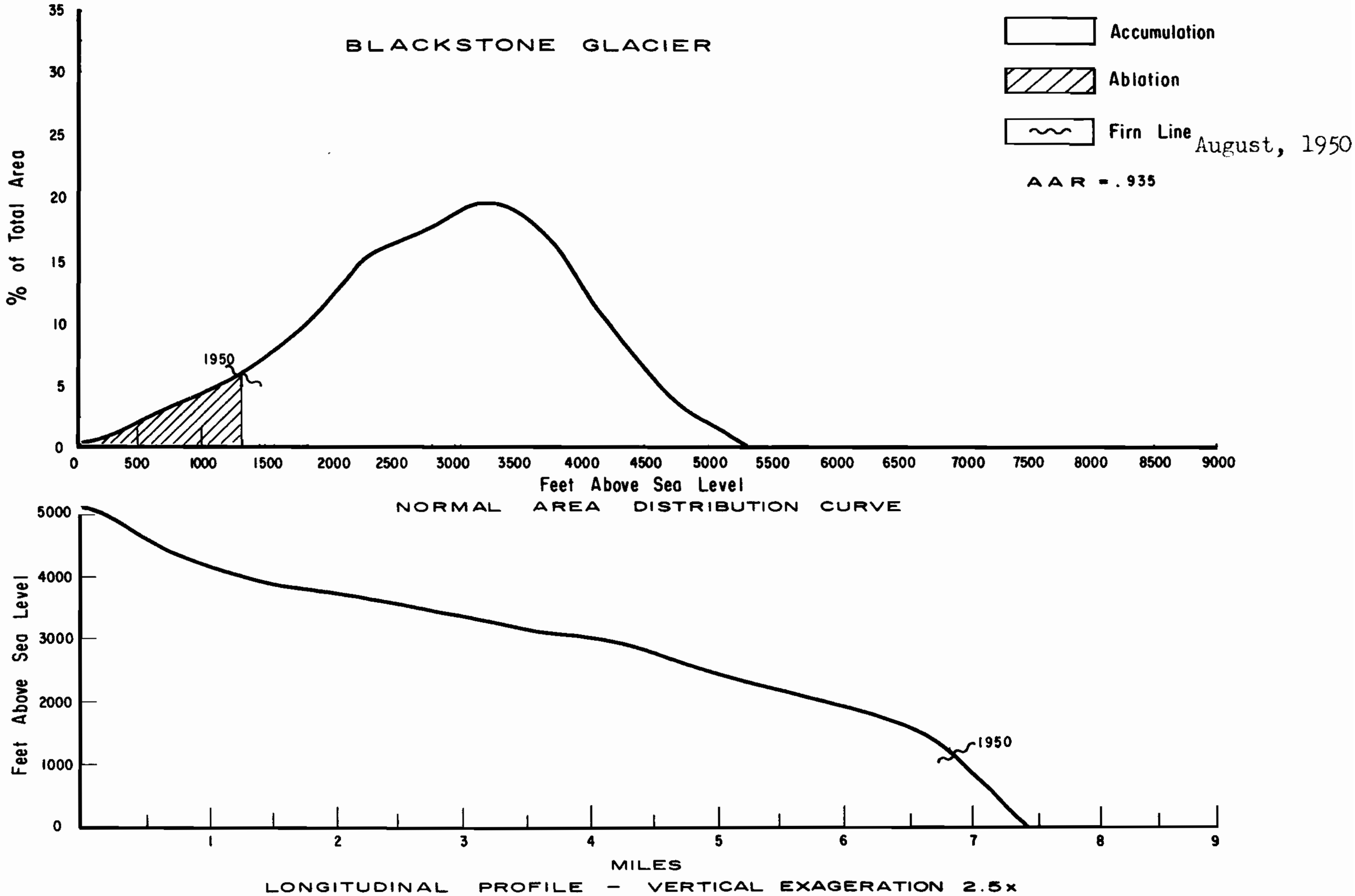
Blackstone Bay was not visited in 1961.

## Summary

Vegetation near the head of Blackstone Bay indicates that the glaciers there have not been more extensive in at least 500 years, or perhaps longer. Their present position is undoubtedly near post-glacial maximum as is the present hochstand of Harriman Glacier.

The small amount of change since 1909 suggests that these glaciers have reached an approximate equilibrium in ablation-accumulation. Figure 34 shows how little a rise or fall of the firn line would affect this balance. For example, if the firn line were to drop as much as 500 feet, it would only affect 2 per cent of the total area. A rise of 500 feet would only affect 2-1/2 per cent of the glacier. This stability is explained on the longitudinal profile (Figure 35) where the firn line is seen near the terminus in a steep area. The steepness of the lower part of the profile indicates the small size of the ablation area. If two of the glaciers, Blackstone and Beloit, were not actively discharging icebergs, they would possibly be expanding.

Figure #35


BLACKSTONE GLACIER
Accumulation
Ablation
Firn Line
August, 1950
AAR = .935
% of Total Area
1950
Feet Above Sea Level
NORMAL AREA DISTRIBUTION CURVE
Feet Above Sea Level
1950
MILES
LONGITUDINAL PROFILE – VERTICAL EXAGERATION 2.5x

## Harriman Fiord

Harriman Fiord is a northwestern arm of Port Wells. It extends for about eight miles northward from Point Pakenham, then turns southwest for twelve miles at Point Doran. The lower part of the arm, from Point Pakenham northward, is called Barry Arm, and the southwest part is Harriman Fiord. About six miles from Point Doran, the Harriman Fiord receives a tributary fiord from the northwest. This is Surprise Inlet, and has Surprise Glacier at its head, which is about two and one half miles from the main fiord junction. At the head of Harriman Fiord is Harriman Glacier, while midway along the north side of the fiord is Serpentine Glacier. In addition there are small, non-tidal ice tongues in Harriman Fiord: Baker, Detached, Cataract, Roaring, Toboggan, Dirty, and Wedge Glaciers.

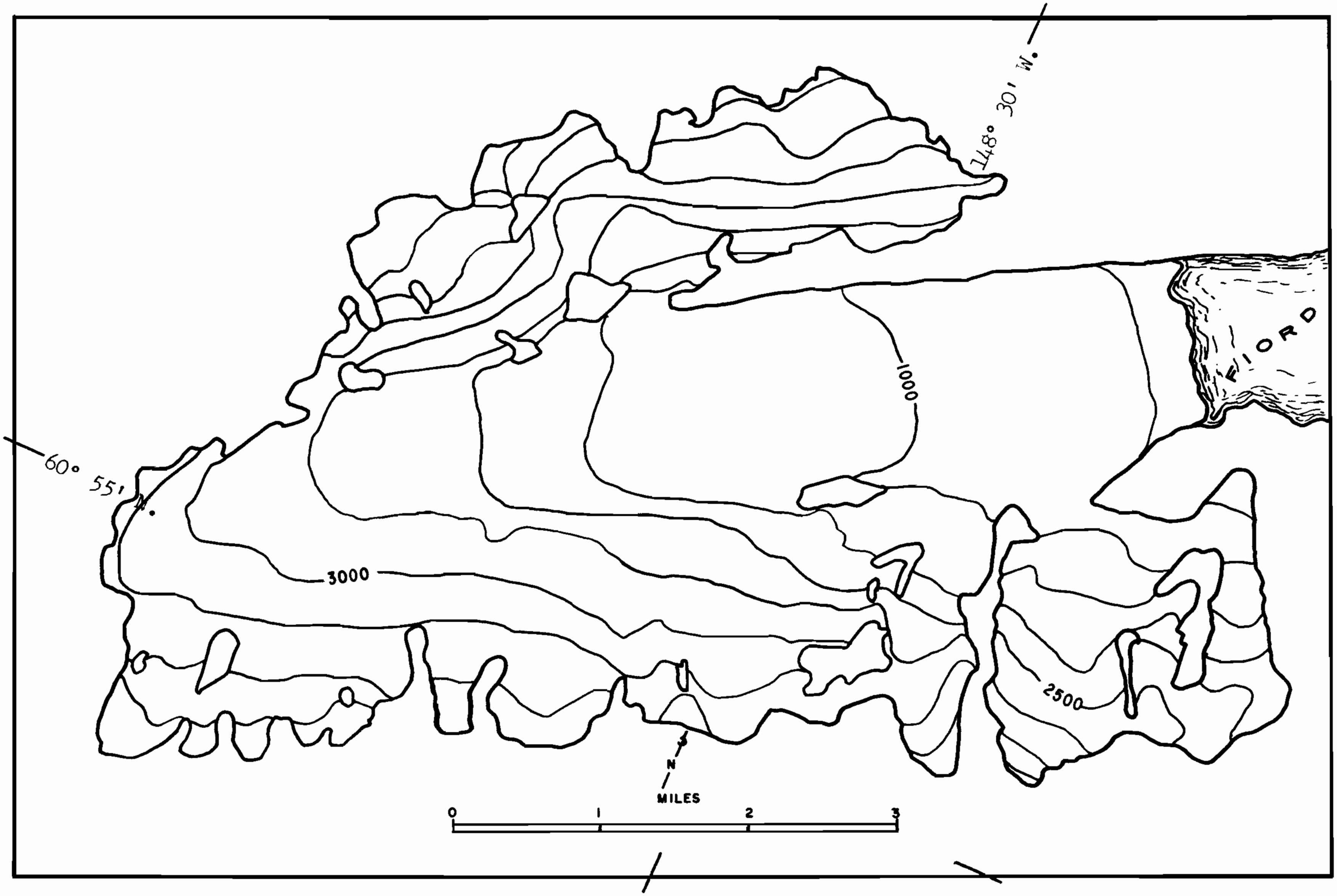
This area lies in the heart of the Chugach Mountains. The fiord is narrow and deep. Steep walls rise from 3,000 to 4,000 feet within a mile of the water, and several peaks within a few miles attain heights greater than 8,000 feet.

The lower part of Barry Arm was shown on the maps of Vancouver (1801), Applegate (Davidson, 1904), Glenn (1899), Castner (Glenn, 1899), and Mendenhall (1900). All of these maps show Barry Glacier extending across the head of the arm. It was not until 1899 that the Harriman party (Gilbert, 1903), in coming close to the ice front, discovered an opening along the western margin which led into the large fiord leading southwest, which they named Harriman Fiord.

## Harriman Glacier

Harriman Glacier is located 12 miles from Point Doran at the head of the southwest branch of Harriman Fiord. The width at the terminus is just over one mile, and the ice front height above water varies from 100 to approximately 200 feet in the center. Calving of ice occurs irregularly, and small bergs are frequently seen in the fiord. This calving is not as frequent as from Surprise Glacier or Harvard Glacier and is much less than one would expect from a glacier of the Harriman size. The gradient of Harriman Glacier is about 625 feet per mile, which is quite steep for this short, wide ice stream. The glacier is about 8 miles long, with an area of approximately 22 square miles (Figure 36). The ice of Harriman Glacier is very clean, having only two small medial moraines along the south side. Many large crevasses extend the entire width of the glacier and are abundant in the first mile and a half above the terminus. This glacier differs from most of the other glaciers in Prince William Sound in not having well-defined tributaries. Instead, most of the basin of the Harriman is covered with snow or firn. Of the total drainage basin, about 76 per cent is snow or icecovered. These snow-sheathed slopes are particularly conspicuous on the southern side of the basin, where rock is visible only along an occasional ridge or mountain peak (Figure 36). The elevation of the mountains along the south side of the basin varies from 3,800 feet near the terminus to nearly 6,000 feet at the head. On the northern side they are somewhat higher, but due to exposure they are slightly less snow-covered. The firn limit on Harriman

Figure #36




Contour Interval 500 feet

**HARRIMAN GLACIER**

Based on U. S. Geological Survey Maps, Seward D-4, D-5

Glacier in 1950, determined from airphotos, was around 1,500 feet above sea level. This position gives an accumulation area ratio of 0.800. Most of the accumulation area is between 2,000 and 4,000 feet elevation (Figure 37). Reference to the area distribution curve (Figure 37) shows the glacier budget to have an extreme sensitivity to changes in firn line position.

Harriman Glacier, discovered by the Harriman expedition of 1899, was named fo the sponsor and leader of that group. The expedition description was by G. K. Gilbert (1903), who did not determine the activity of the glacier at that time. Interpretation of his description, however, has led most investigators to believe that at that time the ice was retreating slowly from a hochstand a few hundred feet in front of the terminus.

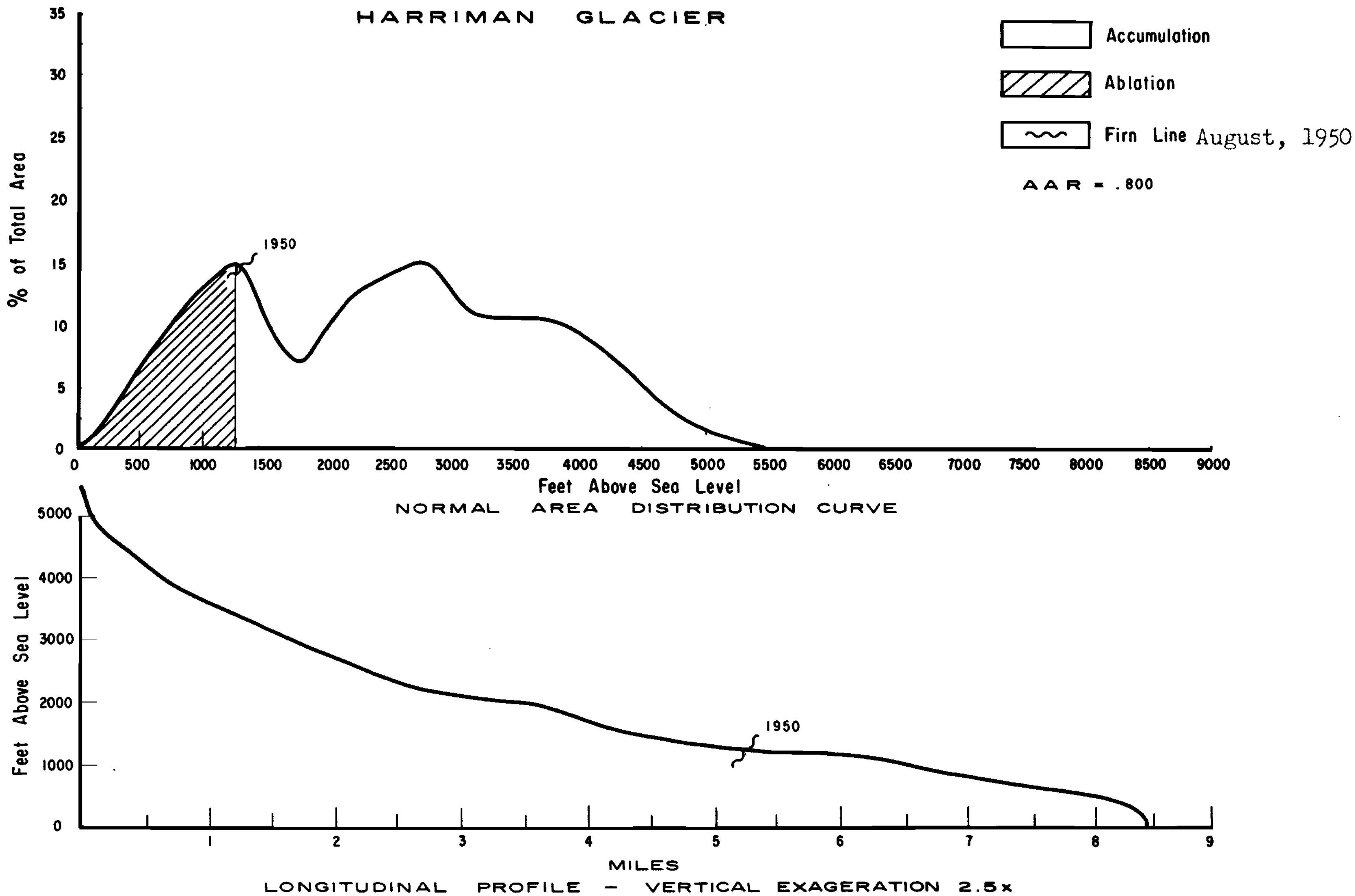
In 1905 and 1911, Grant and his co-workers (1911, pp. 336-337), visited Harriman Glacier and made the following observation:

> Photographs of the eastern side of the front of the Harriman Glacier in 1905 and 1909 show that this side of the glacier retreated approximately 700 feet between these dates. A comparison of an 1899 (Harriman expedition) photograph with the above indicates that between 1899 and 1905 the east side of the glacier retreated about half the above distance.

This would provide a total retreat of about 1,050 feet between 1899 and 1909, or at a rate of approximately 105 feet per year. Descriptions of bare zones and distances from vegetation suggest that the retreat was more or less continuous during the decade following the glacier's discovery.

In 1910, Tarr and Martin (1914, pp. 334-335) found an abrupt reversal of this behavior and concluded that during the previous year the ice had moved forward rapidly. They said: "The 1909

Figure #37

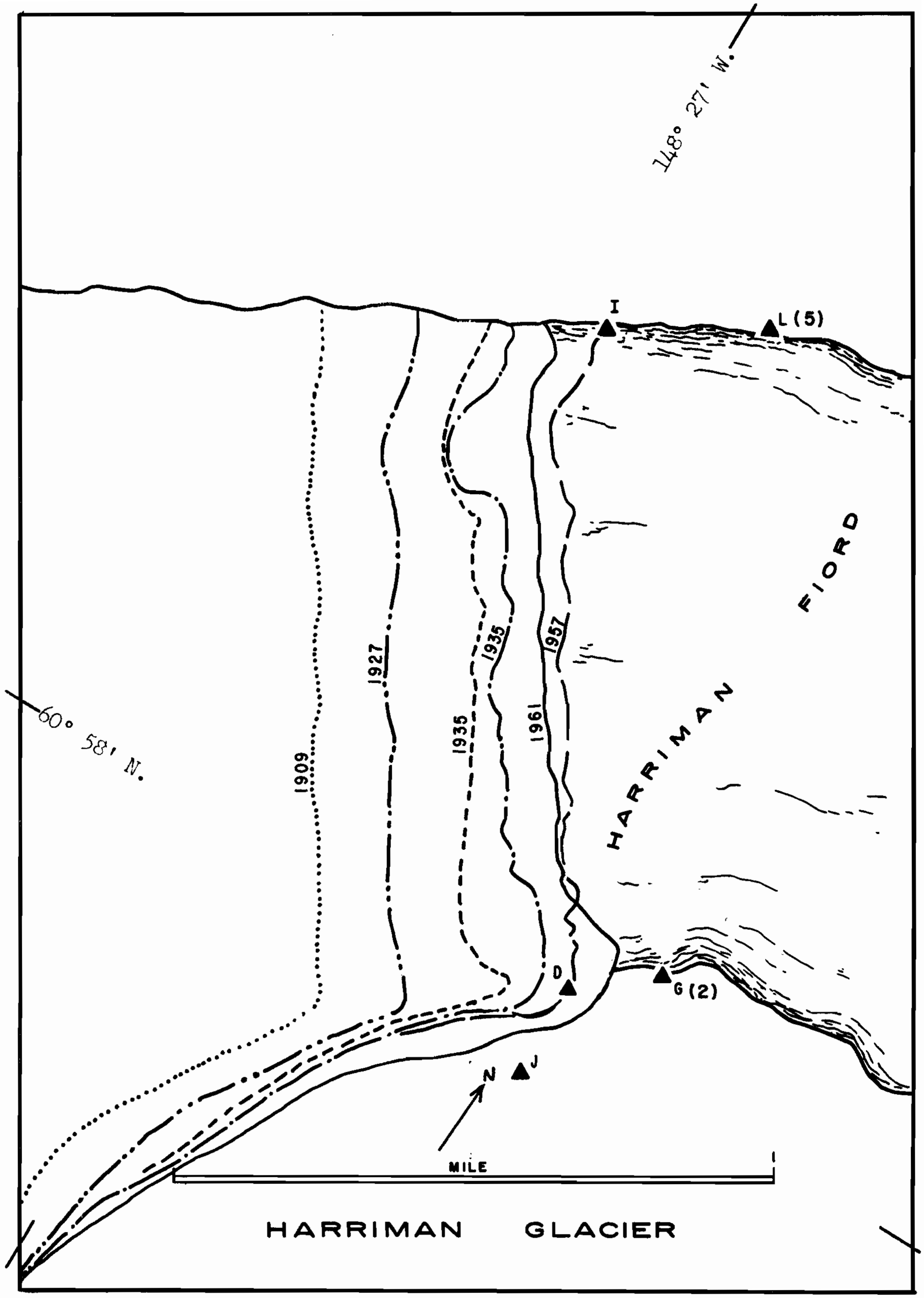

HARRIMAN GLACIER
Accumulation
Ablation
Firn Line August, 1950
AAR = .800
% of Total Area
1950
Feet Above Sea Level
NORMAL AREA DISTRIBUTION CURVE
Feet Above Sea Level
1950
MILES
LONGITUDINAL PROFILE - VERTICAL EXAGERATION 2.5x

observations of Grant and Higgins make it certain that the change from retreat to advance came between 1909 and 1910 and that the whole of the 700 feet advance was during the last year. The eastern margin also advanced, coming forward the whole distance that it had retreated from 1899 to 1910." They also described a "considerable thickening" of the terminus and an increase in iceberg discharge.

W. O. Field (1932) stated that the advance begun in 1910 was apparently still in progress in 1914, 1925, and 1931, and estimated the total forward movement between 1910 and 1931 as 1,500 feet. Field (1937) measured an additional advance of 155 feet between 1931 and 1935.

In 1957, the International Geophysical Year party occupied many of the old survey and photo stations. Measurements indicated a continued advance of an additional 576 feet since 1935, which was uniform across the entire front (Figure 38). Along the southern margin a drainage stream had built a rather large delta in front of the ice, and as the glacier moved across this delta, a push moraine was formed. A thickening of the terminus was indicated by the expansion of the ice along the southern side above the terminus. Here a well-developed heath turf was being plowed up as the thickening ice moved up the valley wall (Figure 39). The ice front across the fiord was a vertical wall, and even where the terminus crossed the delta this wall was quite steep. Calving of icebergs was common, and at low tide, the beaches were littered with stranded pieces (Figure 40).

Harriman Glacier was visited again on August 25, 1961, and many of the old stations were reoccupied for surveying and photo-

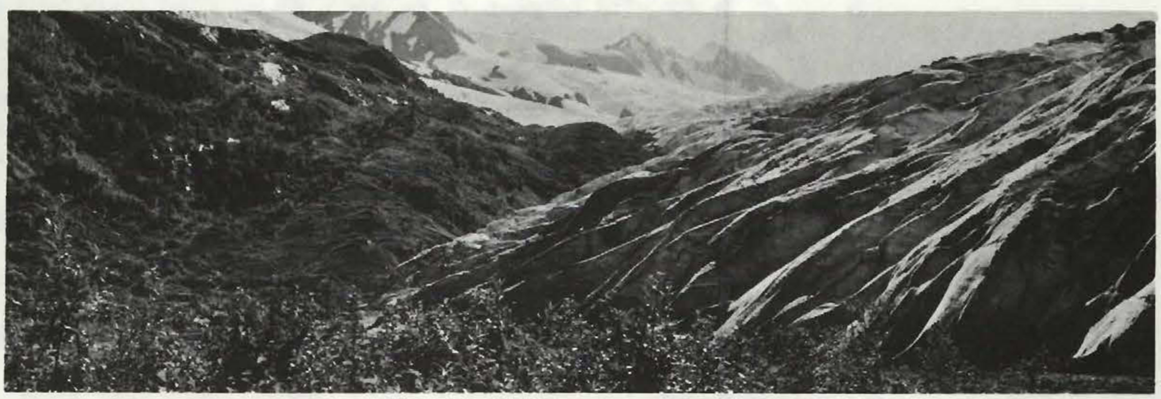



Based on U.S. Geological Survey Map, Seward D-4

Figure #38

Harriman Glacier, south margin, 1931, from Station G (2)
Photo f-31-511 by Wm. O. Field

Harriman Glacier, south margin, 1957, from Station G (2)
Photo M-57-SG145 by M.T. Millett

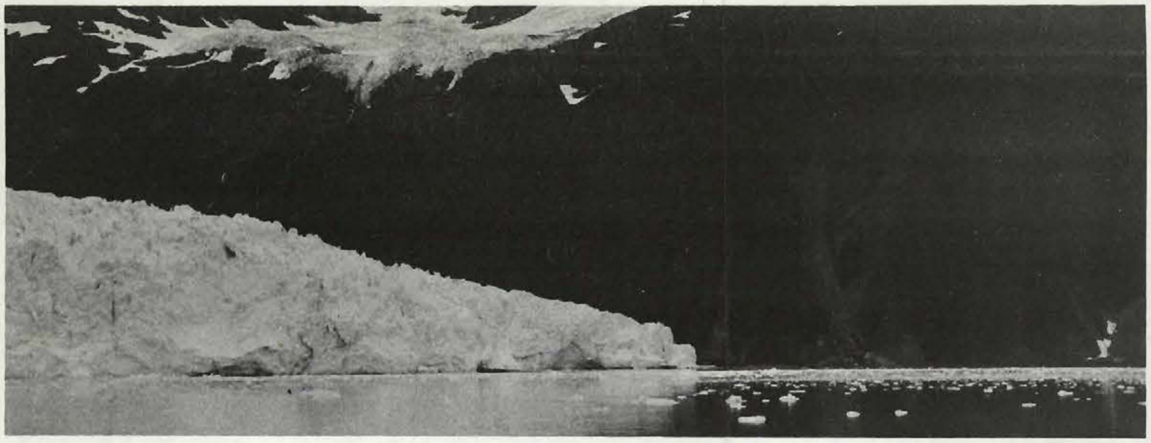


Harriman Glacier, south margin, 1961, from Station G (2)
Photo M-61-179 by M.T. Millett

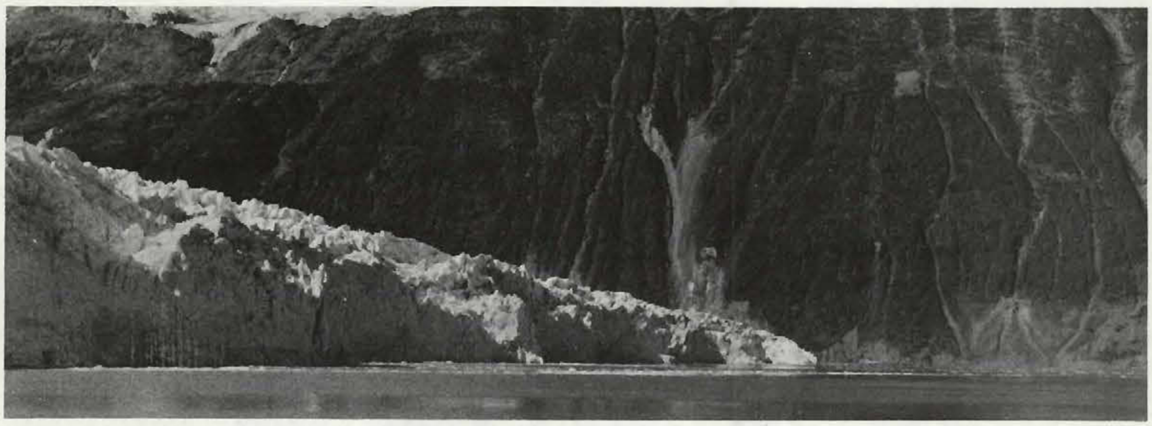
Figure #39

graphy. Because of continued advance, a new survey station and three new photo stations were established. Station G, established by Grant and Higgins in 1909 and occupied by all subsequent investigators, was very close to the ice and was in danger of being overridden. From station G the first impression was that the advance noted directly in front of the station (Figure 38) was characteristic of the entire ice front. However, reference to photographs taken in 1957 indicated a recession of the northern margin of the terminus (Figure 40). Subsequent plotting of the survey data indicated that advance, amounting to 491 feet since 1957; had occurred only along the southern margin, in the delta area, and along the south valley wall (Figure 42). Measurement showed the area covered by the advance since 1957 to be almost exactly equal to the area uncovered by recession in the same period. Along the northern margin there was a noticeable lowering of the ice surface (Figure 39) and a growing bar, adjacent to the ice front, extended nearly 300 feet into the fiord. On the southern side, the slope of the advancing front in the delta area appeared less steep than in 1957. The delta itself had become much larger and now extended several hundred feet into the fiord. A large push moraine, up to six feet high, was found along the delta, and gave further evidence of advance at this point.

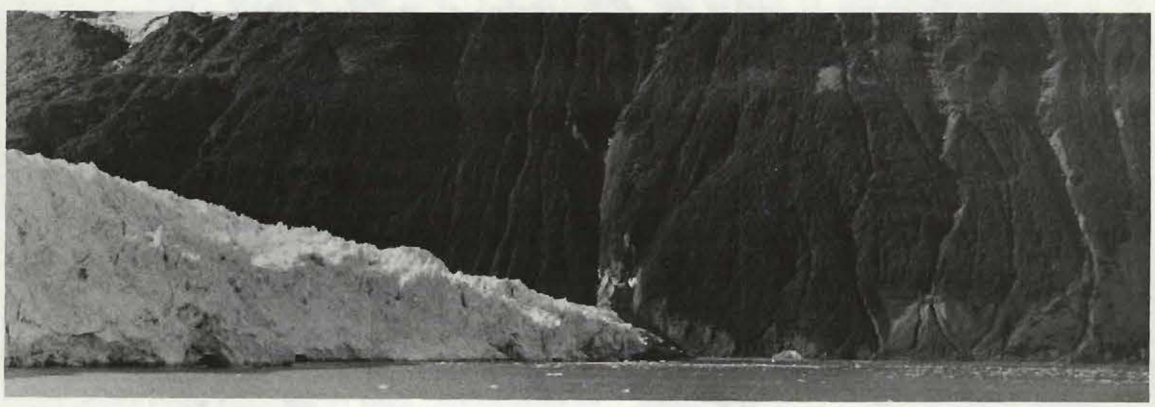
The behavior of the Harriman terminus has been very irregular and inconsistent. Rates of expansion along the southern margin vary from over 1,000 feet per year (1909-10) to 17 feet per year (1935-50), and at times, the southern side advanced vigorously, while the northern side retreated. Reasons for such behavior are not clear; however, this study offers some comment:



Harriman Glacier, north margin, 1931, from Station G (2)
Photo f-31-515 by Wm. O. Field



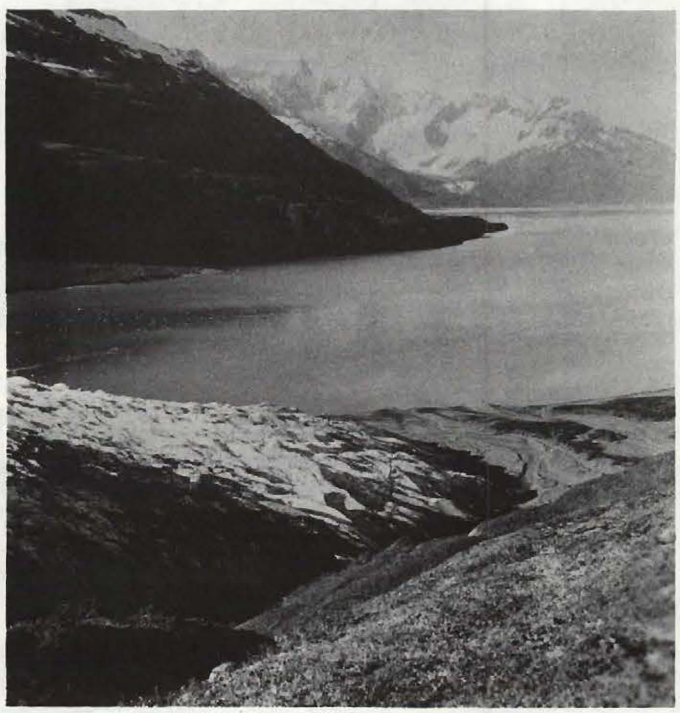
Harriman Glacier, north margin, 1957, from Station G (2)
Photo M-57-SG143 by M.T. Millett



Harriman Glacier, north margin, 1961, from Station G (2)
Photo M-61-177 by M.T. Millett

Figure #40

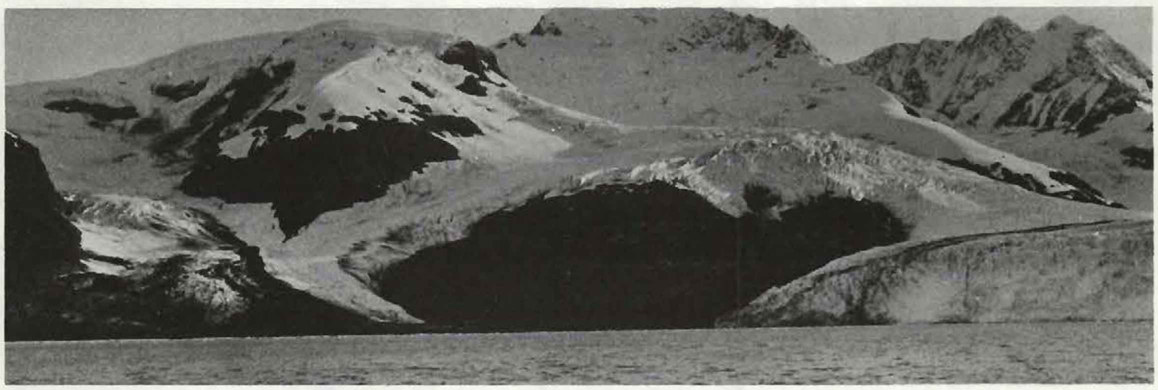
Harriman Glacier, south margin, 1957, from Station JJ
Photo LV-57-B270 by Leslie Viereck



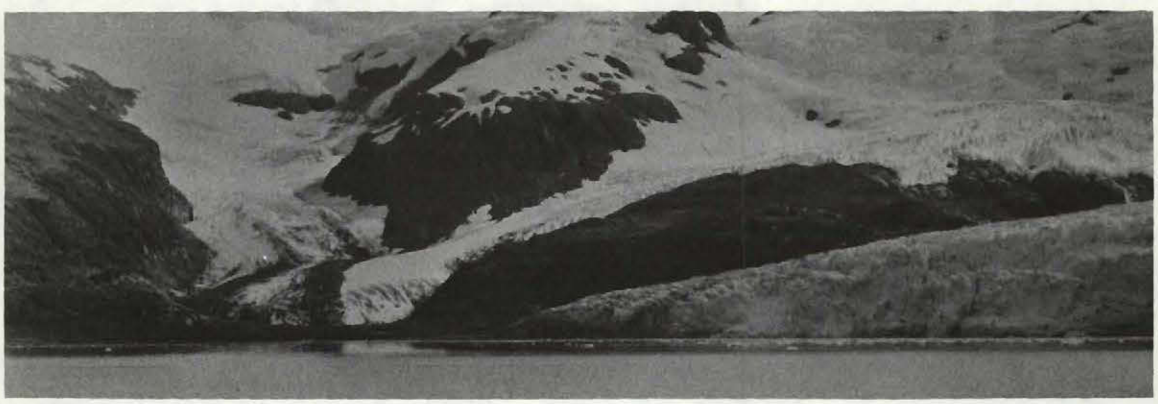
Harriman Glacier, south margin, from Station JJ
Photo M-61-186 by M.T. Millett

Figure #41

Harriman Glaciers South Margin, 1909, from Station H (5)
Photo 7-1 (106) by U.S. Grant



Harriman Glacier, South Margin, 1931, from Station H (5)
Photo f-31-509 by Wm. O. Field



Harriman Glacier, South Margin, 1961, from Station H (5)
Photo M-61-174 by M.T. Millett

Figure #42

1. Figure 37, the area distribution curve, shows that Harriman Glacier is very sensitive to elevation changes in the firn line. For example, if the firn line were to drop 500 feet, the area added to the accumulation zone would be about 13 per cent of the total glacier area. If the firn line were to rise 500 feet, the ablation area would be increased by 9 per cent of the total glacier area.

2. Subglacial and lateral streams are rapidly silting in the fiord. The growth of the delta along the southern margin (Figure 40) is very impressive, and the appearance of the large bar along the northern margin indicates that fiord depths along either side are rapidly decreasing. The fact that over 600 feet of ice front is now grounded and no longer subject to the erosive effect of tidewater has been interpreted by some workers as a logical explanation for the advance of the glacier across the delta on the southern side. However, the northern margin is also now grounded and protected, yet it has retreated an equal distance.

3. Although in 1961 the southern side had advanced and formed a high push moraine on the delta, the height of the ice front was less in 1961 than it was in 1957 (Figure 40). Along the northern margin, downmelting was even more obvious (Figure 39). This suggests that perhaps the major forward thrust is over and it is being felt at different parts of the terminus at different rates. If this theory is valid, the entire front should soon show retreat.

4. Although this glacier has been advancing for nearly 50 years, it has not overridden any trees. However, the well-developed heath turf has led botanists (Gilbert, 1903; Cooper, 1942) to conclude that the fiord has not contained more ice than at present since

at least the 16th century. No vegetation trimlines were found, and the nearest tree (about 2,500 feet from the terminus) was found to have 425 annual growth rings. The lack of forest near the ice was noted by Gilbert (1903, p. 96), who said: "In other localities there has seemed good reason to ascribe absence of forest to recent occupation by ice, but here there is a sort of transition from forest to barren which suggests a climatic limitation." Cooper (1942) suggested that when the present advance ends, the hochstand will represent the post-glacial maximum extension of ice.

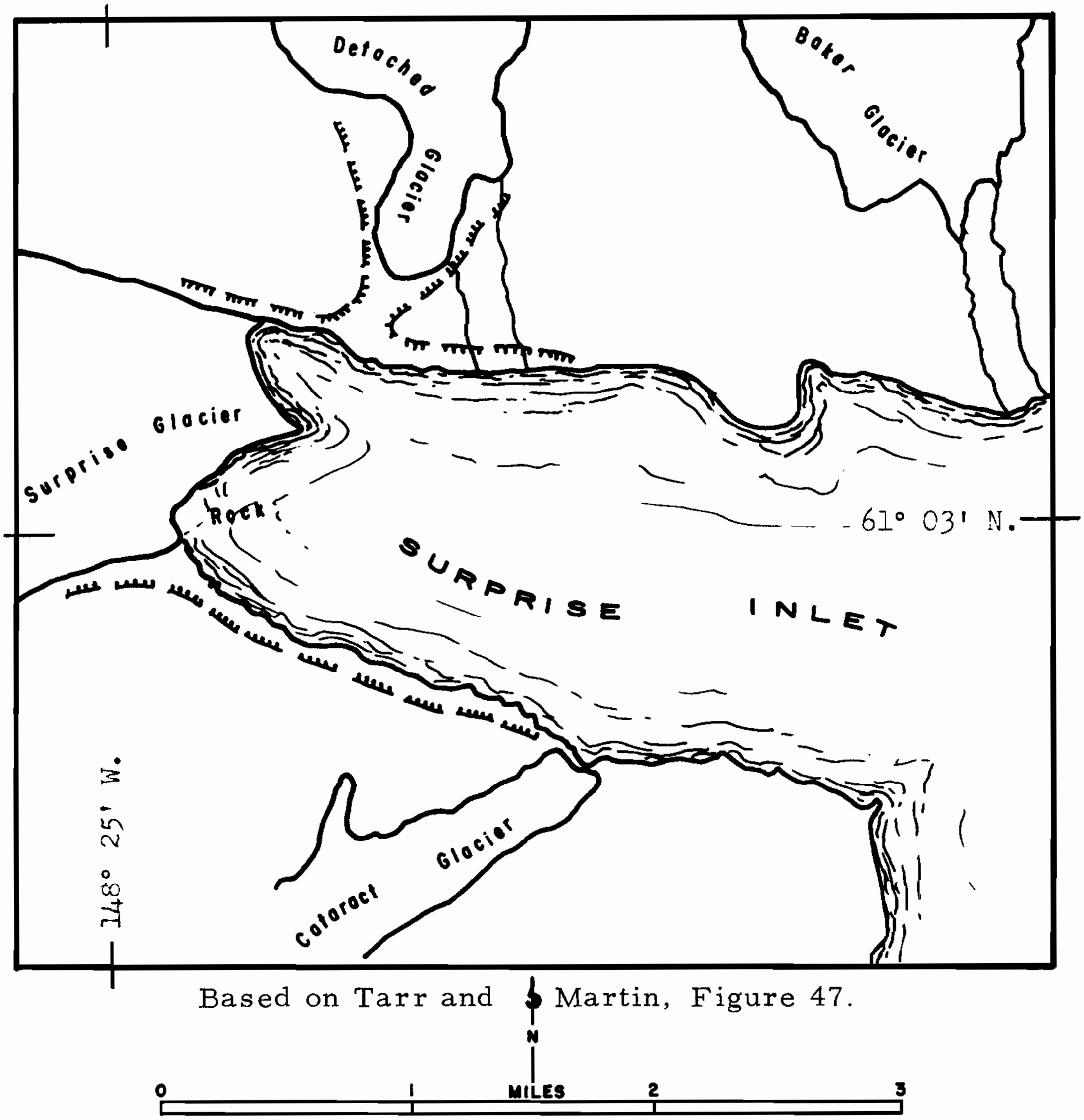
5. The profile (Figure 37) shows one or two broad wave-like bulges which are probably topographically controlled. However, they also may represent kinematic waves. If the climate and configuration of the accumulation area produce wave-like surges, these surges may explain the irregular behavior of the terminus.

## Glaciers of Surprise Inlet

Surprise Inlet, a northwestern branch of Harriman Fiord, is about seven miles from Point Doran. It is about two miles long and one-half mile wide. At the head of the inlet is Surprise Glacier, and there are three small, steep glaciers along the sides of the inlet, Baker and Detached Glaciers on the north, and Cataract Glacier on the south (Figure 43). The ice of all these glaciers is clean except for a lateral moraine on the western margin of Baker and a small medial moraine near the center of Surprise Glacier. The Surprise Glacier fills the head of the inlet except along the southern margin where a very large rock extends nearly a quarter of the way across the ice front. Near the center of the tongue is a large pointed projection of ice extending several hundred feet into the inlet (Figure 43). The ice front is vertical and very active in discharging ice into the sea. The three glaciers along the inlet walls are small, steep ice streams that end several hundred feet above the bay. They are heavily crevassed and have very irregular fronts. Barely-visible trimlines indicate that these glaciers have recently been larger.

All of the glaciers of this inlet were discovered and named by the Harriman expedition of 1899 (Gilbert, 1903). However, Gilbert discussed only Surprise and Cataract Glaciers. The expedition map shows Surprise Glacier very near Cataract Glacier and both Baker and Cataract Glacier at tidewater.

The next account of these glaciers was by Grant and Higgins (1911). From their visits of 1905 and 1909, they found that the sur-




SURPRISE GLACIER

Figure #43

face of Baker Glacier had a steep slope, and that near the sea the ice stream broke over an almost vertical cliff from which the ice fell and accumulated near tidewater. The Harriman expedition's photographs, to which they had access, showed that conditions in 1899 were very similar to those in 1909, although there was some suggestion that the glacier had retreated and then advanced slightly. Grant and Higgins also saw Surprise Glacier and described it as a large tidal tongue ending in a high vertical face at the head of the west arm of Harriman Fiord. Along both sides of the glacier was a bare zone which extended forward nearly to the Cataract Glacier. They observed that the Harriman map of Port Wells showed the front of Surprise Glacier practically at the point where Cataract Glacier reached tidewater, and that photographs taken that year (1899) showed that the two glaciers were separated by a distance estimated to be a quarter of a mile. In 1909, the front of Surprise Glacier was estimated to have retreated over one mile since 1899. How much of this retreat had taken place since 1905 is not clear, for the Grant and Higgins photograph of that year is indistinct. A rock ledge, divided into two parts, projected from the front of the glacier near its south side in 1909. Grant and Higgins reported that this ledge was not visible in 1905.

In 1910, the National Geographic Society's expedition (Tarr and Martin, 1914) was in Surprise Inlet and reported that Baker Glacier was largely unchanged except for a slight advance which was a continuation of the advance between 1905 and 1909 noted by Grant and Higgins. Evidence of an earlier and greater expansion was found in the narrow coastal plain in front of the glacier, where a set of compound, crescentic moraines of different ages was discovered. Botanical evidence as well as shape and position of the moraines led them to conclude that the outer moraine was very much older than the inner one, perhaps as much as a hundred years older. At Surprise Glacier, Tarr and Martin reported that between 1899, when the Harriman expedition mapped Surprise Glacier, and their visit in 1910, the ice front had retreated about 6,500 feet. In 1899, the dark-colored southern edge of the terminus coalesced with the western edge of Cataract Glacier, a detail overlooked by Grant and Higgins in their statement that in 1899 the two glaciers were separated by a quarter of a mile. In 1910, a pronounced ice cape projected forward 1,000 feet, just north of the middle of the glacier. On the glacier's southern side, two rock ledges were visible beneath the ice, the larger one being about 600 feet long. These ledges, seen by Grant and Higgins in 1909 but not in 1905, increased in area from 1909 to 1910. Tarr and Martin noted that Detached Glacier had changed very little, if any, between 1899 and 1910. The Harriman map and several 1899 photographs show that by then, it had already separated from Surprise Glacier. However, they believed that by 1910 Cataract Glacier was expanding; for at the western margin, advancing ice was overriding shrubs of willow and alder, and there were ice blocks sliding from the cliffs into vegetation.

Dora Keen (1915), who visited this area in 1914, reported that Baker Glacier was continuing to advance, and estimated it to be 1,000 feet ahead of the 1910 position. Detached, Surprise, and Cataract Glaciers, however, appeared to be unchanged between 1910 and 1914.

The next investigator to visit Surprise Inlet was W. O. Field (1932). In 1931, he found that the total retreat had been over a mile and a quarter since 1899, most of which he considered had been accomplished before 1909. He felt that the most significant fact about Surprise, Serpentine, and Barry Glaciers was that no advance was detected in 1909, 1910, and 1914, whereas nearly all the other glaciers in the region advanced. Field reported a considerable retreat at Baker Glacier which left it in a condition similar to that observed in 1905. Almost the same fluctuations were noted for Cataract Glacier, which had advanced between 1910 and 1914, then retreated.

In 1935, Field (1937, pp. 75-76) reported a reversal of the pattern of retreat:

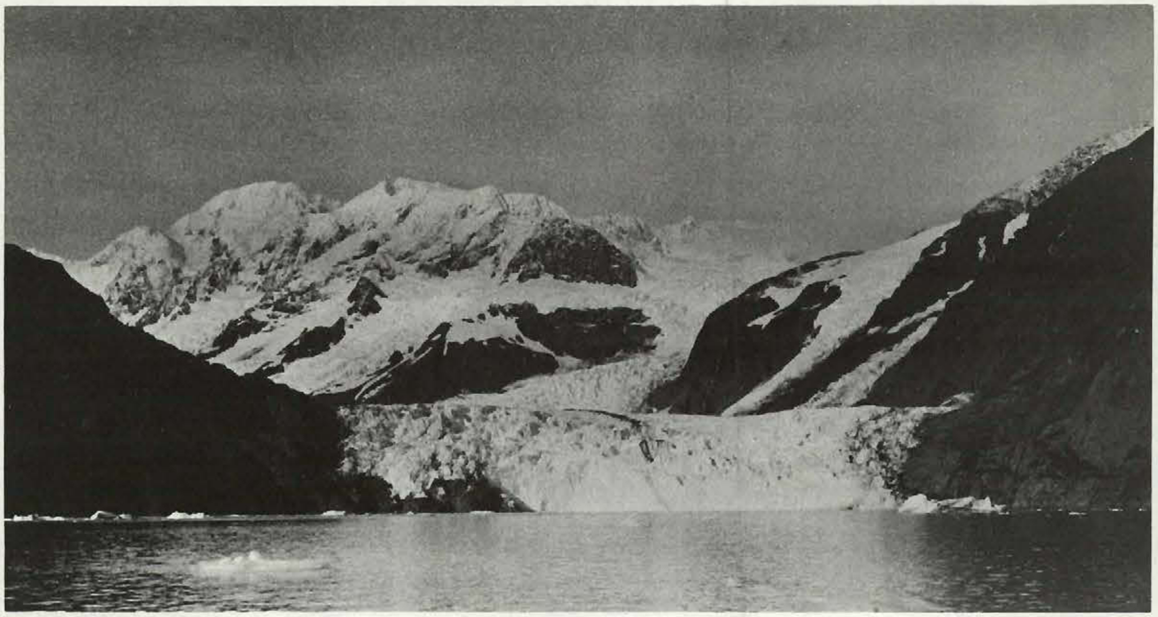
> Between 1931 and 1935 the conspicuous ice tongue of Baker Glacier came forward 150 to 200 feet, the eastern part of the terminus became thicker and advanced slightly, and the snow-and-ice fan below the terminus increased in size. In a neighboring cirque the lower ice tongue of Detached Glacier had advanced about 100 feet since 1931.
>
> Surprise Glacier advanced slightly at its north side between 1931 and 1935. Although small, the change is interesting in view of the rapid retreat from 1899 to 1910 and the subsequent slower recession from 1910 to 1931. Cataract Glacier changed considerably between 1931 and 1935. The whole lower part of the glacier increased in volume and spread laterally. The terminus advanced from a point 50 to 100 feet above sea level to contact with tidewater in one place. The present advance, however, is still well inside the limits of that of 1909 to 1914.

From a study of airphotos taken in 1947, Field (1948) stated that no appreciable change had occurred in the terminus of Surprise Glacier from 1935 to 1947. The terminus of Cataract Glacier receded from tidewater to an elevation of 100 to 200 feet between 1935 and 1941, then had not undergone any further significant change.

Photographs taken by D. N. Brown (1950) in 1947 indicate that Baker Glacier remained in its advanced condition of 1935 until 1947.

In 1957, the I. G. Y. party visited Surprise Inlet and took comparative photographs from all of the existing photo stations (Figures 43A, 44, 45). Surprise Glacier seemed to be in exactly the same position as in 1910, 1914, 1931, and 1947. Viewed from a distance, a slight downmelting since 1931 was evident. The biggest change was in the condition of the tributaries. These hanging glaciers had diminished in size noticeably between 1931 and 1957. Detached Glacier had receded so far up the steep valley wall between 1935 and 1957 that it was difficult to see it from the inlet. A comparison of 1935 and 1957 conditions at Cataract Glacier showed an appreciable shrinking of the entire lower part of the ice stream, involving a retreat of the terminus from tidewater to an elevation of a few hundred feet. Baker Glacier showed the greatest change of all. Its recession and shrinking had put the ice front well back from its 1931 position.

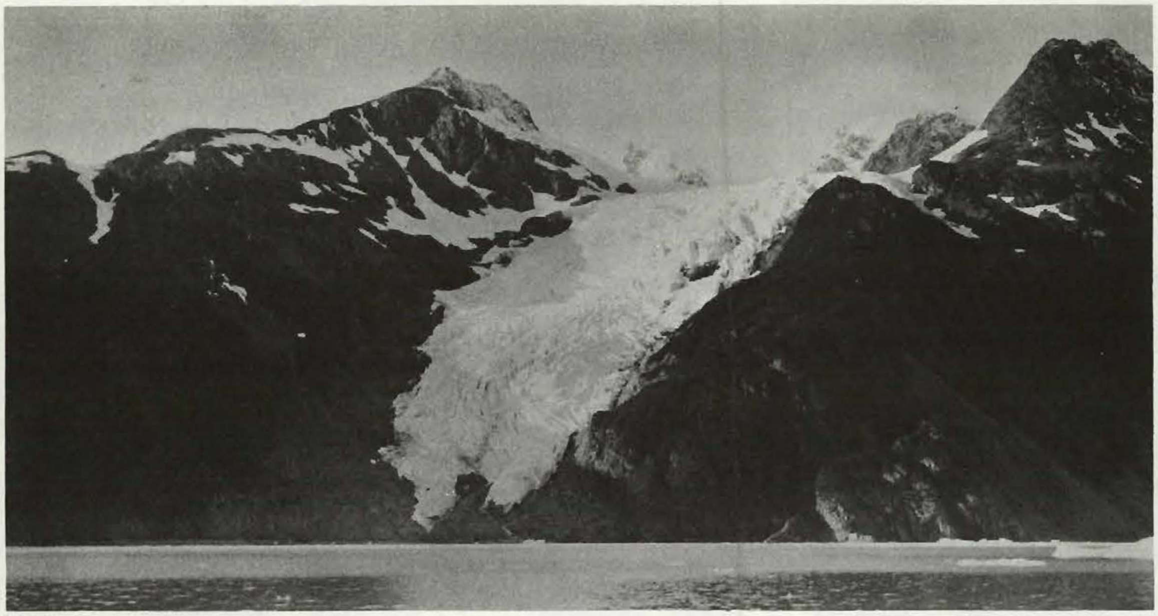
In 1961, Surprise Inlet was visited again, and comparative photographs were taken from all the stations. Recession was noted for all four glaciers. The greatest recession was at Detached Glacier where the rapid shrinkage of 1935-1957 was continuing. From a station on the opposite side of the inlet, Detached Glacier was seen to be disappearing above a rock shelf, with only a small tongue hanging over near the eastern margin. Baker Glacier had also receded slightly from 1957 to 1961.



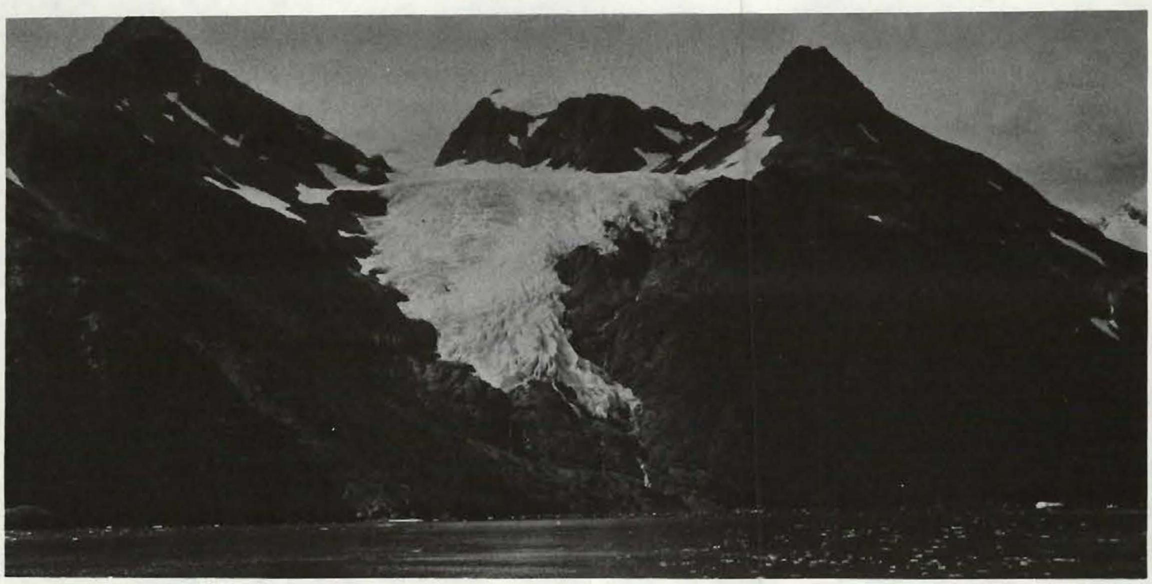
Surprise Glacier, 1931, from boat
Photo f-31-492 by Wm. O. Field

Surprise Glacier, 1961, from boat
Photo M-61-168 by M.T. Millett

Figure # 43A

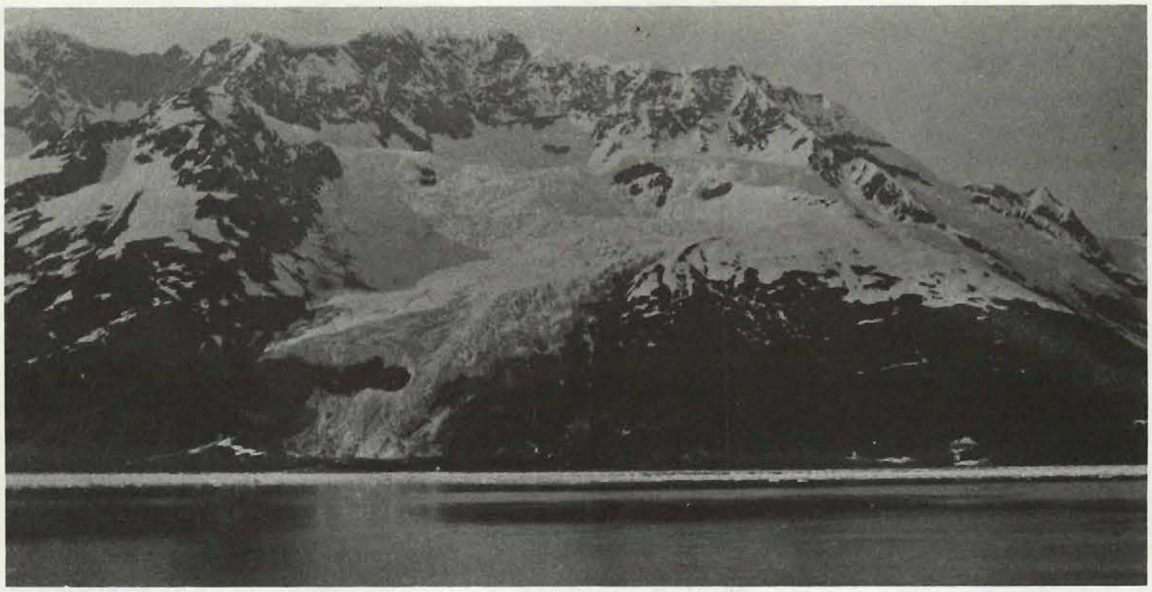


Cataract Glacier, 1931, from boat
Photo f-31-493 by Wm. O. Field

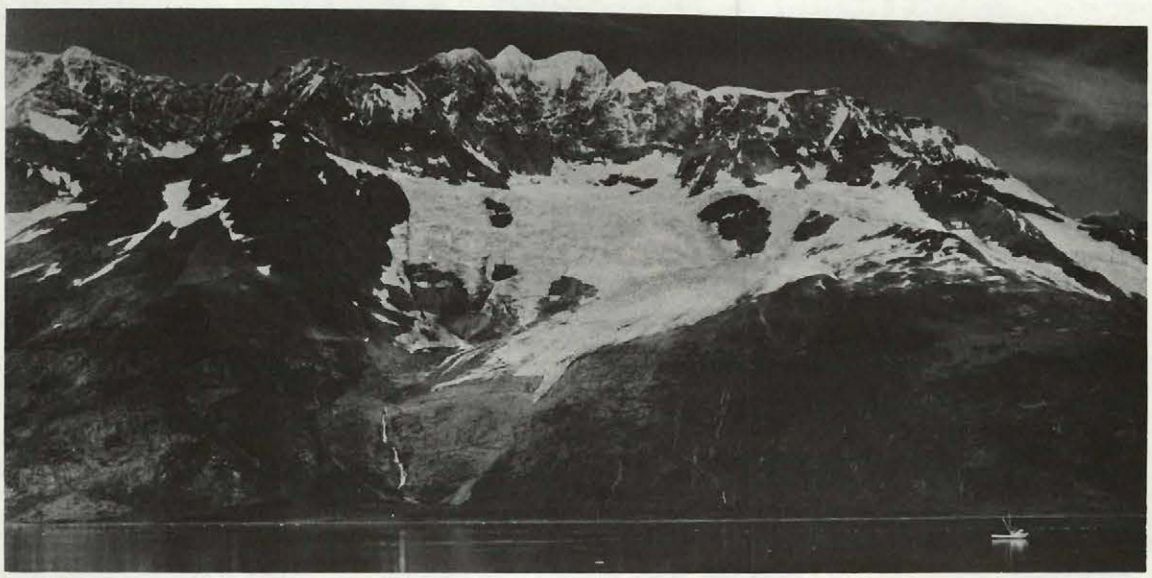


Cataract Glacier, 1961, from boat
Photo M-61-167 by M.T. Millett

Figure #44



Baker Glacier, 1909, from Station F (Harriman)
Photo 9-2 (198) by U.S. Grant



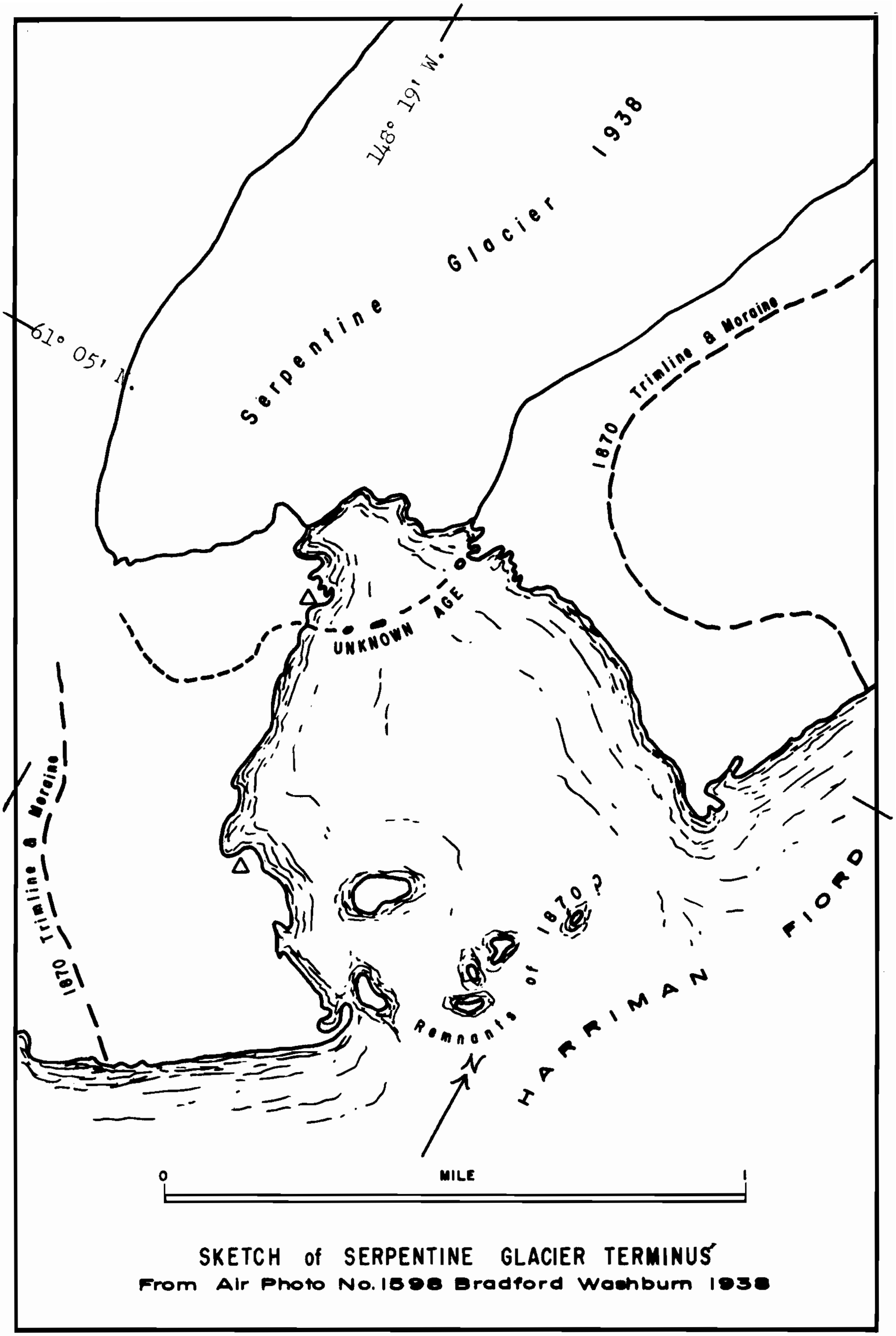
Baker Glacier, 1961, from Station F (Harriman)
Photo M-61-159 by M.T. Millett

Figure #45

## Serpentine Glacier

Serpentine Glacier is located on the north side of Harriman Fiord about five miles from Point Doran. About 7-1/2 miles long and covering approximately 14 square miles, it originates in deep cirques on the south side of Mount Gilbert and Mount Muir and descends to sea level. The eastern half of its mile-wide terminus ends in a shallow cove off Harriman Fiord, while the other half projects a short distance farther south on the land (Figure 46). The tidal portion of the front has a steep slope standing in a few feet of water into which small icebergs calve irregularly. The western half of the terminus ends aground with a gently sloping front. The entire terminal area is heavily covered with ablation moraine. Above the terminus, large medial and lateral moraines expand until at the front there is a continuous cover, except near the tidal portion and in crevasses. Surrounding the terminus is a large bulb-shaped terminal moraine, part of which is under water in the entrance to the cove.

Serpentine Glacier was first described and mapped by the Harriman expedition (Gilbert, 1903) in 1899. Gilbert described it as a broad stream, of low grade, fed by four or five tributaries descending steeply from amphitheaters in the encircling mountains. Though it reached the sea, it yielded few bergs, but was building a moraine barrier along most of its front. Its medial and lateral moraines were conspicuous, especially the northern lateral. The only observed fact bearing on its recent history was the absence of trees from the valley walls near it.



148° 19' W.
Serpentine Glacier 1938
61° 05' N.
1870 Trimline & Moraine
UNKNOWN AGE
1870 Trimline & Moraine
Remnants of 1870 ?
HARRIMAN FIORD
N
0
MILE
1
SKETCH of SERPENTINE GLACIER TERMINUS
From Air Photo No.1598 Bradford Washburn 1938


Figure #46

In 1905 and 1909, Grant and his co-workers (Grant and Higgins, 1911) visited Serpentine Glacier and described morainic accumulations in front of the glacier and a large bare zone along the sides. These they interpreted as indicative of a recent advance which occurred prior to 1899. In 1905, the position of the ice front was approximately the same as in 1899; and in 1909 the ice front was farther back than at either of the other dates. The retreat from 1905 to 1909 was perhaps a quarter of a mile. However, from the pre-1899 hochstand to the 1909 position, the glacier had retreated approximately half a mile in the center and on the eastern side and three-quarters of a mile on its western side.

In 1910, the National Geographic Society's expedition (Tarr and Martin, 1914) studied Serpentine Glacier and said that, between the time of its discovery by the Harriman expedition in 1899, and its studies in 1910, the terminus of the Serpentine Glacier had not changed appreciably. They felt that there was clear evidence that not many years earlier Serpentine Glacier had extended at least a mile farther and that it had ended in Harriman Fiord with a tidal ice front of 1-1/2 miles or more in length. This was suggested by terminal and lateral moraine deposits and by a bare zone near the terminus of the glacier. Most of the terminal moraine was covered at high tide and the glacier terminated in the shallow water of a bay. Outside of this moraine was an older one of undetermined age.

Serpentine Glacier was not visited again until 1931, when W. O. Field (1932, p. 393) occupied many of the old photo stations and established a new one close to the front. Comparing Serpentine to Barry Glacier he said:

> In the next valley is Serpentine Glacier, whose recent behavior has been somewhat similar in that a general retreat has occurred amounting to about half a mile since 1899. About half of this took place between 1905 and 1910, and the rest since 1914.
>
> Perhaps the most significant thing about Surprise, Serpentine, and Barry Glaciers is that no advance was detected in 1909, 1910, and 1914, whereas nearly all the other ice fronts in the region experienced some sort of forward movement at that time.

During his visit in 1935, Field (1937, p. 75) observed:

> Serpentine Glacier did not change between 1931 and 1935 except that a small part of the terminus advanced about 50 feet. Probably, as in the case of the advanced tongue of Barry Glacier, this can be attributed to increased protection from tidewater.

An airphoto by Bradford Washburn in 1938 (#1598) shows a prominent, mostly-submerged moraine varying from 700 to 2, 000 feet from the present terminus and considerably within the moraine described earlier by Tarr and Martin (1914). This was apparently formed after 1899 and very possibly after 1910 (Figure 46).

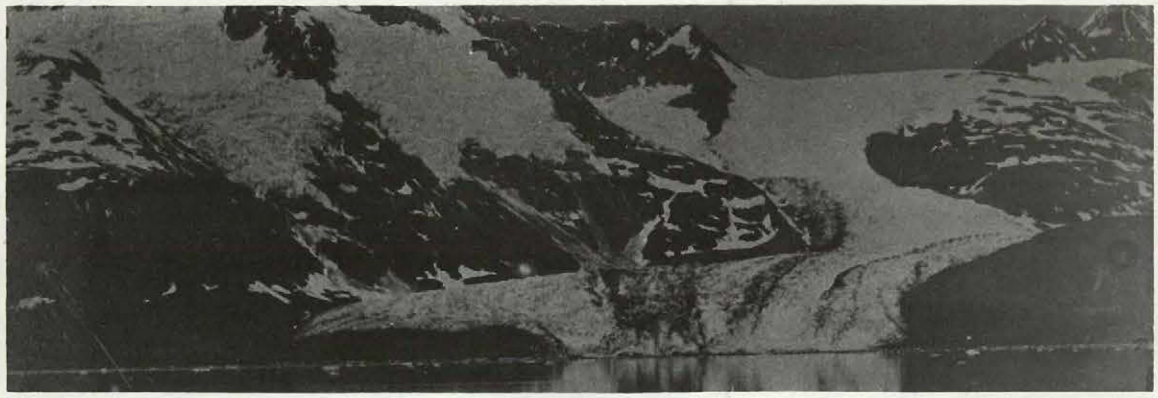
Pictures taken by D. N. Brown in 1949 (1952) show the glacier had advanced considerably since 1935. The whole central part of the front had moved forward about 350 feet, bringing it close to, but not as far out as the moraine seen in Washburn's 1938 airphoto.

In 1957, the I. G. Y. party was at Serpentine Glacier and occupied all the existing photo stations. It could be seen that the ice had receded about 150 feet from the 1949 position. The inlet had become silted in behind the submerged moraine and the glacier front now stood in only a few feet of water. Directly adjacent to the outermost cape was a small push moraine. The ice of the western part of the terminus was in nearly the same position as in

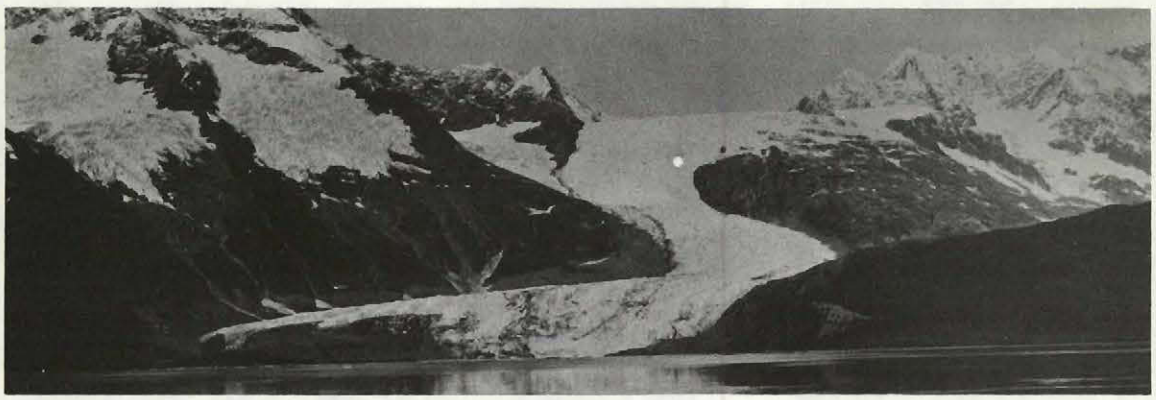
1935; however, considerable downmelting had occurred and the ablation moraine cover was continuous and very thick.

Observations and photographs (Figures 47 and 48) of the 1961 visit indicated that a small advance had occurred during 1957, as a small moraine was found marking the terminus position of that year. This advance was observed only in the tidal half of the terminus. Downmelting of the entire terminus was obvious and the silting in of the bay was nearly complete.

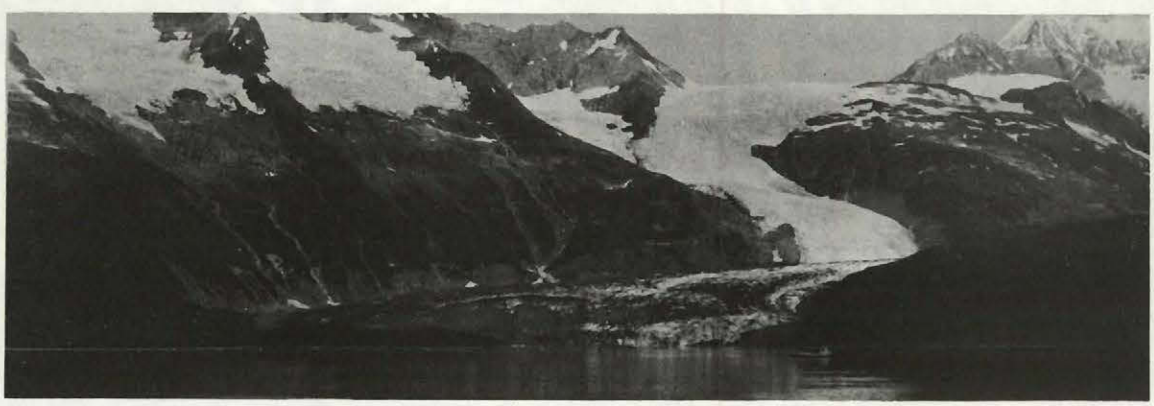
The interesting history of the terminal behavior of Serpentine Glacier is well preserved and is fairly accurately dated by vegetation (Tarr and Martin, 1914). The age of the trees on the outermost moraine dates an advance of not later than the first decade of the 19th century. On the inner moraine the oldest vegetation indicates that the ice retreated from there no later than the 1870's. Since this last maximum, the front had retreated at least one mile by 1910, and by 1931 a further recession of a quarter of a mile had occurred. Despite this loss, a small advance was underway which probably continued until 1949. By 1957, the front had retreated again, and this retreat continued to 1961, at which time the front was still forward of its 1935 position. Some time since the 1870 hochstand, a moraine was formed fairly near the present ice front. This moraine is seen only from the air as a crescent submarine ridge and has not been dated.



Serpentine Glacier from Station B, 1910
Photo No. 167 by Lawrence Martin

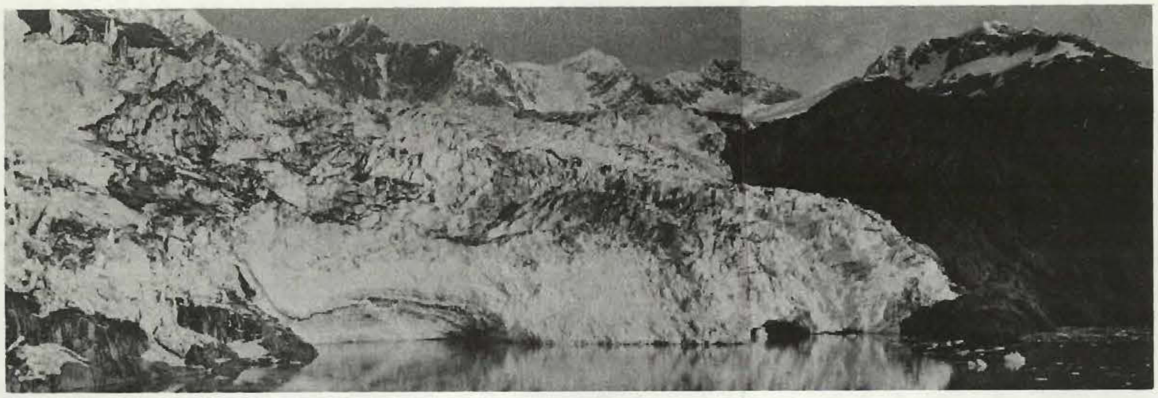


Serpentine Glacier from Station B, 1931
Photo F-31-464 by Wm. O. Field



Serpentine Glacier from Station B, 1961
Photo M-61-153 by M.T. Millett

Figure #47



Serpentine terminus from Station A, 1935
Photos f-35-477,478 by Wm. O. Field

Serpentine terminus from Station A, 1957
Photos M-57-SG124,125 by M.T. Millett

Serpentine terminus from Station A, 1961
Photos M-61 SG198,199 by M.T. Millett

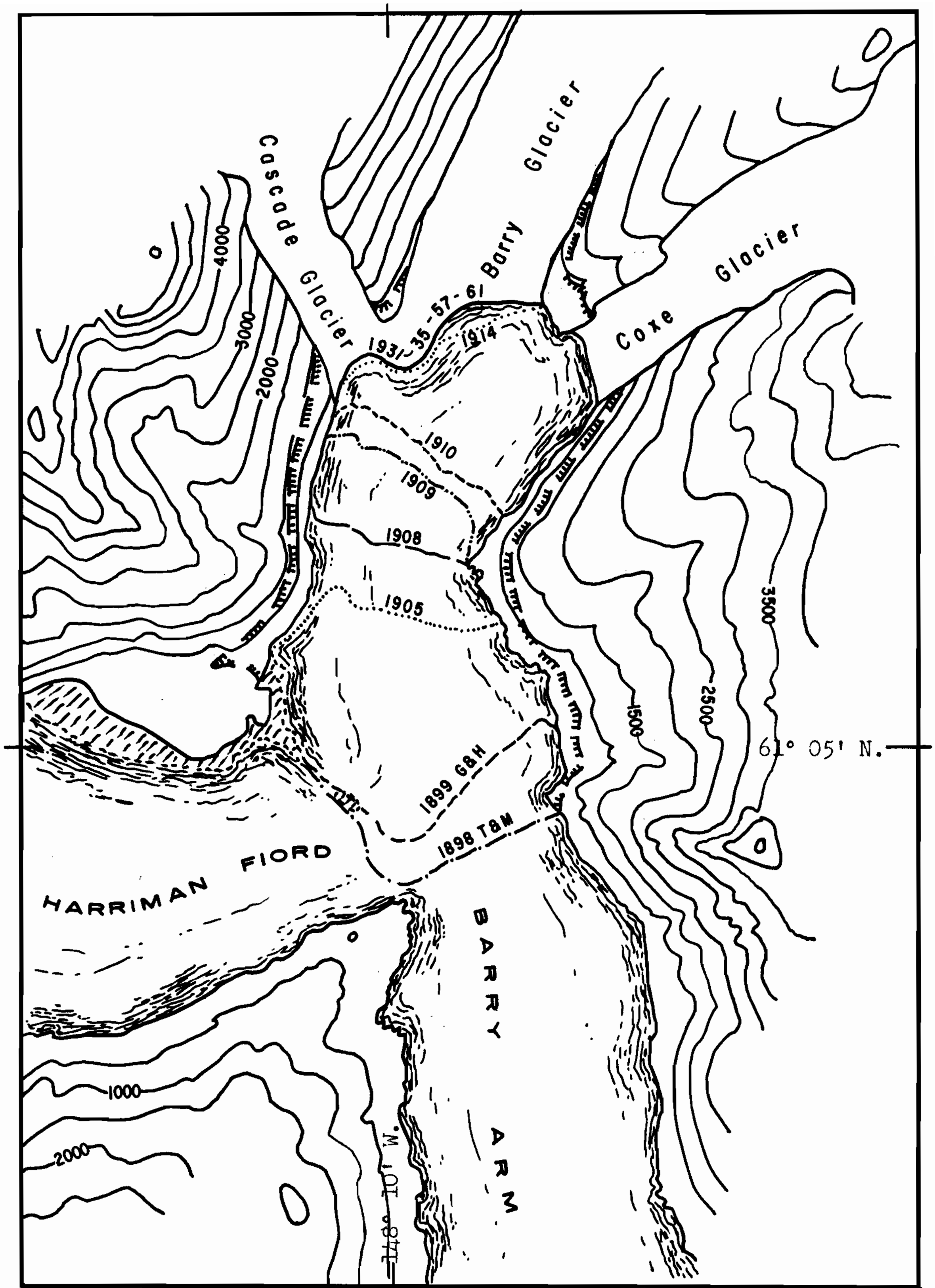
Figure #48

## Small Glaciers of Harriman Fiord

Along the south shore of Harriman Fiord are three small glaciers, Dirty, Wedge, and Toboggan. All of these small glaciers are less than two miles long and have areas of about one square mile. Dirty Glacier and Toboggan Glacier descend to about 200 feet above sea level, and Wedge ends nearly 1,000 feet above tidewater. With the exception of a small advance of Toboggan Glacier between 1905 and 1909 (Grant and Higgins, 1911), all of these tongues have been steadily retreating since first observed. Since all of these ice streams are small, they have been given only casual observation.

## Glaciers of Barry Arm

Barry Arm, in the northwest part of Prince William Sound, is about ten miles long and connects Harriman Fiord with Port Wells (Figure 49). At the head of Barry Arm are three separate glaciers, Barry, Cascade, and Coxe, which are treated together because of their relationship to each other. Until 1913, these three tongues were joined and formed a single, but much expanded, Barry Glacier. Of the three present glaciers, Barry, with an area of approximately 40 square miles and a length of over 15 miles, is the largest. Both Cascade and Coxe are 5 to 6 square miles in area and each has a length of 6 to 7 miles. Both descend over 3,000 feet in the last mile and have very steep gradients. Barry, on the other hand, is very flat. All three descend to tide-water; however, Cascade and Coxe usually have a zone of exposed rock between the ice and the water. Near its western margin, where it is contiguous to Cascade Glacier, Barry Glacier has a gentle front and some exposed rocks, but the rest of the front is vertical ice. The termini of all three glaciers are heavily crevassed, especially in the lower parts of Cascade and Coxe. Ice falling from the lower parts of Cascade and Coxe, and calving along the vertical face of Barry produce small icebergs in the inlet at all times. Barry and Cascade Glaciers both have well-defined lateral moraines on either side. A medial moraine in Cascade Glacier is sometimes prominent and sometimes difficult to discern. Ice of Coxe Glacier is very clean and no moraines are obvious. In the few hundred feet where the margins of Barry and Cascade coalesce, a prominent medial moraine is formed.




Based on Tarr and Martin, map 8.

N

0 MILES 2

Contour Interval 500 feet

GLACIERS of BARRY ARM

Figure #49

The earliest account is in Vancouver's map and Whidbey's description (1801, p. 183):

> Between these points (Pigot and Pakenham) a bay is formed, about a league and a half deep towards the N. N. W., in which were seen several shoals and much ice; the termination of the bay (unnamed) is bounded by a continuation of the above range of lofty peaks.

Vancouver did not enter the inlet but showed the head of the bay completely filled with a glacier.

The next investigator was Applegate (Davidson, 1904, p. 28), who was in Port Wells in 1887, 93 years later. According to Davidson, Applegate's map is based on that of Vancouver. However, some distances are greater, and his shoreline is somewhat different. Applegate's chart shows a 1-1/2 mile wide ice front of a great glacier coming down to the sea. This he locates 7 miles northward from Point Pakenham. There is no indication of any opening toward the west.

In 1898, an army exploration led by W. R. Abercrombie (1900) was in this area, and according to Davidson (1904, p. 30) Abercrombie reported:

> In the Barry Arm, at nine miles from point Pakenham, the map locates the face of the Barry Glacier that comes square upon the water; three or four miles behind the front this glacier branches, the main glacier running north, the smaller northwest.

In the following year, the Harriman expedition (Gilbert, 1903) was close to the front in Barry Arm when it discovered the opening along the western margin that led to an inner fiord, which they named Harriman Fiord. In its description of Barry Glacier, the Harriman party suggested that the low gradient of the lower part indicated a glacier of considerable size, perhaps one of the largest in Port Wells. Connected with the eastern edge of the ice was a long, narrow tongue which was attached to the shore, evidently a remnant left by the glacier at some very recent date when its front was more extensive. In the same area, the forest was separated from the ice by a bare zone several hundred feet wide. Translating these facts into terms of glacial history, Gilbert concluded that at some time within the century the Barry Glacier had been somewhat larger than when he saw it. However, he felt it had not exceeded the limit marked by the neighboring forest trimline for a number of centuries.

Six years later, in 1905, a series of visits was begun by Grant and his co-workers (Grant and Higgins, 1911). They concluded that the findings of the Harriman expedition were for the most part valid, and that the Barry Glacier was rapidly retreating. They also reported that botanical evidence suggested that the recent hochstand had occurred about 25 years prior to 1909.

In 1910, the National Geographic Society's expedition studied Barry Arm and produced an excellent map and many photographs (Tarr and Martin, 1914). They reported that the amount of retreat of Barry Glacier during the previous year was about 1,600 feet on the eastern side and 500 feet on the western side. At the terminus of the glacier, the vertical thinning by ablation during the 3-1/2 mile retreat from 1898 to 1910 amounted to 900 feet on the western, and 1,000 feet on the eastern side. Between the Cascade and Barry Glaciers, the ice surface had lowered 650 feet, and between Coxe and Barry Glaciers, it had lowered 700 feet.

In 1914, Dora Keen visited Barry Arm (1915). In her photos and description, one finds the first indication of the separation of Barry Glacier into the three presently-known tongues. Recession had continued at a rapid pace until 1914, exposing a large area of deep water. B. L. Johnston (1917) made several observations during the interval 1910 to 1914, and these confirmed Miss Keen's findings.

A comparison of Keen's 1914 pictures with those by Field (1932) taken in 1931, shows that the retreat ended in 1914 and that the ice fronts were in almost exactly the same positions in 1914 and 1931. This conclusion was further reinforced by later work, for Field visited Barry Arm again in 1935 (1937, p. 75) and reported:

> On the south side of Barry Glacier the ice front advanced 150 to 200 feet between 1931 and 1935, apparently because the constant dumping of debris from a heavy medial moraine is reducing the depth of this part of the inlet, curtailing the subsurface melting of the ice, and allowing the glacier to move forward over its own sediments. Except for this the glaciers remain the same as they have been since 1914.

Field took an oblique airphoto of Barry Glacier in 1935 and the advance was obvious in this photograph. In addition, from a study of more airphotos taken in 1947, Field (1948) concluded that no appreciable change seemed to have occurred in the termini of Barry, Cascade, Serpentine, Baker, and Surprise Glaciers from 1935 to 1947, but that Coxe Glacier appeared to have experienced a small advance.

D. N. Brown (1952) in 1949, and G. G. Burdick (U. S. Forest Service, unpublished) in 1950, took pictures that show the rocks at the base of Cascade Glacier less covered than in earlier photographs.

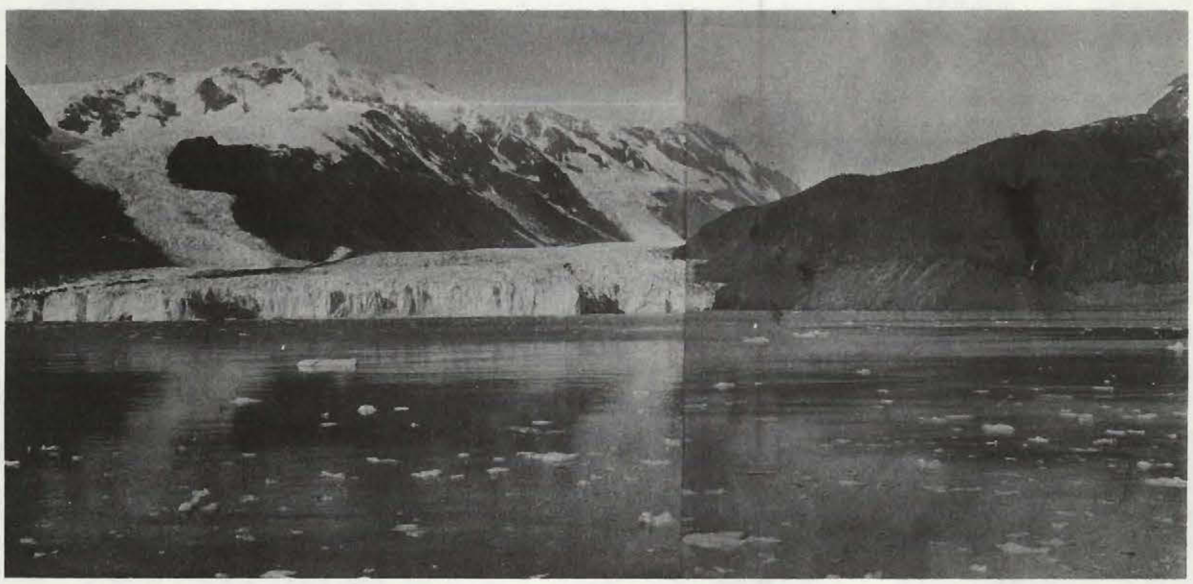
In 1957, the I. G. Y. party spent a few hours in Barry Arm and took photographs from all the previously established stations (Figures 50 and 51). A careful study of previous photographs and conditions in 1957 indicated near-stable conditions. If any changes had occurred they were not noticeable. Botanical dating along the trimline confirmed Tarr and Martin's conclusion that the ice began to retreat from its maximum position in 1898.

In 1961, the author was again in Barry Arm and took photographs. Very little change was observed other than a slight decrease in the northern margin of Coxe and the eastern margin of Barry, and a slight emergence of the rocks in the west-central part of the Barry terminus.

The recession of Barry Glacier from 1898 to 1914 was the greatest of any glacier in Prince William Sound. This recession was also one of the most fully documented. Since 1914, Barry Glacier has remained relatively stable with only minor changes being observed.

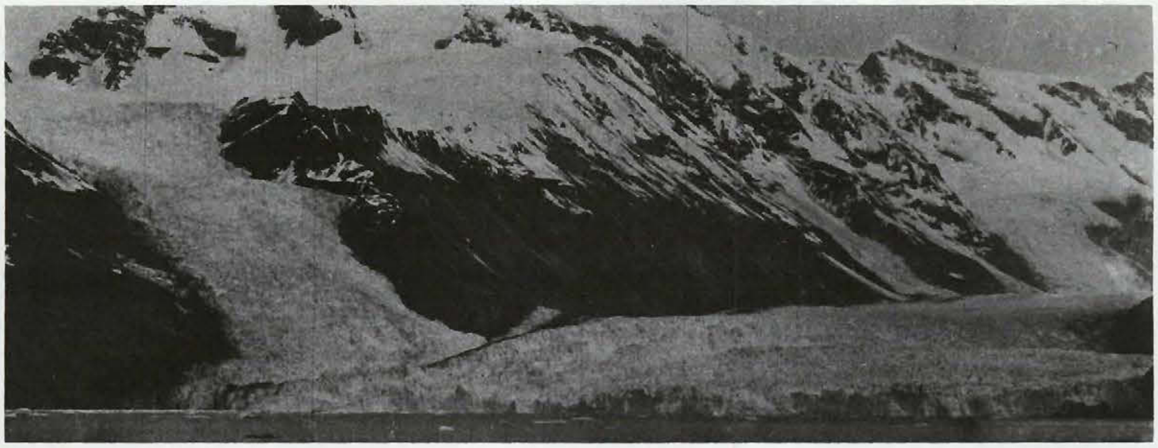
The upper parts of the Barry Glacier and its tributaries have not been mapped, and the area distribution, gradient, etc., are unknown. The stability of the ice fronts since 1914 suggests an equilibrium between ablation and accumulation.


Barry Glacier from Pt Doran, 1899
Photo 127 Harriman expedition

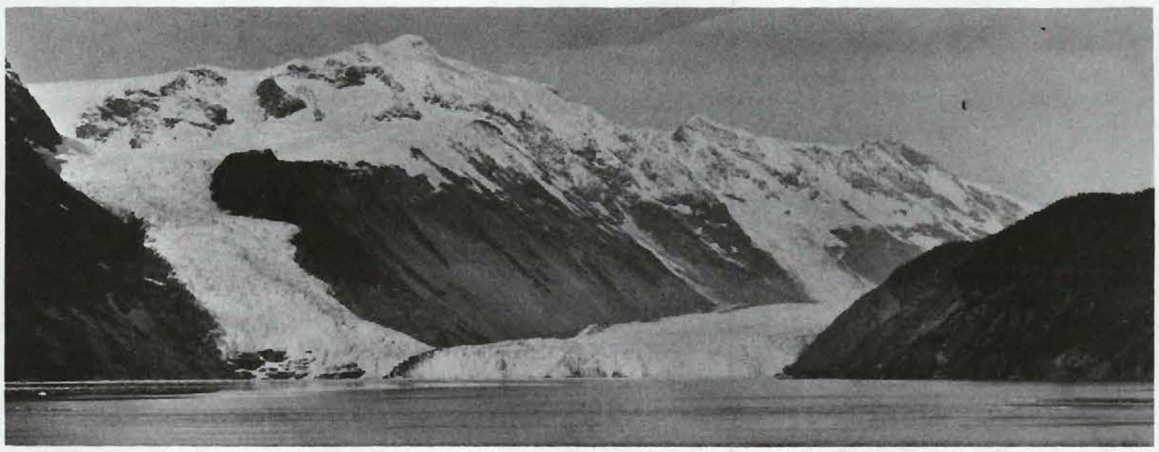


Barry Glacier from Pt Doran, 1905
Photos 686, 684 by Paige

Figure #50



Barry Glacier from Pt Doran, 1909
Photo 98 by U.S. Grant



Barry Glacier from Pt Doran, 1931
Photo f-31-417 by Wm. O. Field

Barry Glacier from Pt. Doran, 1961
Photo M-61-SG151 by M.T. Millett

Figure #51

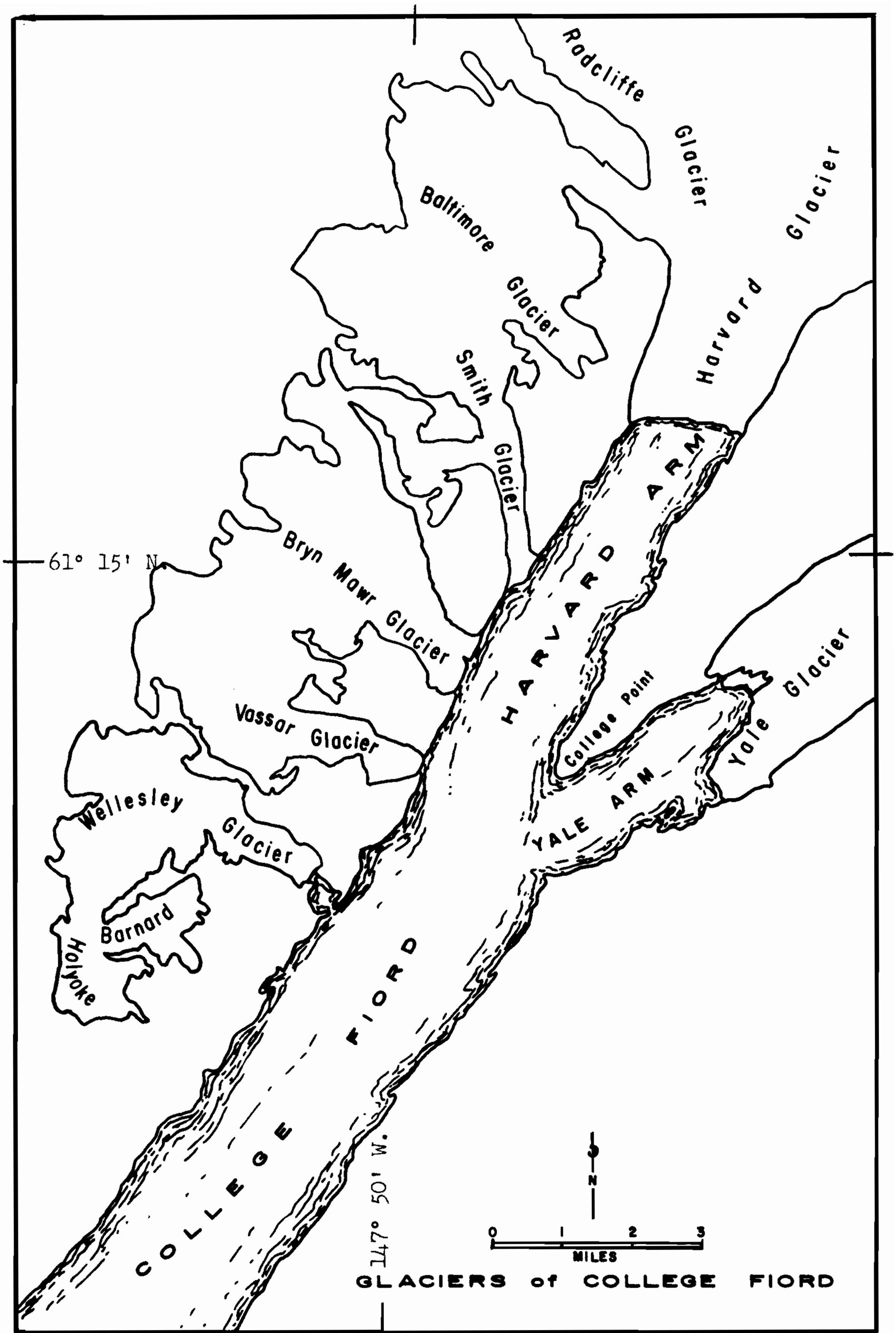
## College Fiord

### Introduction

The College Fiord of Port Wells is located in the northwestern part of Prince William Sound. It is about 24 miles long, and it has a general north-northeasterly orientation. The width of the fiord varies from 2 to 3 miles, and the walls nearly everywhere are precipitious. On its eastern shore, College Fiord has a broad inlet 9 miles north of Port Wells. Farther north, at College Point, the fiord bifurcates, following its original direction for 6 miles as Harvard Arm and a northeasterly direction for 3 miles as Yale Arm (Figure 52). At the heads of these two arms are located Harvard and Yale Glaciers, the two major ice streams of the fiord. Besides these two major glaciers, several of the minor ice tongues of the fiord have been studied, many more or less imperfectly.

### Harvard Glacier

The terminal area of Harvard Glacier has been studied carefully; however, its upper reaches are unmapped and poorly known. Consequently, its profile, area distribution curve, and accumulation area ratio cannot be given. Airphotos suggest an area of 150 square miles and a length of about 24 miles. The accumulation area drains ice and snow from the general region of the highest points of the central Chugach Mountains. From the terminus of Harvard Glacier, four large tributaries can be seen along the western side and one along the eastern side. All of these tributaries are steep, cascading




Based on U.S. Geological Survey Maps, Anchorage A-2, A-3, B-2, B-3

Figure #52

glaciers similar to the smaller glaciers of College Fiord. The most important of the Harvard tributaries is the first tributary on the west, Radcliffe Glacier. From the position of the medial moraine on Harvard Glacier it appears that 40 per cent of the ice of the terminus may come from Radcliffe Glacier. The next tributary on the northeast, Eliot Glacier, seems to furnish approximately 20 per cent of the ice at the terminus. The only visible tributary along the eastern side is the Lowell Glacier, and the medial moraine formed at its junction with the Harvard indicates that only a small amount of Lowell ice reaches the Harvard terminus. The northern one-fourth of the Harvard terminus is covered with moraine, and prominent medial moraines are found near the center and near the east margin where they nearly coalesce with a lateral moraine. The entire front has a high vertical face standing in deep water. In 1910 (Tarr and Martin, 1914), this ice front was estimated to be 350 feet high, but in 1961 it appeared to be slightly lower. The visible part of the glacier is heavily crevassed and the active front discharges ice into the fiord almost constantly. On either side of the terminus, vegetation is found growing right up to the ice front. Fiord depths one-half mile in front of the terminus have been found to be over 100 fathoms.

The earliest mention of Harvard Glacier was by Whidbey (Vancouver, 1801, pp. 312-314), who, in 1794, described the head of the fiord as being terminated by "a firm and compact body of ice reaching from side to side, and greatly above the level of the sea." He also found a great deal of floating ice in the fiord, and described the thunderous noise accompanying the calving of icebergs. However, he came no closer than six miles to the front, and his map is too vague to determine the terminus position accurately.

In 1887, Applegate (Davidson, 1904) visited this area, and his map shows the head of the fiord filled with a tidal glacier. This map was also made from too great a distance to be accurate.

In 1898, a U. S. military expedition led by W. R. Abercrombie (1900) mapped the upper part of Port Wells, and Davidson (1904) interpreting the map, reported two tidewater glaciers in the extreme northern part of Port Wells. These were described as being 17 miles north of Point Pakenham. In the same year, Glenn (1900), like Abercrombie a member of a military reconnaissance, also noted the presence of two large tidal glaciers at the head of the fiord.

In the following year, the Harriman expedition (Gilbert, 1903) visited College Fiord and named most of the glaciers. A small-scale map was made and photo stations were established. Unfortunately the party did not approach the terminus closely, and the photographs are deficient in detail at critical points.

In 1905 and 1909, Grant and parties (Grant and Higgins, 1911) visited Harvard Glacier and estimated the frontal cliff to be 350 feet high and actively discharging ice into the fiord. They also reported that the position of the west side of the front of the glacier was approximately the same in 1899 and 1905. But in 1909 they observed that the entire ice front had advanced half a mile.

The National Geographic Society's expedition (Tarr and Martin, 1914) was in College Fiord in 1910. Regarding Harvard Glacier, Tarr and Martin's comments mirror those of Grant, disagreeing only on the amount of advance between 1905 and 1909; this they put at 200 yards, in contrast to Grant's suggestion of half a mile. They also observed that in the year since Grant's last observation, further advance had amounted to only 100 to 150 feet. The advance in 1910 had resulted in increased crevassing in the lateral moraines on either margin of Harvard Glacier near the terminus, and in the overriding and destruction of forest on each side. At the western edge of the glacier, where the advance of 1910 seemed to be due to activity of the Radcliffe tributary, a push moraine was being formed on the beach. Along the glacier's margin, a short distance to the northward, the moraine was made up largely of tangled fragments of trees and roots, mixed with soil, moss, peat, gravel, and till. There were well-developed peat rolls, and in places the push moraine was 15 feet high. One of the trees which had just been overturned was a spruce 12 inches in diameter and probably over 100 years old, indicating that the glacier had not previously advanced as far as the 1910 stage for at least a century.

Dora Keen (1915), in attempting to climb Mt. Marcus Baker, went up Harvard Glacier several miles. The group was stopped by bad weather, but did determine the elevation of the firn line on Harvard Glacier and did report that advance had continued since 1910.

In 1935, W. O. Field (1937) estimated that, between 1905 and 1931, Harvard Glacier had advanced 2,000 feet on its eastern side; and that by 1935, it was nearly 200 feet in advance of its position in 1931. On the western side, the ice had continued its invasion into mature vegetation. Discovery of a 248 year-old tree (see also

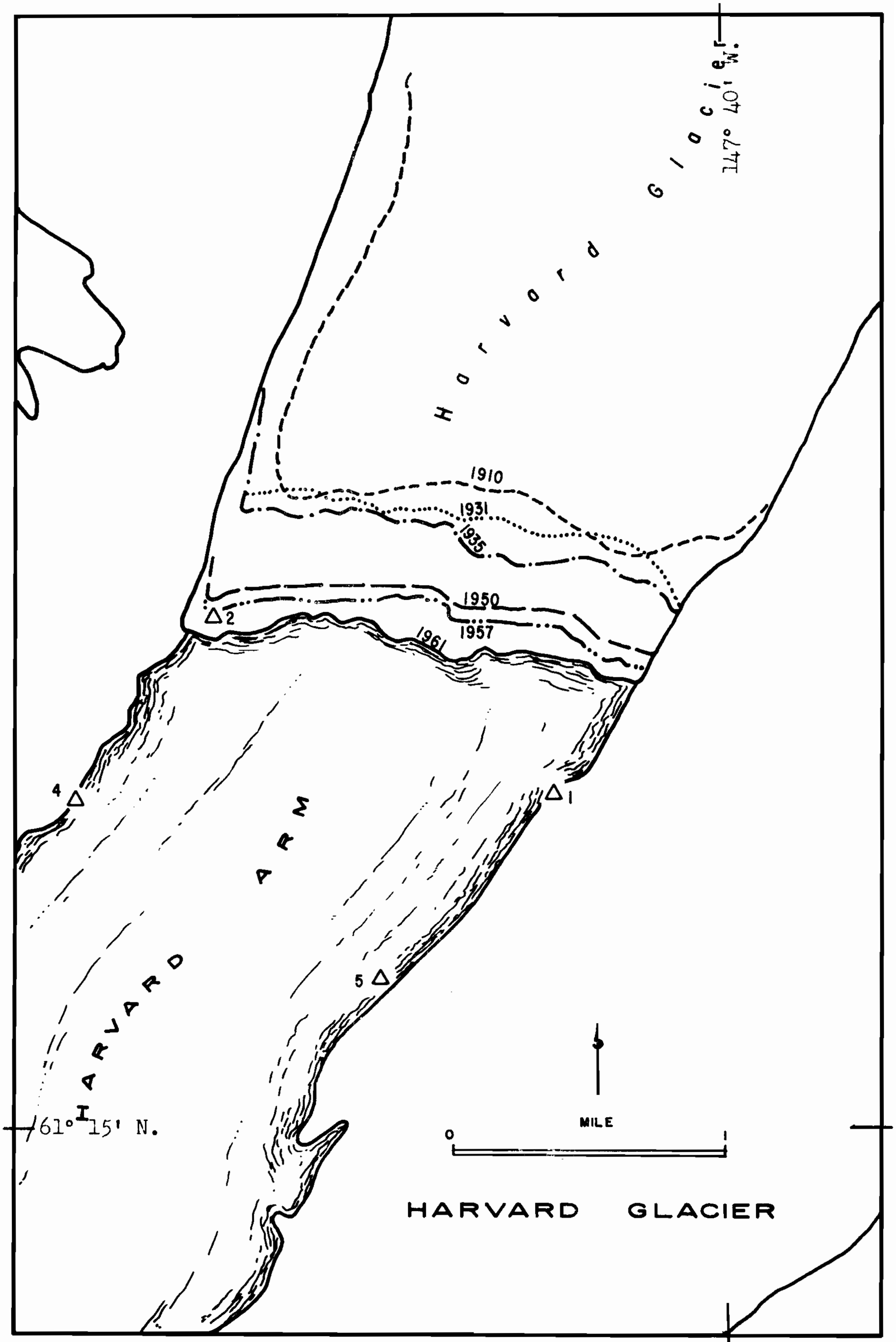
Cooper, 1942) less than 500 feet from the ice led him to conclude that Harvard Glacier had then reached its greatest advance in 2-1/2 centuries.

Photographs taken by D. N. Brown in 1949 (1950), and air-photos taken by the U. S. Air Force in 1954 and 1957, show a slow continuation of the forward movement.

In 1957, the I. G. Y. party spent a day at Harvard Glacier occupying old photo stations and surveying the terminus (Figure 53). In 1935, a new station had been set up exactly 1, 500 feet from the terminus along the western shoreline, but by 1957 this station was covered by the advancing ice. Advance on the eastern side was nearly 1, 200 feet, in the same period. The ice along both margins was into the vegetation and was obviously still moving forward.

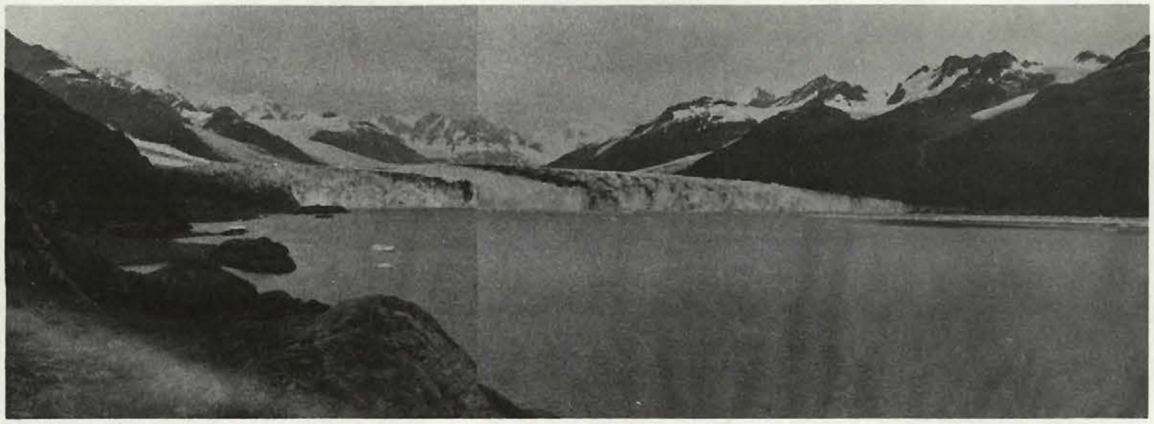
In 1961, the front was again surveyed and photographed (Figure 54) from established stations. By triangulation, it was determined that the western margin had advanced about 425 feet and the eastern margin 100 feet since 1957. The ice front was very active, and no halt in the steady forward movement appeared likely in the near future.

The relative amounts of ice supplied by the glacier and its tributaries is conjectural. In 1957, the medial moraine that marked the limit of Radcliffe ice appeared to be farther from the margin than in earlier years, suggesting an increase in Radcliffe ice in the main stream. This apparent increase in the proportion of Radcliffe ice continued from 1957 to 1961. However, one must consider that, just as the other glaciers along the western side of College Fiord enter the fiord from hanging valleys, Radcliffe

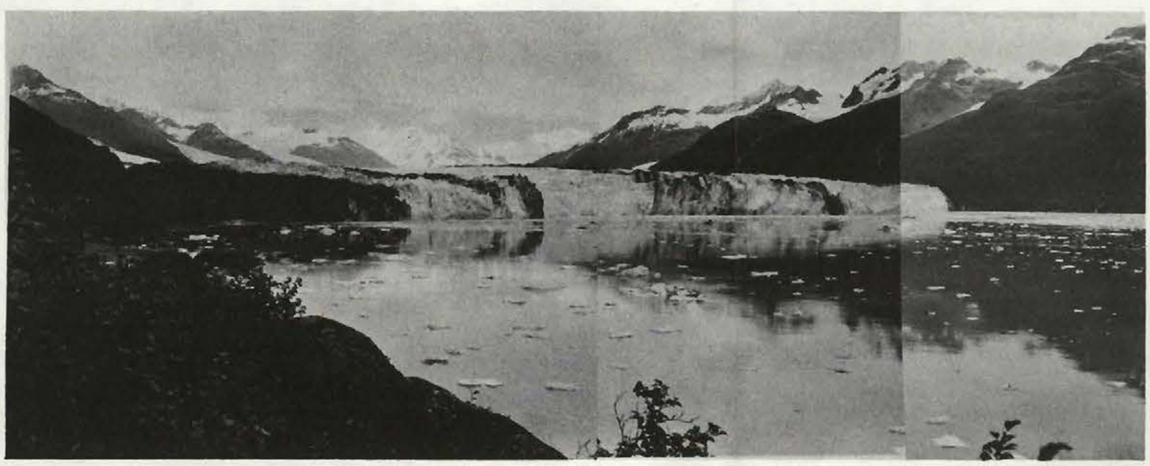



Based on Tarr and Martin, Map 7.

Figure #53



Harvard Glacier, 1935, from Station B (4)
Photos f-35-523,524 by Wm. O. Field



Harvard Glacier, 1961, from Station B (4)
Photos M-61-111,112,113 by M.T. Millett

Figure #54

may enter Harvard Glacier from a hanging valley. This would mean that Radcliffe ice rides out over Harvard ice, giving a false impression of Radcliffe's contribution to the main ice stream.

## Summary

The activity of Harvard Glacier in 1899 is unknown. However, this glacier is different from all of the others in Prince William Sound in that it has had an uninterrupted history of advance since 1905.

## Yale Glacier

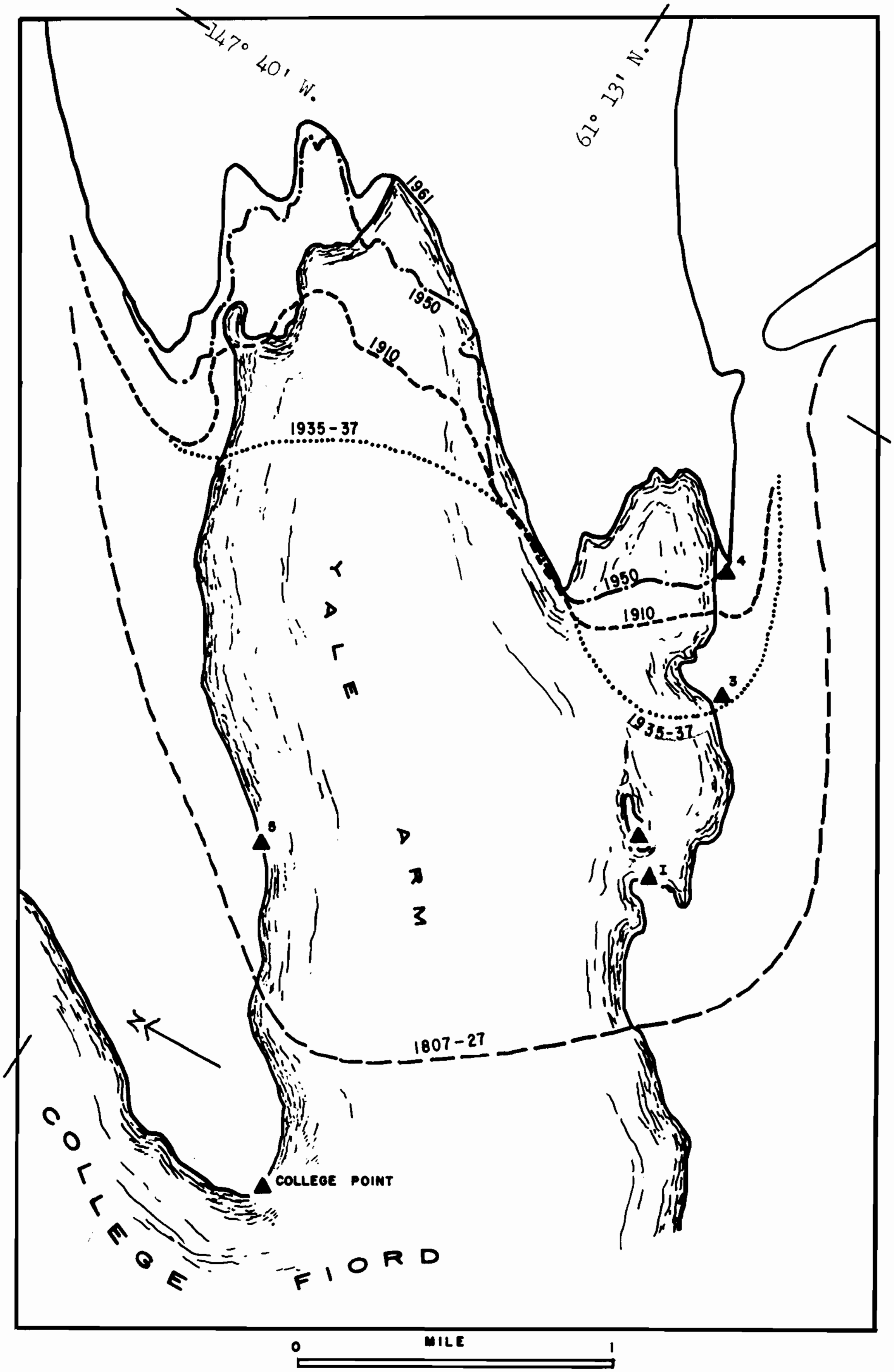
Yale Glacier is located at the head of Yale Arm in College Fiord (Figure 52). Like Harvard Glacier, the upper reaches of Yale have not been accurately mapped, only a few simple maps of glacier termini being available. These maps show that Yale Glacier is about a mile and three-quarters wide; and, according to Field (1932), the glacier has a known length of 20 miles. It originates on the northwestern side of Mt. Witherspoon (12, 000 feet) and flows southwestward to the sea. The terminus is easily divided into four areas: (1) along the western margin nearly one-half of the terminus is aground; (2) in the middle of the arm is a section of active ice cliff, discharging ice into deep water; (3) east of the center a rather large island is emerging; (4) between this island and the southern margin is another vertical face, which calves a great deal of ice into the eastern part of the bay. The front is very irregular and along the eastern side projects 1-1/2 miles farther downstream than in the middle and west (Figure 55). The glacier has a rather steep gradient, and large crevasses extend as far up the glacier as can be seen from the fiord. The eastern half of the ice stream is clean, except for a moraine along the edge. The western half is quite dirty, and a series of ogives is found near the margin. There are no medial moraines.

There are two sets of vegetation trimlines found along the valley walls (Figure 55). The upper is about 900 feet above sea level at the terminus, and the lower is at about 300 feet elevation. From the shore to the top of the first trimmed area there is very little plant life, and from a distance this area appears to be bare. From the lower trimline to the upper the area is covered with dense alders, salmonberry, and willows. The upper trimline is marked by a fairly dense stand of spruce trees, none of which is found below the trimline.

The earliest references to Yale Glacier are the maps of Whidbey, 1794, and Applegate, 1887. Neither men approached the glacier nearer than 12 miles, and their maps are highly generalized. Davidson's description (1904, p. 29) of their work merely states: "At three miles from the main glacier [Harvard] there is a moderately deep recession of the shoreline, into which falls a large glacier from the northeast."

The first description and photographs of Yale Glacier are from Mendenhall (1900), who was in the area in 1898. Glenn, a member of this expedition, described it as an active glacier constantly discharging ice into the fiord.

Rock ledges were exposed beneath the middle of the ice front and the eastern half exhibited "the rough pinnacled front of a still-




YALE GLACIER

Based on Tarr and Martin, Map 7.

Figure #55

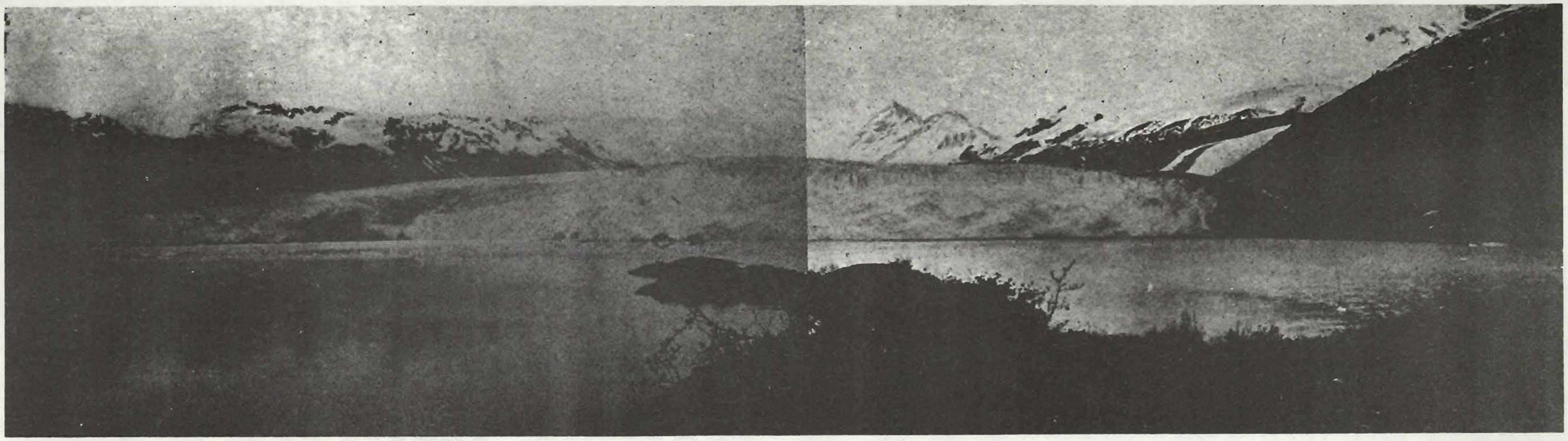
advancing stream. Its western front is of dead-white ice" (Tarr and Martin, 1914, p. 307).

The following year the Harriman expedition was at Yale Glacier. The map by Gannett, the description by Gilbert, and the photographs by other members of the group clearly show no change since the previous year. In explaining the dirty ice near the western margin, Gilbert made an interesting observation which has since been confirmed. He said, "A blackening, west of the middle, by glacial drift suggests that a rock knob may lie near the surface, ready to develop into a nunatak or island if the glacier shall diminish" (Gilbert, 1903, p. 83). A very large rock knob which has recently emerged can be seen in Figure 58.

The photographs (Figure 56), map, and descriptions by Grant and Higgins (1911, pp. 323-324) from the visits in 1905 and 1909 show that Yale Glacier had maintained essentially the same terminus position since 1898. In describing the trimlines, they said:

> At the time of our visit in 1909 there was a very narrow bare zone on each side of the glacier. On the east side the ice is separated from grass and alders by but a few rods of rock debris. Possibly these narrow bare areas are due to no more than the rapid melting away of the ice in the summer. Although the sides of the fiord are barren of trees they are clothed with a tangle of salmonberry bushes and alders up to the line where the scattering timber begins. This line is very distinct on each side of the fiord. It is practically horizontal at an elevation of 900 feet (estimated) and probably marks the lateral margin of the great ice stream which once occupied the entire fiord.

The nearness of the ice to vegetation led Grant and Higgins (1911, p. 324) to conclude: "The growth of a mature alder thicket close down to the ice indicates that the glacier front is now close to its maximum advance in a period of perhaps fifty or more years." Grant and Higgins (1911, p. 324) were the first to describe the



Panorama of Yale Glacier, 1909, from Point I
Photos 91 and 92 by D.F. Higgins

Panorama of Yale Glacier, 1931, from Point I
Photos f-31-343,344,345 by Wm. O. Field

Figure #56

irregularity of the front and to offer an explanation as to why it had been overlooked by previous workers: "Careful examination of the Harriman expedition photographs shows that the ice front was then probably as now. The irregular shape may have been overlooked in a rather cursory survey, for we have noticed that in a perspective view ice fronts are very deceiving and that a seemingly straight wall of ice often shows very unexpected variations when most closely examined."

In the following year, 1910, the National Geographic Society's expedition visited Yale Glacier (Tarr and Martin, 1914) and reported that the entire glacier was vigorously advancing. It was able to determine accurately 750 feet of forward movement of the eastern margin. A comparison of photographs showed that all of this advance took place between July 1, 1909, and July 15, 1910.

The only observer of record between 1910 and 1931 was Dora Keen (1915). One of her photos suggests that the eastern margin was no further advanced in 1914 than in 1910.

In 1931, Field (1932) found further advance, estimated to total a quarter of a mile since 1899, on the eastern side. Four years later, he (Field, 1937) estimated a further advance of about 200 feet, and found the glacier invading thick alders. An airphoto taken early in the season of 1937 by Bradford Washburn shows the whole length of the terminus in tidewater. The rocks that had been conspicuous since the first picture was taken in 1898 do not show on Washburn's photograph. Although this apparent terminus position may have been a seasonal condition, it does suggest that the glacier remained at a maximum until at least 1937.

In 1949, D. N. Brown (1950) reoccupied two photo stations at Yale Glacier. His pictures show that the earlier advance was over, and a retreat was clearly indicated by bare zones along the margins and especially by the size of the emerging rock near the center (Figure 57). An examination of airphotos taken by the United States Air Force in 1950, 1954, and 1957 shows that a slight advance took place on the eastern side and center of the glacier during that period.

The 1957 I. G. Y. party spent two days at Yale Glacier, occupying most of the existing photo stations and establishing two new ones. Distances from moraines to the ice were measured and botanical dating of the trimlines was carried out. The rocks near the center of the glacier were visible, but the advance since Brown's visit in 1949 had nearly covered them. Evidence of advance along the margins was lacking; in fact, stagnant, detached ice along the east valley wall indicated retreat.

The trimlines and moraine formed by the 1935-1937 advance were easily distinguishable, and the distance from the moraine to the terminus indicated a net frontal retreat of 2,100 feet. The height of the 1935 trimline at the 1957 terminus was about 300 feet, representing a considerable downmelting. The bare zone below the lower trimline had only a few non-woody plants, and appeared very fresh. The botanists dated the higher, older trimline in spruce trees at 1807-1827, and concluded that, prior to that time, the ice had not advanced further since at least 1650 A. D. The high trimline at Yale Glacier is evidence of an unusual event in this region--pronounced retreat of a trunk glacier long enough ago to

Panorama of Yale Glacier, 1935, from Point I
Photos f-35-466,467,468 by Wm. O. Field

Panorama of Yale Glacier, 1947, from Point I
Photos 88,89,90 by D.N. Brown

Figure #57

permit development of the alder thicket stage in the normal plant successional series. Only a few other glaciers in Prince William Sound have had such an early maximum and those glaciers that have experienced an early hochstand are located elsewhere than in the College Fiord area.

In 1961, the terminus of Yale Glacier was remapped for the first time since Tarr and Martin's work of 1910. All of the old photo stations were reoccupied (Figure 58) and three new ones set up in conjunction with the surveying. The ice had receded since 1957, particularly in the area between the emerging rock island and the eastern margin, where a prominent protruding point had become an embayment. The emerging rock was less covered than in 1957 but more covered than in 1949. A considerable lowering of the ice in the area just above the terminus suggested that the present retreat would continue. Ice along the margin showed little change.

The emerging rock cape near the center of the glacier serves as an interesting indicator of recent changes in the terminus. This rock, seen first in the pictures of Yale Glacier taken by Mendenhall in 1898, was nearly covered in 1909 and became progressively less visible until 1941 when the retreat began. By 1949 and 1950, the exposed rock was a rather large area which was again nearly covered during the mid 1950's, then again uncovered during the late 1950's and early 1960's. Net recession from 1935 to 1961 totals nearly 1,000 feet along the western margin, 2,000 feet along the eastern margin, and perhaps as much as 3,000 feet in the active ice cliff between the emerging rock cape and the eastern margin.

Panorama of Yale Glacier, 1957, from Point I
Photos mm-57-175,186,177 by M.T. Millett

Panorama of Yale Glacier, 1961, from Point I
Photos M-61-123,124,125 by M.T. Millett

Figure #58

This recent terminal recession is matched by the growth of the lateral barren zones along the east margin as the ice surface has lowered from the hochstand of 1935-1937. The vegetation trimline remained a conspicuous feature in 1961.

Summary

Yale Glacier has fluctuated considerably since it was first photographed in 1898 and initially mapped in 1910 (Figure 55). It was retreating or stationary from 1898 to 1909. It was advancing from 1910 until at least 1937. Following a considerable recession after 1937, another slight advance occurred between 1950 and 1957. Since 1957, a continuous retreat has been observed. Thus a possible maximum in 1910 or later was followed by a strong maximum in 1935-1937, and a minor one in the mid 1950's. Judging by the emerging rock cape, however, important minima occurred in about 1898 and 1950. By 1961, it was found that recession was underway again.

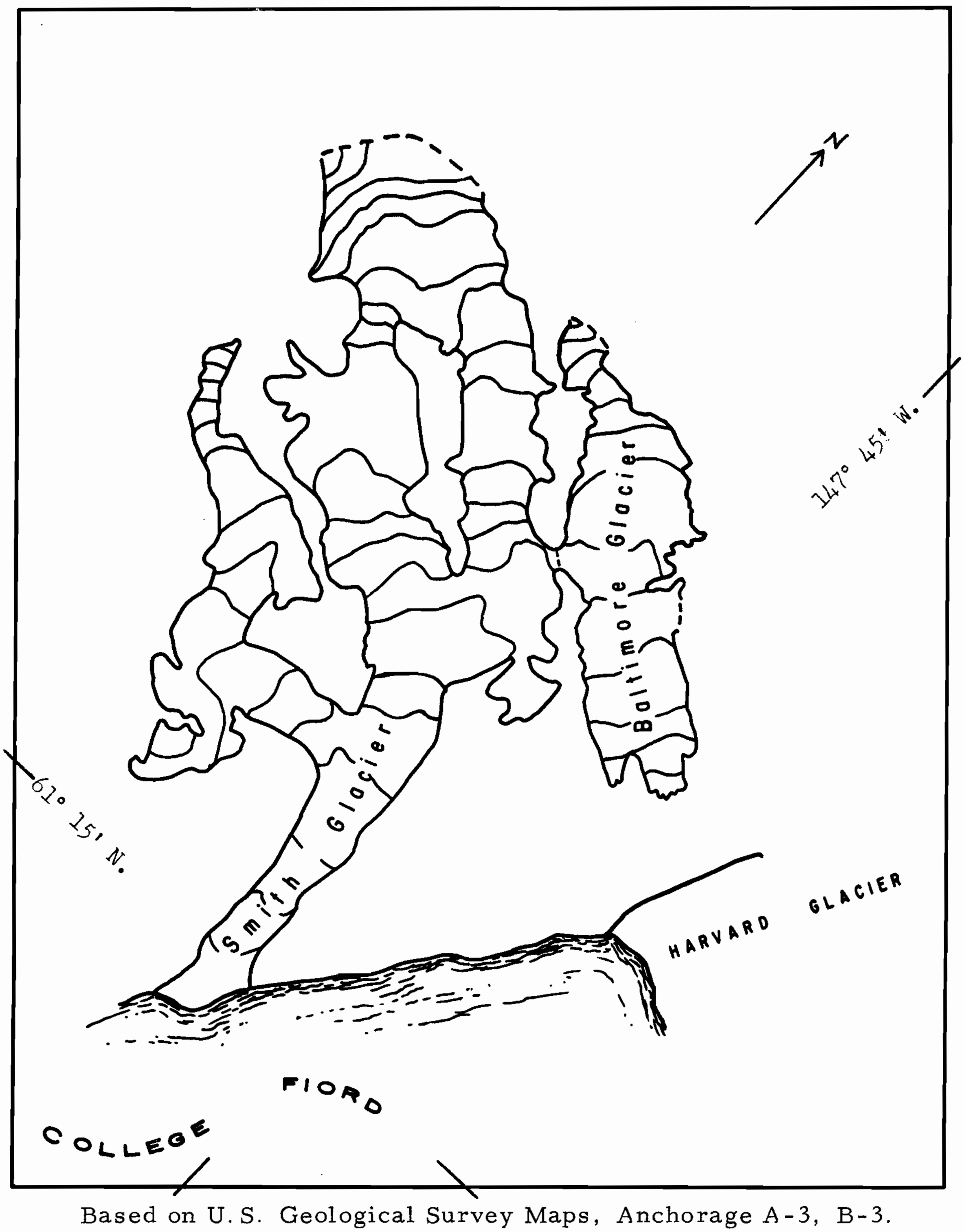
## Smith Glacier

Besides the two major glaciers, College Fiord has four secondary glaciers and several minor ones. The four secondary glaciers--Smith, Bryn Mawr, Vassar, and Wellesley--have received quite careful observation since their naming by the Harriman expedition in 1899.

Smith Glacier is located in the Harvard Arm of College Fiord, about 2-1/2 miles south of Harvard Glacier on the western side (Figure 52). It is 6 miles long and has an area of nearly 6-1/2 square miles (Figure 59). It originates high on a peak in the range that runs parallel to College Fiord, and descends from over 10,000 feet to sea level in magnificent cascades, terminating in a vertical tidal face. From its collecting area it swings sharply to the south and enters the fiord at approximately a 45° angle. In the lower part of its course, it has a very shallow valley, the surface of the ice being nearly flush with the face of the mountain. The entire surface, as far up as can be seen, is heavily crevassed and appears to be one giant icefall; but despite this broken surface, two medial moraines are distinctly visible. Along the southern margin is found a large lateral moraine, which expands near the terminus to cover nearly half the ice front.

The only information on the firn line position is from Dora Keen's observations (1915) on the nearby Harvard Glacier in August, 1914. At that time the firn line on Harvard was at about 3,000 feet elevation. Since these glaciers are just a few miles apart, it seems reasonable to assume that there would be no great difference in the firn line position from one to the other. With the firn line at 3,000 feet elevation, the area distribution curve (Figure 60) shows an accumulation area ratio of 0.800. The accumulation area is unusual, having two distinct peaks on the area distribution curve (Figure 60), with large accumulation areas found between 3,000 feet and 4,250 feet elevation and again between 5,250 and 6,000 feet elevation.

Smith Glacier was perhaps referred to by Whidbey in 1794 (Davidson, 1904) when he described the upper part of College Fiord. The glacier appeared on Applegate's map of 1887 (Davidson, 1904),



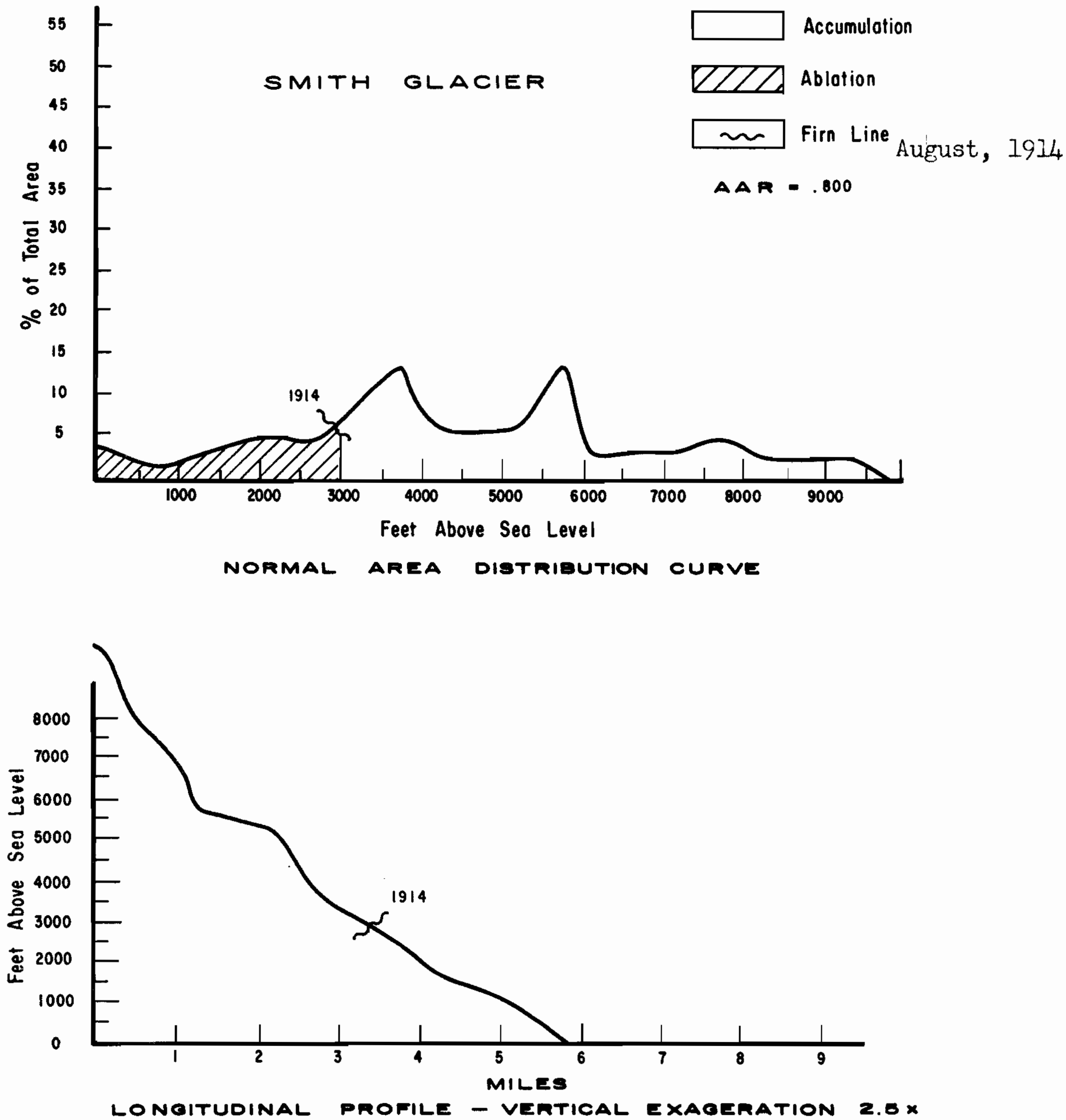

Based on U.S. Geological Survey Maps, Anchorage A-3, B-3.

MILES
0 1 2 3

Contour Interval 500 feet

SMITH GLACIER

Figure #59



SMITH GLACIER
Accumulation
Ablation
Firn Line
August, 1914
AAR = .800
% of Total Area
55
50
45
40
35
30
25
20
15
10
5
1914
1000
2000
3000
4000
5000
6000
7000
8000
9000
Feet Above Sea Level
NORMAL AREA DISTRIBUTION CURVE
Feet Above Sea Level
8000
7000
6000
5000
4000
3000
2000
1000
0
1914
1
2
3
4
5
6
7
8
9
MILES
LONGITUDINAL PROFILE — VERTICAL EXAGERATION 2.5 x


Figure #60

and he described it only as being a tidal glacier.

The ice stream received its name from the Harriman expedition of 1899 (Gilbert, 1903). Gilbert described it briefly as a tidal glacier of a magnitude similar to the Radcliffe.

In 1905 and 1909, Grant and coworkers (Grant and Higgins, 1911) were in College Fiord, but Smith Glacier was again only very generally described as a tidal glacier of similar character to Bryn Mawr Glacier.

In 1910, the National Geographic Society's expedition (Tarr and Martin, 1914) became the first to make a careful study of the terminus, and to date this remains the only party that has done more than photograph the glacier from the fiord. Tarr and Martin concluded that the description and the photographs made by the Harriman expedition showed that Smith Glacier had changed very little from 1899 to 1909. In July, 1910, Smith Glacier was actively advancing, apparently having commenced to do so since Grant's visit of the year before. It was impossible to tell exactly how much the tidal terminus of the glacier had moved forward since 1909, but there was undoubtedly an advance of several hundred feet. Upstream from the terminus, the ice was advancing into forest and destroying shrubs.

Photographs taken in 1914 by Dora Keen (1915) show that the advance continued at least until that year. How long this condition lasted is unknown; but in 1931, W. O. Field (1932, p. 379) estimated the position of the front to be the same as in 1899. He said:

> Smith Glacier advanced nearly 1,000 feet between 1899 and 1910. During the next four years there was a slight advance and a subsequent retreat followed after 1914 by another advance of considerable proportions. Since then a great retreat and general shrinkage has reduced the glacier to the condition of 1899.

Field visited the area again in 1935 (1937), and reported that Smith Glacier had not changed appreciably in volume or in the position of its terminus from 1931 to 1935. However, he did note that the lower course of the glacier was less moraine-covered and contained large areas of white, deeply-crevassed ice.

Airphotos taken by Bradford Washburn in 1937, and by the U. S. Army in 1941, and photos taken from the fiord by D. N. Brown in 1947 and 1949, suggest that Smith Glacier advanced slightly and became thicker during that period. Airphotos taken in 1950 by the U. S. Air Force, however, show that the glacier was then shrinking.

In 1957, the I. G. Y. party was in College Fiord. All existing photo stations were occupied for photography; and, in addition pictures were also taken from the fiord (Figure 61). A comparison of conditions with those shown in earlier photographs indicated that Smith Glacier was receding from a late 1940 maximum, and was in a position similar to that of 1935.

When this area was visited again in 1961, photographs were taken and comparisons made with earlier observations. Since 1957, recession had continued, exposing an area of bedrock under the northern margin of the terminus (Figure 61). Downmelting was obvious in the moraine-covered portion of the southern part of the front, the tidal area was considerably reduced, and only a small amount of ice was lost by calving.

Photographs of 1931 (Figure 61) show a large dirty patch on the south margin that extended a third of the way across the ice. This patch moved rapidly down the glacier, and by 1957 covered the southern part of the terminus.

Smith Glacier, 1931, from Point O College Fiord
Photo f-31-379 by Wm. O. Field

Smith Glacier, 1957, from Point O College Fiord
Photo M-57-SG172 by M.T. Millett

Smith Glacier, 1961, from Point O College Fiord
Photo M-61-117 by M.T. Millett

Figure #61

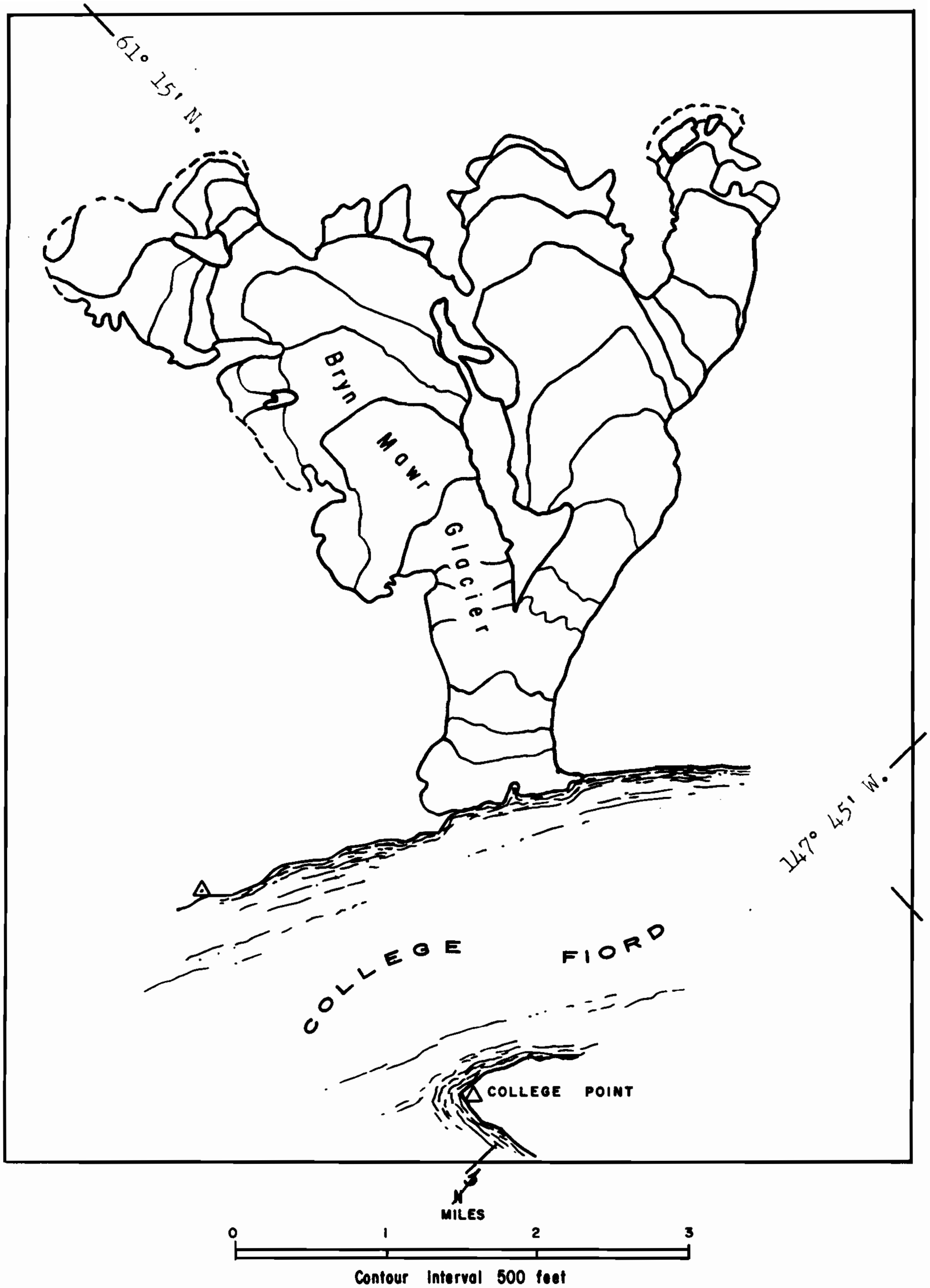
## Summary

Studies of terminus movement for Smith Glacier show that there was an advance sometime between 1914 and 1931 and another in the late 1940's or early 1950's. Retreat conditions were observed in 1899, 1931, and 1961.

## Bryn Mawr Glacier

Bryn Mawr Glacier is located 5 miles from the head of College Fiord on the western side (Figure 52). It is the largest of four cascading ice streams which descend to tidewater from the crest of the mountains west of College Fiord. It is 5-1/2 miles long and covers an area of 9 square miles (Figure 62). Its longitudinal profile (Figure 63) shows three distinct breaks, producing three large icefalls, and two areas of less steep gradient. One mile above the terminus the glacier is split into two arms of about equal size. A well-developed medial moraine extends from the junction of these tributaries to the sea. Lateral moraines along either margin are prominent, and along the northern side they cover a very large area. In the past, the tongue has been bulb-shaped; but, in 1957 it had a deep indentation in the center where there was a vertical tidal face. Along the margins of the terminus, the ice is aground and has a low-angled slope. Both marginal areas are heavily covered with ablation moraine.

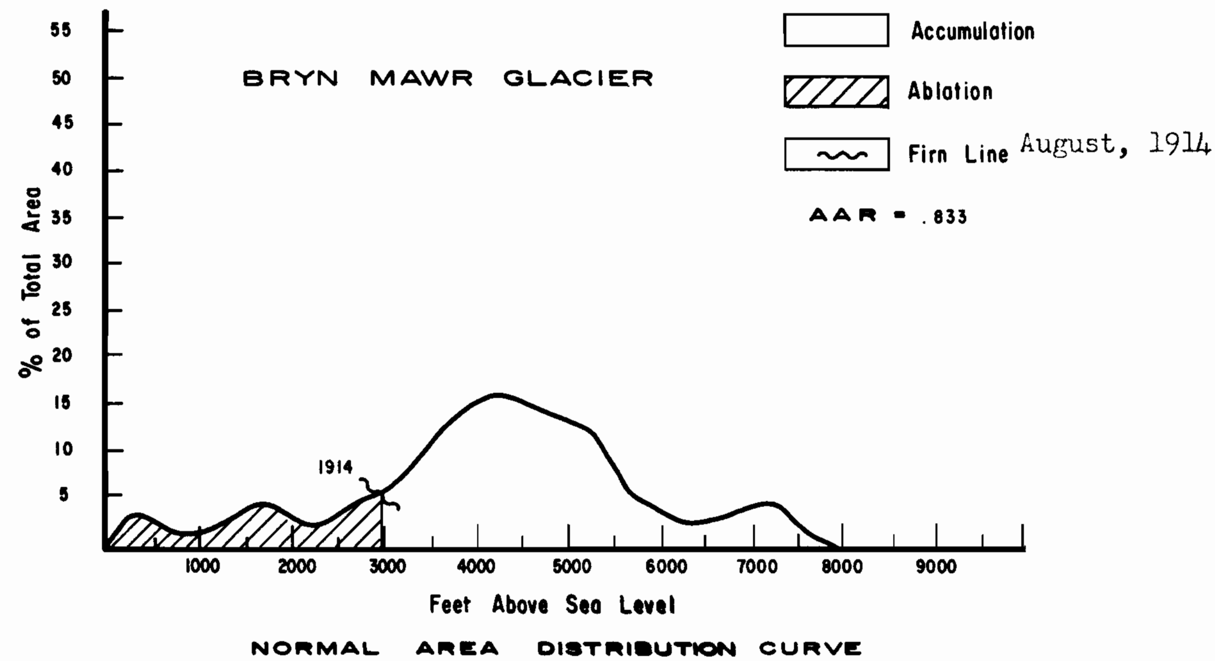
The best information on firn line elevations for this part of Prince William Sound dates from 1914 (Dora Keen, 1915), when it was observed that on the nearby Harvard Glacier the firn line elevation was around 3,000 feet. Airphotos of 1950 show it to be




Based on U.S. Geological Survey Maps, Anchorage A-3, B-3.

BRYN MAWR GLACIER

Figure #62


BRYN MAWR GLACIER
Accumulation
Ablation
Firn Line August, 1914
AAR = .833
% of Total Area
55
50
45
40
35
30
25
20
15
10
5
1914
1000
2000
3000
4000
5000
6000
7000
8000
9000
Feet Above Sea Level
NORMAL AREA DISTRIBUTION CURVE

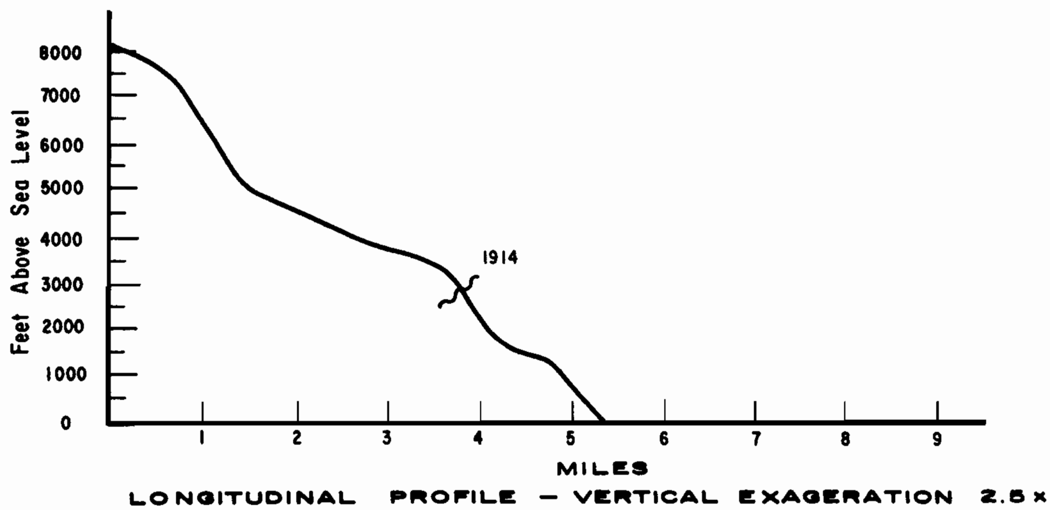

Feet Above Sea Level
8000
7000
6000
5000
4000
3000
2000
1000
0
1914
1
2
3
4
5
6
7
8
9
MILES
LONGITUDINAL PROFILE — VERTICAL EXAGERATION 2.5 x

Figure #63

around 2,700 feet elevation on Yale Glacier. Even using the higher of these two figures, the accumulation area ratio is still approximately 0.833. Most of the accumulation area is found between 3,500 and 5,500 feet elevation (Figure 63).

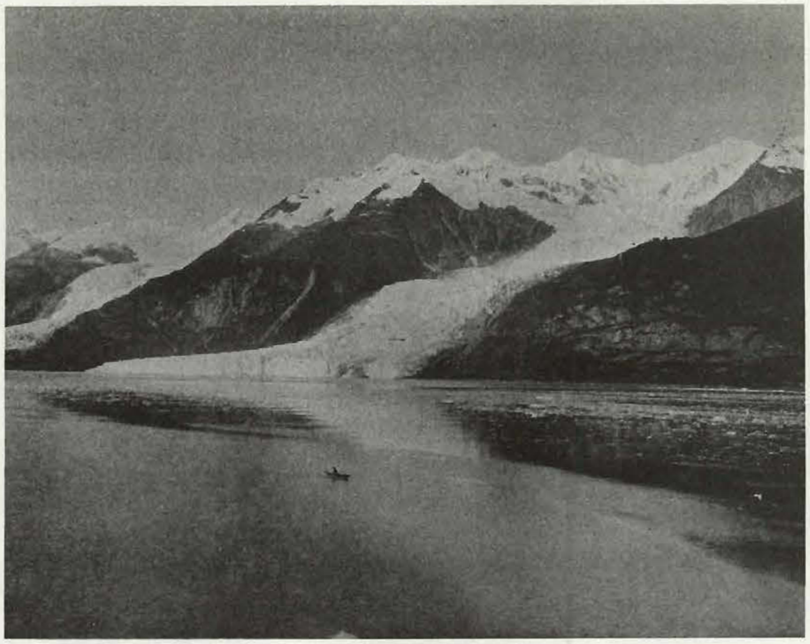
Bryn Mawr Glacier was first mentioned, though not by name, by Whidbey (Davidson, 1904, p. 25), who described College Fiord as "being full of ice bodies, some afloat, some on the ground near the shore in 10 to 12 fathoms of water." The only glacier identifiable from his account is Harvard, at the head of the bay. In 1887, Applegate remapped this fiord (Davidson, 1914, p. 29) and said:

> In the northwest part of the head are six glaciers coming down from the northwest directly upon the water, two of them feeding the main glacier.

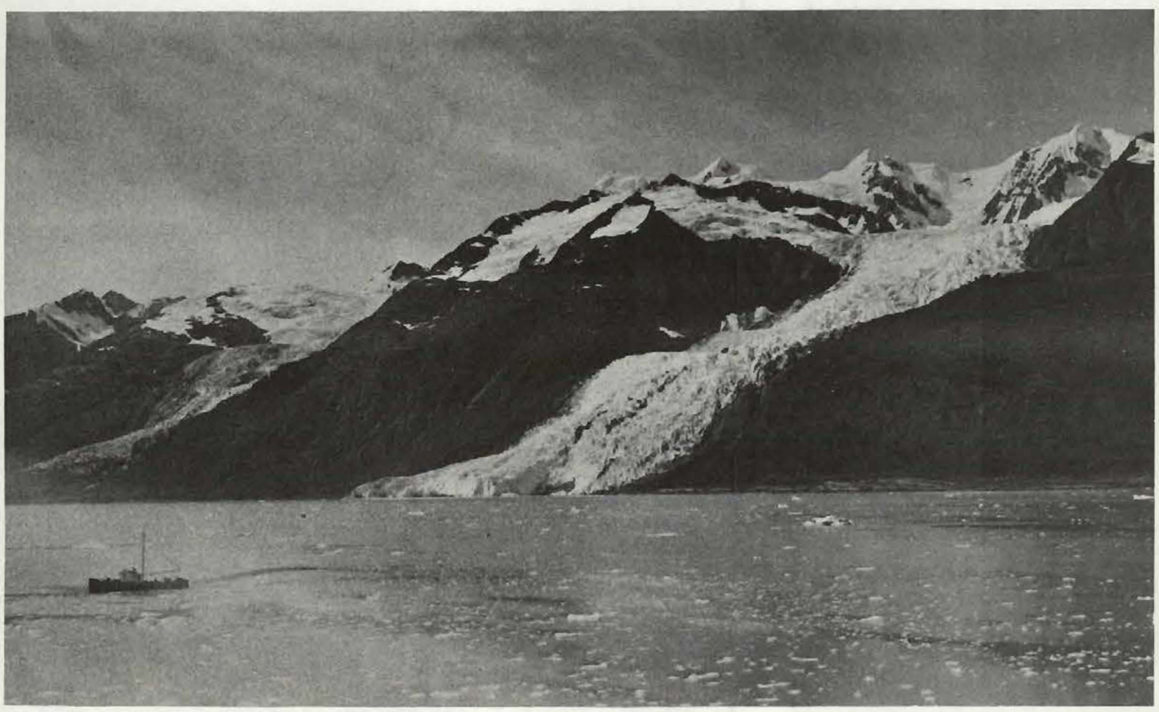
The Harriman expedition (Gilbert, 1904) photographed and named Bryn Mawr Glacier, but did not describe it.

The next description of Bryn Mawr was by Grant and Higgins (1911), who found that the Bryn Mawr Glacier was the largest and the most attractive of those on the western side of College Fiord. They described it as a veritable ice cascade. A comparison of the photographs taken in 1899 with those taken in 1909 indicated that the glacier was farther advanced in 1909, and that its front, especially the southern half, was deployed more widely on the shallow bottom of College Fiord. A photograph taken in 1905 (Figure 64) and an impression gained by these men four years later indicated that the glacier was less advanced at the earlier date, and that it was then at approximately the same position as in 1899.

In 1910, the National Geographic Society's expedition (1914), in describing Bryn Mawr Glacier, noted a considerable advance



Bryn Mawr Glacier, 1914, from Station K
Photo 223.4 by Dora Keen



Bryn Mawr Glacier, 1935, from Station K
Photo f-35-479 by Wm. O. Field

Figure #64

between July, 1909, and July, 1910. That there had also been pronounced forward movement was evident by comparing the conditions in July, 1910, with those shown in a photograph taken by the Harriman expedition in 1899. In this interval, the Bryn Mawr Glacier had advanced several hundred feet, most of the advance apparently taking place during 1910. All along its northern margin, the Bryn Mawr Glacier was advancing into forest, where it was killing spruce trees up to 5 inches in diameter; suggesting that the glacier had not been so extensive for a half century. The area on the southern margin was also being overridden by advancing ice. This area was part of a crescentic terminal moraine with knobs and basins built by the glacier at a time of much greater expansion. It had since grassed over and was partly covered with alders and spruce trees, some as much as 65 years old. It was concluded that it had been at least 65 years since the terminal moraine had been built.

Dora Keen reported in 1914 (1915) that Bryn Mawr Glacier was more advanced in that year than in 1910.

The gap occurring in the observations between 1914 and 1931 is unfortunate, because the duration of advance reported by Miss Keen is unknown. By 1931, the front had receded to its position of greatest retreat (Field, 1932). By 1935, Field (1937, pp. 73-74) reported:

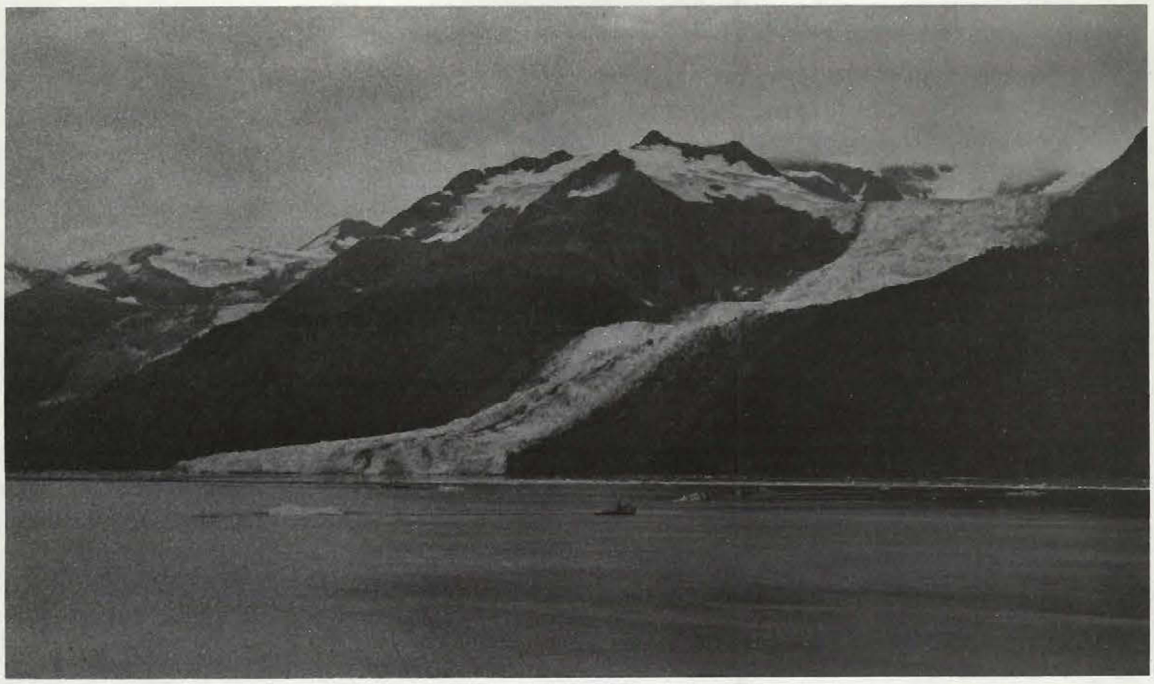
> Bryn Mawr Glacier advanced slightly and spread laterally between 1931 and 1935. The south margin of the terminus had pushed forward about 200 feet. A new feature not present in 1931 was an extensive cover of surface moraine on the north branch of the glacier which was undoubtedly the remains of an avalanche from one of the many oversteepened slopes above the upper part of the glacier. This debris had already been trans-

ported to the lip of the terminal cascade and was forming a new medial moraine.

This advance, however, did not last long. An airphoto taken in 1937 by Bradford Washburn shows the front somewhat less advanced than in 1935. A vigorous advance then began which is evident in airphotos taken in 1947 (U. S. Army) and 1950 (U. S. Air Force) and is corroborated by D. N. Brown's (1952) photographs taken in 1947 and 1949. The maximum advance seems to have occurred about 1950 when the front was slightly further forward than during the maximum between 1914 and 1931.

In 1957, the I. G. Y. party visited Bryn Mawr Glacier (Figures 64, 65, 66). Recession of the southern margin since 1935 was measured at 275 feet. The terminus was no longer bulb-shaped, but had a deep indentation in the center where a tidal face discharged small icebergs.

During this visit, vegetation on the moraines was dated and part of the recent history clarified. The advance observed in 1910 was invading vegetation of an age that suggested that a previous ice maximum had occurred in the early 1880's. In 1947 and 1949, advancing ice was again invading a stand of trees. End moraines of this advance were carefully studied, and evidence of two recent advances was found. The outer moraine was formed 5 to 10 years before or in the period of 1947 to 1952, while the inner moraine was probably under 5 years of age. A tree pushed over by the earlier advance was 86 years old at the point where it protruded from under the moraine, but it could have been much older. This dating by vegetation indicated that in 1950, the glacier was at its furthest advance since at least 1871.

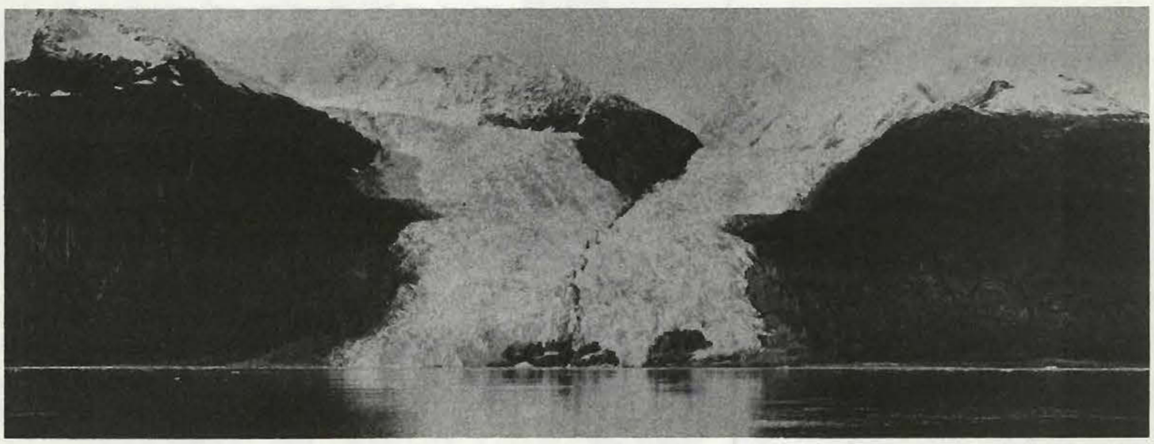


Bryn Mawr Glacier, 1957, from Station K
Photo M-57-SG166 by M.T. Millett

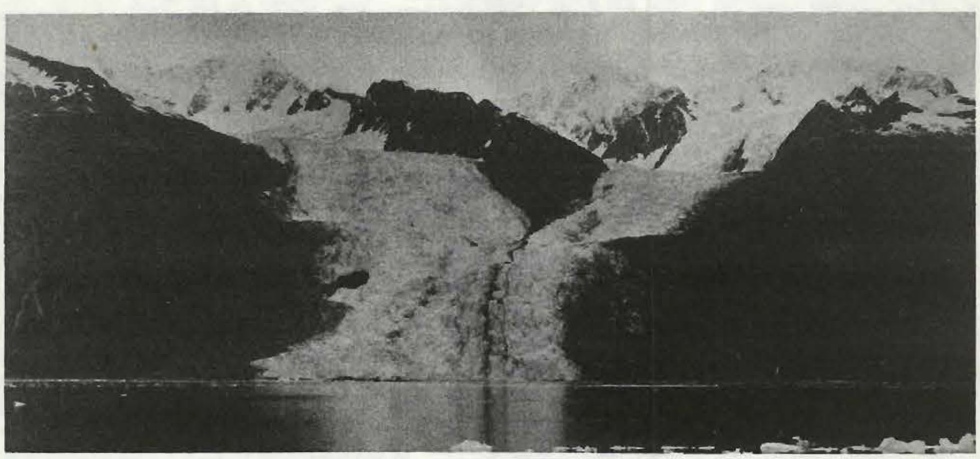
Bryn Mawr Glacier, 1961, from Station K
Photo M-61-116 by M.T. Millett

Figure #65

Bryn Mawr Glacier, 1914, from Point O College Fiord
Photo 223.8 by Dora Keen



Bryn Marw Glacier, 1931, from Point O College Fiord
Photo f-31-378 by Wm. O. Field



Bryn Mawr Glacier, 1961, from Point O College Fiord
Photo M-61-118 by M.T. Millett

Figure #66

In 1961, old photo stations were occupied and conditions were observed at the terminus. The front had continued to retreat, and considerable downmelting was observed in grounded areas on either side of the embayment. Above the terminus, thinning along the margins had exposed bedrock on the southern side, just below the first step (Figure 66). Rapid melting had left large blocks of moraine-covered ice isolated from the main body, and calving in the central part had made the embayment deeper.

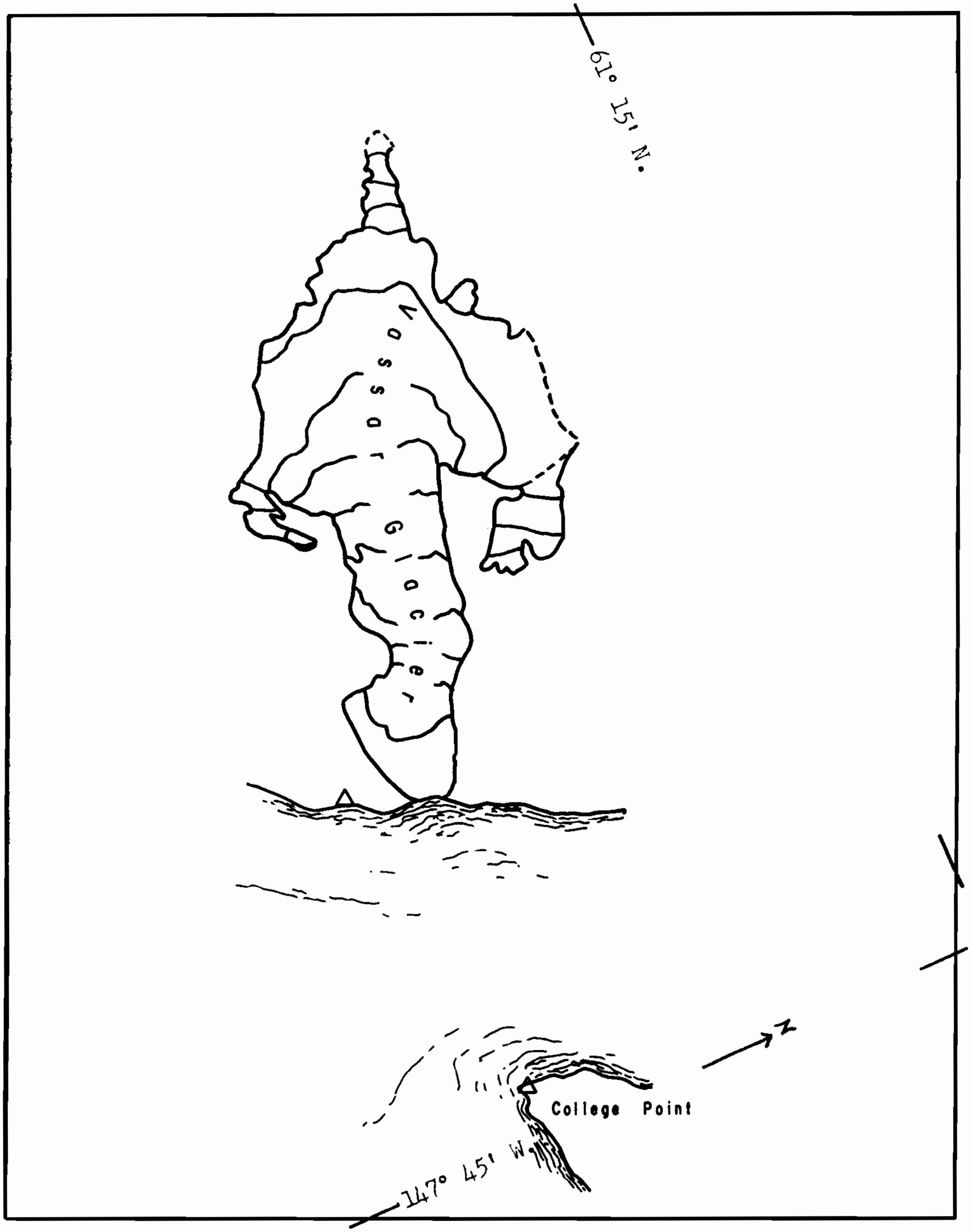
A feature of interest on the Bryn Mawr Glacier is a surface dirt patch similar to that noted on the Smith Glacier, which appeared on the second ice fall above the terminus in 1935 (Field, 1937) and has probably affected subsequent behavior of the glacier. This patch apparently resulted from an avalanche in the upper area of the north branch. The presence of the patch forms an interesting contrast to conditions up to 1931. Then the glacier surface on the lower two steps was free of moraine, except fo the prominent narrow medial moraine which issued from the junction of the north and south ice streams at the base of the second step. The large surface patch was not visible from the fiord in 1931, but by 1935 it covered three-quarters of the glacier surface on the second step, and a narrow tongue had reached the terminus. By 1941, it covered the northern part of the second step and almost the whole surface of the first step. By 1950, it had become an expanded northern lateral moraine occupying a third of the surface of the second step and over half of the first step. Virtually the same condition persisted in 1957, and in 1961 about half the northern ice stream of the first step was still covered. The movement down the glacier has been at a rate of about 1,000 feet per year, at the same time moving slowly toward the northern margin. As the patch approached the terminus, the movement downstream became slower and the movement across the surface became more rapid.

Summary

The recent history of the terminus shows that an advance occurred sometime between 1914 and 1931, but all physical evidence of this advance has been destroyed. Another advance occurred around 1950. The greatest retreat recorded to date was in 1931; however, the 1961 recession came near to the same point.

## Vassar Glacier

Vassar Glacier is the fourth ice tongue from the Harvard terminus on the western side of College Fiord. It is situated between Wellesley Glacier on the south and Bryn Mawr Glacier to the north, and is opposite College Point. This ice stream is over 5 miles in length with an area of 3.7 square miles (Figure 67). While it originates among mountain peaks 7,000 feet high, most of the accumulation area is between 3,500 and 5,000 feet elevation (Figure 68). The firn line is probably at the same elevation as that estimated for the other glaciers near the head of the fiord, about 3,000 feet. With the firn line at this elevation, the area distribution curve indicates an accumulation area ratio of 0.687. The terminus is heavily covered with ablation moraine, and the front has a very low-angled slope, which makes it difficult to determine the ice margins. In the past the glacier has been tidal, but now there is




Based on U. S. Geological Survey Map, Anchorage A-3.

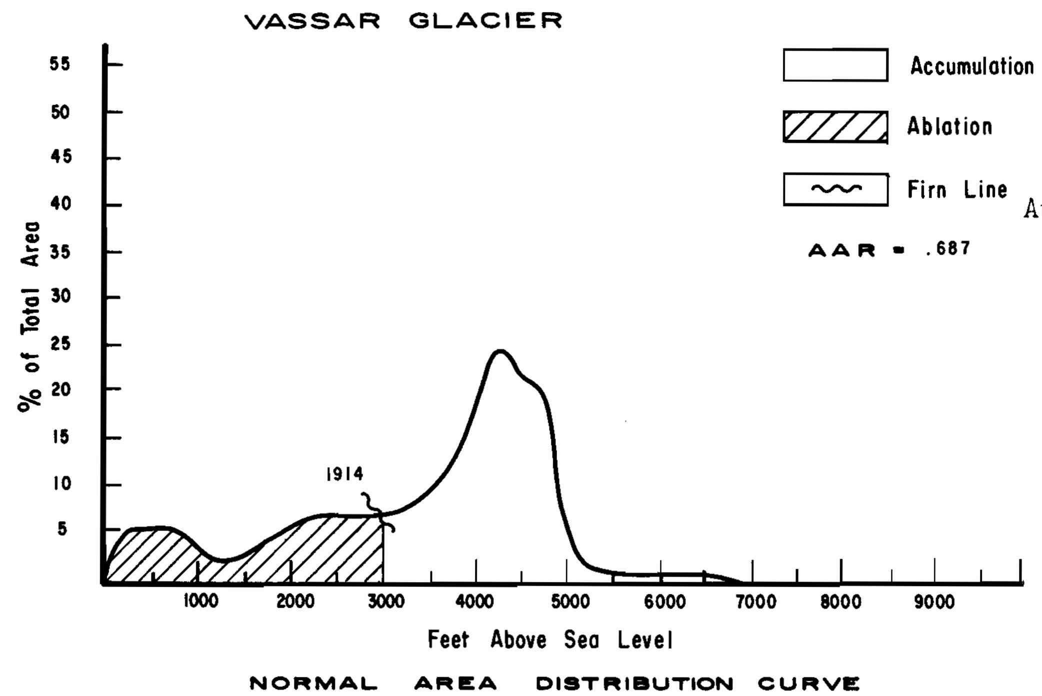
MILES

0 1 2 3

Contour Interval 500 feet

VASSAR GLACIER

Figure #67




August, 1914

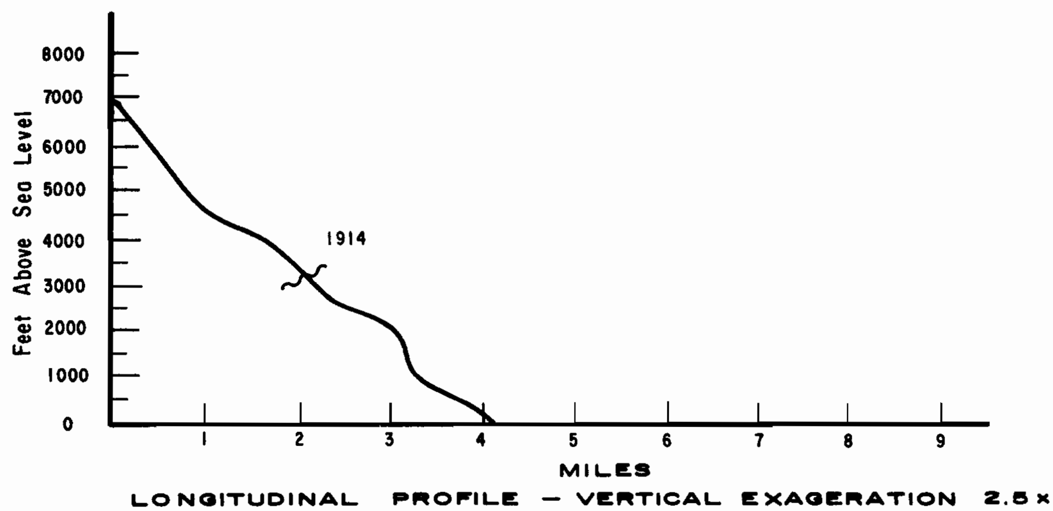



Figure #68

a several-hundred-yard-wide zone with a scattering of vegetation between the buried ice front and tidewater. The ablation moraine masking the terminus extends up the glacier, covering 3/4 of the surface to as far as can be seen. However, a narrow tongue of fairly clean ice along the northern margin descends to an elevation of about 500 feet.

All the observations of this glacier, except one, have been made at a distance and were primarily concerned with the extent of clean ice and the surface moraine cover. This distribution of clean and dirty ice is only a rough criterion of glacial behavior, but it is all that is available.

Vassar Glacier was alluded to by Whidbey (Davidson, 1904) in 1794, and by Applegate in 1887 (Davidson, 1904); but it was not described until 1899, when Gilbert (1903, p. 88) said:

> Next in the series comes the Vassar, parallel to the Smith and Bryn Mawr and exhibiting a similar series of cascades, but of smaller size and less direct in its course. It is cumbered, especially in its lower part, by rock debris, and close inspection was necessary to determine the fact that it was actually tidal.

In 1905 and in 1909, Grant and his colleagues (Grant and Higgins, 1911) visited College Fiord but did not describe Vassar Glacier specifically, though they did include it in a list of tidal glaciers and did show it roughly on their map.

In 1910, Tarr and Martin (1914) made a careful study of the terminal area. They observed that the whole of the lobate lower portion was mantled with thick ablation moraine, which extended up the southern margin of the cascading portion to a height of 1,100 feet, but which ended on the northern margin at an elevation of about 300 feet. In comparison with the other cascading glaciers, Vassar Glacier was the least attractive because the whole of its lower surface was dark and moraine-covered. In 1910, the tidal terminus of Vassar Glacier was not a perpendicular white cliff of clean ice, as was the case with the other tidal cascading glaciers; but it was a low-sloping margin, mantled with rock debris, and similar to the terminus of the Malaspina Glacier at Sitkagi Bluffs. As a result of the slight advance in progress in 1910, a part of the northern portion of the glacier was acquiring a more precipitous cliff and was shedding the debris mantle, revealing the ice in places. Even here, however, in contrast to the glistening white cliffs of the adjacent glaciers, the ice in sight was dirty and marked with wavy horizontal bands of englacial material. Few, if any, icebergs were discharged from this glacier. Conditions at the terminus were not essentially different from 1899 to 1910.

In 1914, Dora Keen (1915) found a further "slight advance" since 1910.

As with the other glaciers of College Fiord, no observations were made of Vassar Glacier between 1914 and 1931. In 1931, Field (1932) reported that Vassar had receded considerably and was perhaps in about the same condition as in 1899. In 1935 (1937, p. 74), he was again in the area and found that the moraine covered terminus of Vassar Glacier had shrunk slightly between 1931 and 1935.

Bradford Washburn's airphoto of 1937, and airphotos taken by the U. S. Armed Forces in 1941, 1947, and 1950, indicate that the glacier's activity at the terminus steadily diminished during those years.

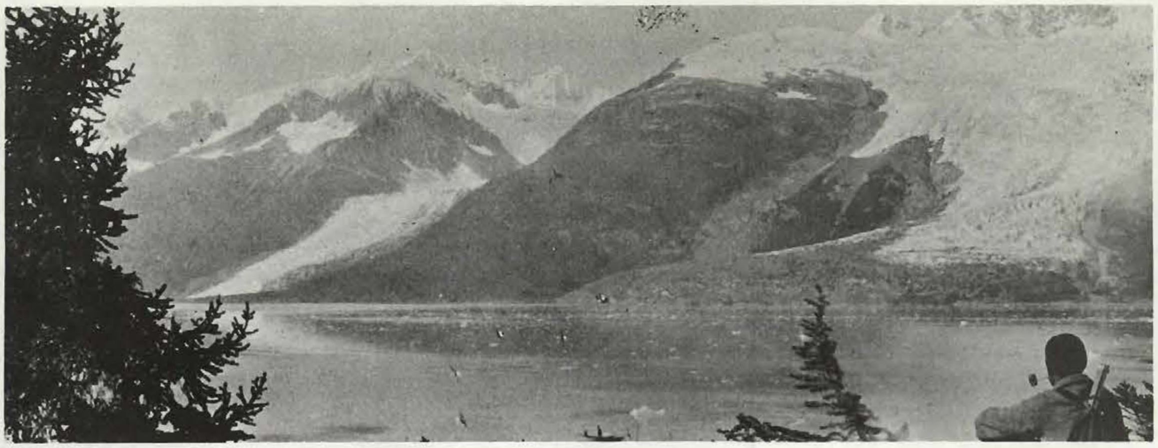
In 1957, a comparison of conditions with previous photos (Figure 69) indicated some increased activity since 1950. The ice was more crevassed and the clean tongue along the northern margin was larger and longer.

Conditions in 1961 were very similar to those in 1957.

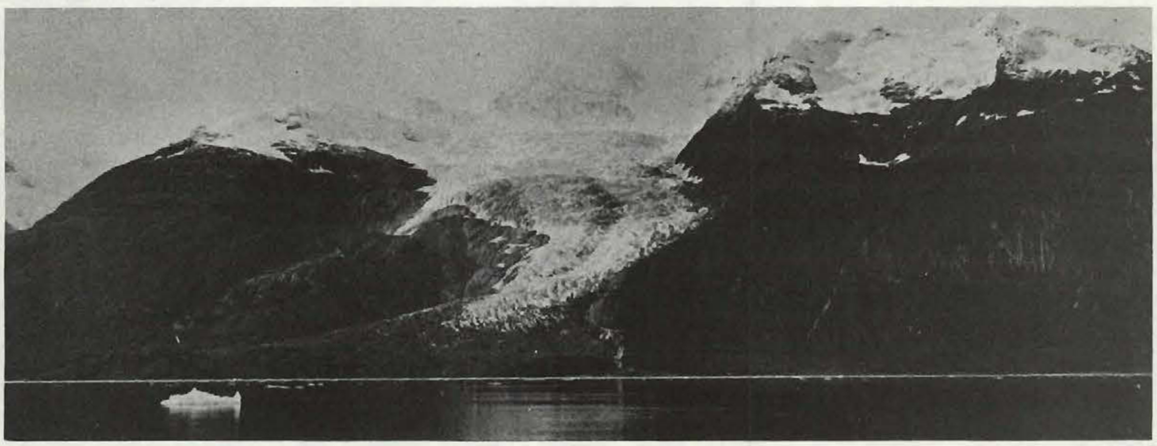
Since first described in 1899 (Gilbert, 1903), the terminal area has been heavily covered with ablation moraine. In the early photos this is shown covering only the bulb-shaped portion (Figure 64) and does not extend above 500 feet elevation. In 1931 and again in 1935, the ice stream above 500 feet was relatively clean, with only a narrow medial moraine present. By 1957, almost the entire glacier, as far as could be seen, was covered. The two glaciers to the north, Bryn Mawr and Smith, each have had a large moraine appear in the early 1930's which has moved to the terminus at varying speeds. The recent dirt cover of the upper Vassar is undoubtedly related to the cover found on Bryn Mawr and Smith and the avalanching, or whatever caused the debris on the other glaciers, occurred here as well. Its delay in appearing and its slow movement suggest a slower rate of flow for Vassar Glacier.

Summary

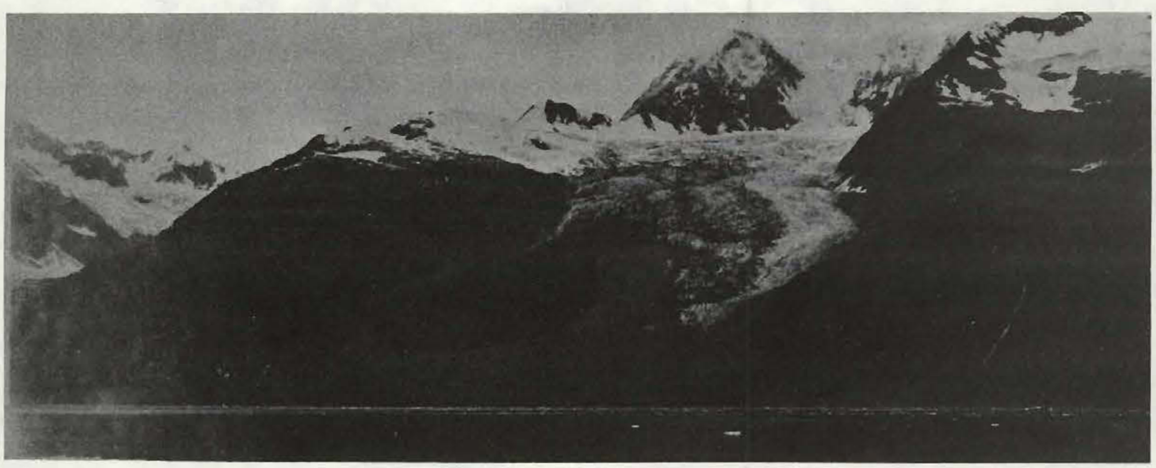
The general trend indicates that a maximum occurred in 1914 or later and that there was a minimum in about 1950. Since then a slight expansion of clean ice suggests renewed activity in the terminal area.



Vassar Glacier, 1914, from Point O
Photo 223.9 by Dora Keen



Vassar Glacier, 1931, from Point O
Photo f-31-377 by Wm. O. Field



Vassar Glacier, 1961, from Point O
Photo M-61-119 by M.T. Millett

Figure #69

## Wellesley Glacier

Wellesley Glacier is the fifth glacier from the Harvard, and is the last large ice stream along the western side of College Fiord (Figure 52). In size, shape, gradient, and orientation, (Figures 70, 71) Wellesley is much the same as the other three glaciers to the north. It is almost 4 miles long and covers 5.7 square miles. Wellesley is a tidal glacier that is located at the head of a shallow bay which is one-half mile long. An old terminal moraine at the edge of the fiord nearly encloses the bay entrance (Figure 70). A small bar almost midway in the terminus makes it appear that the front is in shallow water and during very low tides may be above water. The ice at the terminus is clean and has two small medial moraines just north of the center. The northern margin has a lateral moraine and the southern margin is clean. Distinct trimlines are obvious along either margin. Rocks extend along the water line from the northern margin one-third of the way across the ice front. Presuming the firn line to be at the same elevation as on Harvard Glacier (Keen, 1915), an accumulation area ratio of 0.750 is indicated (Figure 71). A rather large accumulation area is found between 3,500 feet and 5,200 feet elevation.

In 1899, Gilbert (1903, p. 88) named Wellesley Glacier and gave the earliest description of it:

> The Wellesley, last of the tidal series, flows with gentle grade through a mountain trough joining the fiord at right angles, and then cascades to the sea, into which it plunges without notable modification of profiles.

The account of Grant and Higgins (1911) only includes Wellesley in a listing of tidal glaciers. It is not shown on their map.


Based on U.S. Geological Survey Map, Anchorage A-3.

MILES

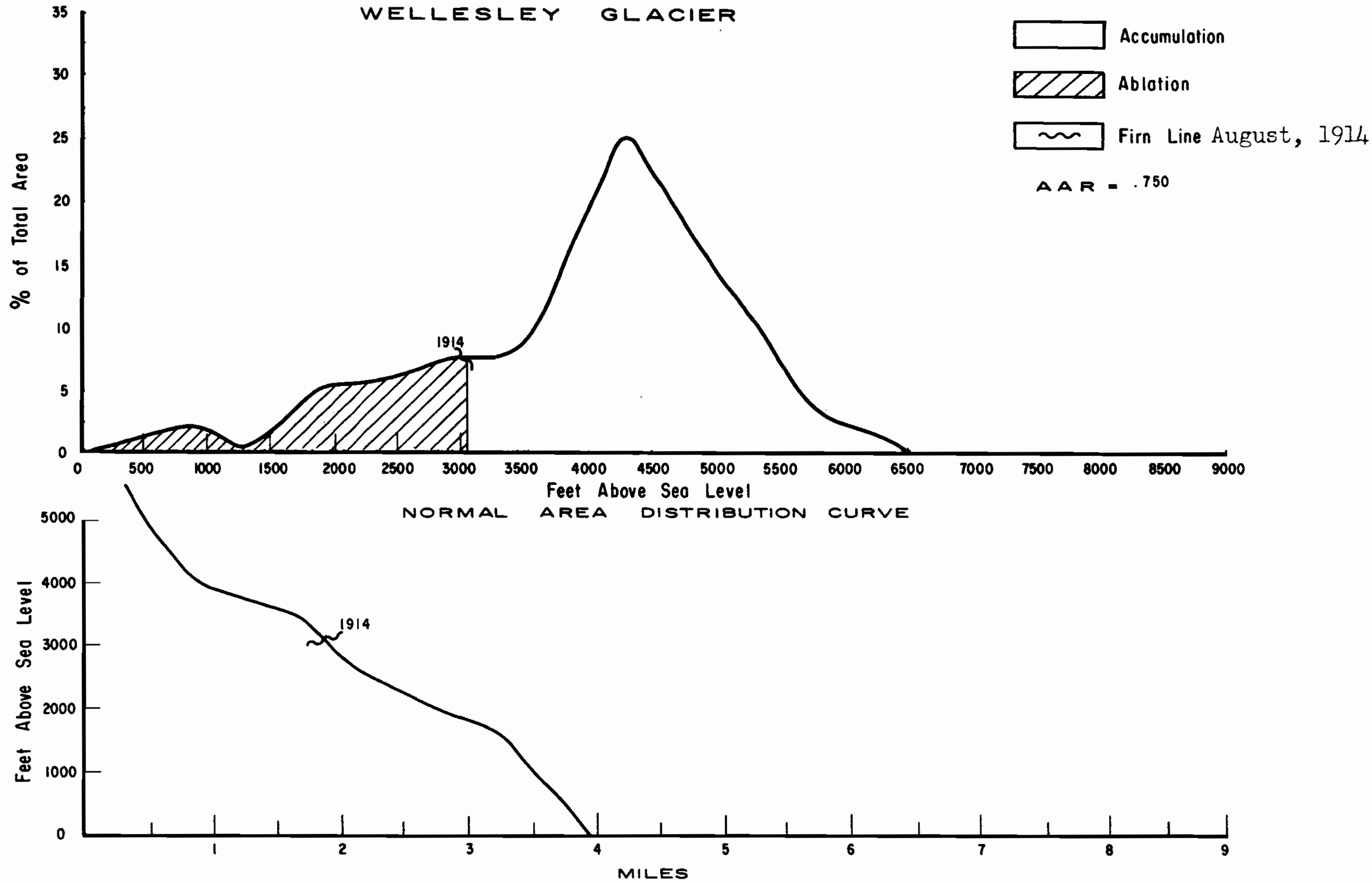
0 1 2 3

Contour Interval 500 feet

WELLESLEY GLACIER

Figure #70

Figure #71




NORMAL AREA DISTRIBUTION CURVE

LONGITUDINAL PROFILE - VERTICAL EXAGERATION 2.5x

In 1910, the National Geographic Society's expedition (Tarr and Martin, 1914) visited Wellesley Glacier and provides the only detailed description of the terminus. Tarr and Martin felt that it was evident that, not long ago, Wellesley Glacier extended at least three-fourths of a mile further, having then an appearance very much like that of Vassar Glacier. In retreating from this more advanced position, the glacier had left along the northern margin a narrow bare zone covered with water 21 to 129 feet in depth. Into this water a projection extended from the south side, marking the site of a former moraine. Although the glacier was in essentially the same position as in 1899, the glacier tongue in 1910 was actively advancing.

Dora Keen (1915) found the front had receded since 1910, and her photographs show the terminus more recessed and less active in appearance than any time before or since.

In 1931, W. O. Field (1937, p. 382) found a change in the trend of behavior:

> After the advance seen in 1909 and 1910 there was a pronounced retreat observed in 1914, and then another advance which by 1931 had thrust the ice front out beyond its position of 1910.

By 1935, he observed (1937, p. 74):

> Wellesley Glacier also expanded laterally between 1931 and 1935, but the position of the terminus has not changed.

Airphotos taken in 1941 and 1947 show little or no changes occurring in these years. However, photographs taken by D. N. Brown in 1949 show what appears to be a wider and more advanced terminus having greater activity. Nevertheless, the surface of the glacier, as seen in a side view, was not appreciably higher than it had been in the 1930's.

In 1957, Wellesley Glacier was observed and photographed (Figure 72), though only from a distance; however, there appeared to have been very little change since 1935.

In 1961, no changes were observed since the previous visit and the tongue was much the same as in 1935.

The terminal moraine that nearly closes off the entrance to the bay, and the morainic features along the sides of the bay indicate that Wellesley Glacier has recently been greater. Vegetation found within these moraines suggests that the recent maximum occurred during the 1890's. By 1899, the ice had receded leaving a conspicuous bare zone. A small advance occurred around 1910 followed by a strong retreat observed in 1914. By 1931, the ice was forward again, reaching a maximum around 1949. This hochstand has been followed by near equilibrium conditions since.

Summary

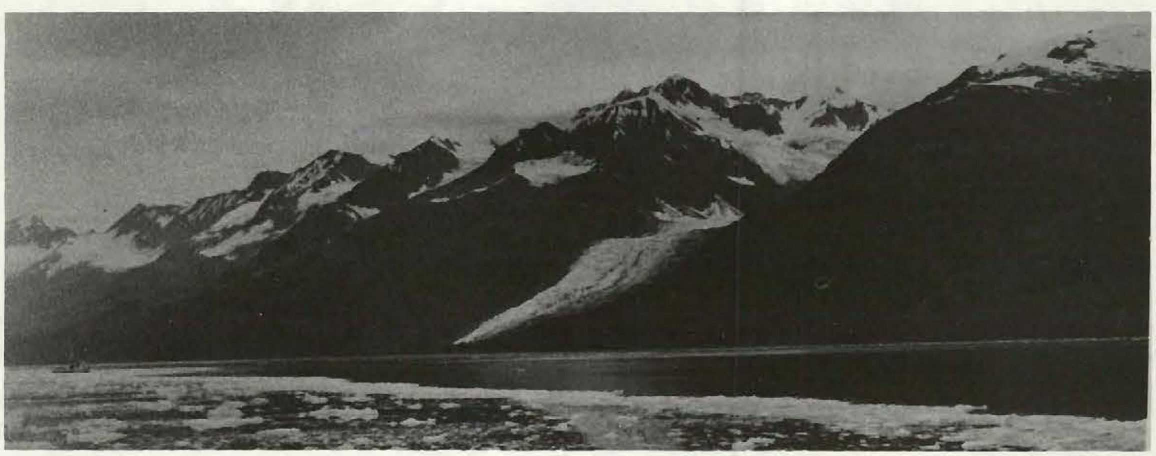
Since it was first photographed in 1899, this glacier has changed less than any other in College Fiord. A few minor fluctuations have been observed, but in general the glacier appears to be in near equilibrium condition.

## Holyoke and Barnard Glaciers

In addition to the larger glaciers in College Fiord, seven other glaciers have been named. These have received only casual mention by investigators. In all cases information is too scanty for trustworthy conclusions.

Wellesley Glacier, 1931, from Point O College Fiord
Photo f-31-376 by Wm. O. Field

Wellesley Glacier, 1957, from Point O College Fiord
Photo M-57-SG169 by M.T. Millett



Wellesley Glacier, 1961, from Point O College Fiord
Photo M-61-120 by M.T. Millett

Figure #72

On the western side of College Fiord, about twelve miles from Point Pakenham, there are two small glaciers, Holyoke and Bernard, that end at an elevation of 1, 400 feet and are over a mile inland from tidewater. These small ice tongues have been mentioned briefly by investigators, but have not been visited or surveyed. Minor fluctuations similar to those of the other steep cascading glaciers have been reported, but on a greatly reduced scale. Since the mid-thirties they have had a pattern of slow steady retreat.

## Baltimore Glacier

Baltimore Glacier is a small ice stream opposite the terminus of Harvard Glacier on the west side of College Fiord (Figure 52). It ends at an elevation of 1, 700 feet, over a mile from tidewater. All observations have been made from a distance, and data have been compiled primarily from a comparison of photographs. The U. S. Geological Survey maps (Anchorage B-2 and B-3), based on 1950 airphotos, show the size and extent of this glacier.

The history of this small glacier has been similar to that of the other steep glaciers along the west side of College Fiord, only on a reduced scale. Since 1935 it has been receding slowly.

## Downer Glacier

Directly opposite Baltimore Glacier, on the eastern side of the Harvard Glacier terminus, is Downer Glacier (Figure 52). This small tongue terminates at an elevation of 1, 700 feet, just over a mile in from tidewater. There have been no detailed observations, only those made from a distance. Since first observed, this small ice tongue has been steadily shrinking with no known interruption.

## Castner Glacier

Opposite the terminus of Yale Glacier, along the southwestern valley wall, is a small glacier sometimes known as Castner Glacier. This small tongue was formerly tributary to Yale Glacier and has been observed only from a distance. It is now over a mile back from the southwestern margin of the Yale terminus and is located in a small valley. Since the earliest observations, this tongue has been retreating slowly but steadily.

## Amherst and Crescent Glaciers

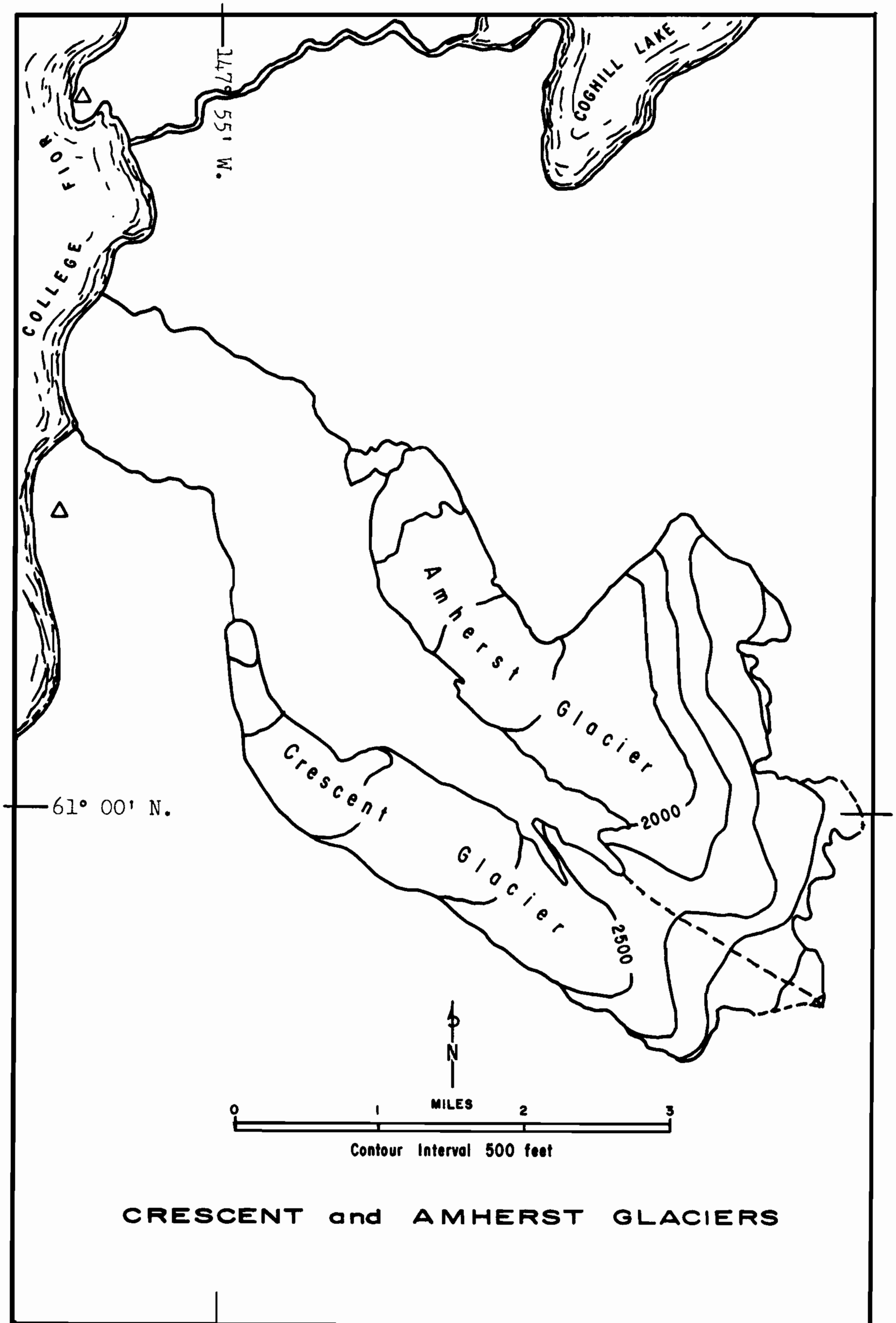
Near the mouth of College Fiord, along the eastern side and about four miles from Point Pakenham (Figure 52), are Amherst and Crescent Glaciers. Both descend from a common snow field, and move around either side of a long high ridge that separates their valleys. The termini of these two small glaciers are about two miles from tidewater at an elevation of less than 200 feet. Trees between the ice fronts and the fiord have obscured the position of the fronts from all previous investigators. These fronts were first visited in 1957 by the I. G. Y. party. Other workers only mention passing these glaciers on the way up the fiord to the main ice streams.

The 1957 party visited Crescent Glacier and built a rock cairn designated as station A. This cairn is on an 8-foot high moraine, 500 to 600 feet from the ice. There was no vegetation inside the moraine, and the age of the alders on and just outside of the moraine suggested that it was about ten years old.

The terminus of Amherst Glacier was seen from a ridge high above the terminus, but the front was not visited. A bare zone in front of the ice suggested a recent history similar to that of Crescent Glacier.

In 1962, the U. S. Geological Survey published maps (Anchorage A-3, Seward D-3) showing the size and extent of these glaciers in 1950 (Figure 73). In 1957, oblique photos taken by the U. S. Navy show the position of the firn line on these glaciers for July 30 of that year. Area distribution curves and profiles have been made from these maps and airphotos (Figures 74 and 75).

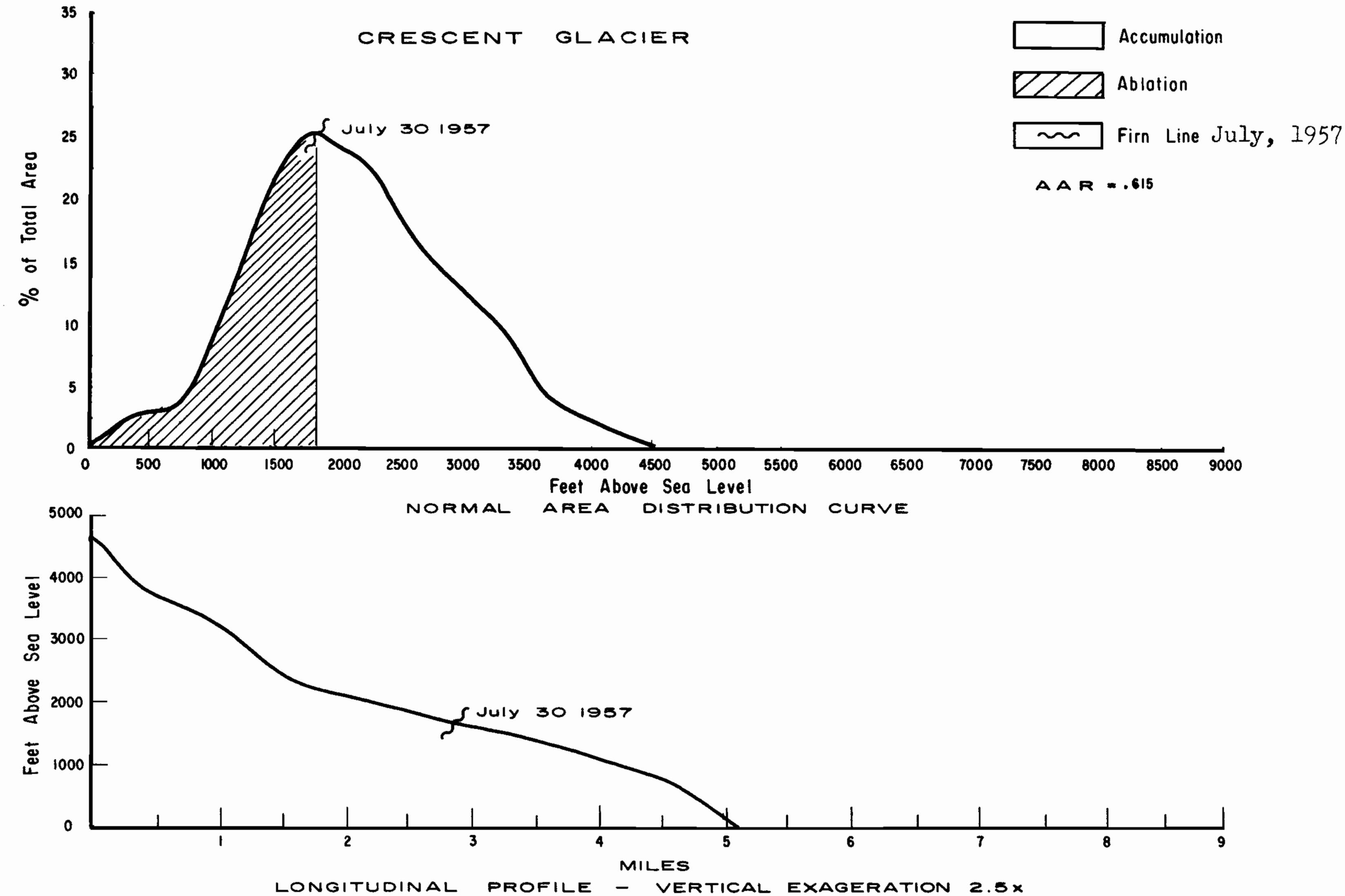
Northeast of these two glaciers are other small tongues that have received little or no attention from investigators.




Based on U.S. Geological Survey Maps, Anchorage A-3, Seward D-3

Figure #73

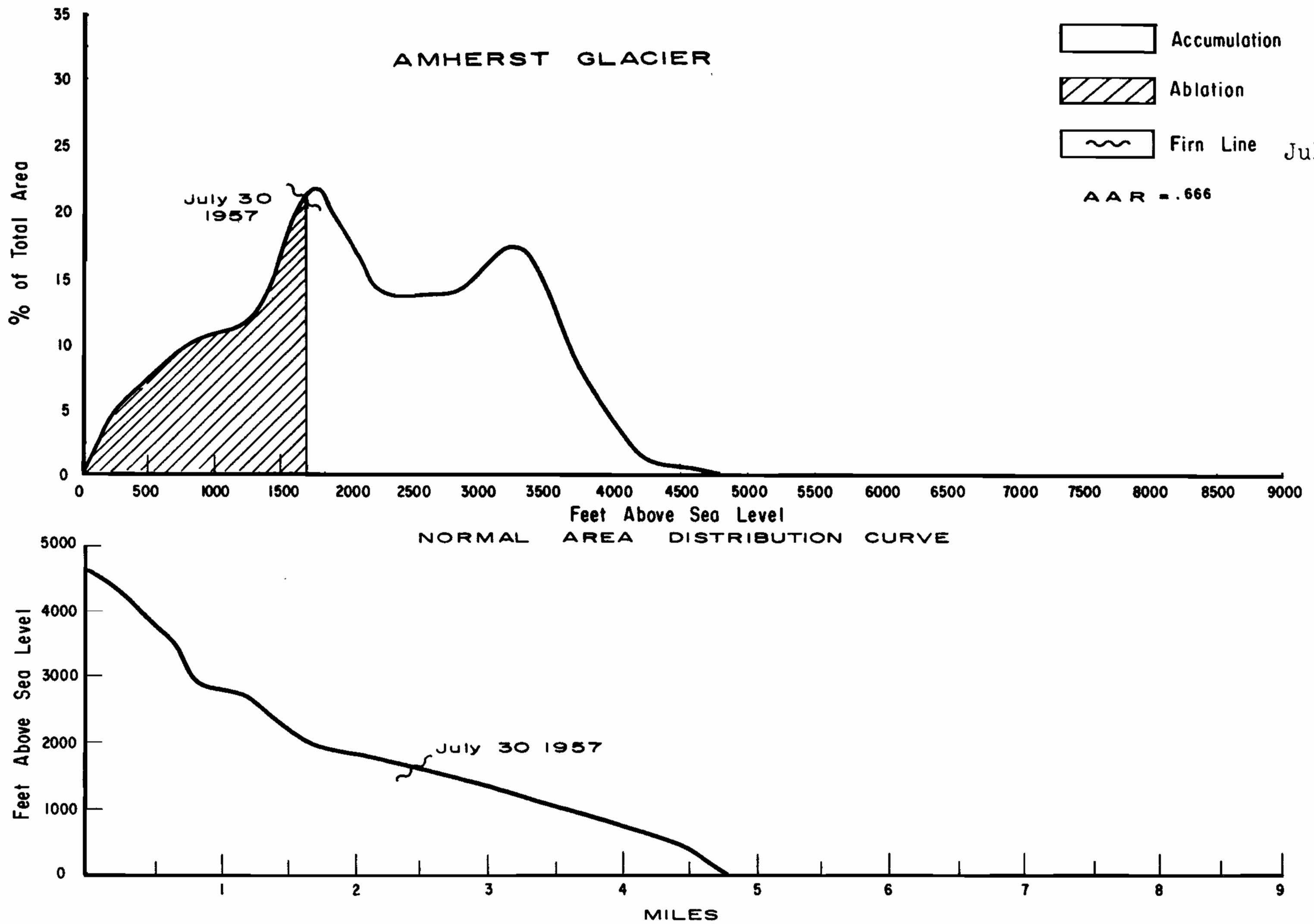
Figure #74



CRESCENT GLACIER
Accumulation
Ablation
Firn Line July, 1957
AAR =.615
July 30 1957
% of Total Area
Feet Above Sea Level
NORMAL AREA DISTRIBUTION CURVE
Feet Above Sea Level
July 30 1957
MILES
LONGITUDINAL PROFILE – VERTICAL EXAGERATION 2.5x

Figure #75

July, 1957



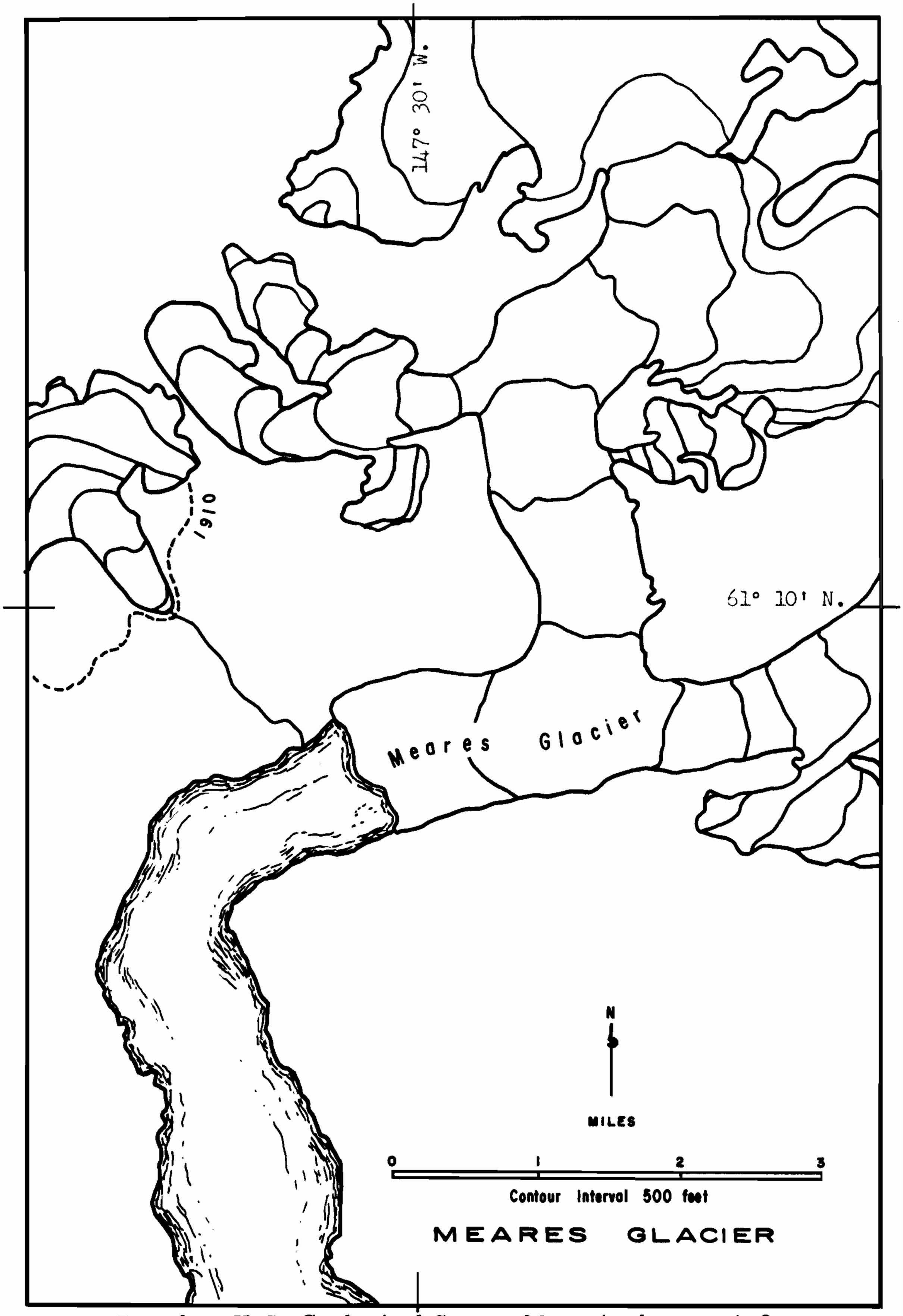

LONGITUDINAL PROFILE - VERTICAL EXAGERATION 2.5x

## Unakwik Inlet

Unakwik Inlet is located halfway between Port Wells and Columbia Bay in the north central part of Prince William Sound. It has one large tidal glacier, Meares Glacier; though there are also two small glaciers high up on the valley walls (Figure 76A). Only the Meares Glacier has been surveyed and carefully described. However, a partial history of the smaller glaciers can be pieced together by studying comparative photographs.

### Meares Glacier

Meares Glacier is located at the head of Unakwik Inlet, filling the head of the inlet with a vertical front that terminates in deep water. The front itself is a mile wide and just over 200 feet high, and the surface above the front is heavily crevassed and calving of ice occurs regularly. The inlet below the glacier is long and narrow and is frequently impassable because of floating ice discharged from the glacier. The ice is clean except for lateral moraines along either side and a medial moraine located near the southern margin. Two miles above the terminus, the main stream makes a $90^{o}$ turn to the north. A tributary from the east enters the main glacier at this bend, and its northern lateral moraine forms the medial moraine along the southern margin of the main trunk. The length and area of Meares Glacier are unknown, its head being in an unmapped area near Mt. Witherspoon. A forest of mature spruce trees is found along the shores of the inlet, and large trees extend right up to the edge of the ice.




Based on U.S. Geological Survey Map, Anchorage A-2

Figure #76A

The earliest account of Meares Glacier is by Fidalgo (Davidson, 1904), who visited the inlet in 1790. Don Francisco Eliza, a commander of the expedition, referred to the glacier as "Volcan De Fidalgo" because of the thundering noises they heard. When they approached the glacier, they saw that these noises were produced by large masses of ice falling from the glacier front.

In 1794, Lieutenant Whidbey (Vancouver, 1801) visited Unakwik Inlet and described its length and location. He also noted that the upper part of the inlet was filled with floating ice. Although Whidbey probably did not see the glacier itself, the presence of floating ice indicates that Meares Glacier was tidal in 1794.

In 1898, Captain E. F. Glenn (1899, p. 24) visited Unakwik Inlet and wrote:

> When we arrived at the head of this inlet we found it divided into two arms, both of which were frozen over. . . . We were unable therefore. . . to examine the glaciers that lay at the head of the two arms.

Meares Glacier was not visited again until 1905 when Grant (Grant and Higgins, 1911) was in Unakwik Inlet, and again in 1909 when Grant and Higgins (1911) photographed, surveyed, and named the ice stream. They described the ice front as being four-fifths of a mile wide and at least 300 feet high. In 1905, the bushes and trees were close to the ice and there was no bare zone visible between the ice and the forest. In 1909, the front of the ice seemed to be a little in advance of its position of four years before. Close to the glacier there was a sparse forest which contained trees estimated to be 10 inches in diameter. Hence the ice was probably as far forward in 1909 as it had been during the last 100 years or more. Their photograph, map, and description show that the second arm of the inlet described by Glenn no longer existed; instead, the head of the inlet was occupied by a glacier made up of two ice streams which joined a mile and a half above the terminus. The fact that there was a single front suggests a vigorous advance between 1898 and 1905 causing these two streams to coalesce and move down the fiord one and a half miles.

In the following year, 1910, the National Geographic Society's expedition was in Unakwik Inlet and described Meares Glacier as being slightly advanced since 1909 (Tarr and Martin, 1914).

W. O. Field (1932) visited Meares Glacier in 1931, and in discussing its activity said that the advance seemed to have continued steadily and that the ice was within a few feet of mature trees, showing that the glacier had not been farther forward for more than a century.

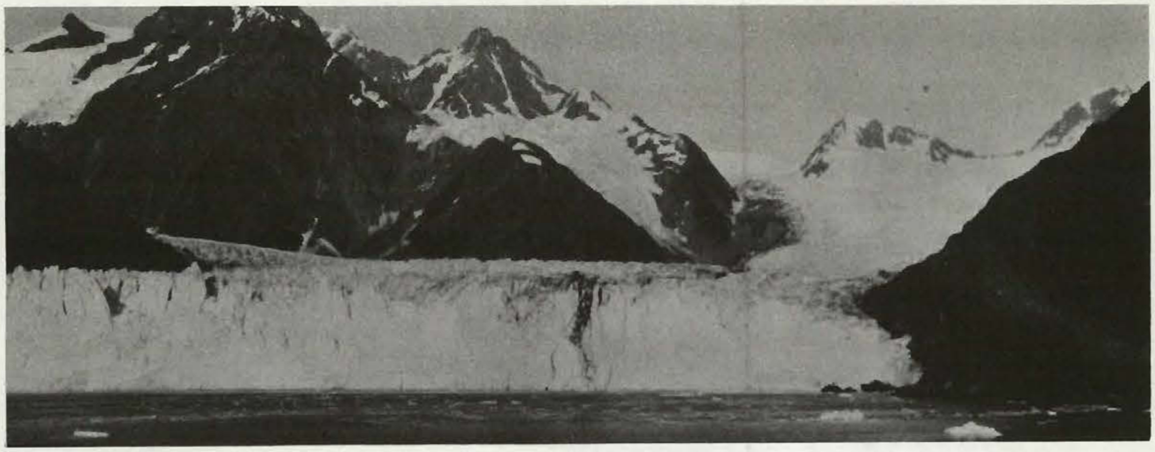
Field again visited Meares Glacier in 1935 (1937) and reported the terminus position as unchanged from 1931 to 1935. William S. Cooper (1942, pp. 10-11) accompanied Field in 1935, and his study of the vegetation led him to conclude:

> If one is to accept Glenn's rather circumstantial account, coalescence of two ice streams into one and advance of two miles occurred between 1898 and 1905. This is not in itself unreasonable, but the subsequent behavior does not agree with that of other Alaskan glaciers that have made sudden advances which almost immediately begin a slow but definite recession. Recent cessation of advance may, however, be preparatory to a phase of shrinkage, and the future history of the glacier will be watched with interest. . . . The forest evidence proves that the ice is as far advanced as it has been for centuries; the wedge of super-glacial forest suggests destruction of vegetation below it by advancing ice. If Glenn's account may be trusted, much of this happened between 1898 and 1905. A careful examination of the ice-forest contact should throw light on the problem.

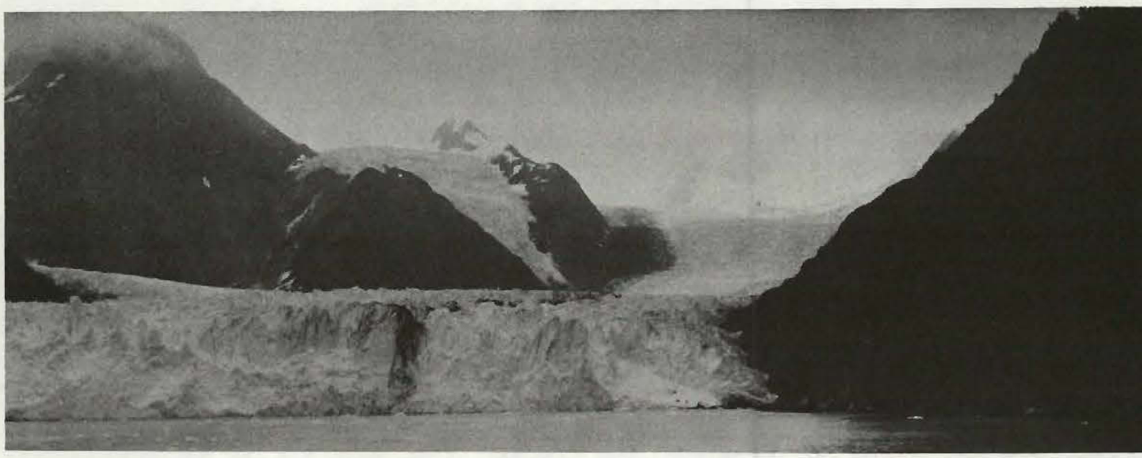
Photographs (Figure 76) taken by D. N. Brown (1952) in 1950 show that Meares Glacier has continued to advance since 1935. In 1954, the United States Air Force took vertical airphotos of Meares Glacier, and these show that the advance through mature vegetation was continuing.

In 1957, the I. G. Y. group spent a day at Meares Glacier photographing, surveying, and studying the vegetation and the terminus (Figures 77, 78 and 79). The ice had continued its advance since last observed and was near its greatest advance in several centuries. Mature spruce trees adjacent to the ice were found to have as many as 280 annual growth rings. The northern margin was in contact with mature trees, but 100 feet south near the shoreline the ice was back of a recently cleared zone about 35 feet wide. Pioneer vegetation was established in this zone, suggesting that the ice had retreated from this small area about five years earlier. Along the southern margin a tongue of ice extended along the rocky bank nearly 200 feet ahead of the main ice front.

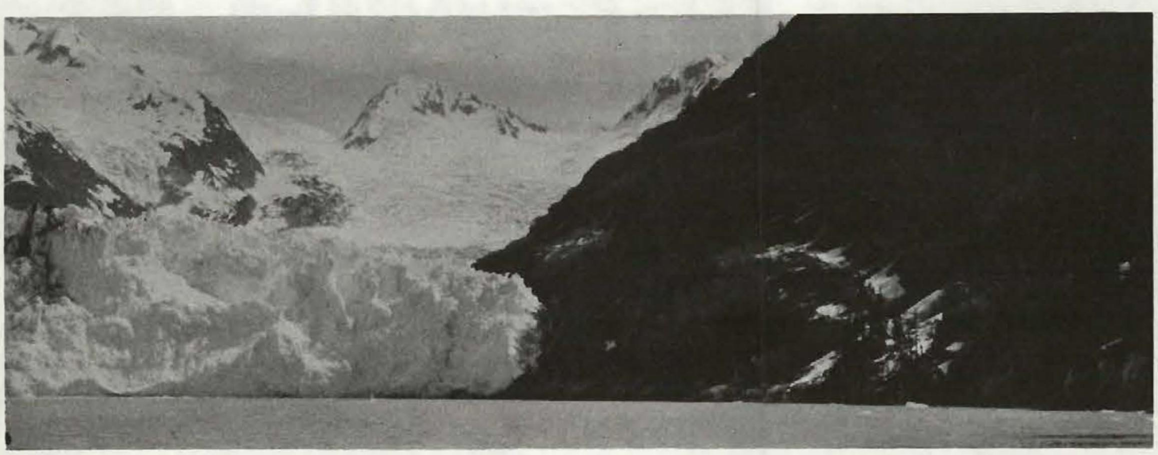
In 1961, Meares Glacier was visited again and was found to be substantially unchanged since 1957, except that the previous pattern of steady advance was offset by a small retreat along the entire front (Figure 77A). The ice at the north margin had withdrawn somewhat from the forest and was 50 to 100 feet from its most advanced position. Along the rock bluff forming the northern shore of the inlet, the terminus had receded nearly 250 feet. Along the southern margin recession was minor, amounting to less than 50 feet. This slight recession, however, may only be temporary since almost the entire terminus was thicker, and the main ice



Meares Glacier, south margin, 1931, from Station F (1)
Photo f-31-298 by Wm. O. Field

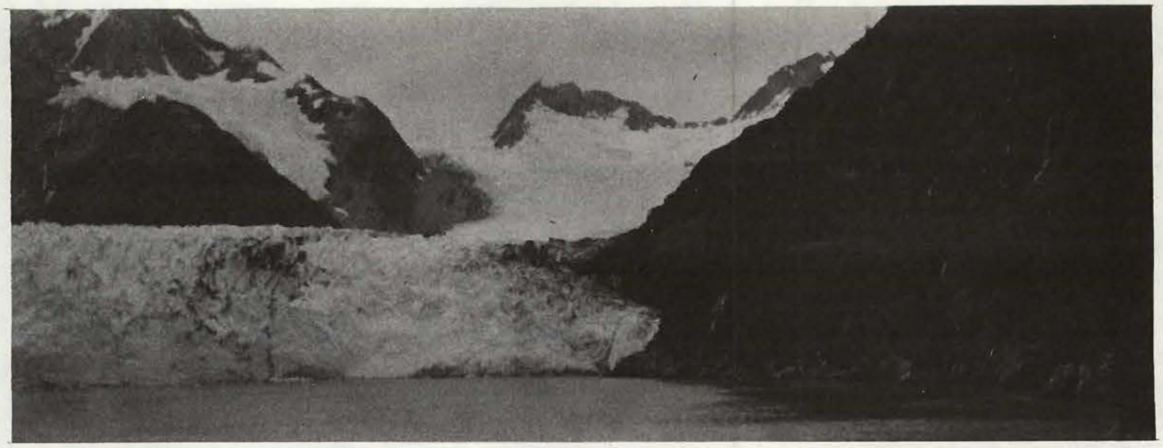


Meares Glacier, south margin, 1935, from Station F (1)
Photo f-35-454 by Wm. O. Field



Meares Glacier, south margin, 1949, from Station F (1)
Photo 132 by D.N. Brown

Figure #76

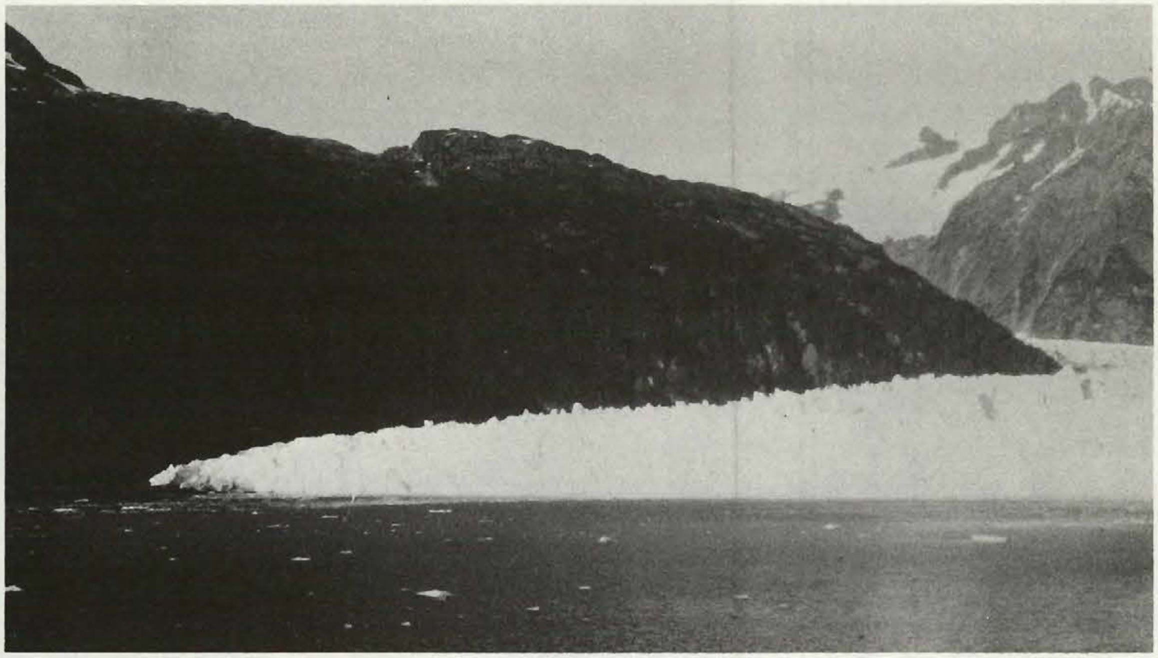


Meares Glacier, south margin, 1957, from Station F (1)
Photo M-57-SG187 by M.T. Millett

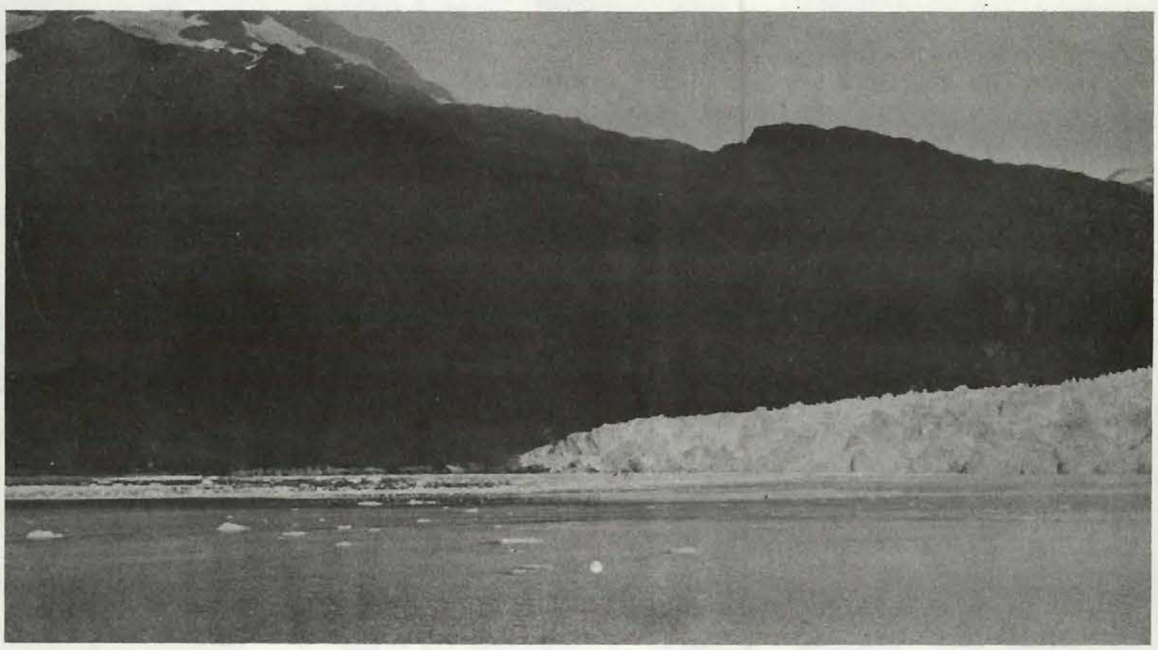
Meares Glacier, south margin, 1961, from Station F (1)
Photo M-61-91 by M.T. Millett

Meares Glacier, north margin, with ice adjacent to old trees, 1957. Photo f-57-R216 by W. O. Field

Figure #77

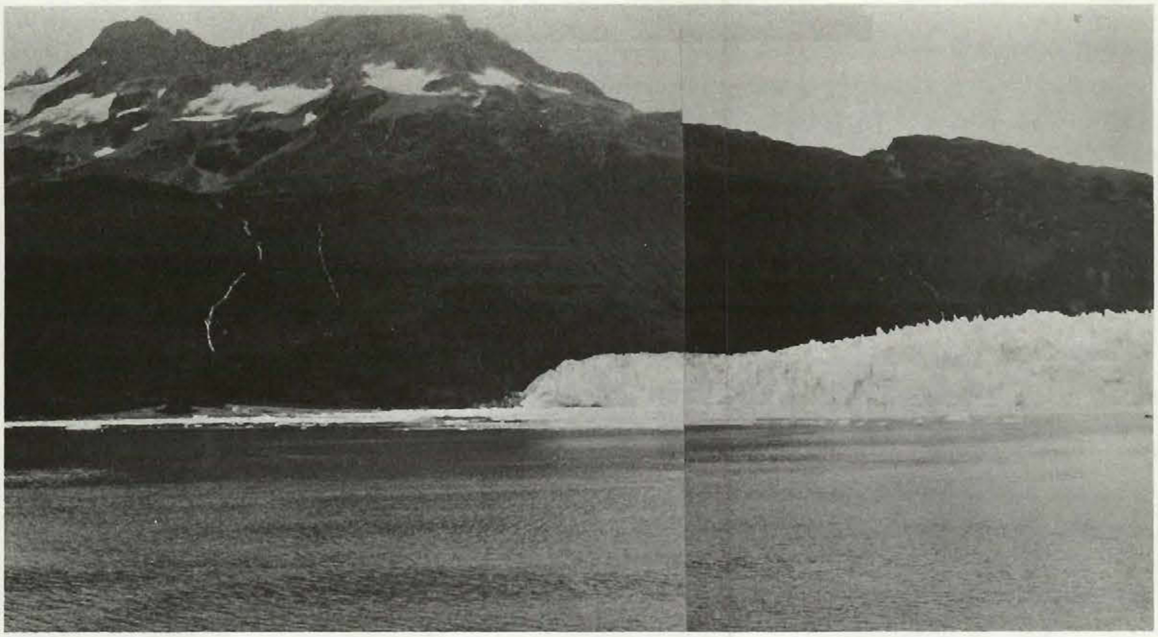


Meares Glacier, north margin, 1931, from Station F (1)
Photo #f-31-297 by Wm. O. Field

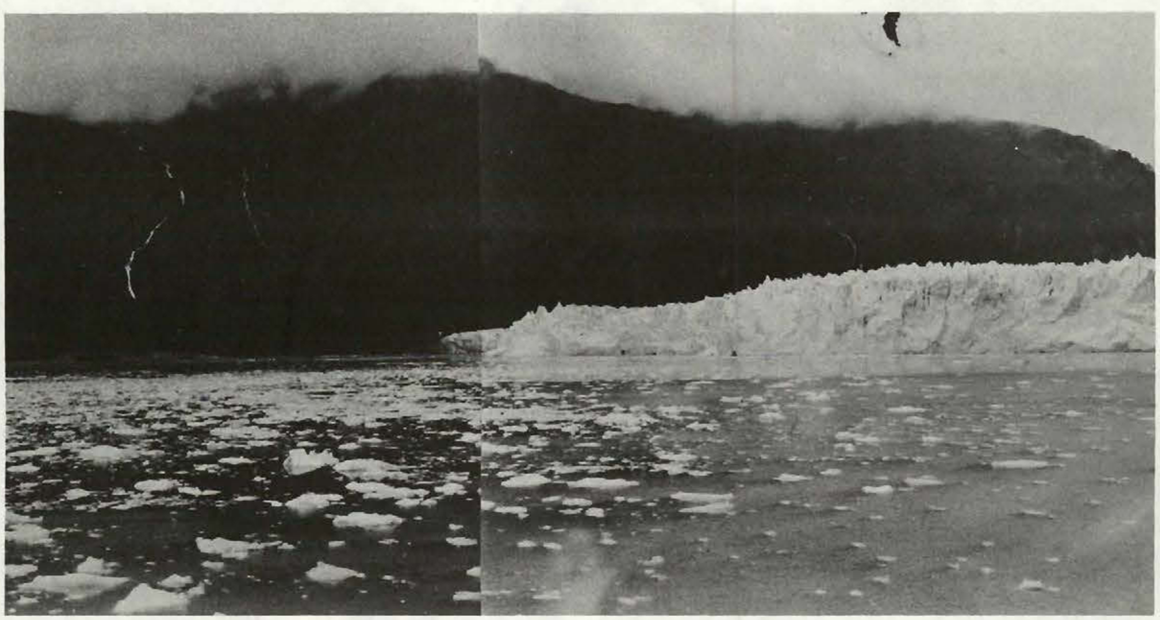


Meares Glacier, north margin, 1935, from Station F (1)
Photo f-35-456 by Wm. O. Field

Figure #78

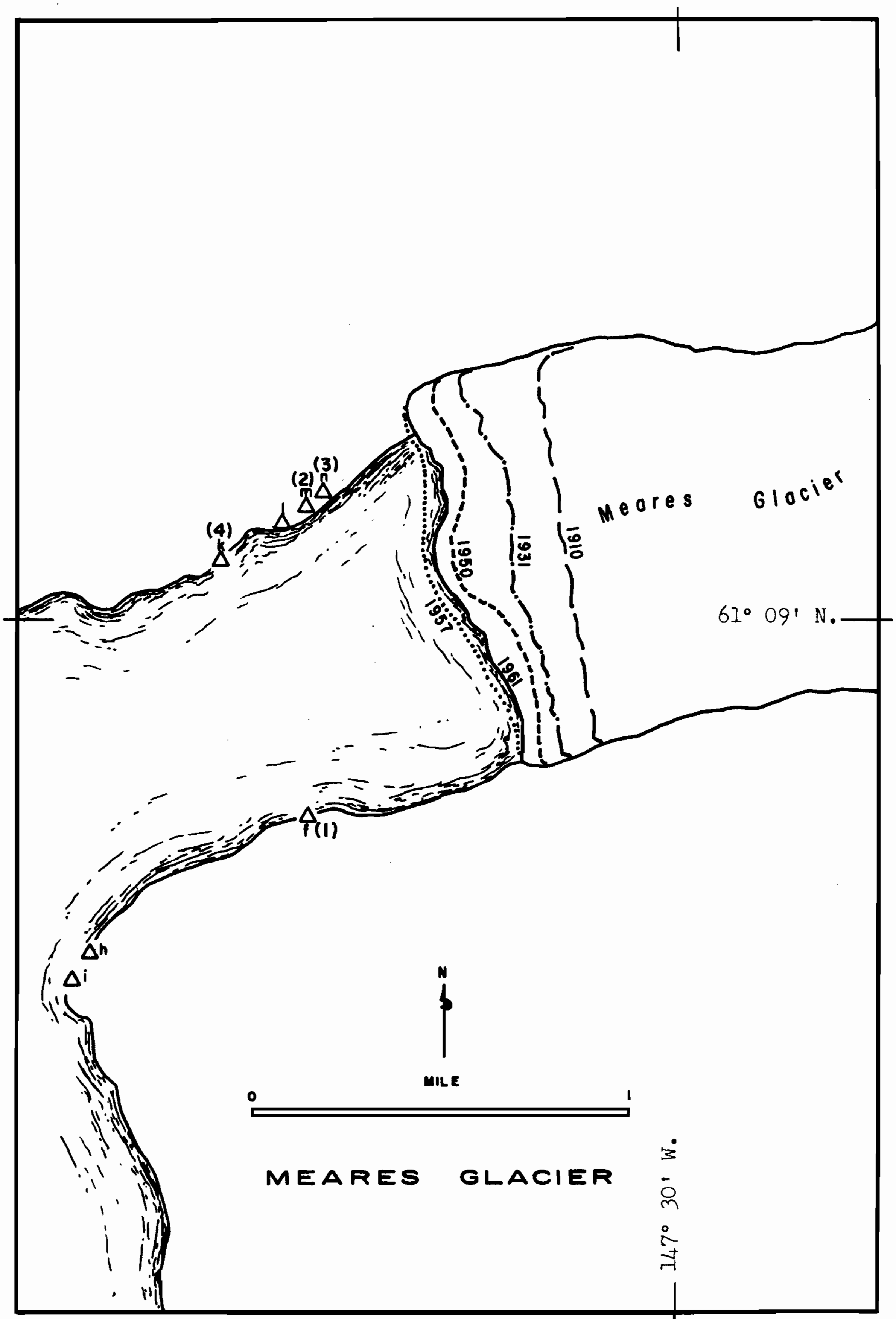


Meares Glacier, north margin, 1957, from Station F (1)
Photos M-57-SG-183-184 by M.T. Millett



Meares Glacier, north margin, 1961, from Station F (1)
Photos M-61-93,94 by M.T. Millett

Figure #79




Based on U. S. Geological Survey Map, Anchorage A-2.

Figure #77A

front near the southern margin was actually ahead of the 1957 position.

## Summary

From 1905 until 1957, Meares Glacier had a history of continuous advance. In 1957, the ice was adjacent to mature trees of nearly 300 years of age, suggesting that the ice had not advanced farther in several hundred years. Increased thickness in most of the terminus since 1957 suggests that the retreat during the previous four years is not likely to continue much longer. The short withdrawal of a segment near the northern margin noted in 1957, and the recession of all of the front except near the southern margin indicate that the advance of the Meares Glacier is perhaps irregular and unsteady. The advance probably will continue with occasional stillstands or even temporary retreats. However, the averaged pattern over many years should be one of slow advance.

## Columbia Glacier

Columbia Glacier, the largest ice stream of Prince William Sound, is located at the head of Columbia Bay between Unakwik Inlet and Port Valdez. Columbia Bay is not strictly a fiord, but a short, broad indentation 4 miles long and 3 miles wide at the entrance. Heather Island, 3 miles long, is somewhat east of the center of the bay and divides it into two parts, of which the western is larger and deeper. Columbia Glacier, with an irregular convex front over 6 miles in length, bounds the bay on the north. This wide terminus is conveniently divided into five parts: (1) the western margin, where the ice stream descends to tidewater along a steep hillside; (2) the western, or main tidal front, a vertical face 2-1/2 miles across; (3) Heather Island terminus, where the ice rides up the northern part of Heather Island; (4) the eastern tidal front, a vertical tidal face 1-1/2 miles long; and (5) the eastern margin where a sloping front is aground for a width of 2 miles. Soundings in front of the two tidal faces show that the eastern bay is shallow (57 feet deep at one-half mile from the front) and that the western, main, bay is quite deep (600 feet at one-half mile from the ice front). The ice front in either bay is an imposing vertical face rising 150 to 200 feet high. Each frontal area is heavily crevassed and is almost constantly discharging ice into the sea. The gradient in the lower part of the ice stream is low, and ice in the terminal area flows laterally into two low valleys along the western margin. Frequently lakes form in these valleys because of the glacier damming the outlets. Icebergs from Columbia Glacier fill these lakes and are left stranded when the lakes drain. A large nunatak is located near the eastern margin 6 miles above the terminus, but most of the ice moves west of the nunatak with only a small tongue flowing east of it. This eastern tongue terminates in the lee of the nunatak, just barely touching the main ice stream.

The glacier originates in a high, unmapped area near Mt. Witherspoon. It forms through glaciers with Tazlina Glacier to the north and Stephens Glacier to the east. In 1955, Nielsen (1963, p. 136) estimated the firn line to be at 3, 600 feet elevation on the large east branch, and said:

> Most of the accumulation area of the Columbia Glacier is above 4, 500 feet, probably well over 50% of it is over 6, 000 feet in elevation, and some accumulation takes place up to at least 12, 000 feet. Possibly the Columbia has the largest total snowfall and snow accumulation area above 6, 000 feet of any glacier on continental North America.

Unfortunately this high area is unmapped, and accumulation area ratios are highly generalized. From airphotos, its length appears to be around 41 miles, and it covers an area of roughly 440 square miles.

In early studies of the terminus, Columbia Glacier was known as Live, Root, and Fremantle Glacier. It was first seen and represented on a map by Whidbey (Vancouver, 1801) in 1794. He described Columbia Bay as being terminated by a solid body of ice, and also noted in the bay, a large number of icebergs, which he saw calving from the tidal ice face. Whether or not he passed between Heather Island and the glacier is not clear, but his map shows a passageway indicating that he possibly did.

In 1887, Applegate (Davidson, 1904) sailed across the mouth of Columbia Bay, and his map, like Vancouver's, shows open water between the glacier at the head of the bay and Heather Island. Since he came no closer than 3-1/2 miles, the accuracy of his map is questionable.

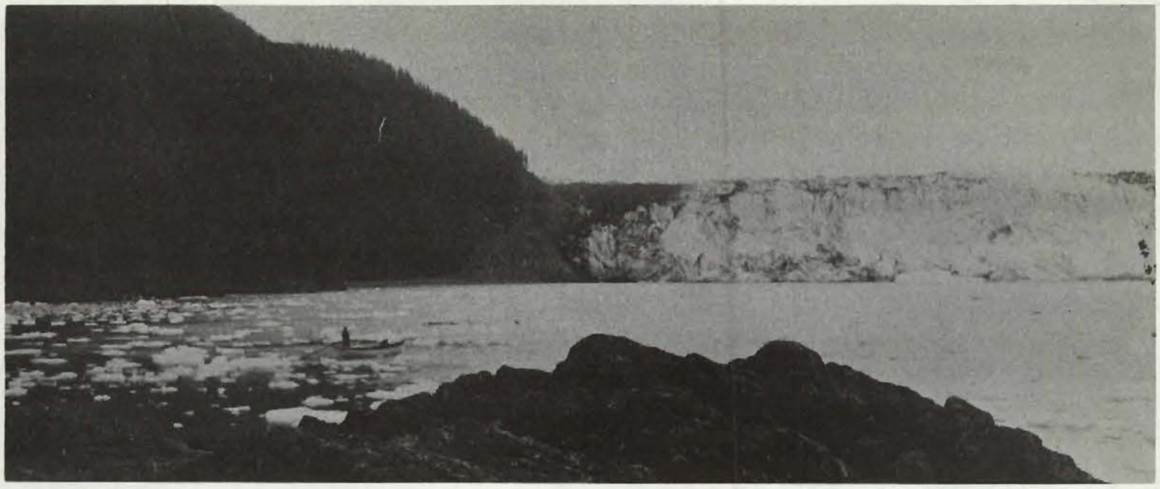
In 1898, Captain O. A. Johnson (Davidson, 1904) in the steamship Dora was in Columbia Bay and estimated the height of the 2-1/2 mile main ice front to be 600 feet. He also reported a sounding of 50 fathoms close to the front.

Abercrombie (1900), in 1898, mapped this area but failed to show Heather Island in Columbia Bay. Lack of detail makes all of these early maps unsatisfactory for determining the position of the glacier front.

The first accurate map and scientific study of Columbia Glacier was made in 1899 by G. K. Gilbert (1903) of the Harriman expedition. He said that at most points along the front the forest of hemlock and spruce approached close to the ice. At the western margin of the main ice cliff, where the glacier crowded against a steep rock slope, there was a belt of bare rock, from 200 to 300 feet wide, between the ice and the forest. This belt was strewn with wood and rock fragments, and trees were freshly overthrown at the margin of the forest. At the time of its attack on the forest, the ice must have been 100 feet deeper than in the summer of 1899, and it also must have extended 800 feet farther southward from the ice front, as shown by a push-moraine of rock at the water margin. A second less massive push moraine lay 160 feet behind the outer push moraine at the water margin. On the island between the two ice cliffs there were also two push moraines of recent date, the nearer one being about 100 feet from the ice front, the other from 300 to 500 feet from the front. The latter was associated with overthrown forest trees, and included within its rocky debris: tree trunks, branches, and folds of peaty soil. The tract between the two moraines was fluted in the direction of ice motion, the corrugations being several feet deep. Gilbert felt that the advance creating the push-moraine and the subsequent melting which laid bare the fluted drift had taken place within one or two years. With the exception of the fluted drift surfaces, the same phenomena were observed on the mainland at the east. There was an inner push-moraine, composed chiefly or wholly of drift, running parallel to the ice margin. There was an outer push-moraine, less regular in its distance from the front and associated with disturbance of the forest and the meadow peat.

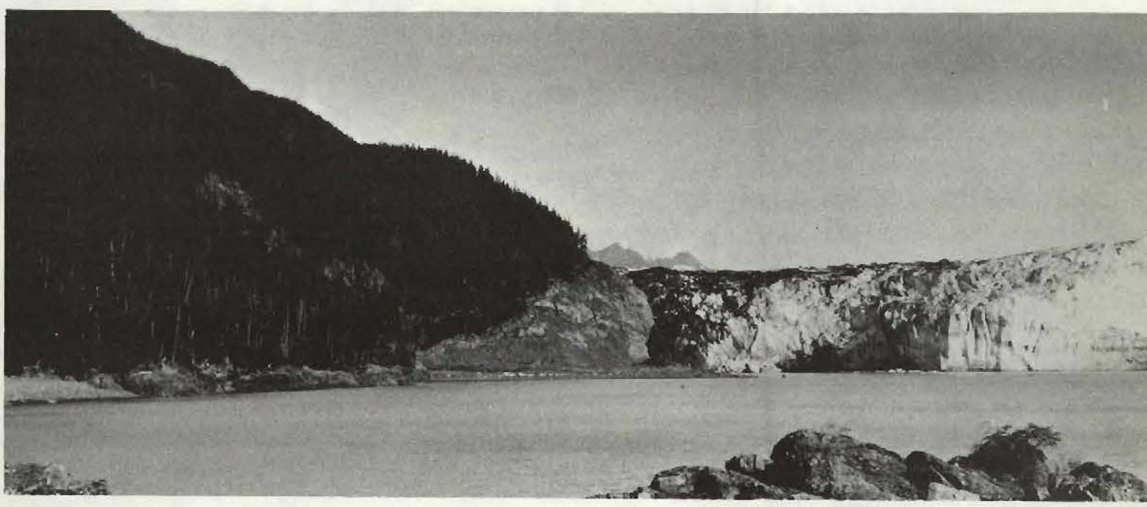
In 1905, 1908, and 1909, Grant (Grant and Higgins, 1911) visited Columbia Glacier. On his early visits, he found the ice to be retreating, but on his later visits it was advancing. The western terminus was not examined in 1905 or 1908, but by 1909 the 200 to 300 foot bare zone reported by Gilbert (1903) was covered, and the ice was advancing into the forest (Figures 80, 81). The position of the western margin was estimated to have advanced 500 feet since 1899, most of the advance taking place since 1908. On Heather Island Grant made the following observation:

> At a date estimated as 1894 a large push-moraine which contains bare dead trees and tilted living trees was formed. We infer a still earlier advance, however, for the bare, dead trees had undoubtedly been killed before the pushing up of this moraine. Then there was a retreat an unknown distance, followed by an advance to form a small push-moraine. In 1899 the distance from the small moraine to the ice was found to be 60 feet. In



Columbia Glacier, west margin, 1899, from Station G
Photo 355 by G.K. Gilbert

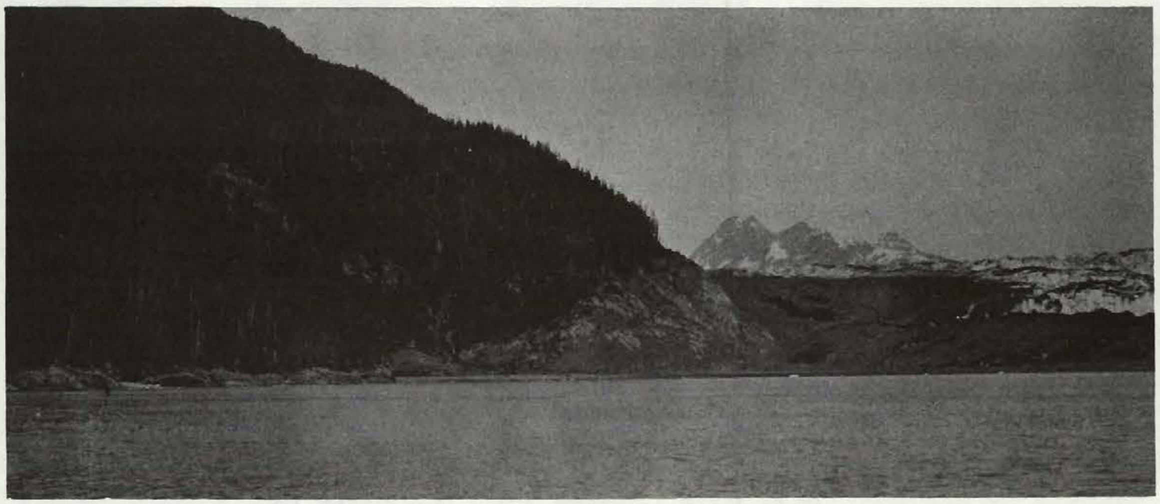
Columbia Glacier, west margin, 1910, from Station G
Photo C11 B by Lawrence Martin



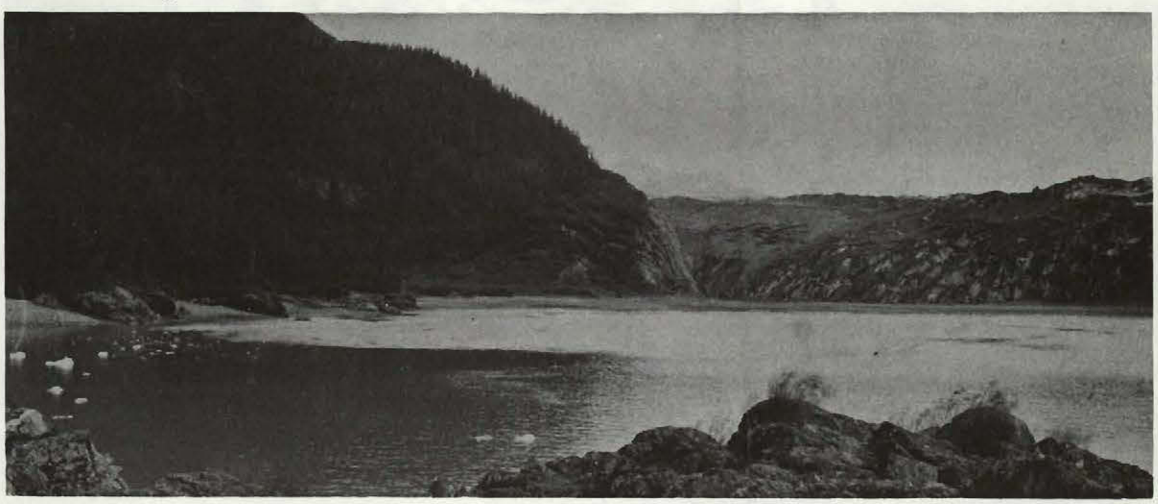
Columbia Glacier, west margin, 1931, from Station G
Photo f-31-58 by Wm. O. Field

Figure #80

Columbia Glacier, west margin, 1935, from Station G
Photo f-35-328 by Wm. O. Field



Columbia Glacier, west margin, 1947 from near Station G
Photo 87 by D.N. Brown



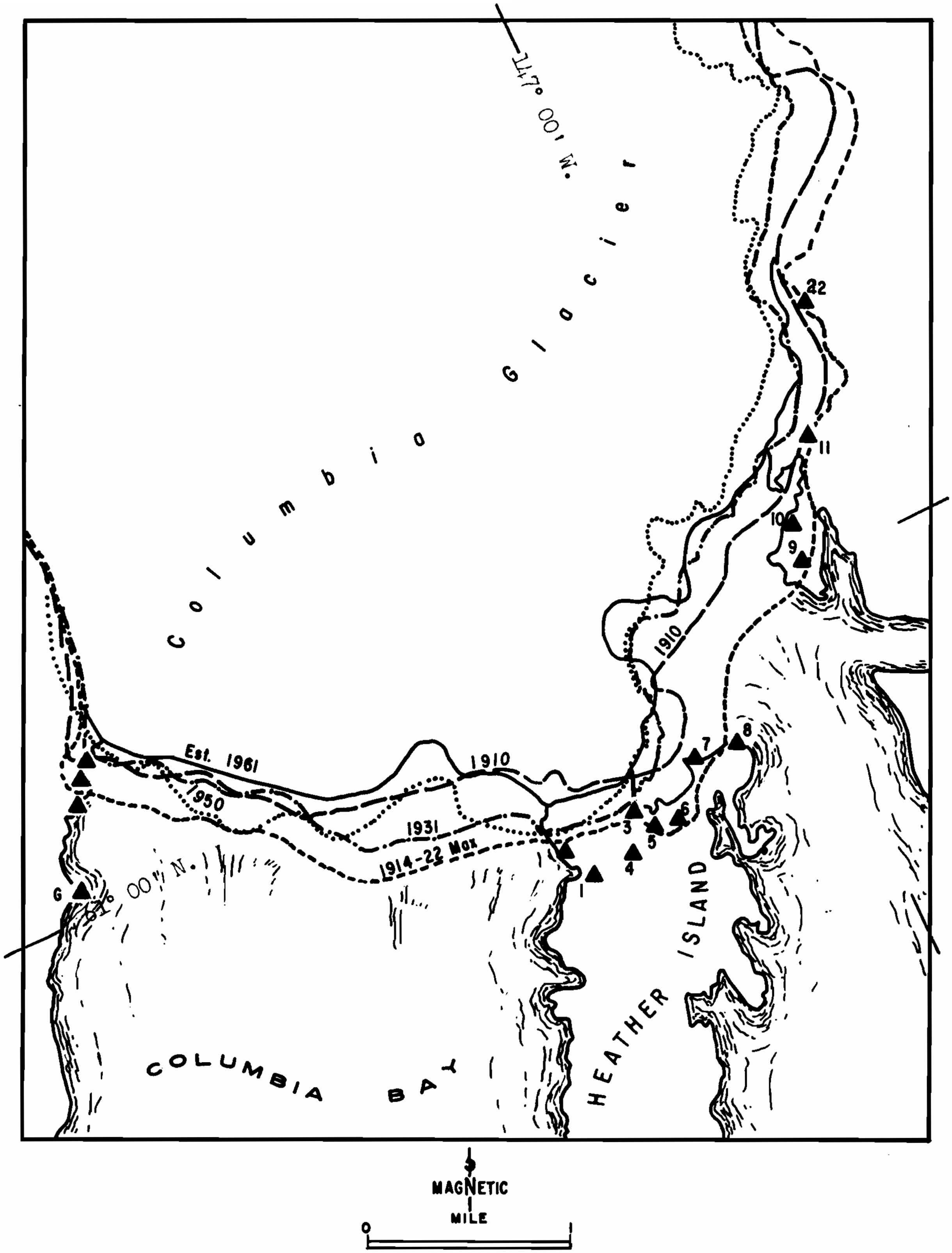
Columbia Glacier, west margin, 1961, from Station G
Photo M-61-86 by M.T. Millett

Figure #81

1905 the ice was still 220 feet north of the small moraine, but in 1908 it had advanced 100 feet. Between July 15, 1908, and June 24, 1909, the ice pushed forward 310 feet, and by August 23, 1909, as observed by Tarr and Martin, it was seventy feet (estimated) farther out and 120 feet ahead of its former (1894) maximum. Between the last two dates there was then an average rate of advance of the front of 1.17 feet per day. The actual rate of movement of the ice was considerably greater than this, for melting was at its maximum during this period (1911, p. 733).

The National Geographic Society's expedition (Tarr and Martin, 1914) made four visits to Columbia Glacier, August, 1909; July, 1910; September, 1910; and June, 1911. During all of these visits the entire front was still advancing. Since 1899, the western margin had advanced approximately 1,250 feet; the Heather Island terminus advanced about 320 feet; and the eastern margin advanced as much as 1,200 feet. In every case the ice had advanced past the 1892 (estimated by Gilbert) position. New lakes were formed by stream damming in the area of the eastern margin, and most of the early photo stations were overridden by the ice. The distributary east of the nunatak was apparently unchanged during this period since it was found that it still touched the main glacier, but contributed no ice to it.

In 1931, W. O. Field (1932) spent several days mapping and studying Columbia Glacier. His map is used as a base map for plotting all known surveying data (Figure 82). By comparing conditions of the glacier with photographs taken by earlier investigators, he found that between 1899 and 1910, the glacier had advanced along the western margin and had continued advancing with one short interruption, until after 1914. A retreat then set in, which continued up through his visit. By 1931, the ice front stood at a point 900




Based on W. O. Field, Figure 18, 1931.

COLUMBIA GLACIER

Figure #82

feet back from its farthest advance, and there had been a corresponding decrease in the thickness of the ice near the western margin, leaving a bare zone of at least 75 feet between the ice and the forest. Thus the ice front in 1931 was in a position intermediate to those of 1899 and 1909. Field also found an unexpected advance of the ice terminus in progress at both the western margin, and Heather Island. At one point on Heather Island he measured this advance as being roughly 3 inches per day.

Four years later, in 1935, Field returned (1937, pp. 69-70) and observed a continuation of the readvance of 1931. He said:

> In 1931 the west end of the ice front and the Heather Island terminus of Columbia Glacier were advancing, but all parts of the ice front were several hundred feet back of their most advanced positions reached between 1908 and the early 1920's. In 1935 it was found that the advance had continued actively on all parts of the front. It was measured at various points as follows: at the west end of the ice front, 342 feet; on Heather Island, 237 feet; and on the eastern land terminus, from 100 to 400 feet. The greatest change had occurred on the east side, where the ice had become very much thicker and far more crevassed. On the west side of the terminus the ice was still more than 500 feet from its recent maximum position. On Heather Island, at one point, it had overridden the terminal moraine of the recent advance and therefore was probably more advanced than for centuries, but at all other points on Heather Island and on the eastern terminus it was still well back of its maximum position.

A series of miscellaneous observations followed. In 1947, M. M. Miller (1947) visited Columbia Glacier and found a recession had taken place along the entire front since 1935. In 1949, however, D. N. Brown (1952) reported an advance occurring at the western margin and on Heather Island between 1947 and 1949. The "Chugach Mountain Expedition of 1955" (Nielsen, 1963) did not make any observations of the terminus, and its sketch map is too generalized to use in determining the position of the front.

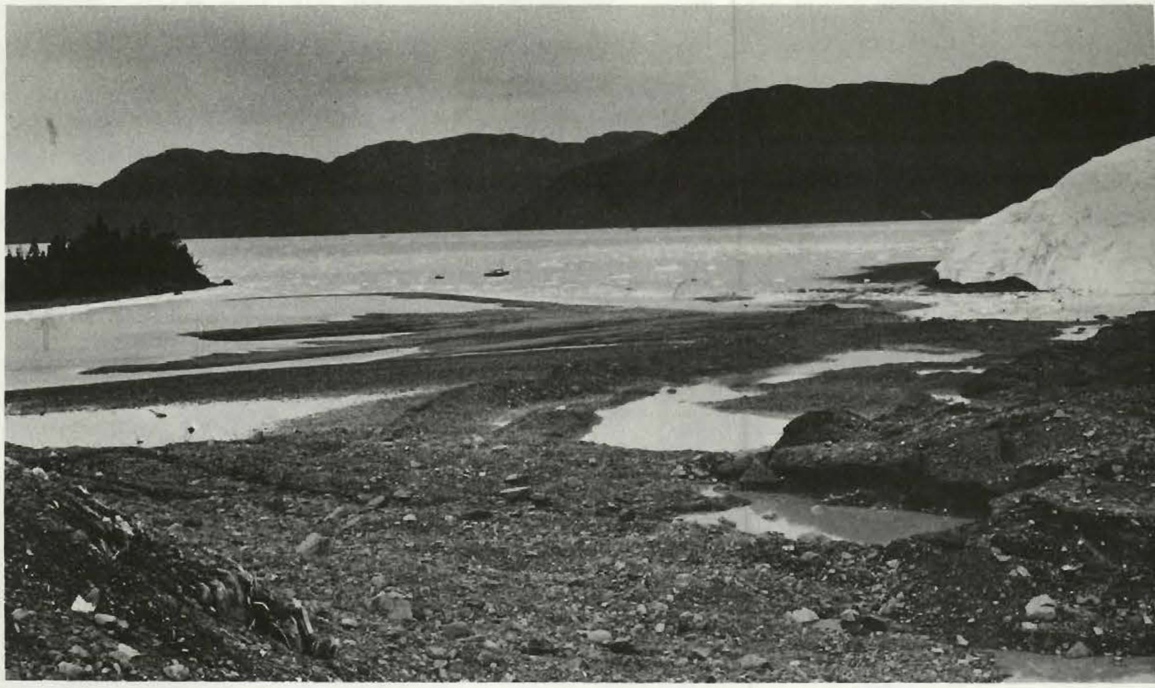
They did, however, spend part of June and July, 1955, making meterological and accumulation studies on the upper glacier. Ablation was measured at base camp, elevation 3,160 feet, from June 17 to July 5. They produced a rough sketch map, estimated total ablation and accumulation, and concluded:

> On the basis of about 40 feet of ablation of bare ice per year at the terminus of the Taku Glacier, the more northerly location of the Columbia might be expected to reduce this to about 30 feet per year. This can be assumed to decrease approximately linearly to zero at the firn line. Knowing the areas between various elevations, it is then possible to estimate the total ablation per year. For the Columbia Glacier this calculation gives about 60 billion cubic feet of ice per year. In order to maintain a steady state or equilibrium condition, this requires an average of 17 feet of snow (density of 0.5) over the whole accumulation area at the end of each ablation season. This is much more snow than what our observations would indicate. Obviously more data will have to be obtained before the contradictory evidence can be rectified. It appears that either the average snowfall is much greater than what our observations would indicate, or the ablation of ice is less than what was estimated in the calculations. Errors may also be involved in the areas of accumulation and ablation.

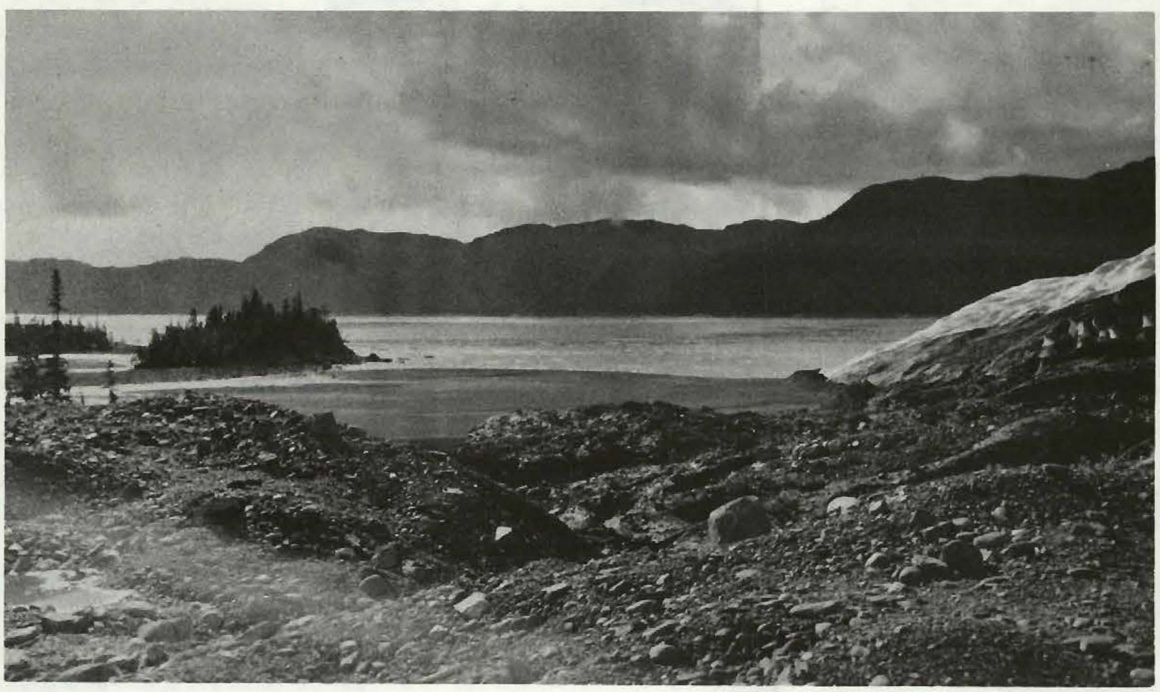
In 1957, Columbia Glacier was studied by I.G.Y. personnel, who remapped the terminus and occupied many old photo stations for comparative pictures. Seven of the 1931-1935 stations on Heather Island were reoccupied and an additional four stations were newly established to provide better coverage of current conditions. Along the eastern terminus five survey-photo stations dating from 1931-1935 were located, but three were so obscured by vegetation that offset stations of greater permanence were established. In addition, four new stations were set up to improve the coverage. The western margin was not visited because of poor weather and heavy ice conditions in the main bay.

The termini on Heather Island and along the eastern margin were fronted by a series of end moraines, which in most cases were continuous and easily identifiable. The oldest moraine was formed by an expansion of the glacier that had not been exceeded in several centuries. The age of this hochstand was estimated by party botanists to have lasted from 1917 to 1922. For simplicity this important advance will be dated as 1920, with the understanding that it reached its greatest position at different points at different times between 1917 and 1922. The advance reported by Field (1932, 1937) was marked by a moraine which at several points was in the same position as the push-moraine shown in 1935 photographs (Figures 82A and 83). This moraine is therefore dated as 1935. In 1957, a third moraine was identified between the 1935 moraine and the terminus. From airphotos taken in 1950 (U. S. Air Force) and photographs taken by D. N. Brown in 1947 and 1949, the date of this moraine is suggested as 1949-1950.

As of 1957, changes in the position of the terminus were as follows: (1) In the main ice cliff little change was noted from the 1935 position. (2) The three moraines (1920, 1935, 1949-1950) are easily identified on Heather Island, although an irregularity occurs in their succession, for at one place the 1935 moraine extends farther out than the 1920 moraine. Since 1935, recession to the 1949-1950 moraine averaged 550 feet, while the distance from the 1949-1950 moraine to the ice averaged 470 feet. (3) As best as can be determined, the eastern ice cliff had receded about 500 feet since 1935. (4) In 1957, the eastern margin of the terminus was fronted by a small push-moraine, and the 1949-1950 moraine was either overrun or not formed. Recession since 1935 ranged from

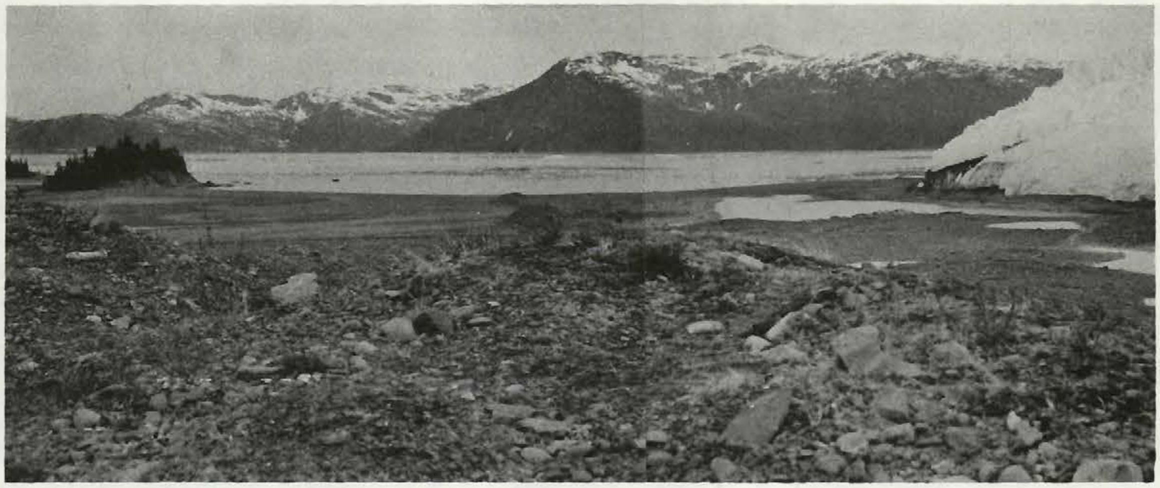


Columbia Glacier, Heather Island terminus and
main tidal face, 1931, from Station 3
Photo f-31-119 by Wm. O. Field

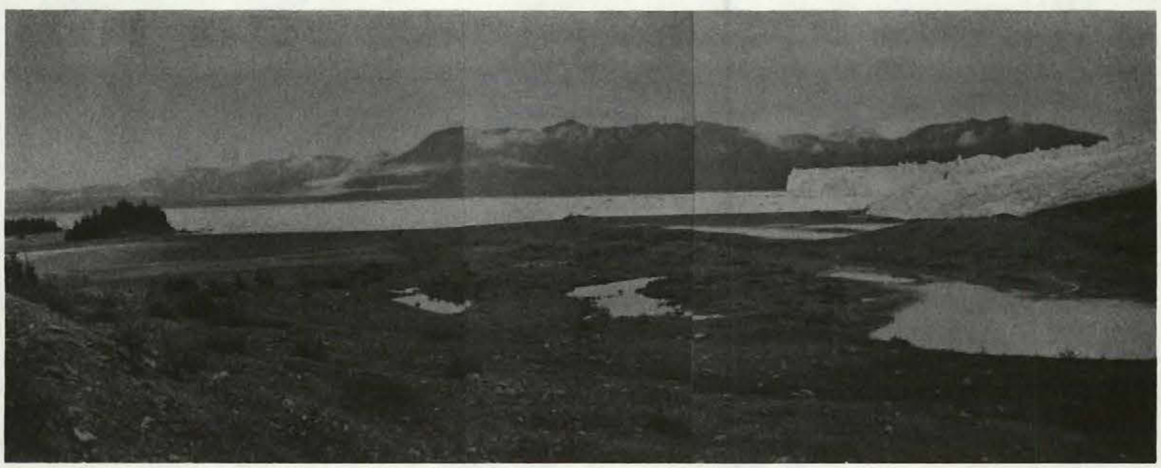


Columbia Glacier, Heather Island terminus and
main tidal face, 1935, from Station 3
Photo f-35-392 by Wm. O. Field

Figure #82A



Columbia Glacier, Heather Island terminus and
main tidal face, 1949, from Station 3
Photos 149, 150 by D.N. Brown



Columbia Glacier, Heather Island terminus and
main tidal face, 1961, from Station 3
Photos f-61-259,260,261 by Wm. O. Field

Figure #83

675 to 950 feet, averaging 810 feet (Figures 84 and 85). There were mature trees less than 300 feet from the outer terminal moraine, one of which was found by party botanists to have 420 annual rings.

In 1961, several days were spent at Columbia Glacier, and the following observations were made. A new moraine, formed mostly since 1957, was found along the entire glacier front. On the eastern side of Heather Island this moraine was forming in 1957, while in other areas it was still in the process of forming in 1961. The age of this most recent moraine is therefore set as 1957-1961. On the western margin the position of the 1957-1961 moraine indicated a retreat of 505 feet since 1935. By 1961, the ice had retreated 20 feet from this latest moraine. The moraine is composed mostly of plowed-up beach material, demonstrating that it was formed by an advance rather than by a period of stagnation of the ice.

As seen from stations on Heather Island, the main ice cliff appeared to have receded about 300 feet since 1957. A rather uniform retreat varying from 150 to 190 feet had occurred along the terminus at Heather Island since 1957. At one point the 1957-1961 moraine indicated that the ice during that period had overridden the 1949-1950 moraine but had stayed within the 1935 moraine. Recession of about 200 feet had occurred along the eastern ice cliff and silting in of the bay was very noticeable. Only the center one-third of this ice cliff was not in shallow water or aground. Bars extended for several hundred feet toward the center of the bay from Heather Island and from the eastern margin (Figures 84, 85). The eastern margin of the terminus (Figure 86) was thicker and every-

Columbia Glacier, eastern tidal front, 1931, from Station 3
Photos f-31-121,122 by Wm. O. Field

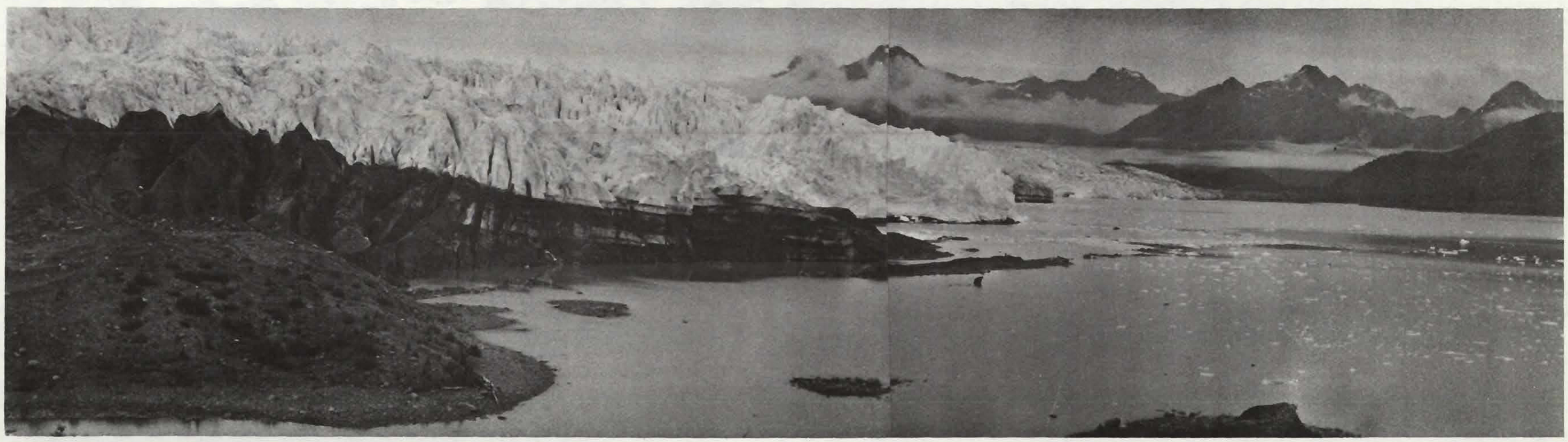


Columbia Glacier, eastern tidal front, 1935, from Station 3
Photos f-35-395,396 by Wm. O. Field

Figure #84

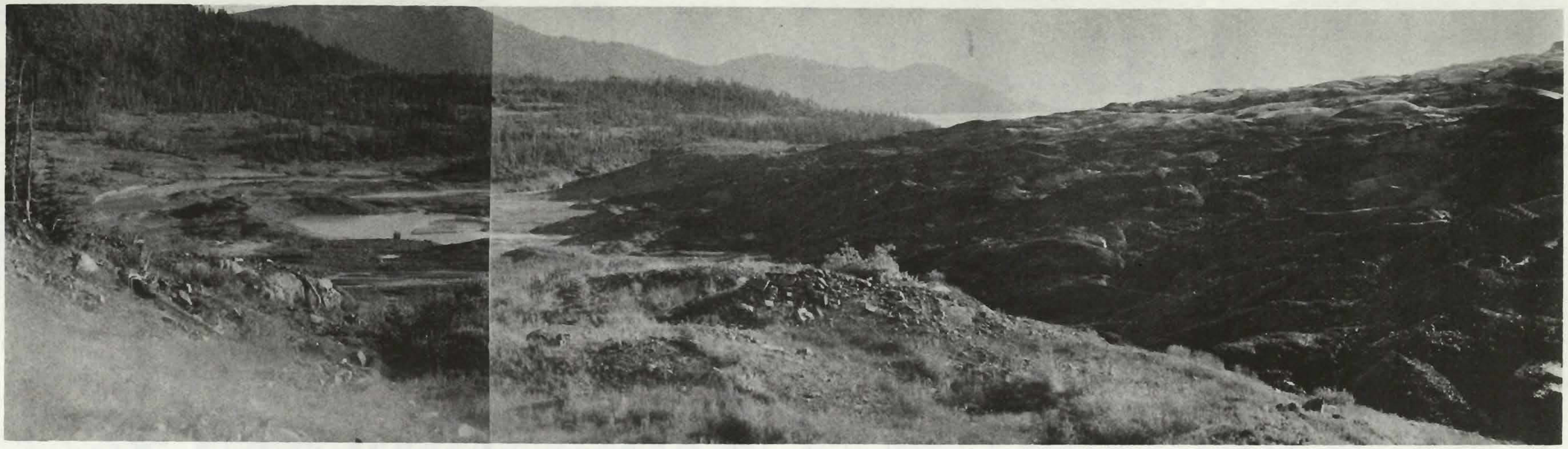
Columbia Glacier, eastern tidal front, 1957, from Station 3
Photos M-57-SG244,245 by M.T. Millett



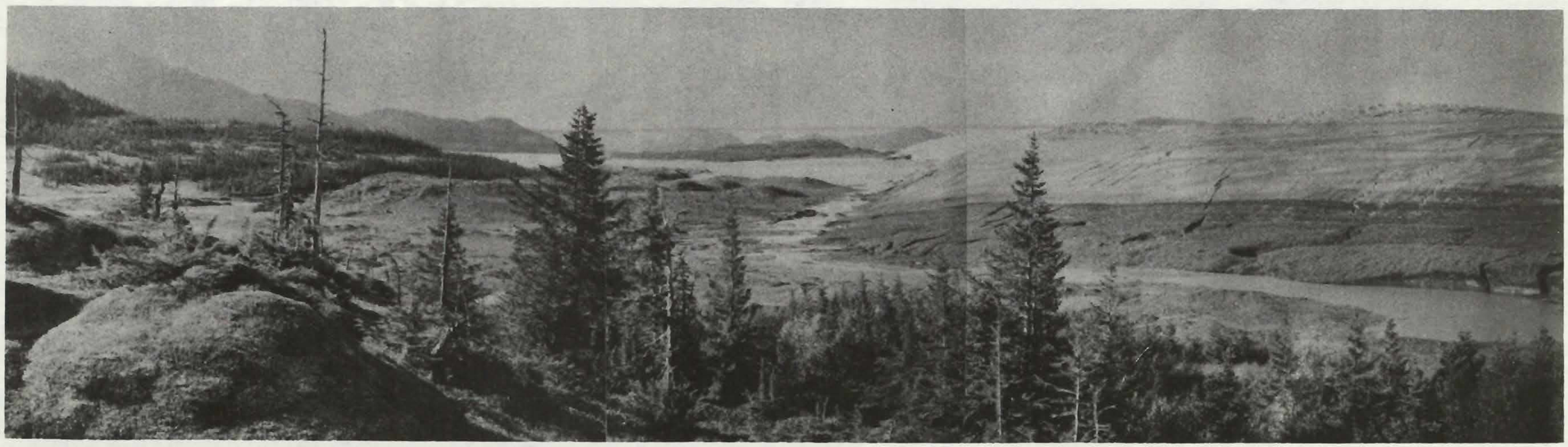


Columbia Glacier, eastern tidal front, 1961, from Station 3
Photos M-61-S78, S79 by M.T. Millett

Figure #85



Columbia Glacier, east margin, 1935 from Station 22
Photos f-35-446,447 by Wm. O. Field



Columbia Glacier, east margin, 1957, from near Station 22
Photos CM-57-H132, H133, H134 by Chas. Morrison

Figure #86

where close to or in contact with the new moraine. This new moraine appeared to have been formed within the last year, and in some parts was still forming. Between 1957 and 1961, advance, measured along five lines, ranged from 150 feet to 550 feet (average 300 feet).

Summary

Since 1899, when the first accurate observations were made, the terminus of the Columbia Glacier has fluctuated back and forth between approximate limits of 1,000 feet on the western side and 4,000 feet on the eastern side. The age of trees on the trimline outside of the 1920 moraine indicates that these fluctuations of the terminus were near the very limit of its most advanced position in more than four centuries. The eastern and western margins seemed to respond to an advance later than the Heather Island front. The 1957 advance on the eastern end of Heather Island seemed to be correlated with the advance of 1960-1961 which occurred on the western margin and along the eastern terminus.

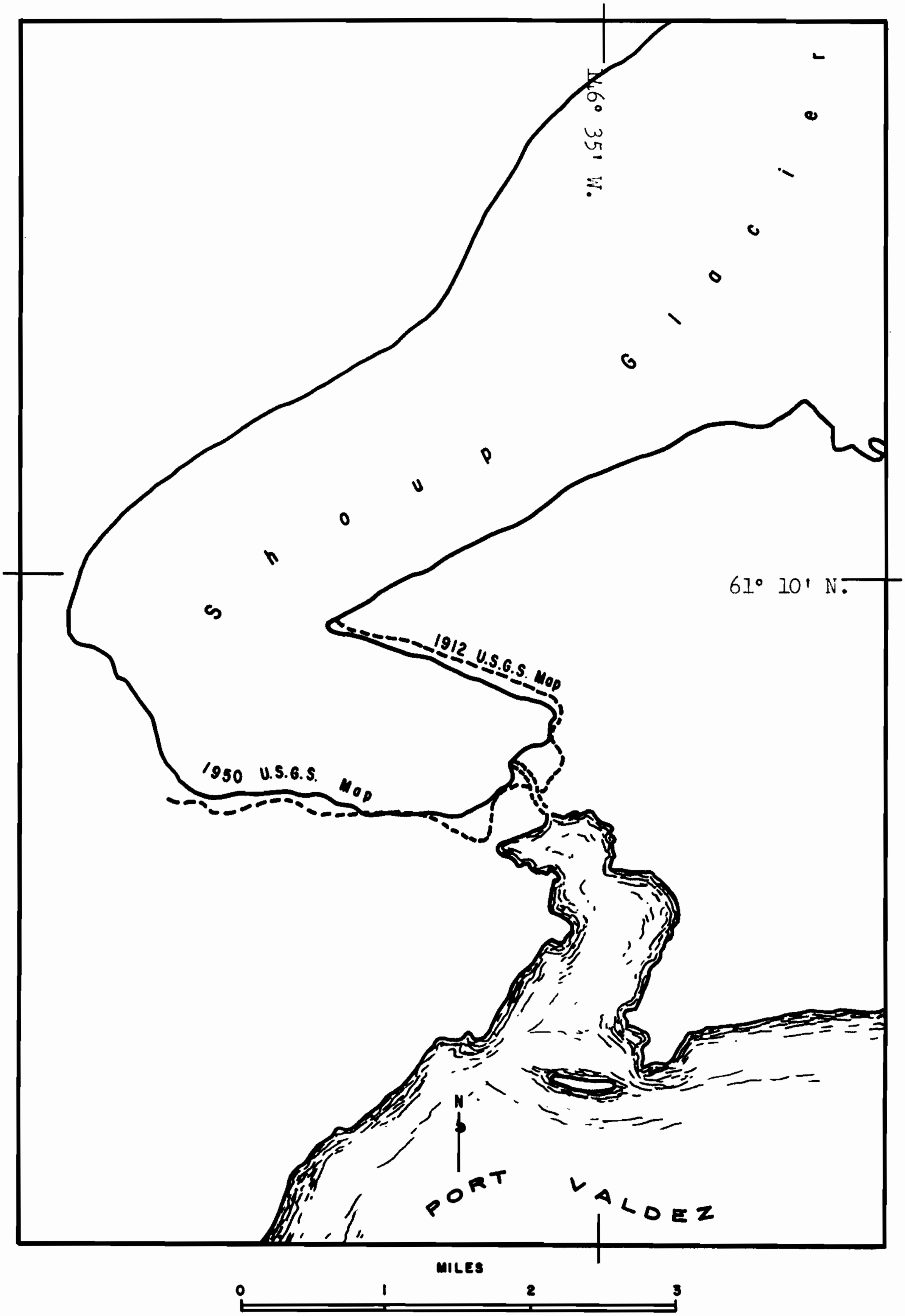
## Port Valdez

### Introduction

Port Valdez is located in the northeastern corner of Prince William Sound and has only two large glaciers that have received the attention of glacier investigators. These are the Shoup and Valdez Glaciers, both originating high in the east-central Chugach Mountains and descending nearly to sea level. Until recently, the Shoup Glacier, at the head of Shoup Bay in the western part of Port Valdez, was a tidal ice front. The Valdez Glacier, located in the western end of Port Valdez, terminates at about 200 feet elevation and is nearly five miles from tidewater.

## Shoup Glacier

Shoup Glacier, once known as Canyon Creek Glacier, is located in the northwestern corner of Port Valdez about two miles from the main fiord at the head of a shallow bay (Figure 87). The ice front is separated from tidewater by an outwash plain and mud flats that vary from 300 to 500 yards in width. The front has a low-angle slope in the center, abuts against a large emerging rock on the north, and has many large sand cones and moraine-covered ice hills on the south. The northern half of the terminus is mainly clean ice with few crevasses, while the southern part is heavily covered with ablation moraine and is rather heavily crevassed just above the front. Shoup Glacier has a low gradient (Figure 88), and 1-1/2 miles above the terminus it makes a 130$^{o}$ turn to the right giving the tongue a peculiar hook shape. The ice stream is over

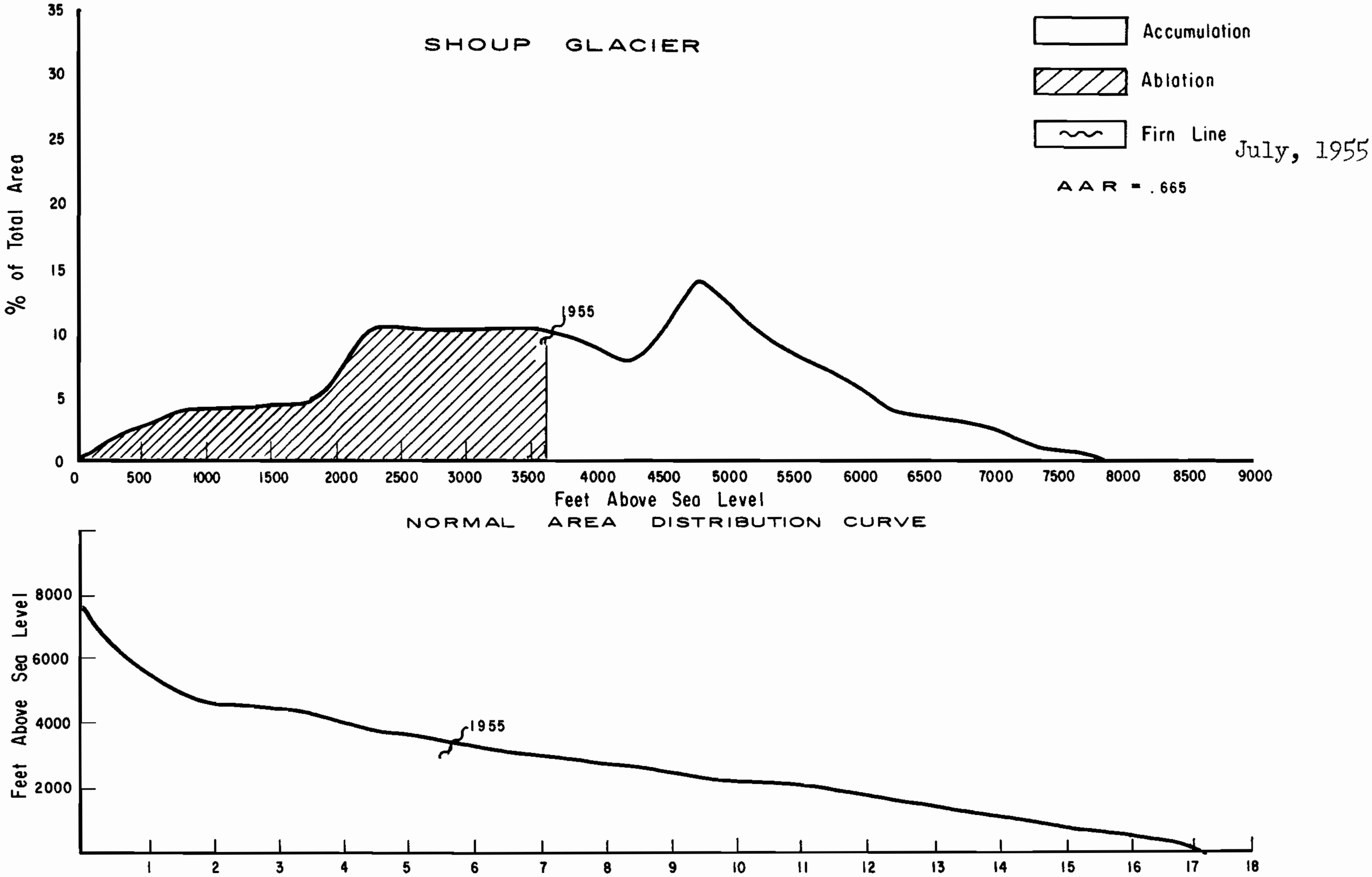



Based on U. S. Geological Survey Maps, Valdez A-7, A-8.

**SHOUP GLACIER**

**Figure #87**

Figure #88




NORMAL AREA DISTRIBUTION CURVE

LONGITUDINAL PROFILE — VERTICAL EXAGERATION 2.5x

17 miles long and covers an area of 62.8 square miles In 1955, Nielsen (1963) found the firn line on the nearby Columbia Glacier, east branch, to be at about 3,600 feet elevation. Since this location is only two or three miles from the Shoup Glacier, the figure probably applies to this glacier as well. If the firn line is at this altitude, the glacier has an accumulation area ratio of 0.665, the lowest ratio observed in Prince William Sound.

The earliest account of Shoup Glacier was by F. C. Schrader (1900), who photographed the terminus in 1898 and described it as a glacier of medium size, which came down to tidewater and gave off many small icebergs. The front of the glacier was about one half of a mile across.

In the same year, Mahlo's map (1900) shows a glacier which he called "Canyon Creek Glacier," at the head of Shoup Bay. This glacier is erroneously depicted as two glaciers which coalesce two miles above the terminus. This same error is shown on three maps (Maps 20 and 21, Twentieth Annual Report, U.S. Geological Survey, Part VII 1900; and map accompanying report XXV, War Dept. Adj. Gen. Office, 1900) which use Mahlo's work as a base map.

In 1905, 1908, and 1909, Grant and his colleagues (Grant and Higgins, 1911) visited Shoup Glacier and reported that a comparison of photographs suggested that the front of the glacier had been practically stationary between 1905 and 1909. The presence of shrubs of considerable size close to the ice front led them to conclude that there had been no appreciable advance beyond the 1909 position for several decades. They also noted that rock ledges, which were not visible in 1900 and 1901, were being exposed in

1905, and in 1909 were nearly 50 feet in front of the terminus.

In 1910, the National Geographic Society's expedition studied Shoup Glacier (Tarr and Martin, 1914, pp. 249-256). In analyzing previous studies, Tarr and Martin said:

> The statement by Grant that the two large rocks not visible in 1901 were being exposed in 1905, is of interest in view of the fact that in 1898, these ledges were already exposed, as shown by Schrader's photograph. Nearly five times as much of the larger rock showed in 1905 as in 1898. In 1908 the two areas of exposed rock ledges were nearly connected, the smaller or westernmost being of about the same size as in 1898 and 1905 while the larger, east, rock ledge was a little longer and higher in 1908 than in 1905. The progressive enlargement of the rock ledge areas between 1901 and 1905, and from 1905 to 1908, seem to indicate slow, though uninterrupted retreat during these years, but the fact that no ledges were visible in 1901, while two ledges were visible in 1898 and 1905 suggests a slight advance of Shoup Glacier between 1898 and 1901. Further evidence of this advance is found in a comparison of the western margin of the glacier in the photographs taken from the same site in 1898 and 1905. The latter, by Grant, shows the ice edge a short distance farther west than in the 1898 picture by Schrader. This advance is also proved by other observations made in 1909. Unfortunately Schrader's photograph does not extend far enough for us to compare the eastern margin of Shoup Glacier in 1898 and 1905. A comparison of Grant's 1905, 1908, and 1909 photographs of the two margins show little, if any, retreat of the two edges.

Shoup Glacier was studied by W. O. Field (1932) in 1931, who found that the front of Shoup Glacier had remained in almost the same position since 1898. However, its appearance had changed considerably. Instead of ending in a vertical cliff, as noted by all former observers, the glacier now ended in a low-sloping front which reached the sea only at high tide.

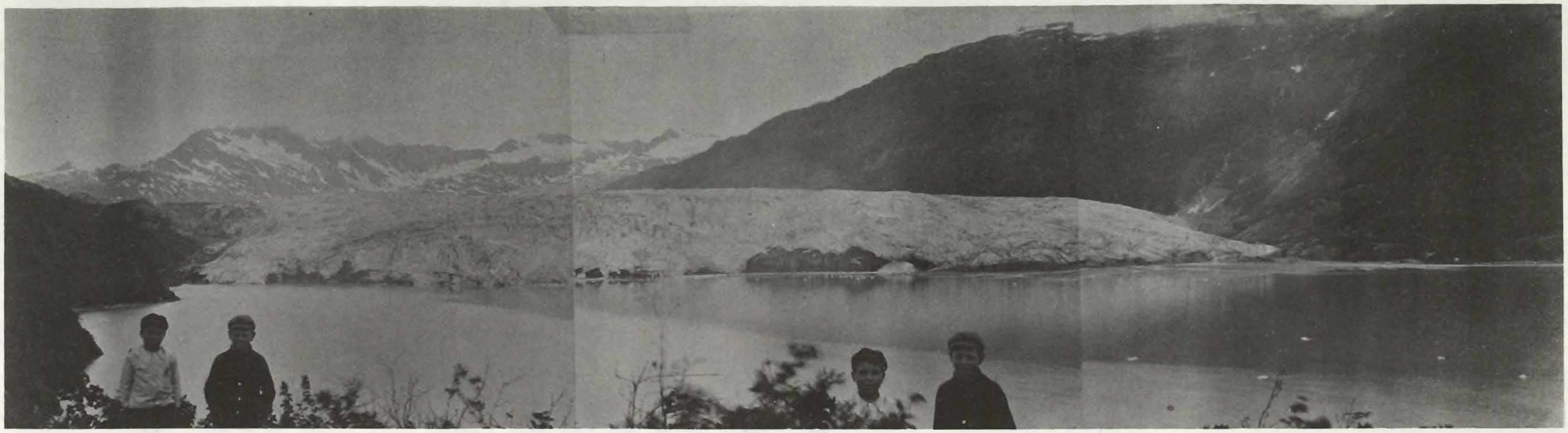
In 1935, Field (1937) again visited Shoup Glacier and found the position of the terminus unchanged since 1931. However, the volume of ice in the lower part of the glacier appeared to have decreased slightly.

Bradford Washburn took an oblique airphoto of Shoup Glacier in 1937, and the U. S. Army and U. S. Air Force took air photos of the glacier in 1941 and 1950 respectively. All of these pictures show downmelting with only a very slight retreat of the ice front.

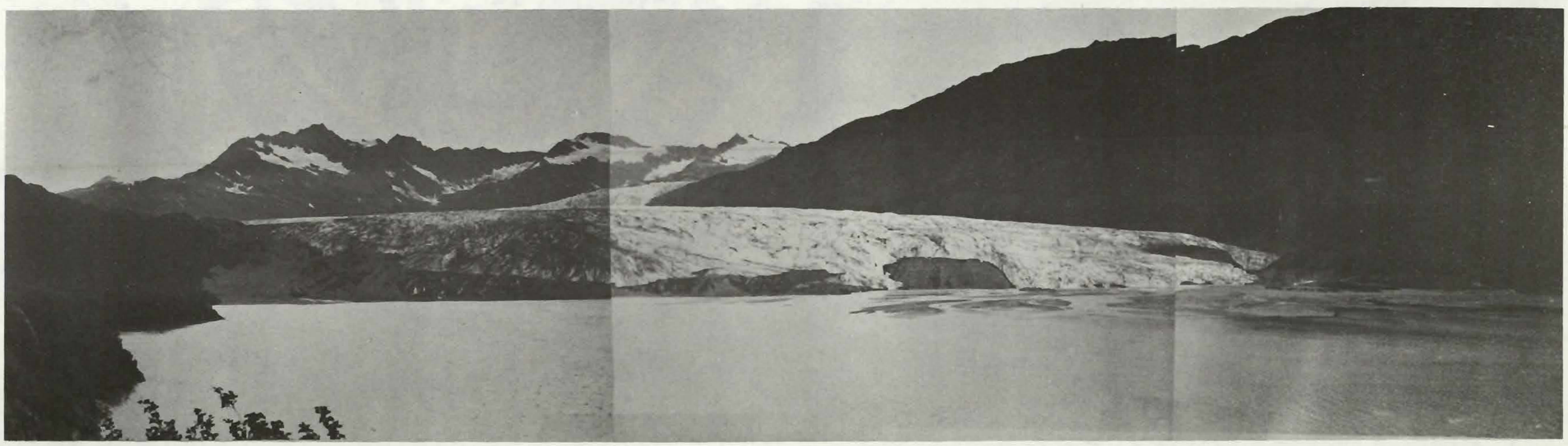
In 1957, the I. G. Y. party visited Shoup Glacier occupying previously established photo stations to duplicate old views. A comparison of conditions with older photos showed a further emergence of the large rock near the northern margin and the emergence of another rock near the center (Figures 89 and 90). The front was within a short distance of its position of 1898. The downwasting, however, was very impressive and must have been at least 300 feet near the terminus. A prominent moraine, up to eight feet high and found along the southern side of the terminus, was not shown by the photographs of 1935, but was in approximately the same position as the terminus in that year. Distance from this moraine to the ice varied from a few feet to as much as 100 feet. A pause in the steady retreat or a slight advance probably produced this moraine.

In 1961, photographs were taken again from the previously established stations, and two new stations were set up for future reference. Conditions at the terminus showed little change since 1957. Downmelting had continued, and a slight retreat of the front had occurred. The ablation moraine along the southern half of the glacier had become heavier.

Vegetation in the terminal area has not yielded a date for the recent maximum of Shoup Glacier; however, a terminal moraine across the mouth of the bay clearly shows that the ice was at this

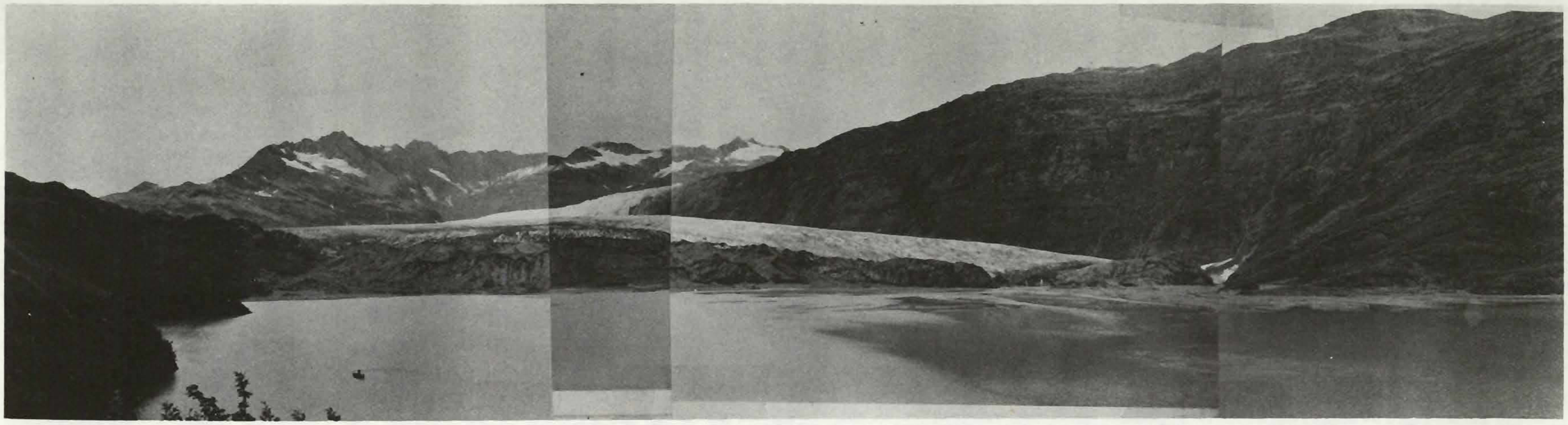


Terminus of Shoup Glacier, 1914, from Station A
Photos 215.3, 215.4, 215.5 by Handy



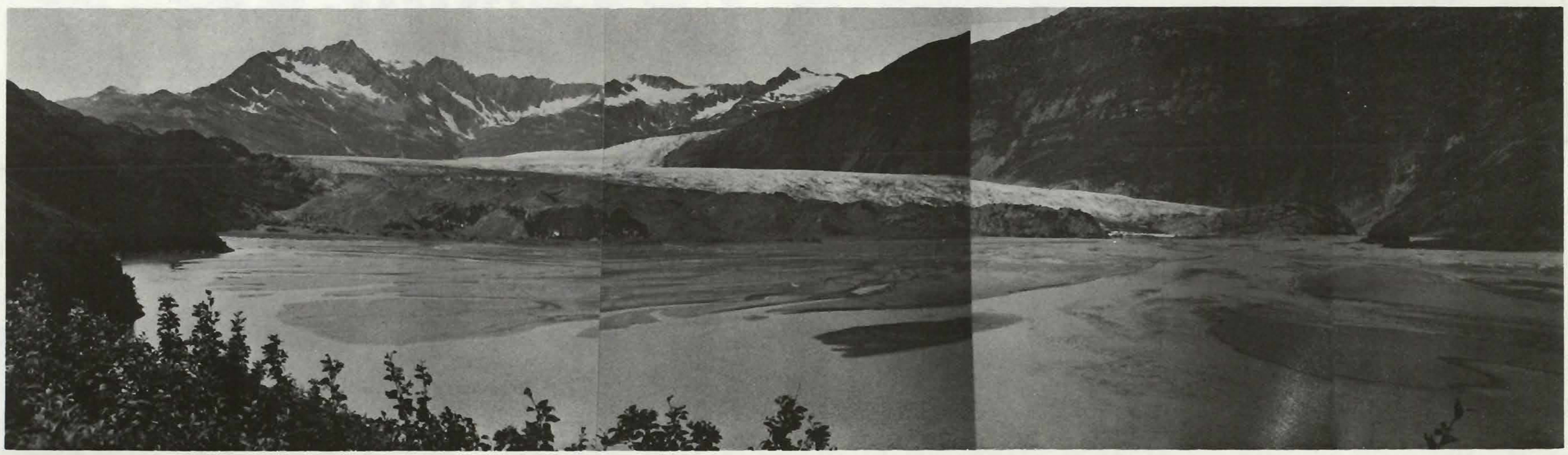
Terminus of Shoup Glacier, 1935 from Station A
Photos f-35-313, 314,315 by Wm. O. Field

Figure #89



Terminus of Shoup Glacier, 1957, from Station A
Photos 276a, 276,277,278 by M.T. Millett





Terminus of Shoup Glacier, 1961, from Station A
Photos M-61-73,74,75,76 by M.T. Millett

Figure #90

point in post-Wisconsin times.

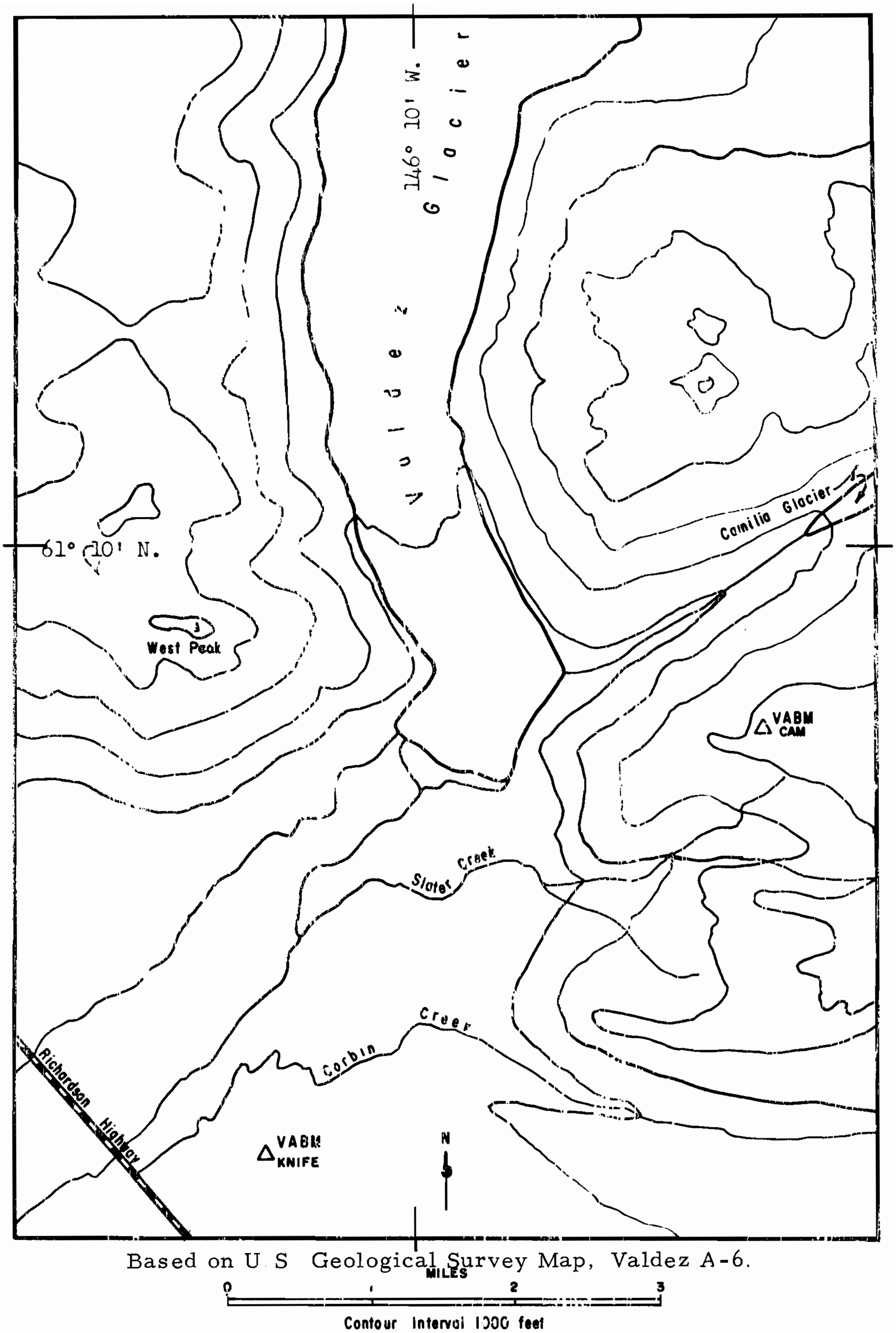
Summary

Since first observed in 1898 (Schrader, 1900) and through 1961, the position of the front has retreated very slowly with temporary halts or slight advances occurring around 1901 and 1935. Downmelting has proceeded rapidly, and the 200 foot high vertical face of 1898 is now a low-angle slope ending just above high tide.

Shoup Glacier is unique in two aspects: it has a very low accumulation area ratio (0.665) (Figure 88), and it has a sharp turn ($130^{\circ}$) just above the terminus (Figure 87). In length and area it is one of the more important glaciers of Prince William Sound.

## Valdez Glacier

Valdez Glacier is located in the northeastern corner of Prince William Sound. It originates in the central Chugach Mountains at around 6,500 feet elevation, and terminates at 300 feet elevation (Figure 91). It is just over 21 miles long and has an area of 62 square miles. The elevation of the firn line for Valdez Glacier is probably very nearly the same as on the nearby Columbia Glacier. Nielsen (1963) found the firn line at Columbia at 3,600 feet elevation. Using this elevation for Valdez Glacier, an accumulation area ratio of 0.705 (Figure 92) is produced. The glacier is about four to five miles wide in the upper parts, but the lower 9 miles average only one mile in width. The ice terminates about four and one-half miles from tidewater on a broad sandy outwash plain just outside of the mountain valley. The terminus of the glacier has a low-angle front

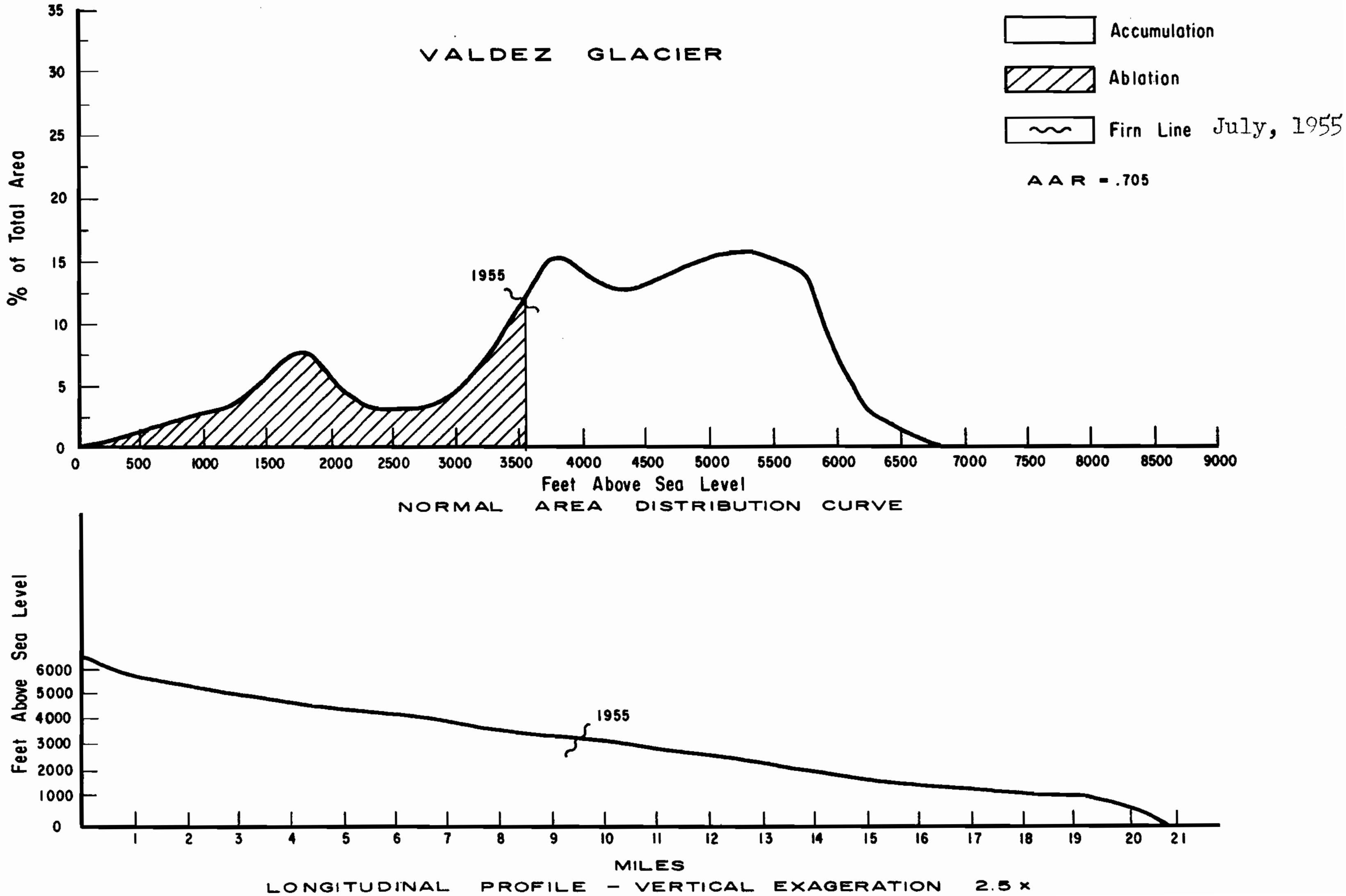



Based on U S Geological Survey Map, Valdez A-6.

VALDEZ GLACIER TERMINUS

Figure #91

Figure #92


VALDEZ GLACIER
Accumulation
Ablation
Firn Line
July, 1955
AAR = .705
% of Total Area
1955
Feet Above Sea Level
NORMAL AREA DISTRIBUTION CURVE
Feet Above Sea Level
1955
MILES
LONGITUDINAL PROFILE - VERTICAL EXAGERATION 2.5 x

that is covered with debris. The surface of the ice at the terminus is smooth with occasional ablation-opened crevasses. Large streams issue from both margins of the ice and join in the center of the outwash plain.

The first account of the Valdez area was by Whidbey (Vancouver, 1801), who entered Puerto de Valdez on June 19, 1794. His map shows no ice but places the head of the fiord about halfway between Valdez Narrows and the present town of Valdez. After entering Valdez Narrows, he noted (Vancouver, 1801, p. 317) a "small brook, supplied by the dissolving of the ice and snow on the mountains, flowed into the arm, which is about five miles from thence terminated in an easterly direction." The latitude given and the description of the fiord are essentially correct; however, Port Valdez is approximately 14 miles in length rather than the 5 Whidbey estimated. The fiord was described as being in the same latitude as what is now known as Columbia Bay where Whidbey had observed great falls of ice from the Columbia Glacier. He indicated surprise in Port Valdez that (p. 317) "in this branch no ice has been seen, notwithstanding it is terminated by shallow water at its head, and is surrounded by similar steep frozen mountains."

After studying Whidbey's map and description, Davidson (1904, p. 36) stated that if the shore on Whidbey's map "really was the limit of the bay, and the water was found shallow, then the whole eastern half of the Port with its 150 fathom depth, was occupied by a low moraine-covered glacier that hid the ice front."

In commenting on this, Tarr and Martin (1914) found six major objections to Davidson's conclusion. First, they felt that

Whidbey did not enter far enough through the narrows to see the whole length of the fiord. Second, no thundering ice falls or floating ice bergs were mentioned, as would be necessary with the stated depth of the fiord. Third, vegetation would have had to follow the melting ice very closely since mature trees were found growing right up to the terminus in 1909. Fourth, no similar ice fluctuations involving eight or nine miles advance and retreat have been found in eastern Prince William Sound. Fifth, if the Valdez Glacier was this extensive in 1794, then the Shoup Glacier, also in Port Valdez near Valdez Narrows, should have been much larger too, and would have been visible to Whidbey. Finally, a very long time would be needed to build the extensive outwash plain which extended 4-1/2 miles to the head of the fiord from the terminus. All of these objections by Tarr and Martin seem valid, and it is possible that Whidbey entered Jack Bay just to the south of the Valdez Narrows. This bay is about five miles long and runs roughly parallel to Port Valdez. There is no ice at the head and it has a shallow shore. It is surrounded by high mountains very similar to those of Port Valdez, and in most other respects fits Whidbey's description of "Puerto de Valdez."

The next account of Valdez Glacier is also erroneous and questionable. In 1882, Petroff (1884, p. 227) stated:

> In Port Valdez, at the northern extremity of the Sound, a glacier exists with a face 15 miles in length at the seashore, while its downward tract can be traced almost to the summit of the Alps. Huge ice bergs drop off its face with a thundering noise almost continually and drift out to sea, and the whole extensive bay is covered with small fragments, making it inaccessible even to boat navigation, and consequently, a safe retreat for seals, which here sport in the thousands. Port Fidalgo in the east and Port Wells in the west also have tremendous glaciers.

Tarr and Martin (1914) point out that even if all the present glaciers in this area were to expand and coalesce, they would still only present an ice front of approximately ten miles in width. In addition, while Port Wells does have many glaciers, Port Fidalgo has none. Vegetation and human records prove that no such expansion could have occurred between 1794 and sometime from 1868 to 1883. Tarr and Martin suggest that an error, possibly of printing or translation has occurred, since Petroff knew the Russian record of that area well.

In 1884, Lieutenant W. R. Abercrombie (1898, pp. 391-392) tried to reach the Copper River from Port Valdez. In his narrative he noted:

> I followed the right shore to Port Valdez, admiring the colossal mountains on each side of the inlet. These mountains are more or less covered with glaciers. . . rounding a sharp turn in the inlet the portage lies between two mountains, the valley being filled with a large glacier. The estimated altitude of the highest part of the portage is about 2,500 feet, and from the base of the mountains on the west to the lake on the east is about 15 miles. . . . it is very difficult to cross.

The distance, summit elevation, and direction cited all indicate that Abercrombie did not ascend the Valdez Glacier. The portage sought was one formerly used (1850-1860) by Copper River Indians on their way to Prince William Sound. A map made in 1885 from Abercrombie's data shows an ice tongue in the vicinity of the Corbin Glacier with a large lake east of it. The map (Allen, 1887, map 2), however, is on such a small scale that identification is impossible. Thus, the specific glacial condition of Port Valdez was uncertain as late as 1884, in spite of considerable earlier exploration.

The next information begins with the gold rush into the Klondike and Copper River areas. The Valdez Glacier became a highway of travel into the interior. Mr. Simonstad of Valdez (Tarr and Martin, 1914), who crossed the glacier in 1898, stated that 5,000 men landed that year, that 4,500 crossed the glacier pass, and that all but two or three hundred of them returned that fall by the same route. In April and May, 1898, U. S. Army detachments crossed the glacier pass several times, using horses to transport thousands of pounds of provisions and equipment. Schrader (1900) and several of the army officers described the glacier with its ice falls, benches, and crevasses. Their descriptions, photographs, and maps indicate only minor fluctuations in the terminus between 1898 and 1909 (Rice, 1900; Schrader and Spencer, 1909).

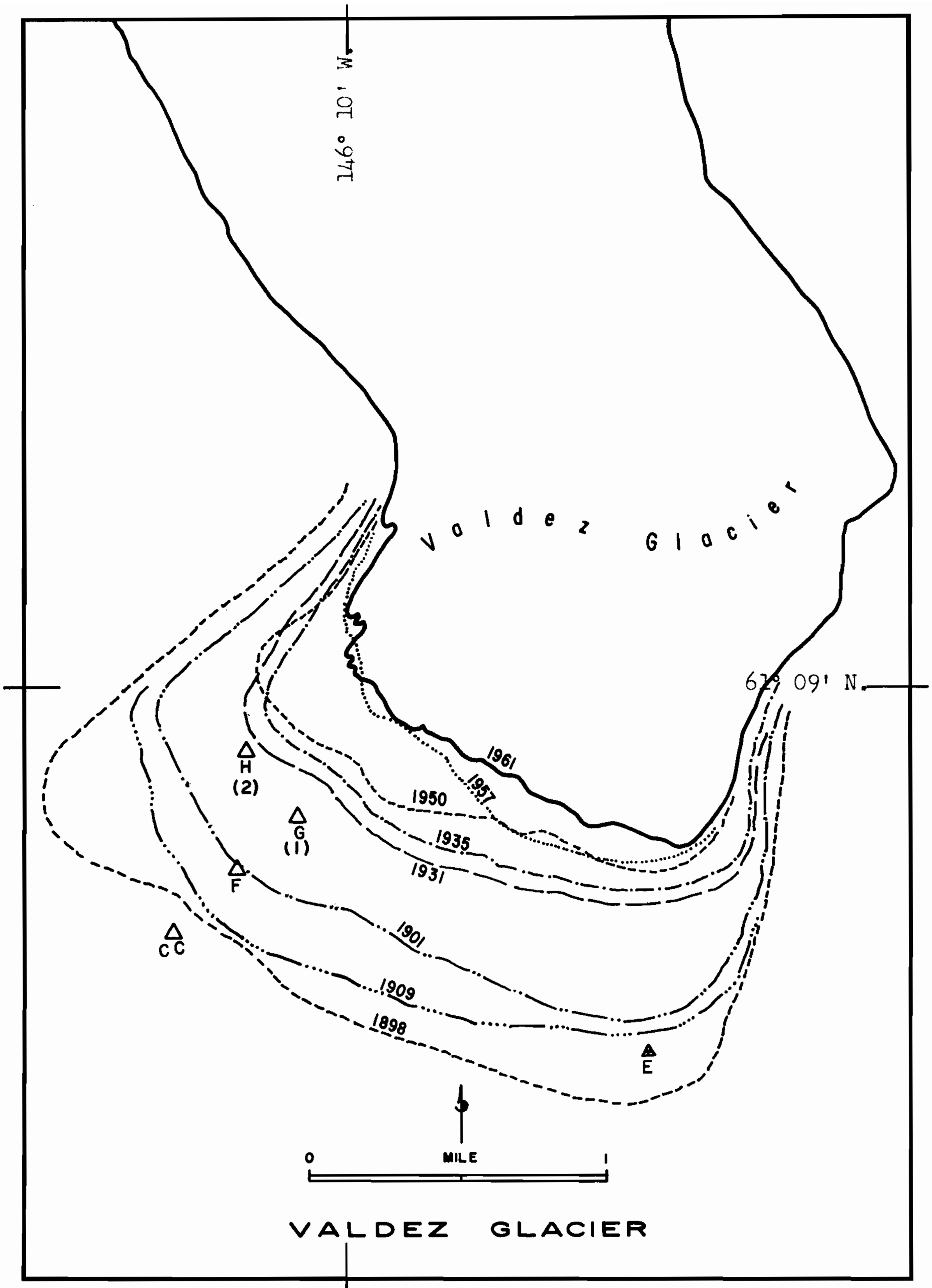
Between 1901 and 1911, L. S. Camicia (Tarr and Martin, 1914), an optician and watchmaker at Valdez, made an annual visit to the glacier and carefully measured the retreat of the ice front. During this ten-year period, he recorded an annual average retreat of about 58 feet. It is unfortunate that he failed to make his visits in 1906 and 1907 because during this time studies by Grant (Grant and Higgins, 1911) showed a surprising advance of 250 to 350 feet.

In 1909, Tarr and Martin (1914) visited the glacier, took many photographs, and prepared a map of the terminus. Their studies of vegetation, moraines, and stream channels suggest that the glacier had been wasting slowly for a very long time without any spectacular changes in the terminal area. Between 1909 and 1914, Reid (1916) reported a 200-foot recession of the ice.

In 1931, Wentworth and Ray (1936) found that considerable change had occurred in the ice front since the earlier visits. There was evidence of downmelting (300 feet) and the front itself had retreated an estimated 56 feet per year. According to Field (1932), the rate of recession between 1911 and 1914 was about 14 feet annually, and from 1914 to 1931 was 73 feet annually. Wentworth and Ray stated that the retreat from the western and eastern margin was probably several hundred yards.

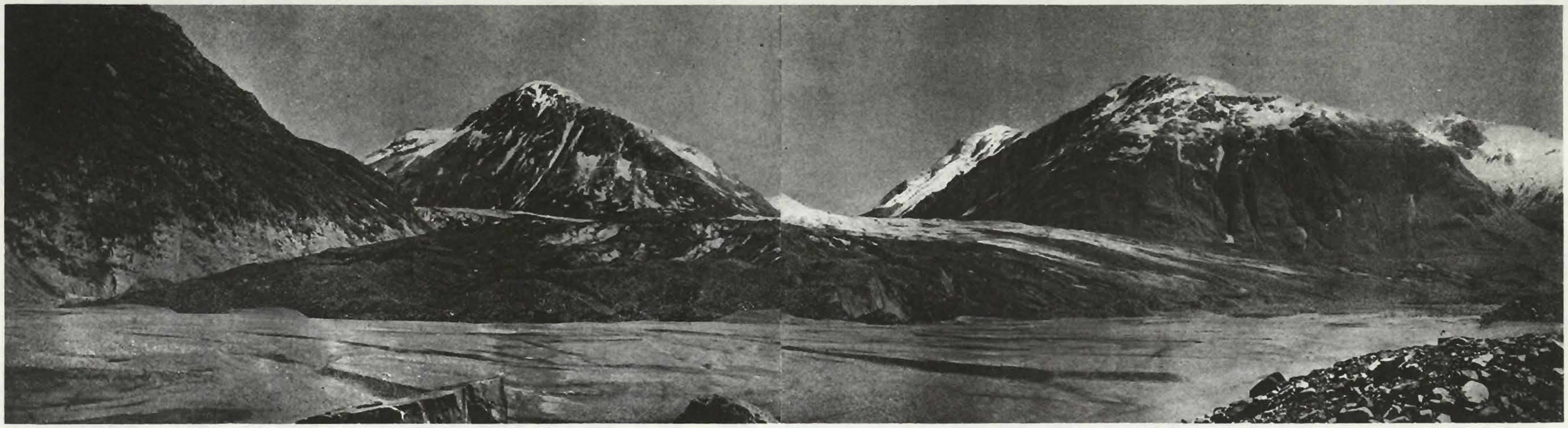
The I. G. Y. party visited the area in 1957 and observed a continuation of the steady retreat. From Tarr and Martin's station E, a retreat of 1,500 feet was noted since 1909. This gives an average retreat of only 33 feet per year from 1909 to 1957, 10 feet less than the 1898-1961 average (Figure 92A). Without exception, all accounts of the glacial terminus describe the heavy cover of debris. In 1957, there were large areas of relatively clean ice (Figure 93), suggesting that perhaps another short advance had occurred recently. This would account for the slower rate of retreat calculated in 1957. The ice along the eastern margin was no longer in contact with the stone buttress beneath east peak, and melt water from the Camicia Glacier was no longer dammed as reported by Tarr and Martin (1914). In 1957, the stream had a channel 20 to 50 feet wide between the ice and the rock wall. Downmelting had continued lowering the ice surface and destroying the benches and irregularities mentioned by Schrader (1900). Since many of the old stations were destroyed by meandering streams or impossible to find because of dense vegetation, the I. G. Y. party established two new stations and reoccupied station E on the eastern side.

In 1961, the terminus was resurveyed (Figure 92A) and old stations reoccupied for photographs (Figure 94). Five new survey



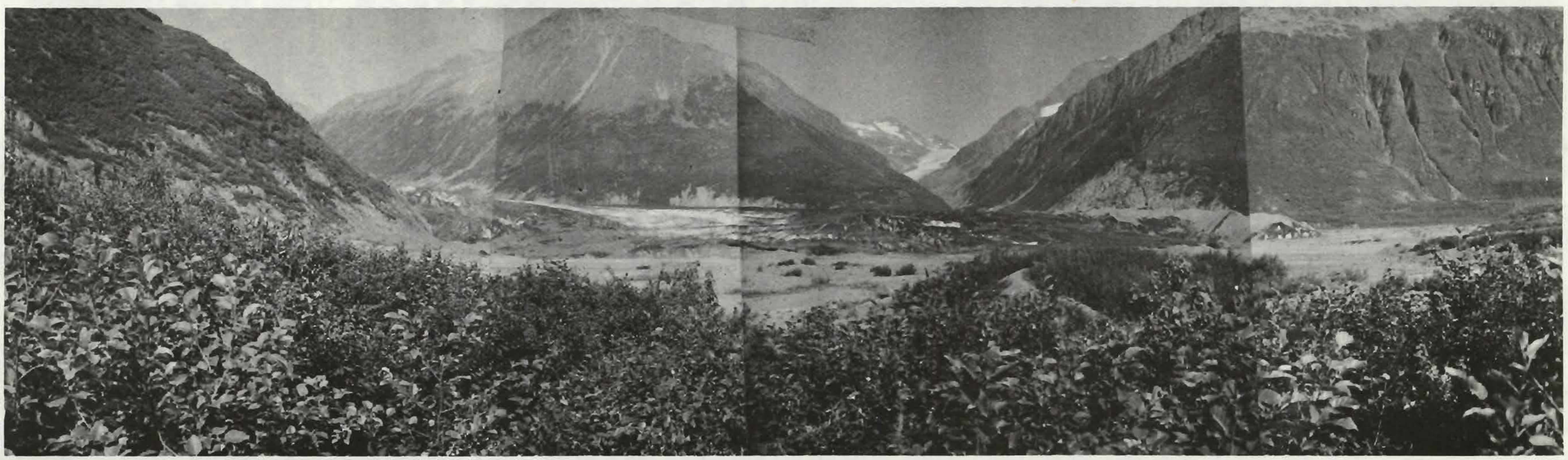

Based on U.S. Geological Survey Map, Valdez A-6.

Figure #92A



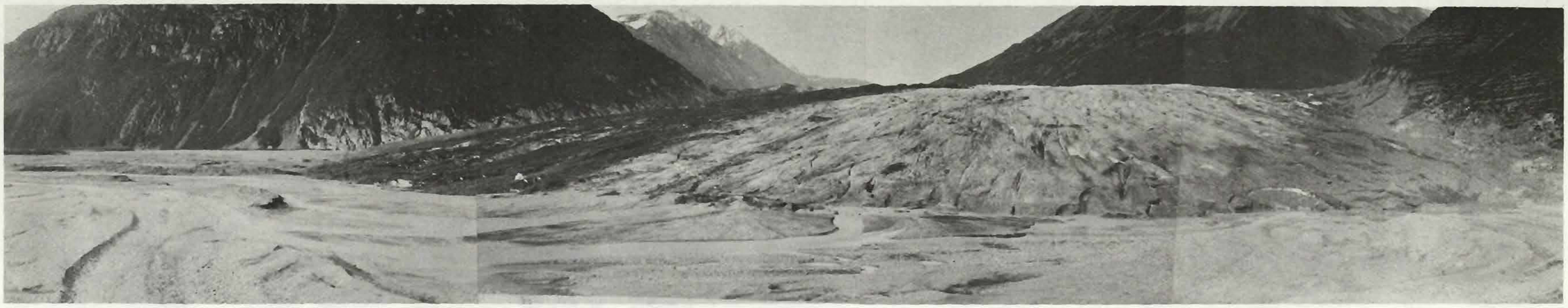
Valdez Glacier, west margin, 1909, from Station C
Photo plate XCIX, Tarr & Martin by P.S. Hunt



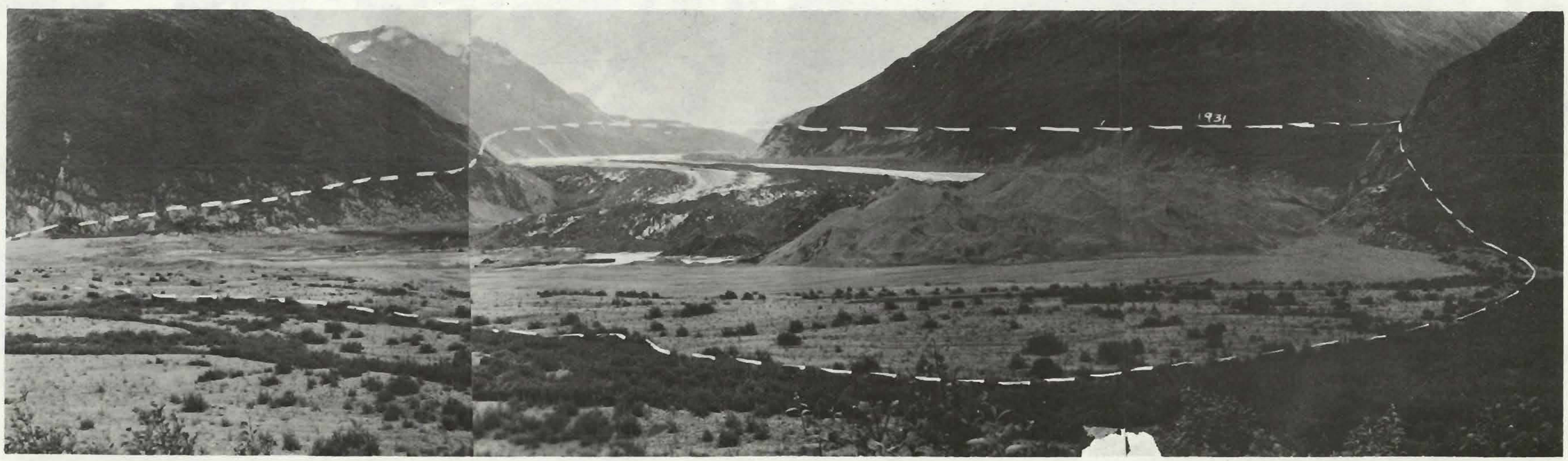


Valdez Glacier, west margin, 1957, from near Station C
Photos LV-57-B171,172,173,174 by Leslie Viereck

Figure #93



Valdez Glacier, east margin, 1931, from Station E
Photos f-31-221,222,223,224 by Wm. O. Field




Valdez Glacier, east margin, 1961, from Station E
Photos M-61-66,67,68 by M.T. Millett

Figure #94

and photostations were established and distances between stations chained. The position of the outermost ice of the terminus had not changed significantly since 1957; however, downmelting had changed the appearance of the front drastically (Figure 94). Several large sand cones along the eastern margin were relatively unchanged, but other surface features were very different. Stream drainage was no longer important along the margins; most of it came from under the ice, upwelling in small lakes at several places near the center. The gap found in 1957 between the ice and the steep rock wall in the southeastern part of the terminus was no longer open. The stream from Camicia Glacier drained under the ice instead of along side of it. The closing of the channel represents an advance of 20 to 50 feet in this part of the terminus since 1957. Small moraines along the frontal position of 1957 were further evidence of a small advance since then. Much of the ice near the outermost points was level or even had a reversed gradient. Near the western margin one such area of reversed gradient appeared to be three or four acres in size. A comparison of photographs (Figures 93 and 94) shows a lowering of the entire lower glacier.

Summary

The history of Valdez terminus has been predominantly one of retreat and downmelting. Two advances, in 1906-1907 and 1957-1958, have done very little to halt the rapid recession. Vegetation trimlines and ice levels in old photographs suggest a loss by downmelting of 800 feet in the present terminal area. Downmelting has produced large areas of thin ice in the terminus. As these melt, recession of the front will be very rapid. Melting in the lower glacier has concentrated debris on the surface, and the ice has become progressively dirtier.

## SUMMARY OF GLACIER TERMINI FLUCTUATIONS

With only one exception (Nielsen, 1963), all studies of the glaciers of the Prince William Sound area have concerned themselves with the fluctuations of the position of the terminus. Maps showing the position of the terminus have been made for only thirteen glaciers; however, good descriptive data is available for nine additional tongues. For those glaciers whose snouts have been mapped, it is possible to compute the area change due to advance or recession of the ice. This has been done in this study and the results are shown in Figure 95. Since the total area of these same glaciers is generally known, the fluctuations of the terminus area have also been plotted as a percentage of the 1950 total glacier size (Figure 96). It has not been possible to plot the fluctuations as a percentage of the total length or area for the other nine ice streams because neither length nor area is known. However, fluctuations measured in absolute values can be determined by measurement of the distance of the ice front from terminal moraines of known age. These measurements have been made by previous investigators and also by the author from conventional surveys and from airphotos. The length fluctuations have been plotted and are shown in absolute values in Figure 97, and as a percentage of 1950 total length in Figure 98. Each glacier is also identified with a letter, shown on the left side of the graph. These letters begin with Bainbridge Glacier as "A" and proceed clockwise around Prince William Sound to Valdez Glacier which is "V." These letters are also used instead of the names to identify the glaciers on subsequent charts and graphs (See also Figure 99.)

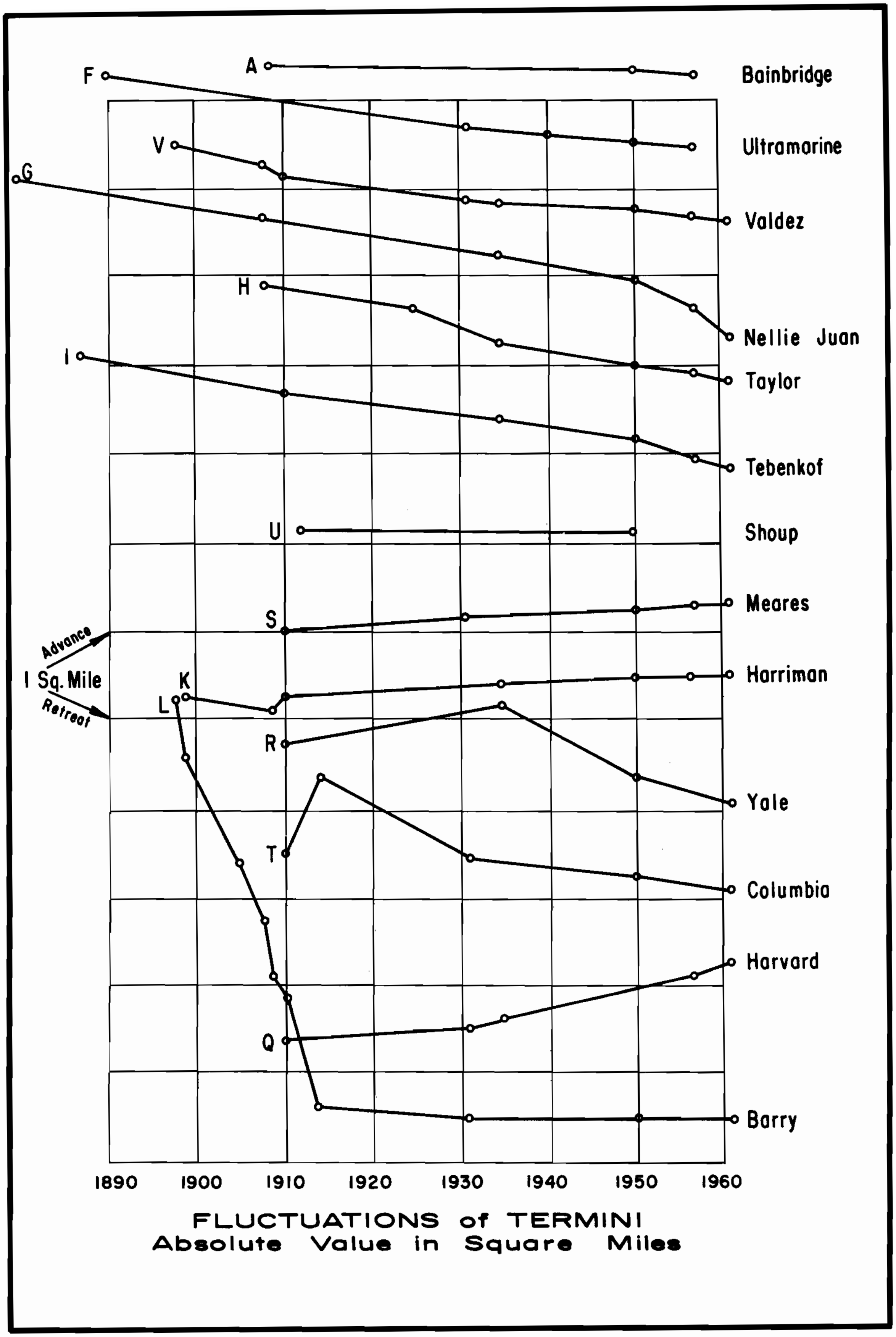

A
Bainbridge
F
Ultramarine
V
G
Valdez
H
Nellie Juan
I
Taylor
Tebenkof
U
Shoup
S
Meares
Advance
1 Sq. Mile
Retreat
K
Harriman
L
R
Yale
T
Columbia
Harvard
Q
Barry
1890
1900
1910
1920
1930
1940
1950
1960
FLUCTUATIONS of TERMINI
Absolute Value in Square Miles

Figure #95

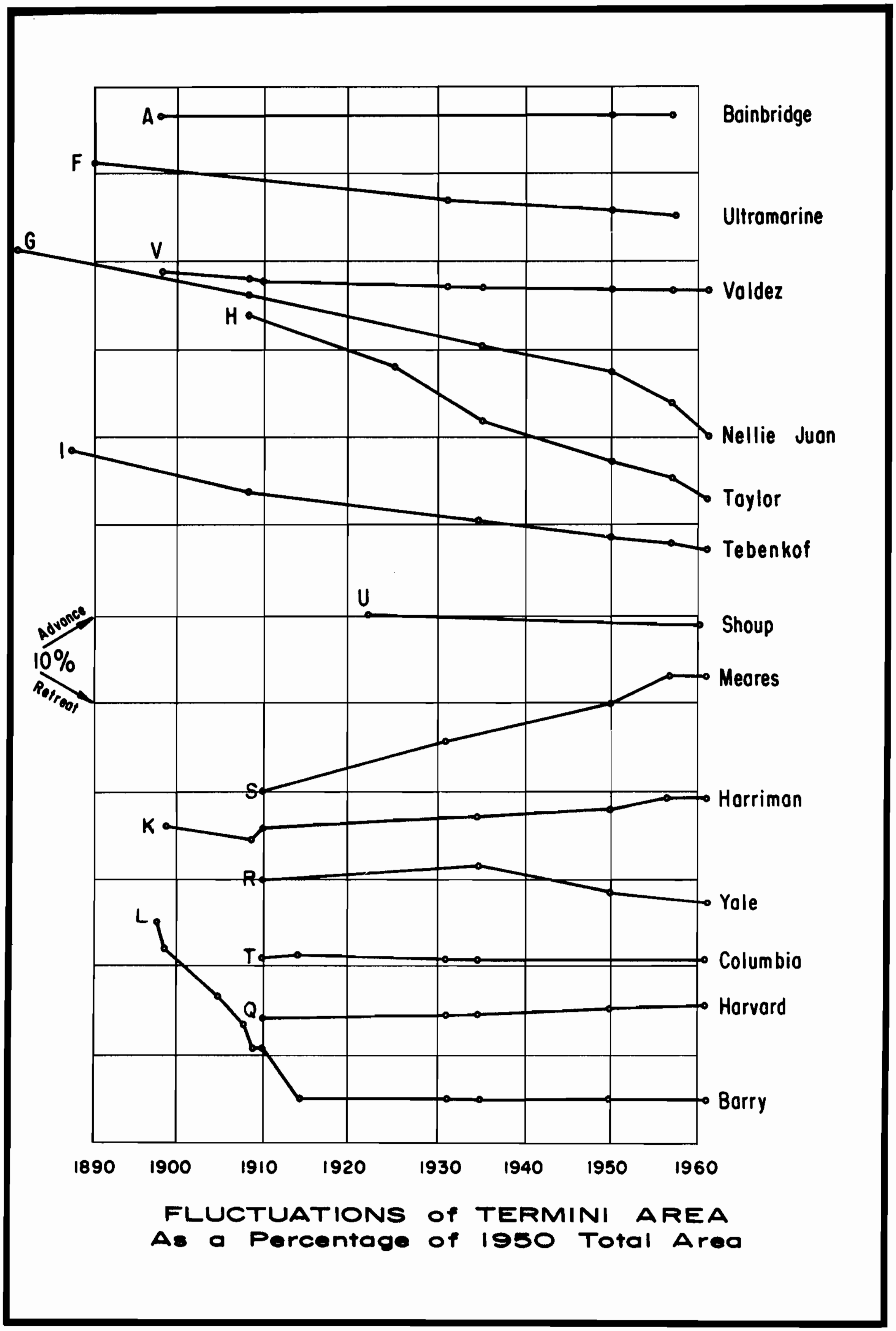

A
F
G
V
H
I
U
Advance
10%
Retreat
S
K
R
L
T
Q
Bainbridge
Ultramarine
Valdez
Nellie Juan
Taylor
Tebenkof
Shoup
Meares
Harriman
Yale
Columbia
Harvard
Barry
1890
1900
1910
1920
1930
1940
1950
1960
FLUCTUATIONS of TERMINI AREA
As a Percentage of 1950 Total Area

Figure #96

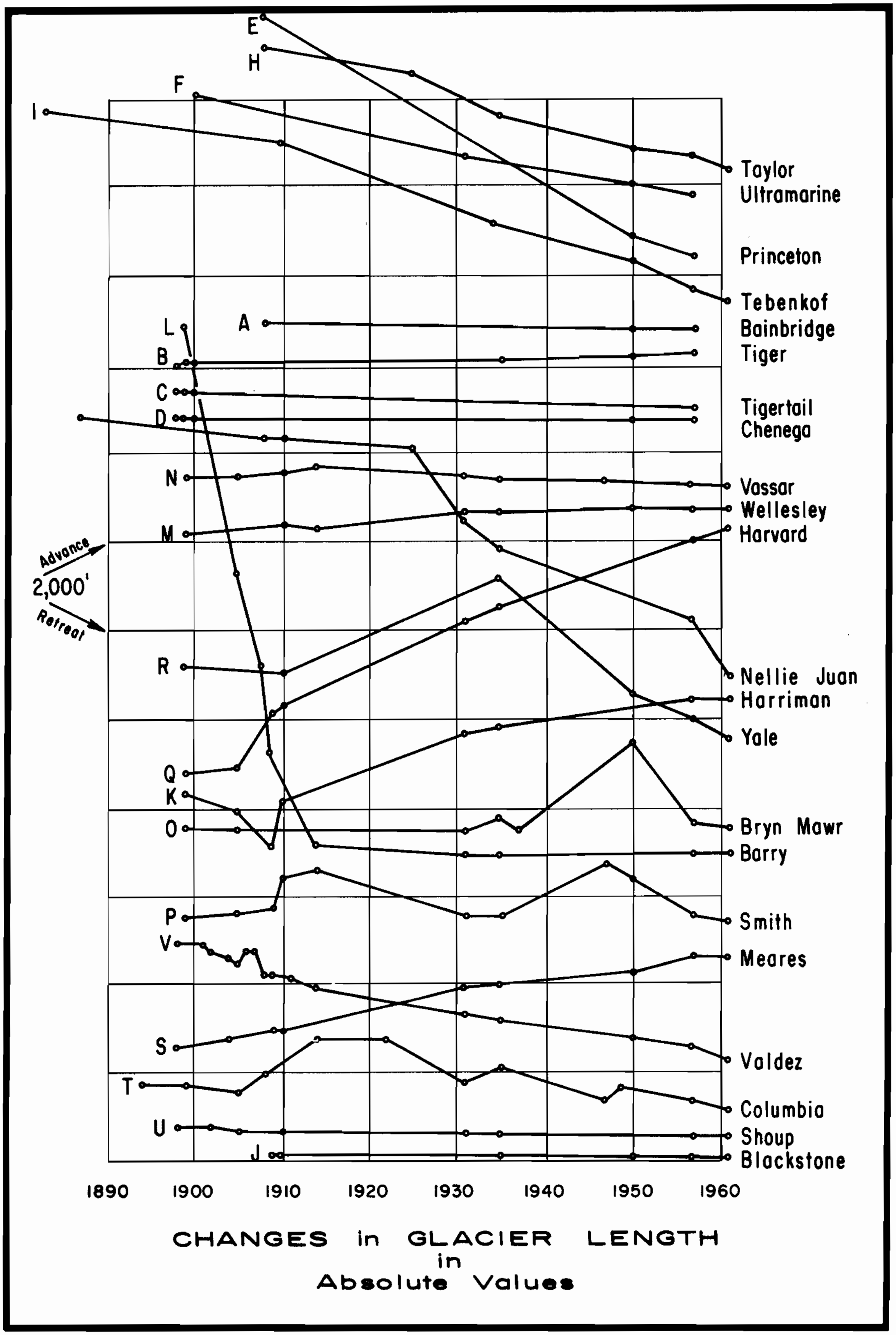

E
H
F
I
L
A
B
C
D
N
M
Advance
2,000'
Retreat
R
Q
K
O
P
V
S
T
U
J
Taylor
Ultramarine
Princeton
Tebenkof
Bainbridge
Tiger
Tigertail
Chenega
Vassar
Wellesley
Harvard
Nellie Juan
Harriman
Yale
Bryn Mawr
Barry
Smith
Meares
Valdez
Columbia
Shoup
Blackstone
1890
1900
1910
1920
1930
1940
1950
1960
CHANGES in GLACIER LENGTH
in
Absolute Values

Figure #97

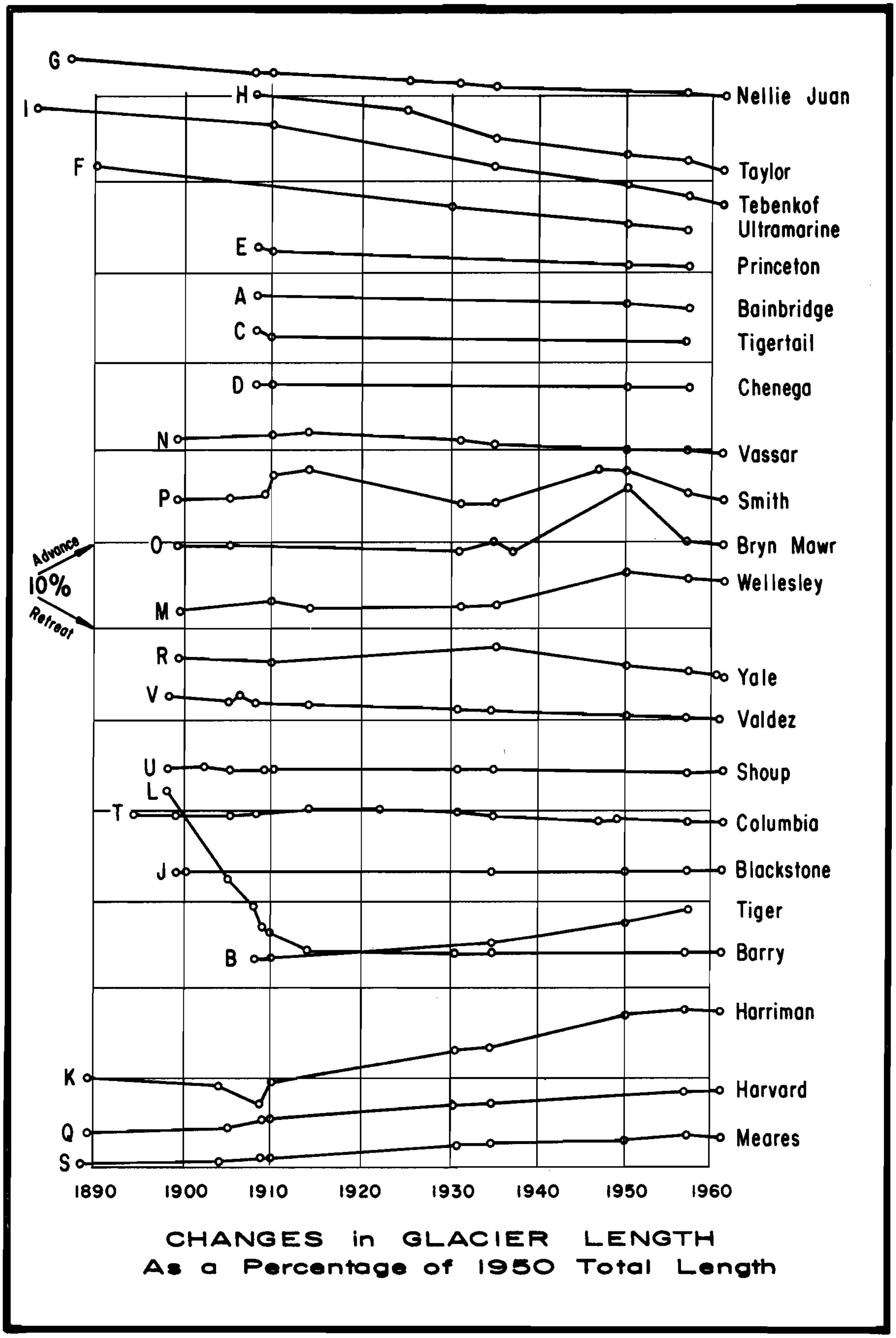

G
H
I
F
E
A
C
D
N
P
O
M
R
V
U
L
T
J
B
K
Q
S
Nellie Juan
Taylor
Tebenkof
Ultramarine
Princeton
Bainbridge
Tigertail
Chenega
Vassar
Smith
Bryn Mawr
Wellesley
Yale
Valdez
Shoup
Columbia
Blackstone
Tiger
Barry
Harriman
Harvard
Meares
Advance
10%
Retreat
1890
1900
1910
1920
1930
1940
1950
1960
CHANGES in GLACIER LENGTH
As a Percentage of 1950 Total Length

Figure #98

Examination of these charts of terminus behavior indicates periods of synchronous advance or recession for various glaciers. The first of these periods of advance is around 1910, when seven glaciers (MTQKNBP) were advancing. Three of these (PTN) reached a maximum around 1914 and then began to recede. The other four have continued to advance to the last observation in 1961. Again, in 1935, at least eight glaciers (TSKQRMOG) were advancing. Four of these were the steadily advancing ones seen in 1910. Another period of small advances occurred between 1947 and 1950. With the exception of the four continually advancing glaciers, the periods 1914-1931 and 1950-1961 were characterized by general recession.

Categories of Glacier Behavior. By using these graphs of glacier advance and retreat, it has been possible to delimit four categories of generalized glacier behavior:

1. Advancing glaciers - those which have had a more or less continuous history of advance and in 1961 were larger than when observed in 1910.

2. Stationary glaciers - those that have not undergone recession or advance during the period 1910-1961, and whose terminus position in 1961 was substantially unchanged from the reported position of 1910.

3. Fluctuating glaciers - those that have undergone both periods of advance and recession between 1910 and 1961, but whose terminus position of 1961 was near that observed in 1910.

4. Retreating glaciers - those that apparently have had a history of continual retreat and in 1961 were more than 300 feet behind their 1910 position.

Using the above criteria the following breakdown for the period 1910-1961 can be made.

Figure 99

| 1. Advancing Glaciers | 2. Stationary Glaciers | 3. Fluctuating Glaciers | 4. Retreating Glaciers |
|---|---|---|---|
| Harvard (Q) | Bainbridge (A) | Yale (R) | Princeton (E) |
| Meares (S) | Tigertail (C) | Bryn Mawr (O) | Taylor (H) |
| Harriman (K) | Chenega (D) | Smith (P) | Ultramarine (F) |
| Tiger (B) | Vassar (N) | Columbia (T) | Tebenkof (I) |
| Wellesley (M) | Blackstone (J) | | Barry (L) |
| | Shoup (U) | | Nellie Juan (G) |
| | | | Valdez (V) |

It can be seen from Figure 99 that great differences in snout behavior are represented by the glaciers of the Prince William Sound area. It is also obvious that there are more retreating glaciers than advancing ones. This is true not only generally but also during each decade since 1912 (Figure 103).

The subsequent chapter analyzes the snout fluctuations in relation to known climatic, climatically-derived, and physiographic factors in an attempt to determine whether there is a pattern to the diversity of observed behavior.

# CHAPTER III

## DATA ANALYSIS

Any change of climate that alters the accumulation or ablation rate of a glacier will eventually result in a change in the terminus area. The response at the terminus, however, will be delayed at a different rate for each glacier. Nye (1960, pp. 397-404) proposed a theory on the response of glaciers to climatic change. This theory held that climatic changes are propagated down the glacier by kinematic waves. He further stated:

> In the lower part, however, the response to climatic change is more complicated. . . . There is first a direct response; and, because of the inherent instability of a compression region, the thickness oscillations due to this effect tend to be in anti-phase with the rate of accumulation. There is also a delayed response which is propagated down the glacier as a traveling wave form. The amplitude of the wave changes as it travels; the inherent instability of the region tends to make it grow, but diffusion tends to diminish it. The effect observed at any point on the glacier, or at the snout, will depend on the combination (interference) between the direct and the delayed responses. A wide variety of resultant responses is possible, depending on the distance of travel of the wave, its period, the diffusion coefficient, and so on--but the response in any given case is calculable. Thus we begin to understand why it is that the glaciers in nature show such a rich variety of individual responses to climatic variations.

In order to calculate or predict snout changes by his theory, Nye requires the measurement of the following five quantities, all of which are functions of the distance down the glacier, and of time: (1) the discharge (the volume of ice per unit time passing through a transverse section of the glacier), (2) the breadth of the glacier at the surface, (3) the height of the surface above an arbitrary datum level (stage), (4) the rate of accumulation or ablation averaged along a transverse line, and (5) the slope of the upper surface. Unfortunately, the glaciers in the Prince William Sound area have not been studied in sufficient detail to provide any of the required data to use this theory. To do so would require the measuring of mass budgets and their changes. Since this type of measurement is not available for the glaciers in the Prince William Sound area, an attempt is made in this chapter to evaluate the relative importance of as many elements of the climatic and physiographic environment as possible, and to determine whether they are related to observed snout movements. This analysis is first applied to climatic conditions, the element that at first glance might be expected to hold the principal key to glacial behavior. Following this, climatically-related factors, physiographic factors, and response to the glaciographic situation are examined in connection with their possible effect on terminus activity.

## CLIMATE AND GLACIER ACTIVITY

### General Description of the Climate of the Prince William Sound Area

Prince William Sound is in the center of a crescent-shaped climatic area which stretches for 1,500 miles along the coast of Alaska from the southeastern panhandle to the Alaskan Peninsula. The main factors influencing the climate of this region are the high latitude, the warm ocean to the south, the great land masses to the north, and the almost continuous range of high mountains fringing the coast. Since there are many bays and fiords that penetrate deep into mountains, the climate as a whole is maritime in nature with some modifying continental influences.

Lying north of the Pacific Ocean, and with the great land masses of Siberia and North America to the west and east, the main part of Alaska is covered during the winter by relatively high atmospheric pressure. Over the immediate water surface to the south there usually exists a west-east trending trough of low pressure, commonly known as the Aleutian Low. This pressure trough marks the location of a major storm track followed by a great many of the cyclonic disturbances of the Northern Hemisphere in their west-to-east movement. Since the coastal mountains of southeastern Alaska and British Columbia act as a barrier to these eastward-moving depressions, many are delayed in the Gulf of Alaska for several days at a time. Sometimes, the Aleutian Low moves north of the coastal ranges, and its associated storms move through central Alaska on a secondary track.

When the lows pursue their normal track over the north Pacific and Gulf of Alaska in winter, northerly and northeasterly winds prevail in Prince William Sound bringing cold temperatures and little precipitation. However, when these lows take the course through central Alaska, southerly to southeasterly winds bring mild temperatures and heavy precipitation. Occasionally, when the Arctic High builds up to an exceptional degree, the northerly winds bring fair and unusually cold weather to all of Alaska. During these periods, ice sometimes forms in the more protected inlets and fiords of Prince William Sound, but winds and strong tidal currents soon break up this ice.

In the summer season, with the building up of pressure over the relatively cooler waters of the North Pacific and the heating of the land surface in the interior during the long days of high latitudes, a near reversal of the winter pressure pattern is created. A relative low forms in the interior of Alaska, and Prince William Sound has southerly to southwesterly winds, mild temperatures, and frequent gentle rain.

In both summer and winter, the precipitation is largely orographic and at sea level accumulates to between 60 and 150 inches in a year. This precipitation falls as a steady, light to moderate rain or snow during 220 to 230 days of the year. In association with this precipitation pattern, cloudiness averages more than 75 per cent, with a typical year being composed of about 275 cloudy, or partly cloudy days, and 90 clear days. Between 35 and 40 per cent of the total precipitation occurs during the fall months of September, October, and November, when the onshore winds are from the south. The snow season, at sea level, extends from November to April. Average depths of fall during the winter vary from about 31 inches at Cordova to over 60 inches at Valdez. Infrequent mild thunderstorms may occur at any time of the year. Heavy fogs drift into Prince William Sound on an average of 20-25 days a year, being more common in the summer.

Adequate climatic data for Prince William Sound are not available. Records have been kept irregularly for as many as six stations, but only two stations have been maintained long enough for meaningful trends and averages to be derived (U. S. Weather Bureau, 1909-1961; Mitchell, 1958). Both of these stations--Cordova and Valdez--are situated in the eastern end of the Sound, very near sea level. Although not located in the center of the area studied, these stations are fortunately placed. Cordova is close to the open sea and therefore is directly subject to oceanic influences. Valdez, on the other hand, lies at the head of a long fiord which penetrates the lofty Chugach Mountains; and, although it is largely dominated by maritime influences, it is different from Cordova in that continental effects are felt.

Data from the two stations, Valdez and Cordova are summarized and presented in Figure 100. From this data it is apparent that temperatures are unusually high for this latitude, and that seasonal and diurnal ranges are rather low. Precipitation is heavy, with a pronounced maximum in the autumn. Because these stations are nearly at sea level, only a small percentage of the precipitation at Cordova and Valdez takes the form of snow. Higher elevations have lower temperatures and greater precipitation with an increasing proportion of snow.

The maritime influences at Cordova and the slight continental influences at Valdez become apparent when records from these two stations are compared. Cordova has a mean annual temperature which is 5.1° F. higher than that of Valdez, and mean monthly temperatures are higher in every month, with temperature differences being much greater in winter. Monthly maxima, however, show that Valdez is warmer in the summer and that Cordova is warmer in the winter. Monthly minima are lower at Valdez all

| Station | Length of record years | Annual Mean | January | February | March | April | May | June | July | August | September | October | November | December |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Mean Temperatures, Fahrenheit** | | | | | | | | | | | | | | |
| Cordova | 42 | 38 | 27 | 26 | 30 | 37 | 43 | 49 | 52 | 53 | 48 | 40 | 31 | 27 |
| Valdez | 42 | 35 | 19 | 21 | 22 | 35 | 43 | 50 | 53 | 53 | 48 | 37 | 26 | 20 |
| **Mean Precipitation, in Inches** | | | | | | | | | | | | | | |
| Cordova | 42 | 148 | 17 | 8 | 10 | 9 | 12 | 11 | 14 | 20 | 20 | 20 | 15 | 5 |
| Valdez | 42 | 60 | 6 | 5 | 4 | 3 | 5 | 4 | 4 | 7 | 8 | 8 | 7 | 5 |

FIGURE #100

CLIMATIC DATA FOR CORDOVA AND VALDEZ
MONTHLY MEANS OF PRECIPITATION AND TEMPERATURE

year long. The contrast between the minima for the year (+6° F. at Cordova and -10° F. at Valdez) is particularly striking.

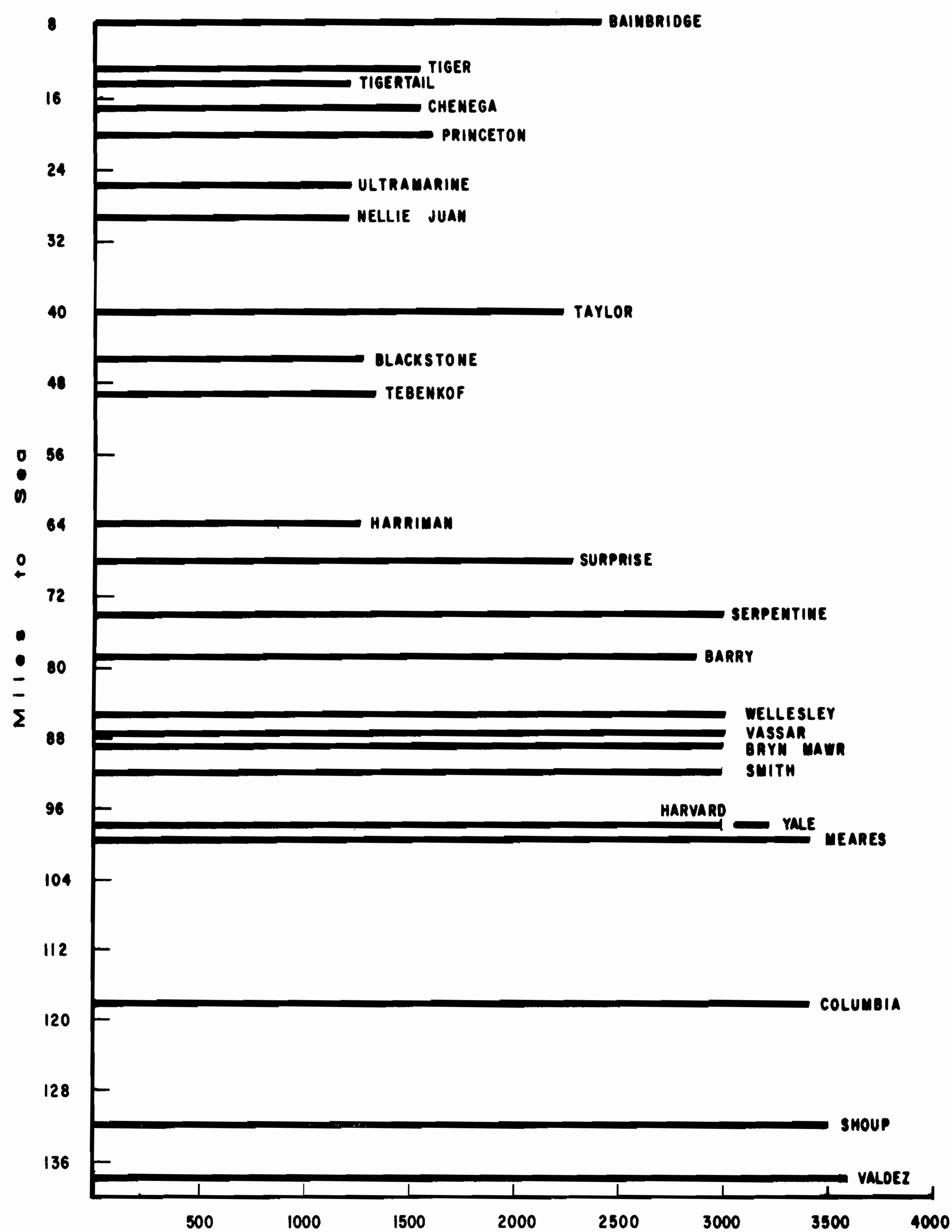
Perhaps the most notable difference between the two stations is in total annual precipitation. Cordova receives 147.5 inches and Valdez less than one-half that amount, 59.8 inches. Cordova receives an average of 122 inches of snow annually and Valdez receives 246 inches, or slightly more than twice the amount of Cordova. Seasonal distribution of precipitation is about the same at the two stations.

The climate of the inner, ice-surrounded fiords is thus decidedly more severe than that along the open coast; and is less maritime, with continental effects being felt. One of the effects of being further from the open sea is shown by the elevation of the firn lines (Figure 101). Those glaciers nearer the open ocean usually have lower firn lines, while those farther away have higher ones.

## Recent Climatic Trends in the Prince William Sound Area

Owing to the great year to year variability of the Alaskan climate, any gradual long-term trends in temperature or precipitation may not be shown by the incomplete climatological records. However, in the years for which climatic records are available (1912-1961), there are easily distinguishable periods when temperature and/or precipitation were above or below the fifty-year mean.

The ten-year means of precipitation and temperature for Valdez and Cordova are shown in Figure 102. However, in only five of the twenty cases are there ten consecutive years of observations,

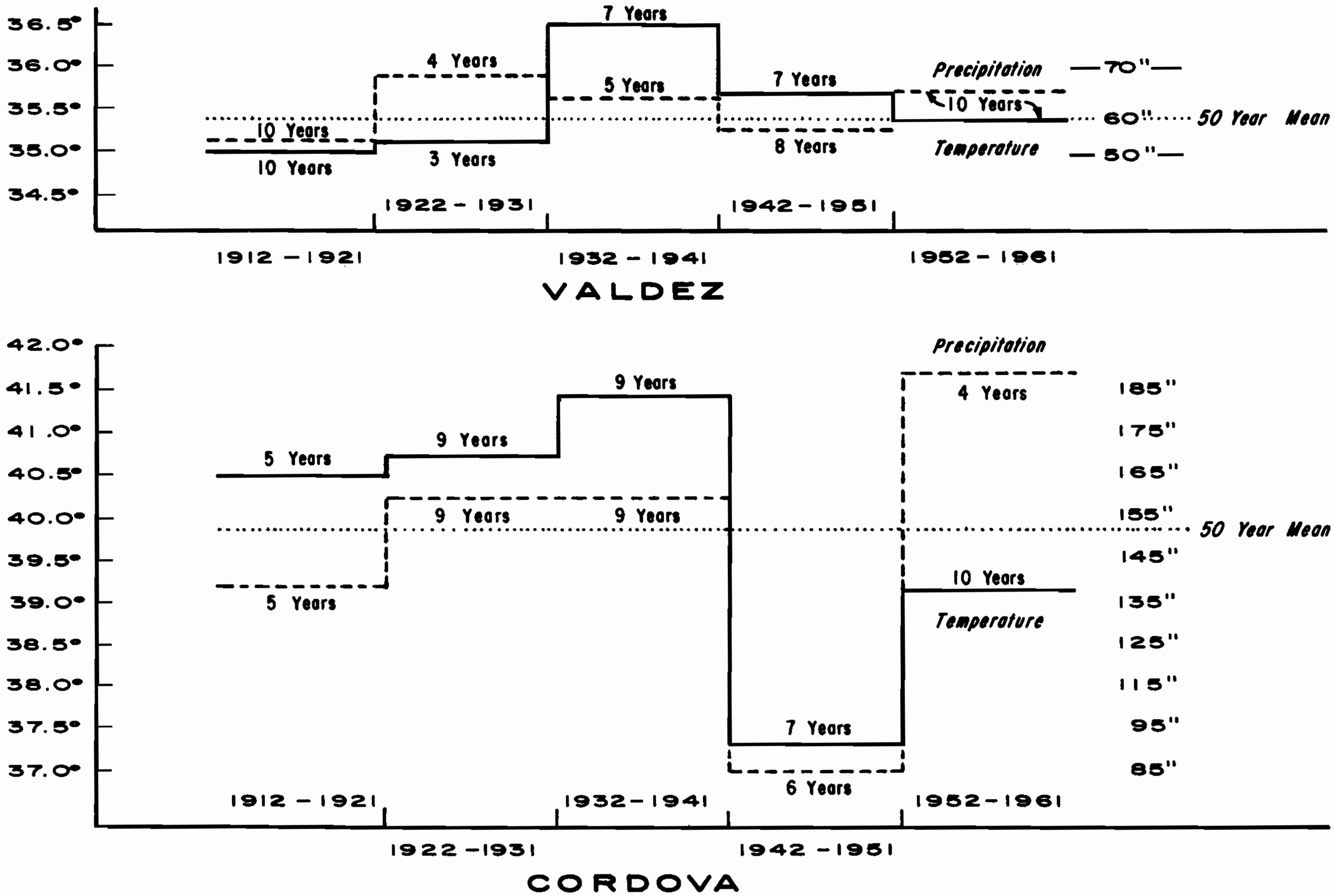



Relationship of Firn Line Elevation and Distance from the S.W. Entrance of Prince William Sound

Figure 101

Figure #102






10 Year Mean Temperature and Precipitation for Valdez and Cordova
No. of years of record indicated in each interval

and some of the other ten-year means have been computed with as few as three years' records. Nevertheless, these means are useful, and the parallel trends of the records from two stations increase the reliability of the limited data.

Precipitation. In the time interval, 1912-1921, both stations averaged slightly below normal precipitation. ("Normal," in this description, refers to the fifty-year mean.) This is followed by a nearly-equal increase for both stations during 1922-1931, when they had above normal moisture. In 1932-1941, the precipitation at Valdez dropped slightly, but was still above the fifty-year mean, while Cordova continued at the same above-normal rate as in the previous decade. In the next ten-year period, 1941-1952, both stations dropped below normal; Valdez only slightly, but Cordova very markedly. In the following decade, 1952-1961, both stations experienced an increase in precipitation that placed them above their fifty-year means.

Records of clear and cloudy days have been kept too intermittently to be significant. In addition, these observations were no longer recorded after 1946.

Temperature. In the decade 1912-1921, Valdez experienced slightly below normal temperatures, while Cordova was somewhat warmer than its fifty-year mean. Both stations had a slight rise in the 1922-1931 period, but Valdez was still cooler than normal. In the decade 1932-1941, both stations recorded a rather strong increase in temperature, putting both stations well above their fifty-year means. Between 1942 and 1951, both stations cooled considerably; Valdez still remaining slightly above normal, and Cordova dropping far below normal. From 1952 to 1961, temperatures rose at Cordova though they still remained below normal. At Valdez a drop of temperature occurred, taking the decade mean down to the fifty-year mean.

In both temperature and precipitation, Cordova and Valdez recorded an almost steady increase during the three decades from 1912 to 1941. This was followed by a decade of near-normal moisture and temperature for Cordova. In the most recent decade, 1952-1961, Valdez remained near the fifty-year mean, while Cordova was cooler and much wetter than normal.

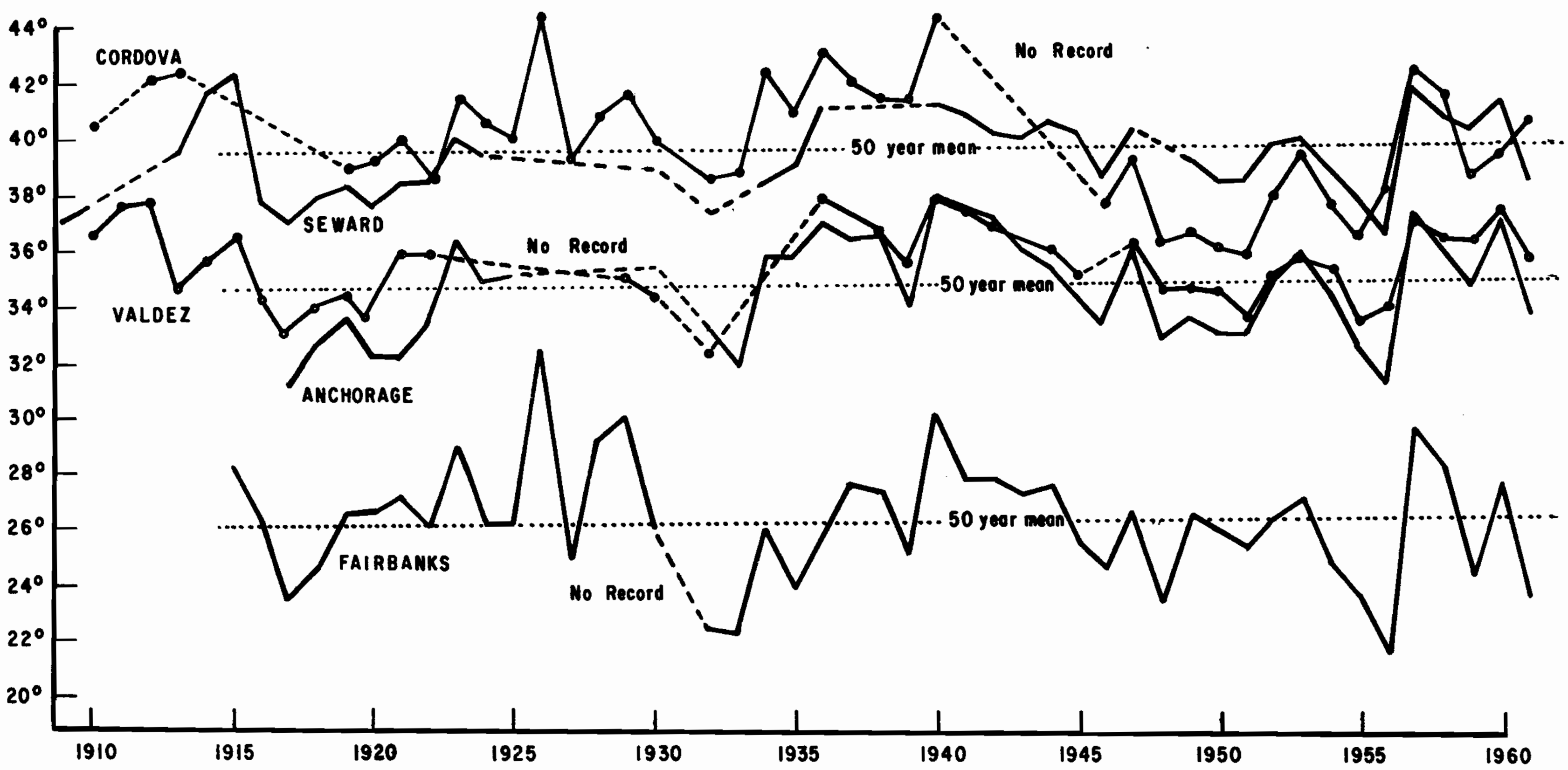
Climatic Trends. Despite the gaps in the records, the annual means of precipitation and temperature (Figure 103) show a close relationship between the climate of Prince William Sound and that of other parts of the state during the last five decades.

Characteristics of the longer-term climatic trends cannot be determined from the existing climatic records. However, pollen studies in the area (Heuser, 1955) and geobotanical studies (Karlstrom, 1961) indicate a post-Wisconsin climatic history similar to that of the rest of northwestern North America, except that there was a slightly later date for the so-called "Little Ice Age." At least two ecologists (Heuser, 1955, 1960; Cooper, 1942) have proposed that the late post-glacial surge of ice which has slackened elsewhere is only now reaching its maximum in Prince William Sound.

## Relationship Between Climatic Fluctuations and Terminus Fluctuations

At the end of Chapter II, 22 of the glaciers in the Prince

Figure #103

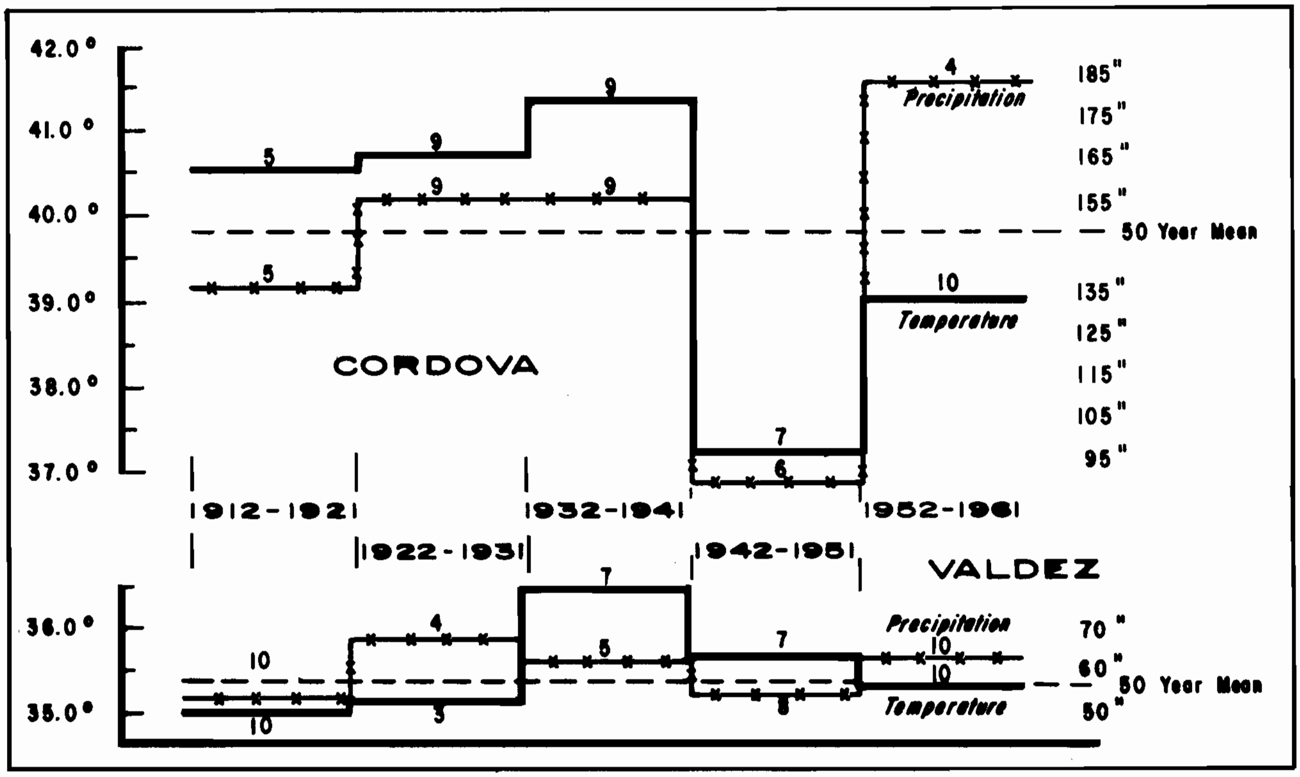


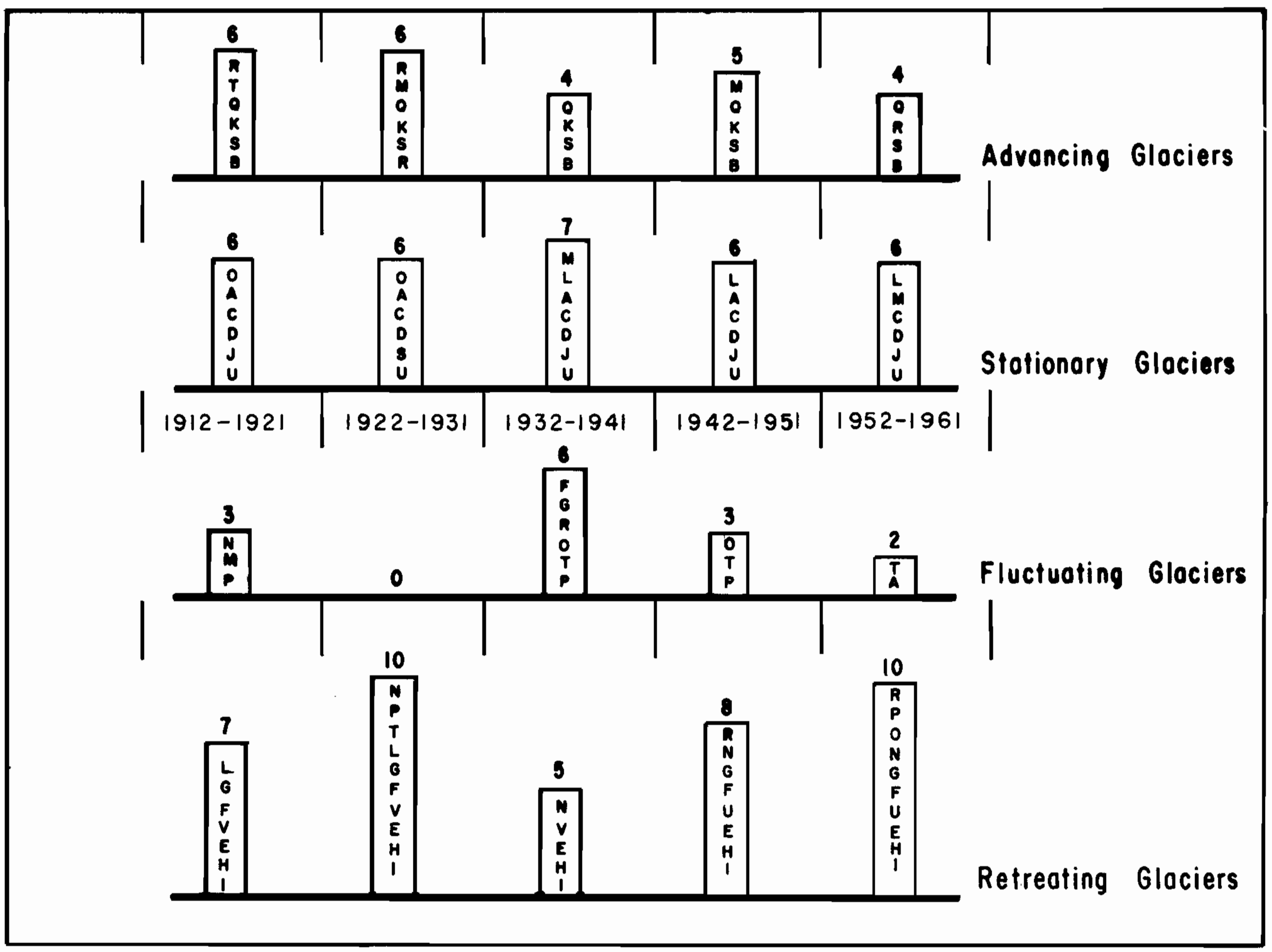

Mean Annual Temperatures
for
FAIRBANKS, ANCHORAGE, CORDOVA, SEWARD and VALDEZ

William Sound area were classified into four categories: advancing, retreating, fluctuating, and stationary. To see if there is a direct connection between climate and these patterns of behavior, the activity of the glacier snouts has been compared with the ten-year means of precipitation and temperature (Figure 104).

Because a lag in the terminus response to climatic change will always be present, though differing for each glacier, this comparison is not very significant, and is given only to show a lack of correlation between sketchy climatic data and glacial terminus change. During the decade 1932-1941, while temperature increased and precipitation remained about the same, or decreased, the number of advancing glaciers was slightly reduced, the number of stationary glaciers increased slightly, and the number of fluctuating glaciers increased greatly. The number of retreating glaciers also decreased slightly. In the following decade, 1942-1951, when at both weather stations precipitation and temperatures fell considerably from the previous ten-year period, some glaciers continued to advance; but the number which were stationary remained about the same, the number of fluctuating glaciers decreased, and the number of retreating glaciers increased. In the most recent decade, 1952-1961, precipitation increased in both areas to far above normal at Cordova, and slightly above normal at Valdez. Temperatures at both stations were below normal. This increase of precipitation with below-normal temperatures would seem to produce favorable conditions for glacier growth. However, the opposite is to be noted in that the number of advancing glaciers decreased, the number of stationary glaciers remained the same, the number

Climatic Data of Valdez and Cordova




Glacier Activity of the Prince William Sound Area

Figure #104

of fluctuating glaciers dropped, and the number of retreating glaciers increased greatly. The wide variation from the assumed pattern of behavior does not necessarily indicate a low correlation between climate and snout behavior in Prince William Sound, but demonstrates the complexity of this relationship and the inadequate data available for analysis.

## CLIMATOGRAPHIC FACTORS AND GLACIER ACTIVITY

Several factors of the physical environment, firn line elevation, glacier orientation, and distance from the sea, while not strictly climatic factors, are climatically related and are here termed "Climatographic Factors." To determine the influence of these factors in glacier terminus behavior, the termini fluctuations have been plotted according to their behavior categories and the value of the factors investigated.

### Firn Line Elevation.

Firn line elevation is generally considered an important factor in glacier health. Therefore, the glaciers were plotted according to the height of their firn lines above sea level (Figure 105). Contrary to what one might expect, many of the retreating glaciers in the Prince William Sound area have low firn lines, and some of the advancing glaciers have high firn lines. This random distribution points out the danger of using this single criterion to judge snout behavior.

FIGURE #105

ELEVATION OF THE FIRN LINE, FEET ABOVE SEA LEVEL

| | 0-1250 | 1250-1700 | 1700-2500 | 2500-3200 | +3200 |
|---|---|---|---|---|---|
| 1. Advancing | K | | B | MQ | S |
| 2. Stationary | C | JD | A | N | U |
| 3. Fluctuating | | FIE | | OP | RT |
| 4. Retreating | G | | H | L | V |

Elevation of Accumulation Area.

Glaciers were next plotted according to the mean elevation of their accumulation areas as computed from topographic maps (Figure 106). Data for five glaciers is not known exactly and has been estimated from airphotos and descriptions. Most of the retreating glaciers have low elevation accumulation areas while most of the advancing glaciers have accumulation areas of medium or medium high altitudes; however, the correlation is not very high and is not felt to be very significant.

FIGURE #106

ELEVATION OF MEAN ACCUMULATION, FEET ABOVE SEA LEVEL

| | 0-2600 | 2600-3500 | 3600-4500 | +4500 |
|---|---|---|---|---|
| 1. Advancing | | KB | S | MQ |
| 2. Stationary | | CJDA | N | UTR |
| 3. Fluctuating | | | L | PO |
| 4. Retreating | EFGI | | H | V |

Orientation.

Studies of glaciers in the Rocky Mountains (Millett, 1956) indicated the importance of glacier orientation to ablation and glacier health. If this orientation factor is generally valid, it should also be important to glaciers elsewhere; the ice streams of Prince William Sound accordingly were plotted with respect to their orientation (Figure 107). Again, a random distribution was obtained. The previous studies suggested that early afternoon sun was the most effective in ablation. Glaciers in each category are found with almost every possible orientation and suggest that orientation is not an important factor in snout behavior in Prince William Sound.

FIGURE #107

ORIENTATION OF TOTAL GLACIER

| | N $315^{o}$-$45^{o}$ | E $45^{o}$-$135^{o}$ | S $135^{o}$-$225^{o}$ | W $225^{o}$-$315^{o}$ |
|---|---|---|---|---|
| 1. Advancing | K | BM | | SQ |
| 2 Stationary | CJ | UAND | | |
| 3. Fluctuating | | O | TP | R |
| 4. Retreating | IG | HF | VLE | |

To see whether orientation of the accumulation area or the ablation area may be important, these were also plotted according to compass points (Figures 108 and 109). Grouping in these charts indicates that some advancing and stationary glaciers have their tongues oriented toward the north and east, whereas several re-treating or fluctuating snouts point more to the south and east.

However, there is no really significant correlation of glacier orientation and snout activity.

Mild temperatures are found near sea level in Prince William Sound because of onshore winds from the large body of warm water to the south. However, no specific wind direction data exist for the area. Thus it has not been possible to determine the relationship of glacier orientation to winds.

FIGURE #108

ORIENTATION OF GLACIER TERMINUS

| | N $315^o$-$45^o$ | E $45^o$-$135^o$ | S $135^o$-$225^o$ | W $225^o$-$315^o$ |
|---|---|---|---|---|
| 1. Advancing | | BMK | QS | |
| 2. Stationary | JC | ADU | N | |
| 3. Fluctuating | | | OPT | R |
| 4. Retreating | GI | F | EHLV | |

FIGURE #109

ORIENTATION OF ACCUMULATION AREA

| | N $315^o$-$45^o$ | E $45^o$-$135^o$ | S $135^o$-$225^o$ | W $225^o$-$315^o$ |
|---|---|---|---|---|
| 1. Advancing | | BKM | | QS |
| 2. Stationary | J | ACDN | | U |
| 3. Fluctuating | | | OPT | R |
| 4. Retreating | I | FGLV | HE | |

Distance to the Sea.

To determine whether or not distance from the open sea was of importance to snout fluctuations, the glaciers were next plotted according to their distance from the southwest entrance to Prince William Sound (Figure 110). Grouping in this chart shows most advancing glaciers rather far from open water, while many retreating ones are much closer to the sea. However, the scattering of glaciers shown on the chart suggests that this factor is not very important.

FIGURE #110

MILES FROM THE SEA (SW ENTRANCE)

| | 0-20 | 20-60 | 60-100 | +100 |
|---|---|---|---|---|
| 1. Advancing | B | | MQKS | |
| 2. Stationary | ACD | J | N | U |
| 3. Fluctuating | | | ROP | T |
| 4. Retreating | E | FGHI | L | V |

## PHYSIOGRAPHIC FACTORS

Size.

The first physiographic factor considered is glacier length. In the high Canadian Arctic, snout behavior has been found to be related directly to glacier size (Müller, 1962). The ice streams of Prince William Sound have, therefore, been plotted according to snout behavior and length to see whether there is any correlation between these factors in this part of Alaska (Figure 111). While there is no consistent pattern or direct correlation between snout behavior and glacier length for these glaciers, it is obvious that most of the stationary and retreating glaciers are between 5 and 10 miles in length. This, however, is not significant, since most of the glaciers in the other categories are also of this length.

FIGURE #111

GLACIER LENGTH, MILES

| | 0-5 | 5-10 | 10-20 | 20-30 | +30 |
|---|---|---|---|---|---|
| 1. Advancing | M | BK | S | Q | |
| 2. Stationary | C | NAJ | DV | | |
| 3. Fluctuating | | OP | | R | T |
| 4. Retreating | | EFGHI | L | V | |

Since the area covered by a glacier is also an indicator of size, the glaciers were next compared according to their total area (Figure 112). Using these comparisons, it was found that while there is a slight tendency for the smaller glaciers to be less active than the larger ones, no clearcut relationship seems to exist between glacier area and snout behavior.

FIGURE #112

GLACIER AREA, SQUARE MILES

| | 1-10 | 10-20 | 20-100 | +100 |
|---|---|---|---|---|
| 1. Advancing | M | | BKS | Q |
| 2. Stationary | CN | A | JR | O |
| 3. Fluctuating | OP | | U | T |
| 4. Retreating | HG | FI | ELV | |

Glacier Gradient.

The glaciers were next plotted according to the mean gradient of the total glacier (Figure 113), but little or no significance can be seen in the grouping. They were next plotted by the gradient of the accumulation areas (Figure 114) and then by the gradient of the ablation areas (Figure 115). The scattering of glaciers throughout the graphs suggests the unimportance of gradient on snout behavior.

FIGURE #113

MEAN GRADIENT OF TOTAL GLACIER, FEET/MILE

| | 200-400 | 400-600 | 600-800 | + 800 |
|---|---|---|---|---|
| 1. Advancing | | BQ | SK | M |
| 2. Stationary | D | AV | J | NC |
| 3. Fluctuating | T | R | | PO |
| 4. Retreating | V | FIE | LG | H |

FIGURE #114

GRADIENT OF ACCUMULATION AREA, FEET/MILE

| | 200-400 | 400-600 | 600-800 | + 800 |
|---|---|---|---|---|
| 1. Advancing | | B | | MK |
| 2. Stationary | D | JA | U | NC |
| 3. Fluctuating | | | | PO |
| 4. Retreating | VE | FGI | | H |
| Insufficient data for QSRTL | | | | |

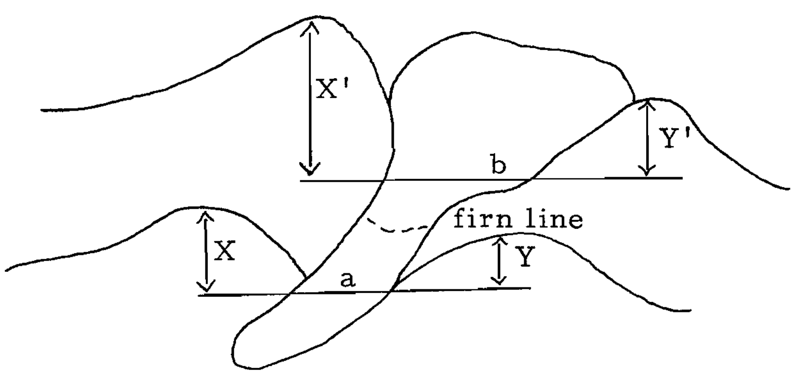
FIGURE #115

GRADIENT OF ABLATION AREA, FEET/MILE

| | 200-400 | 400-600 | 600-800 | +800 |
|---|---|---|---|---|
| 1. Advancing | K | | | MB |
| 2. Stationary | U | A | C | JND |
| 3. Fluctuating | | | | OP |
| 4. Retreating | V | I | EFGH | |
| Insufficient data for QSRTL | | | | |

Physiography of Surrounding Area.

The significance of physiography to snout behavior was calculated in the following way:




$\frac{X + Y}{a}$ = Physiography near terminus (this was usually figured at 1,000' elevation).

$\frac{X' + Y'}{b}$ = Physiography in accumulation area.

X and Y = Heights of flanking slopes near the terminus, in feet, above glacier level at a.

X' and Y' = Heights of flanking slopes near the center of accumulation, in feet, above glacier level at b.

Thus, the greater the resulting number, the more rugged the relief. This number is referred to as the physiographic index.

All of the glaciers were plotted to show the physiographic index for both accumulation and ablation areas (Figures 116 and 117). The fact that there are glaciers with both large and small numbers for the physiographic index of their ablation areas suggests that this factor is not meaningful in snout behavior. However, two rather pronounced groupings of ice streams with similar numbers of physiographic index in the accumulation area indicate that stationary and retreating glaciers are found in areas with little relief, while advancing and fluctuating ones tend to have greater relief near their accumulation areas.

FIGURE #116

PHYSIOGRAPHIC INDEX NEAR TERMINUS, ABOUT 1000 FT. ABOVE SEA LEVEL

| | Little Relief .015-.090 | Moderate .090-.140 | Rugged .140-.180 | Very Rugged +.180 |
|---|---|---|---|---|
| 1. Advancing | M | | KQBS | |
| 2. Stationary | NJ | RAU | D | C |
| 3. Fluctuating | TPO | | | |
| 4. Retreating | I | FG | | HVLE |

FIGURE #117

PHYSIOGRAPHIC INDEX IN ACCUMULATION AREA

| | .015-090 | .090-.140 | .140-.180 | +.180 |
|---|---|---|---|---|
| 1. Advancing | S | KQMB | | |
| 2. Stationary | CJUAD | N | | |
| 3. Fluctuating | | TOR | | P |
| 4. Retreating | EFGI | | H | VL |

<u>Sensitivity to Firn Line Change.</u>

Firn line elevation data for Prince William Sound are scattered over many years and come from many sources. A few firn line positions have been plotted from direct observation, many from airphotos, and some estimated from firn line elevations on nearby glaciers. Some of the observations were made as early as 1914 (Dora Keen, 1915), and many firn line altitudes were determined from airphotos which were made in late summer, though before the ablation season ended. In an attempt to smooth out possible inequalities in these data, where sufficient information is available for a glacier, the percentage of total glacier area involved in a $\pm$ 250' shift of firn line elevation has been plotted (Figure 118). It is perhaps significant that all of the retreating glaciers are sensitive to a shift of the firn line and show that a large percentage of their area is near the firn line. On the other hand, the advancing and stationary glaciers are affected little by any movement of the firn line.

FIGURE #118

PERCENTAGE OF GLACIER INVOLVED IN $\pm$ 250' CHANGE OF FIRN LINE POSITION

| | 0-8% | 8-12% | 12-20% | +20% |
|---|---|---|---|---|
| 1. Advancing | MB | | K | |
| 2. Stationary | JD | CAN | U | |
| 3. Fluctuating | OP | | | |
| 4. Retreating | | | VI | EFGH |
| Insufficient data for SRTLQ | | | | |

## RESPONSE TO GLACIOGRAPHIC SITUATION

### Accumulation Area Ratio.

Meier and Post (1962) introduced a new characteristic of glaciers by dividing the accumulation area into the total glacier area to arrive at the AAR (accumulation area ratio). If the ablation area and the accumulation area are equal, an AAR of .500 is produced. When the accumulation area is greater than the ablation area, the AAR is more than .500. This ratio seems much more meaningful than simple firn line elevations. The glaciers of Prince William Sound were plotted according to their behavior and their AAR (Figure 119), and it was found that some of the low AAR glaciers were those with retreating snouts, and some with high AAR's were advancing or stationary. Although the two glaciers with the highest AAR's were stationary glaciers, they end in deep fiords and calve heavily.

FIGURE #119

ACCUMULATION AREA RATIO (AAR)

| | .600-.700 | .700-.800 | .800-.900 | +.900 |
|---|---|---|---|---|
| 1. Advancing | | K | BM | |
| 2. Stationary | UN | A | C | JD |
| 3. Fluctuating | | P | O | |
| 4. Retreating | IE | HFGV | | |

Calving Activity.

The actual behavior of calving glaciers is difficult to determine because the number and size of calved bergs are unknown. However, snouts of all the glaciers were plotted according to the amount of calving which was observed during 1957 and 1961 (Figure 120). This graph indicates that the retreating snouts are generally non-calving glaciers that terminate on land. Most of the heavy-calving tongues are advancing or stationary.

FIGURE #120

CALVING ACTIVITY OF TERMINUS

| | None | Light | Medium | Heavy |
|---|---|---|---|---|
| 1. Advancing | | M | K | BQS |
| 2. Stationary | ACNU | | | DJ |
| 3. Fluctuating | | OP | R | T |
| 4. Retreating | EFHIV | L | G | |

## Summary of Tabulated Information

There were no climatic, climatographic, physiographic, or glaciographic response factors which showed a clear-cut relationship to snout behavior. In almost every case glaciers of differing characteristics had similar terminus response, or glaciers of similar characteristics had different terminus response. There were, however, factors where there were suggested or uncertain trends.

# INTEGRATION OF DATA

## Ranking of Glaciers

To evaluate the vague correlations found, the glaciers were next ranked by each climatographic, physiographic, and response factor to see how the most active glaciers compared with the least active. The glaciers were ranked according to the magnitude of the various factors and the theoretical response each ice stream should have to that factor. In other words, since glacier size has been considered a favorable factor to glacier expansion, the largest glacier is ranked Number 1, and the smallest, Number 22. The glacier with the lowest firn line is Number 1, etc.

The glaciers were first ranked according to the positive influence of the climatographic factors (Figure 122). They were next ranked according to physiographic factors (Figure 123), but because of insufficient map data some glaciers could not be ranked according to all physiographic factors. Elevation of the mean accumulation area was considered as both a physiographic and climatographic

| CLIMATOGRAPHIC FACTORS | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Elevation of Firn Line | Distance from the Sea (SW Entrance) | Elevation of Mean Accumulation Area | Orientation to the Effects of the Sun | | | | | |
| BAINBRIDGE | 11 | 1 | 7 | 9 | | | | | |
| TIGER | 9 | 2 | 9 | 8 | | | | | |
| TIGERTAIL | 1 | 3 | 12 | 3 | | | | | |
| PRINCETON | 8 | 5 | 12 | 16 | | | | | |
| CHENEGA | 7 | 4 | 9 | 5 | | | | | |
| ULTRAMARINE | 6 | 6 | 16 | 5 | | | | | |
| NELLIE JUAN | 1 | 7 | 16 | 3 | | | | | |
| TAYLOR | 10 | 8 | 7 | 11 | | | | | |
| TEBENKOF | 4 | 10 | 14 | 1 | | | | | |
| BLACKSTONE | 4 | 9 | 9 | 1 | | | | | |
| HARRIMAN | 1 | 11 | 12 | 5 | | | | | |
| BARRY | 12 | 12 | | 21 | | | | | |
| WELLESLEY | 13 | 13 | 3 | 9 | | | | | |
| VASSAR | 13 | 14 | 5 | 9 | | | | | |
| BRYN MAWR | 13 | 15 | 5 | 11 | | | | | |
| SMITH | 13 | 16 | 1 | 16 | | | | | |
| HARVARD | 13 | 17 | | 13 | | | | | |
| YALE | 18 | 17 | | 13 | | | | | |
| MEARES | 19 | 19 | | 13 | | | | | |
| COLUMBIA | 19 | 20 | | 21 | | | | | |
| SHOUP | 21 | 21 | 3 | 16 | | | | | |
| VALDEZ | 21 | 22 | 2 | 16 | | | | | |

Figure #122

| GLACIER RANKING ACCORDING TO PHYSIOGRAPHIC FACTORS | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Size (Area) | Length | Total Gradient | Gradient of Accumulation Area | Gradient of Ablation Area | Physiography in Accumulation Area | Physiography Near Terminus | Elevation of Mean Accumulation | Response to ±250' Change of Firn Line |
| BAINBRIDGE | 13 | 9 | 15 | 12 | 14 | 18 | 12 | 7 | 8 |
| TIGER | 10 | 11 | 12 | 10 | 7 | 12 | 9 | 9 | 3 |
| TIGERTAIL | 22 | 22 | 5 | 5 | 8 | 14 | 1 | 12 | 5 |
| CHENEGA | 3 | 6 | 21 | 16 | 6 | 21 | 8 | 9 | 2 |
| PRINCETON | 11 | 9 | 16 | 17 | 12 | 20 | 5 | 12 | 16 |
| ULTRAMARINE | 14 | 15 | 13 | 14 | 10 | 22 | 14 | 16 | 17 |
| NELLIE JUAN | 18 | 17 | 11 | 11 | 9 | 17 | 15 | 16 | 14 |
| TAYLOR | 16 | 15 | 6 | 6 | 11 | 4 | 2 | 7 | 15 |
| TEBENKOF | 15 | 11 | 14 | 13 | 13 | 19 | 16 | 14 | 13 |
| BLACKSTONE | 9 | 14 | 8 | 9 | 1 | 15 | 22 | 9 | 1 |
| HARRIMAN | 11 | 13 | 10 | 7 | 15 | 5 | 6 | 12 | 11 |
| BARRY | 8 | 7 | 9 | | | 3 | 4 | | |
| WELLESLEY | 20 | 21 | 3 | 2 | 4 | 10 | 19 | 3 | 4 |
| VASSAR | 21 | 20 | 1 | 3 | 3 | 6 | 20 | 5 | 9 |
| BRYN MAWR | 17 | 19 | 4 | 4 | 2 | 10 | 21 | 5 | 6 |
| SMITH | 19 | 17 | 1 | 1 | 5 | 2 | 18 | 1 | 7 |
| HARVARD | 2 | 2 | 19 | | | 7 | 7 | | |
| YALE | 6 | 3 | 18 | | | 9 | 11 | | |
| MEARES | 7 | 8 | 7 | | | 13 | 10 | | |
| COLUMBIA | 1 | 1 | 22 | | | 8 | 17 | | |
| SHOUP | 4 | 4 | 17 | 8 | 16 | 16 | 13 | 3 | 10 |
| VALDEZ | 5 | 4 | 20 | 15 | 17 | 1 | 3 | 2 | 12 |

Figure #123

factor and is shown on both charts. The glaciers were then ranked by the degree of response they showed to their glaciographic situation (Figure 124).

Summary of Glacier-Ranking Charts

Just as is the case with the charts analyzing the effects of the separate factors of the physical environment, the charts ranking the glaciers show a striking lack of correlation between glacier terminus behavior and the environmental conditions. There is not one factor where a definite relationship exists. The pattern for the cause of terminus fluctuations is neither produced nor explained by individual factors nor by combinations of them. The ranking of the glaciers by individual factors produced no close correlation to observed snout behavior. This also was the case when the combined rankings were considered. The fluctuations of glacier termini are thus found to be more complex than was previously thought. Some of the recent work of other investigators of Alaskan glaciers seems to bear out this conclusion.

## COMMENT ON RECENT STUDIES APPLICABLE TO PRINCE WILLIAM SOUND

Application of previous studies of Alaskan glaciers to the glaciers of Prince William Sound is usually questionable because these studies often consider only a single factor, or at best selected factors. One such study is the recent work by Meier and Post (1962). As a part of this study, glacier health and snout behavior are estimated from several factors, including the accumulation area ratio (AAR) and the snout appearance. All of the glaciers of Prince

| RESPONSE TO GLACIOGRAPHIC SITUATION | | | | | | | |
|---|---|---|---|---|---|---|---|
| | Average AAR | Calving Activity | Changes in Terminus Area Absolute | Changes in Terminus Area as % of 1950 Glacier Area | Glacier Length Changes Absolute | Glacier Length Changes as a % of 1950 Total Length | Total Activity of Terminus (Advance & Recess.) |
| BAINBRIDGE | 11 | 14 | 5 | 6 | 10 | 15 | 17 |
| TIGER | 5 | 1 | | | 5 | 4 | 20 |
| TIGERTAIL | 3 | 14 | | | 13 | 9 | 19 |
| CHENEGA | 1 | 1 | 4 | 4 | 7 | 7 | 21 |
| PRINCETON | 16 | 14 | | | 22 | 22 | 2 |
| ULTRAMARINE | 9 | 14 | 9 | 11 | 19 | 20 | 11 |
| NELLIE JUAN | 13 | 6 | 13 | 14 | 20 | 19 | 3 |
| TAYLOR | 11 | 14 | 12 | 13 | 20 | 18 | 10 |
| TEBENKOF | 15 | 14 | 11 | 12 | 21 | 21 | 9 |
| BLACKSTONE | 1 | 1 | | | 8 | 8 | 21 |
| HARRIMAN | 7 | 6 | 2 | 1 | 2 | 1 | 6 |
| BARRY | | 10 | 14 | 10 | 16 | 17 | 11 |
| WELLESLEY | 6 | 10 | | | 4 | 2 | 15 |
| VASSAR | 14 | 14 | | | 12 | 14 | 16 |
| BRYN MAWR | 4 | 10 | | | 6 | 6 | 4 |
| SMITH | 8 | 10 | | | 9 | 12 | 5 |
| HARVARD | | 1 | 1 | 3 | 1 | 5 | 7 |
| YALE | | 6 | 10 | 9 | 15 | 16 | 1 |
| MEARES | | 1 | 3 | 2 | 3 | 3 | 13 |
| COLUMBIA | | 1 | 8 | 5 | 13 | 10 | 8 |
| SHOUP | 17 | 14 | 6 | 7 | 10 | 11 | 18 |
| VALDEZ | 10 | 14 | 7 | 8 | 18 | 13 | 14 |

Figure #124

William Sound have high AAR's and some with similar AAR's have very different snout behavior. For example, there are seven glaciers with AAR's between .700 and .800. Of these, four are retreating ice streams, one fluctuating, one stationary, and one advancing. The picture is further complicated by the fact that the two glaciers with the highest AAR's (+.900) have stationary termini. Meier and Post's suggestion that glaciers with asymmetric area-altitude distribution are exceptions to these authors' generalized behavior predictions appears to be applicable to the Prince William Sound area.

Other recent work in the area includes the study of the Columbia Glacier by Nielsen (1963). This study of a single ice stream reaches conclusions based on climatic data taken from the Juneau ice field about 500 miles away, and applies it to ablation in Prince William Sound. The great difference between the influence of climatic factors on adjacent glaciers in Prince William Sound is so uncertain that borrowing from 500 miles away seems likely to produce great inaccuracy and unreliability. If the other glaciers of Prince William Sound were evaluated by the same criterion, a completely erroneous picture of snout behavior would be reached.

The use of a single factor also appears to restrict the validity of the recent work of Mercer (1961) in Prince William Sound. Here again some climatic data were borrowed from the Juneau ice field, 500 miles distant. The movements of glacier termini have not followed the patterns he predicted. For example, Mercer found that the Snow River Glacier had what he called a very high MBI (Mass Budget Index), and reasoned that this glacier should be advancing vigorously. In the same year that Mercer's work was published, the author flew over the terminus of the Snow River Glacier and observed that it had a low-angle front, small recessional moraines, and trimlines that indicated that the snout had been receding recently, and was then in a state of recession. Mercer's predicted snout behavior for other glaciers is similarly erroneous. Bainbridge Glacier and Taylor Glacier have nearly similar MBI's. Bainbridge Glacier is in approximate equilibrium, while Taylor is one of the fastest-receding glaciers in Prince William Sound.

Recently, Bengston (1962) explained that the stationary condition of Brady Glacier in southeastern Alaska is the result of protection from tidal action given by a large bar of outwash in front of the terminus. But this theory does not appear to be applicable to other similarly-situated glaciers in Prince William Sound which have the same type of bar built in front of the terminus, but which have continued to recede. For example, the Nellie Juan Glacier, after building a large bar completely across the terminus, has continued to calve at a very rapid rate into a rather deep lake behind the bar. On the other hand, the Barry Glacier receded very rapidly until early 1914, and apparently has since been stabilized in deep water. The Princeton Glacier has recently receded onto the land, and thus removed itself from any tidal action, but continues a rapid retreat. The terminus of the Columbia Glacier ends both on land and in deep water, and recession has been the greatest along the grounded part of the terminus, which is the opposite of what one would expect if Bengston's theory were applicable to the glaciers of Prince William Sound.

Hoinkes (1955, 1962) and Hoinkes and Rudolph (1962) have shown that radiation variation, as measured by the duration of summer sunshine and the number of days with snowfall, is in agreement with the behavior of European Alpine glaciers during the last 60 years. Unfortunately, no radiation studies have been made in the Prince William Sound area and the weather records from nearby sea-level stations do not give the needed information.

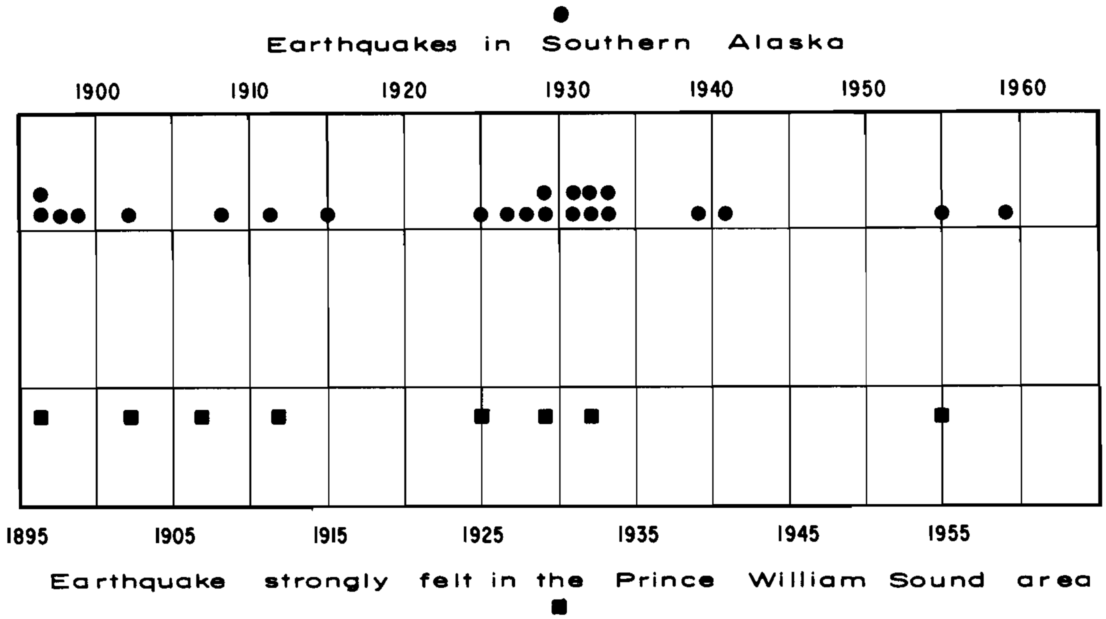
In 1914, Tarr and Martin (1914) proposed a theory that some glacier advance was the result of snow and ice added to the accumulation area as a result of avalanching from surrounding slopes due to earthquake shaking. They used this theory to explain the unusually rapid expansion of several glaciers in the Yakutat Bay area shortly after the turn of the century. This area had been violently shaken by earthquakes in 1899. Some short glaciers responded with a sudden expansion in a few years; longer glaciers, according to their length, took longer to react. Not all of the glaciers of the area were affected, but some experienced a sudden rapid increase in thickness and crevassing near the tongue and had a forward movement of the terminus of as much as 2 miles. In most cases this growth ended as quickly as it began.

Although weather records indicated an unusually high amount of precipitation in previous years, Tarr and Martin dismissed climatic control for this rapid growth, holding that a peculiarity in the methods of measurement made the records inaccurate.

More recent research (Miller, 1958) suggests that the climatic record of the period 1880-1900 is valid, and that the increased precipitation and slight lowering of temperature could account for the expansion of the ice tongues just after the turn of the century.

There are no recording seismic stations in or near Prince William Sound, and the accounts of earthquakes felt there are vague and subjective. Nevertheless, the U. S. Coast and Geodetic Survey has published a list (U. S. Dept. of Commerce, 1958) of earthquakes that were felt, or should have been felt, in the area (Figure 125).

Using the criteria of Tarr and Martin, there appears to be no close correlation between earthquakes and glacier advances in Prince William Sound. A severe shock, followed by several after-shocks in 1896, apparently did not affect any glaciers except, perhaps, the Barry Glacier. Even this is questionable, since it is not known whether the advanced state of the glacier reported in 1898 represented a recent advance or the culmination of an older one. There were severe shocks in 1903 and 1908 which may have accounted for a sudden advance of six glaciers in 1910, except that these glaciers vary in length from 4 to 41 miles, and that the effect of the possible growth due to avalanching should have been felt at different years according to the length of the ice stream. There were also eleven glaciers which did not participate in this sudden growth. In some cases the rapid growth was short-lived, while in others it has continued through 1961. A series of earthquakes, beginning in 1925 and continuing through 1933, may have had some connection with advances of eight glaciers between 1931 and 1935. However, again the length of the ice stream appeared to have nothing to do with the time at which the growth occurred. At least four glaciers had small advances in 1949-1950, while no record of earthquakes preceded them.




Earthquakes of southern Alaska, 1895-1958, taken from "Earthquake History of the United States, Part 1, Continental United States and Alaska", U.S. Department of Commerce, 1958.

Figure #125

A severe shock in 1954 may have affected three glaciers in 1955-1957. However, two of these were the same length--20 miles, and the third was twice as long--41 miles.

Since the earthquake avalanche theory specifies that expansion of the terminus, due to added ice in the accumulation area, requires more or less time according to the length of the glacier, the fact that glaciers of variable length advanced simultaneously in Prince William Sound indicates that earthquakes are of secondary importance and not the main factor causing glacier advance in this area. In addition, after a glacier has undergone a rapid advance, due to earthquake avalanching, the advance is followed by an equally rapid retreat. Since the snow which would normally feed the glacier slowly over a period of years was suddenly avalanched from the surrounding slopes, a period of starvation should follow an earthquake shaking. In the case of at least three glaciers in Prince William Sound, the advances reported in 1910, 1935, and 1937 which may have been initiated by earthquakes have not been followed by retreat, but have continued through the last observation in 1961.

The severe earthquakes of March, 1964, had their epicenter in Prince William Sound. Investigators went immediately to examine and to photograph the ice snouts from the air. In assessing the value of Tarr and Martin's earthquake theory, preliminary evidence suggests that not only must the avalanching of ice and snow be considered, but also the flow of rock debris onto the glacier surface, as this latter appears to retard normal ablation seriously.

It becomes apparent that solutions or proposals that utilize single, or selected factors, cannot explain the complex picture of snout behavior found in the Prince William Sound area.

CHAPTER IV

# SUMMARY AND CONCLUSIONS

## Summary

The purpose of this thesis has been to determine trends in glacier terminus movements in the Prince William Sound area and, as far as possible, to relate these trends to climatic, climatographic, physiographic, and glaciographic factors.

From summarized previous work, compiled map information, photographs, and field work done by the author, it has been possible to reconstruct the generalized terminus behavior of twenty two major ice streams in the Prince William Sound area. The findings have been described for each glacier separately and have been plotted together in graph form to show (1) length changes of glaciers in absolute values, (2) changes in length as percentage of total glacier length, (3) recession or advance by area in absolute values, and (4) area change as a percentage of total glacier area (Figures 95, 96, 97, 98). From these graphs it has been possible to place each of the glaciers into one of the following categories of behavior: advancing glaciers, fluctuating glaciers, stationary glaciers, and retreating glaciers. Some of the plotting was hampered by a lack of maps for the upper parts of several of the major glaciers.

In order to assess the influence of the physical environment on snout fluctuations, the glaciers and their categories of behavior have been compared with the following climatographic factors: elevation of the firn line, elevation of the accumulation area, orientation of the accumulation area, generalized orientation of the entire glacier, orientation of the terminus, and the distance of the glacier from the open sea.

The glaciers and their categories of behavior were next compared with the following physiographic factors: length, area, gradient, physiographic index, and sensitivity to firn line change. The final factors considered were those of the glaciographic situation: accumulation area ratios, and calving activity.

In evaluating the effect of the various factors, the glaciers were each given a rank according to the theoretical influence of each factor in producing glacier growth and snout expansion.

The application of the work of other investigators of Alaskan glaciers to the glaciers of the Prince William Sound area has been considered, and has been found to be of limited significance.

## Conclusions

The poor correlation between climatic changes and the snout responses of the glaciers of the Prince William Sound area is not surprising since the lag factor for each glacier is different, owing to various elements of the physical environment. However, when glacier behavior was compared with the climatic, physiographic, and glaciological factors, it had been expected that some factors would show a rather high correlation with snout behavior. Unfortuanately, this was not the case. The wide scattering of behavior types in the charts indicates that no single factor nor combination of factors could be used to explain past behavior or to predict future behavior. Snout response appears to be more complex than previously thought. Weidick (1959, p. 184) reached a similar conclusion in his study of snout behavior in Greenland. In his summary he said:

> In any case, it is here true, that as in Alaska and Spitzbergen, the movements of these glaciers seem to differ owing to changes in the feed routes or other circumstances not directly reflecting climatic changes, for which reason these glaciers as indicators of climatic changes must be regarded with some skepticism.

Meier (1958, Vol. LI, p. 43) also recognized that this was a complex problem and said:

> In order to predict the length, shape or thickness of a glacier it is necessary to understand the dynamics of the flowing ice. This subject is a vital but still poorly understood link between glaciers and climate. . . . It is not possible to relate climate to glacier length or shape in a quantitative manner at the present time.

Ahlmann (1953, p. 17) not only saw the problem, but also suggested a solution:

> Every glacier has its own period of variation, which is, however, dependent on the more pronounced climatic fluctuations and changes. Measurement of the position of the glacier terminus alone cannot give satisfactory knowledge of the relation between its variations and the climate. It is necessary to investigate the whole glacier.

Not only climatic factors, but also physiographic and glaciographic ones influence glacier tongue behavior; however, so far little is known about the magnitude of this influence of individual factors, either for single glaciers or for whole glacier areas. The results of this study indicate that to assess properly the influence of the environment on glacier health one must include all of the known physiographic and climatic factors of the region according to their importance, but to do this the importance of each factor must be first determined for both the individual and the general case.

Studies by geomorphologists and other earth scientists have attempted to determine past climatic changes by reconstructing glacier snout movement through analysis of moraines and associated features. However, the low correlation between climate and snout movements of the glaciers of the Prince William Sound area suggests that such studies must be treated very carefully, particularly where the record is for a short period of time.

## Recommendations for Future Work

In order to evaluate the relationship of climate and physiography to the glaciers of the Prince William Sound area in years to come, the following suggestions and recommendations evolve from this study:

1. An additional weather station should be set up in Prince William Sound. The most suitable place would be at the former Indian village on Chenega Island, which is within six miles of seven large glaciers. Such a station would greatly supplement climatic data from the other two stations on the eastern side of the Sound. In addition, future glacier studies in Alaska should attempt to collect climatic data at all elevations to measure the vertical distribution of wind, temperature, and precipitation.

2. Future snout studies should be supplemented with mass budget studies where the glacier is considered as a whole. The results of the present study suggest that snout studies on their own are of limited value, and that their continued use should be carefully reconsidered, and perhaps reduced.

3. Selected glaciers of different terminus behavior in Prince William Sound should be carefully studied to evaluate the importance

of each physiographic and climatic factor in order to determine its influence. Mass budgets should be determined for these glaciers in a comprehensive study. At least three glaciers are found in the western side of Prince William Sound which would provide a picture of different behavior under nearly-equal circumstances. Harriman, an advancing glacier; Tebenkof, a receding glacier; and Bainbridge, a stationary glacier; would lend themselves to easy evaluation and comparison.

4. A study should be inaugurated to determine the rate and importance of calving to ice streams and the relationship of calving to terminus movement.

5. Mapping in the two remaining areas should be completed. These areas include Mt. Witherspoon, with the collecting areas of four of the largest ice streams of Prince William Sound, and also the area of Point Doran in Harriman Fiord. Since good coverage with topographic maps exists for the rest of the area, the completion of these two areas is very important.

# BIBLIOGRAPHY

# BIBLIOGRAPHY


Abercrombie, W. R. (1899) Reports of Explorations in the Territory of Alaska, 1898. No. 25, War Department, Adj. General's Office, pp. 299-455.

Ahlmann, Hans W:son (1948) Glaciological Research on the North Atlantic Coasts. "The Royal Geographical Society Research Series," No. 1.

_______ (1953) Glacier Variations and Climatic Fluctuations. ("Bowman Memorial Lecture Series," No. 3) American Geographical Society, New York.

Aliverti, G. (1960) "A Propos des Vagues des Glaciers: Aspects Observes Sur la Langue et Sur le Front du Glacier du Lys (Mont Rose)," General Assembly of Helsinki. International Association of Scientific Hydrology, Pub. No. 54, pp. 574-77.

Allen, H. T. (1887) "An Expedition to the Copper, Tanana, and Koyukuk Rivers," Senate Executive Document 125, 49th Congress, 2nd Session, Map 2.

Baird, P. D., and others (1950) "Baffin Island Expedition, 1950: A Preliminary Report," Arctic, III, No. 3, pp. 131-49.

Baird, P. D. (1952) "Method of Nourishment of the Barnes Ice Cap," Part I, Journal of Glaciology, II, No. 11, pp. 2-9.

Baird, P. D., Ward, W. H., and Orvig, Svenn (1952) 'The Glaciological Studies of the Baffin Island Expedition, 1950."

Bengston, K. B. (1962) "Recent History of the Brady Glacier, Glacier Bay National Monument, Alaska," Symposium of Obergurgl. International Association of Scientific Hydrology, Pub. No. 58, pp. 78-87.

Bogvad, R. (1940) "Quaternary Geological Observations, etc., in Southeast and South Greenland," Meddeleser om Gronland, CVII, No. 3.

Bondarev, L. G. (1960) "Evolution of Some Tien Shan Glaciers During the Last Quarter of the Century," General Assembly of Helsinki. International Association of Scientific Hydrology, Pub. No. 54, pp. 412-19.

Bostock, H. S. (1948) "Physiography of the Canadian Cordillera, with Special Reference to the Area North of the Fifty-Fifth Parallel, Canada," Geological Survey, Memoir, No. 247.

Brown, Douglas M. (1947, 1949, 1950) Unpublished photographs on file at the American Geographical Society, New York.

_______ (1952) "Glaciers Advance!" Appalachia, June, 1952, pp. 38-46.

Canada, Dominion Water and Power Bureau (1948, 1949, 1950, 1952-1954, 1956) Study of Glaciers in Banff and Jasper National Parks. On file at the American Geographical Society, Department of Exploration. (Mimeographed.)

Capps. S. R (1931) "Glaciation in Alaska," U. S. Geological Survey Professional Paper, 170-A.

Cook, Frank A. (1960) "Ice Studies of the Canadian Geographical Branch," Polar Record, X, No. 65, pp. 123-25.

Cook, James (1784) A Voyage to the Pacific Ocean, etc. London, II, pp. 353-81.

Cooper, William S. (1937) "The Problem of Glacier Bay, Alaska: A Study of Glacier Variations," Geographical Review, XXVII, No. 1, pp. 37-62.

_______ (1942) "Vegetation of the Prince William Sound Region, Alaska; With a Brief Excursion into Post-Pleistocene Climatic History," Ecological Monographs, XII, No. 1.

Crary, A. P., Cotell, R. D., and Secton, T. F. (1952) "Preliminary Report on Scientific Work on 'Fletcher's Ice Island,' T3," Arctic, V, No. 4, pp. 211-23.

Davidson, George (1904) "The Glaciers of Alaska That Are Shown on Russian Charts or Mentioned in Older Narratives," Transactions and Proceedings of the Geographical Society of the Pacific, 2nd Series, III.

Debenham, Frank (1954) "The Ice Islands of the Arctic: A Hypothesis," Geographical Review, XLIV, No. 4, pp. 495-507.

Eugster, V. (1962) "Recent Changes in Small Glaciers in the Pizol and the Sardona (Low Alps of Eastern Switzerland)," Symposium of Obergurgl. International Association of Scientific Hydrology, Pub. No. 58, pp. 166-72.

Field, W. O. (1932) "The Glaciers of the Northern Part of Prince William Sound, Alaska," Geographical Review, XXII, No. 3, pp. 361-88.

_______ (1932) "The Mountains and Glaciers of Prince William Sound, Alaska," American Alpine Journal, I, pp. 445-58.

______ (1937) "Observations on the Alaskan Coastal Glaciers in 1935," Geographical Review, XXVII, No. 1, pp. 63-81.

______ (1948) "The Variations of Alaskan Glaciers, 1935-1947," General Assembly of Oslo. L'Union Geodesique et Geophysique Internationale, pp. 272-82.

______ (1949) "Glacier Observations in the Canadian Rockies, 1948," Canadian Alpine Journal, XXXII, pp. 99-114.

Field, W. O., and Baird, P. D. (1951) "Report on North American Glaciers," General Assembly of Brussels. International Association of Scientific Hydrology, Tome 1, pp. 120-28.

Field, W. O., and Heuser, C. J. (1954) "Glacier and Botanical Studies in the Canadian Rockies, 1953," Canadian Alpine Journal, XXXVII, pp. 127-40.

Field, W. O., and others (1958) Geographic Study of Mountain Glaciation in the Northern Hemisphere. American Geographical Society, Part 2A.

Finsterwalder, R. (1960) "On the Measurement of Glacier Fluctuations," General Assembly of Helsinki. International Association of Scientific Hydrology, Pub. No. 54, pp. 325-34.

Flint, R. F. (1947) Glacial Geology and Pleistocene Epoch. John Wiley and Sons, Inc., New York.

Forel, Mercanton, Renaud (1880-1959) "Les Variations des Glaciers des Alpes Suisses," Rapports Annuels, 1880-1959, Dans la Revue Les Alpes, Bern.

Fristrup, Borge (1960) "Recent Investigations of the Greenland Ice Cap," International Geographical Congress Guidebook, pp. 142-70.

Gilbert, G. K. (1903) Glaciers and Glaciation: Harriman Alaskan Expedition. Doubleday-Page and Co, New York.

Glenn, E. F. (1899) Reports of Explorations in the Territory of Alaska, 1898. War Department, Adj. General's Office.

Goldthwait, R. P. (1951) "Development of End Moraines in East-Central Baffin Island," Journal of Geology, LIX, No. 6, pp. 567-77.

Goldthwait, R. P., McKellar, I. C., and Kronk, C. (1963) "Fluctuations of Crillon Glacier System, Southeast Alaska," Bulletin of the International Association of Scientific Hydrology, VIII[e] Année No. 1, pp. 45-56.

Grant, U. S., and Higgins, D. F. (1910) "A Reconnaissance of the Geology and Mineral Resources of Prince William Sound, Alaska," U. S. Geological Survey Bulletin, 443.

_______ (1910) "Glaciers of Prince William Sound and the Southern Part of the Kenai Peninsula, Alaska, Part I," Bulletin of the American Geographical Society, XLII, No. 10, pp. 721-38.

_______ (1911) "Glaciers of Prince William Sound and the Southern Part of the Kenai Peninsula, Alaska, Part II," Bulletin of the American Geographical Society, XLIII, No. 5, pp. 321-38.

_______ (1911) "Glaciers of Prince William Sound and the Southern Part of the Kenai Peninsula, Alaska, Part III," Bulletin of the American Geographical Society, XLIII, No. 6, pp. 401-17.

_______ (1911) "Glaciers of Prince William Sound and the Southern Part of the Kenai Peninsula, Alaska, Part IV," Bulletin of the American Geographical Society, XLIII, No. 10, pp. 721-37.

_______ (1913) "Coastal Glaciers of Prince William Sound and Kenai Peninsula, Alaska," U. S. Geological Survey Bulletin, 526.

Heuser, C. J. (1953) "Radiocarbon Dating of the Thermal Maximum in Southeastern Alaska," Ecology, XXXIV, pp. 637-40.

_______ (1955) "Pollen Profiles from Prince William Sound and Southeastern Kenai Peninsula, Alaska," Ecology, XXXVI, pp. 185-202.

_______ (1958) "Pleistocene and Postglacial Vegetation of Alaska and the Yukon Territory," Eighteenth Biology Colloquium, Arctic Biology, pp. 62-72.

_______ (1960) "Late Pleistocene Environments of North Pacific North America," American Geographical Society, Special Publication 35.

Hoel, A., and Werenskiold, W. (1962) "Glaciers and Snowfields in Norway," Norsk Polarinstitutt Skrifter, No. 114.

Hoinkes, H. (1955) "Measurements of Ablation and Heat Balance on Alpine Glaciers (With Some Remarks on the Cause of Glacier Recession in the Alps)," Journal of Glaciology, II, No. 17, pp. 497-501.

Hoinkes, H. and Rudolph, R. (1962) "Variations in the Mass-Balance of Hintereisferner (Oetzal Alps), 1952-1961 and Their Relation to Variation of Climatic Elements," Symposium of Obergurgl. International Association of Scientific Hydrology, Pub. No. 58, pp. 16-28.

Johnson, B. L. (1915) "Mining on Prince William Sound, etc.," U. S. Geological Survey Bulletin 622E.

_______ (1917) "Retreat of Barry Glacier, Port Wells, Prince William Sound, Alaska, Between 1910 and 1914," U. S. Geological Survey Professional Paper, 98.

Karlstrom, T. N. V. (1961) "The Glacial History of Alaska: Its Bearing on Paleoclimatic Theory," Solar Variations, Climatic Change, and Related Geophysical Problems. Annals of the New York Academy of Sciences, VC, Art. 1, pp. 290-340.

Keen, Dora (1915) "Studying the Alaskan Glaciers," Bulletin of the Geographical Society. Philadelphia, XIII, pp. 25-32.

_______ (1915) "Exploring the Harvard Glacier," Harper's Magazine, CXXXII, pp. 113-25.

Kick, W. (1962) "Variations of Some Central Asiatic Glaciers," Symposium of Obergurgl. International Association of Scientific Hydrology, Pub. No. 58, pp. 223-29.

Kincer, J. B. (1941) "Climate in Alaska," Climate and Man. U. S. Department of Agriculture Yearbook, pp. 1211-15.

Kovalyov, P. V. (1962) "The Fluctuations of Glaciers in the Caucasus," Symposium of Obergurgl. International Association of Scientific Hydrology, Pub. No. 58, pp. 179-84.

Krinsley, D. B. (1961) "Late Pleistocene Glaciation in Northeast Greenland," Symposium on Arctic Geology. Calgary, II, pp. 747-51.

Lawrence, D. B. (1950) "Glacier Fluctuation for Six Centuries in Southeastern Alaska and Its Relation to Solar Activity," Geographical Review, XL, No. 2, pp. 191-223.

_______ (1951) "Glacier Fluctuations in Northwestern North America Within the Past Six Centuries," General Assembly of Brussels. International Association of Scientific Hydrology, Tome I, pp. 161-66.

Lawrence, D. B., and Elson, J. A. (1953) 'Periodicity of Deglaciation in North America Since the Late Wisconsin Maximum," Geografiska Annaler, XXXV, No. 2, pp. 83-104.

McFarlane, V. T. (1946) "Glacier Investigations in Banff, Yoho, and Jasper National Parks," Canadian Alpine Journal, XXIX, pp. 265-73.

Mathews, W. H. (1951) "Historic and Prehistoric Fluctuations of Alpine Glaciers in the Mount Garibaldi Map-Area, Southwestern British Columbia," Journal of Geology, LIX, No. 4, pp. 357-80.

Meares, John (1790) Voyages Made in the Years 1788 and 1789 from China to the Northwest Coast of America, London, pp. 11-40.

Meek, Victor (1948) "Glacier Observations in the Canadian Cordillera," Canadian Geographical Journal, XXXVII, pp. 190-209.

_______ (1948) "Glacier Observations in the Canadian Cordillera," Extrait des proces-verbaux des seances del' Assemblee General d'Oslo (19-28 aout 1948) de l'Union Geodes. et Geophys. Internatl., UGGI, pp. 264-75.

Meier, Mark F. (1958) "Research on South Cascade Glacier," Mountaineer Annual, LI, pp. 40-47.

_______ (1960) "Mode of Flow of Saskatchewan Glacier, Alberta, Canada," U. S. Geological Survey, Professional Paper, 351.

Meier, M. F., Rigsby, G. P., and Sharp, R. P. (1954) "Preliminary Data from Saskatchewan Glacier, Alberta, Canada," Arctic, VII, No. 1, pp. 3-26.

Meier, M. F., and Post, A. S. (1962) "Recent Variations in Mass Net Budgets of Glaciers in Western North America," Symposium of Obergurgl. International Association of Scientific Hydrology, Pub. No. 58, pp. 63-77.

Mendenhall, W. C. (1900) "A Reconnaissance from Resurrection Bay to the Tanana River, Alaska, in 1898," Twentieth Annual Report of the U. S. Geological Survey, Part 7, pp. 273-326.

Mercanton, Forel, Renaud (1880-1959) "Les Variations des Glaciers des Alpes Suisses," Rapports Annuels, 1880-1959, Dans la Revue Les Alpes, Bern.

Mercer, J. H. (1954) "The Physiography and Glaciology of Southernmost Baffin Island," Ph.D. dissertation, McGill University.

_______ (1956) "Geomorphology and Glacial History of Southernmost Baffin Island," Bulletin of the Geological Society of America, LXVII, No. 5, pp. 553-70.

_______ (1956) "The Grinnel and Terra Nivea Ice Caps, Baffin Island," Journal of Glaciology, II, No. 19, pp. 653-56.

_______ (1961) "Estimation of the Regimen and Former Firn Limit of a Glacier," Journal of Glaciology, III, No. 30, pp. 1053-62.

_______ (1961) "The Response of Fiord Glaciers to Changes in the Firn Limit," Journal of Glaciology, III, No. 29, pp. 850-58.

Miller, Maynard M. (1947) "Aerial Survey of Alaskan Glaciers, 1947," American Alpine Journal, VII, No. 2, pp. 174-77.

_______ (1958) "The Role of Diastrophism in the Regimen of Glaciers in the St. Elias District, Alaska," Journal of Glaciology, III, No. 24, pp. 292-97.

Millett, Marion T. (1956) "Glaciation of Middle Boulder Creek, Colorado," Unpublished Master's thesis, University of Colorado.

_______ (1960) "Advance of the Muldrow Glacier, 1957," Bulletin of the Geological Society of America, LXXI, No. 12, p. 2068.

Mitchell, J. M., Mr. (1958) "The Weather and Climate of Alaska," Weatherwise, II, No. 5, pp. 151-60.

Moffitt, Fred H. (1954) "Geology of the Prince William Sound Region, Alaska," U. S. Geological Survey Bulletin, 989-E.

Müller, Fritz (1962) "Glacier Mass-Budget Studies on Axel Heiberg Island, Canadian Archipelago," Symposium of Obergurgl, International Association of Scientific Hydrology, Pub. No. 58, pp. 131-42.

Murray, H. J. (1945) "Profiles of the Aleutian Trench," Bulletin of the Geological Society of America, LVI, No. 7, pp. 10-15.

Munday, W. A. Don (1928) "Explorations in the Coast Range of British Columbia," Geographical Review, XVIII, No. 2, pp. 196-214.

_______ (1931) "Retreat of the Coast Range Glaciers," Canadian Alpine Journal, XX, pp. 140-42.

Nielsen, L. E. (1955) "Regimen and Flow of Ice in Equilibrium Glaciers," Bulletin of the Geological Society of America, LXVI, No. 1, pp. 1-8.

_______ (1963) "A Glaciological Reconnaissance of the Columbia Glacier, Alaska," Arctic, XVI, No. 2, pp. 134-41.

Nye, J. F. (1960) "The Influence of Climatic Variations on Glaciers," General Assembly of Helsinki, International Association of Scientific Hydrology, Pub. No. 54, pp. 397-404.

_______ (1960) "The Response of Glaciers and Ice-Sheets to Seasonal and Climatic Changes," Proceedings of the Royal Society, CCLVI, pp. 559-84.

Petrof, Ivan (1884) "Population, Industries, and Resources of Alaska," Tenth Census of the United States, 1880, VIII.

_______ (1900) The Population and Resources of Alaska, 1880. Washington, D. C., U. S. Government Printing Office, pp. 55-281.

Portlock, Nathaniel (1789) Northwest Coast of America. London, p. 240.

Reid, H. F. (1895-1916) "Variation of Glaciers," Journal of Geology, Vols. 3-24.

Renaud, Mercanton, and Forel (1880-1959) "Les Variations des Glaciers des Alpes Suisses," Rapports Annuels, 1880-1959, Dans la Revue Les Alpes, Bern.

Rice, J. F. (1900) In Abercrombie's Copper River Exploring Expedition, Alaska, 1899, Washington.

Schrader, F. C. (1900) "A Reconnaissance of a Part of Prince William Sound and the Copper River District, Alaska, in 1898," 20th Annual Report of the U. S Geological Survey, Part 7, pp. 341-423.

Schrader, F. C., and Spencer, A. C. (1909) "Geology and Mineral Resources of a Portion of the Copper River District, Alaska," U. S. Geological Survey Bulletin, 374.

Seton Karr, H. W. (1887) Shores and Alps of Alaska, London, pp. 228-29.

Sharp, R. P. (1951) "Accumulation and Ablation on the Seward-Malaspina Glacier System, Canada, Alaska," Bulletin of the Geological Society of America, LXII, No. 7, pp. 725-43.

______ (1956) "Glaciers in the Arctic," Arctic, IX, Nos. 1 and 2, pp. 78-117.

______ (1960) "Glaciers," Condon Lectures, Oregon State System of Higher Education.

Shumskiy, P. A. (1963) "On the Theory of Glacier Variations," Bulletin of the International Association of Scientific Hydrology, VIII^e Année No. 1, pp. 45-56.

Tarr, R. S., and Martin, Lawrence (1914) Alaska Glacier Studies, National Geographic Society, Washington, D. C.

Taylor, W. (1936) "Glacier Retreat in Garibaldi Park," Canadian Alpine Journal, XXIV, pp. 103-108.

Thorington, J. M. (1925) The Glittering Mountains of Canada, Philadelphia, John W. Lea.

______ (1927) "The Lyell and Freshfield Glaciers, Canadian Rocky Mountains, 1926," Smithsonian Miscellaneous Collection, LXXVIII, pp. 1-8.

______ (1931) "Lyell and Freshfield Glaciers," Canadian Alpine Journal, XX, pp. 138-40.

______ (1938) "Notes on Saskatchewan and Freshfield Glaciers," American Alpine Journal, III, pp. 219-20.

______ (1945) "Freshfield and Lyell Glaciers," American Alpine Journal, V, pp. 435-36

U. S. Department of Commerce (1959) Earthquake History of the United States, Part 1, Continental United States and Alaska, 1895-1958." U. S. Government Printing Office.

Vancouver, George (1801) A Voyage of Discovery to the North Pacific Ocean and Around the World, London, V, pp. 318-49.

Vanni, M. (1962) "Variations in Italian Glaciers and the Glaciological Survey of 1961," Symposium of Obergurgl. International Association of Scientific Hydrology, Pub. No. 58, pp. 160-65.

Vaux, George, Jr. (1910) "Observations on Glaciers in 1909," Canadian Alpine Journal, II, pp. 126-29.

Weideck, A. (1958) "Frontal Variations at Upernaviks Isstrom in the Last 100 Years," Meddeleser fra Dansk Geologisk Forening, Bd. XIV, Hefte 1.

______ (1959) "Glacial Variations in West Greenland in Historical Time," Meddeleser om Gronland, CLIX, No. 4.

______ (1963) "Glacial Variations in West Greenland in Post-Glacial Time," Bulletin of the International Association of Scientific Hydrology, VIII$^{e}$ Annee No. 1, pp. 75-84.

Wentworth, C. K., and Ray, L. L. (1936) 'Studies of Certain Alaska Glaciers in 1931," Bulletin of the Geological Society of America, XLVII, No. 6, pp. 879-934.

West, Robert (1955) "The Recent History of the Commander Glacier," Canadian Alpine Journal, XXXVIII, pp. 99-101.

Wheeler, A. O. (1920) "Notes on the Glaciers of the Main and Selkirk Ranges of the Canadian Rocky Mountains," Canadian Alpine Journal, XI, pp. 121-46.

______ (1934) "Records of Glacial Observations in the Canadian Cordillera, 1933 and 1934," Canadian Alpine Journal, XXII, pp. 172-87.

Weather Bureau, U. S. Department of Commerce (1909-1961) Climatological Data - Alaska, Annual Summaries 1909-1961.