RF 1469

Institute of Polar Studies
Report No. 9

Land Forms Produced by the Wastage of the Casement Glacier, Southeast Alaska

by

Robert J. Price
Institute of Polar Studies

Prepared for
National Science Foundation
Washington 25, D.C.
February, 1964

The Ohio State University
Research Foundation
Columbus, Ohio 43212

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ABSTRACT

An area of 15 square miles between the terminus of the Casement Glacier and the shore of Muir Inlet, in the Glacier Bay National Monument, was studied for a period of eleven weeks during the summer of 1962 and revisited briefly in 1963. The Muir Inlet area contains numerous well-documented and rapidly retreating glaciers and has proved to be a most accessible laboratory for studies in deglaciation. Previous studies in this area revealed that the wastage of the broad ice-bulb terminus of the Casement Glacier has produced many meltwater channels, eskers, and kames. Aerial and ground photographs taken since 1907 have enabled the author to map the position of the ice front of the Casement Glacier at various stages of its wastage.

By studying the available photographs and by mapping, in the field, the existing deposits and erosional forms, information has been obtained about the nature of ice wastage and the processes involved in the development of eskers and meltwater channels. The Casement Glacier has retreated from Muir Inlet across a ridge of Hysithermal gravels topped by Little Ice Age till. Since 1929 the ice front of the Casement Glacier has retreated down a "reverse-slope," i.e., the altitude at the base of the ice front has become progressively lower. Although the underlying topography was an obstacle to the free movement of meltwater from the Casement Glacier west to Muir Inlet, three major meltwater channels were established at an early stage and continued to function until an alternate route, south to Adams Inlet, was established. Glaciofluvial deposition was active on the "reverse-slope" and numerous eskers were formed.

One large esker system was mapped in detail; gravel ridges 30 to 60 feet high form a complex system one mile long and half a mile wide. Photographic evidence and the form of this and other esker systems studied indicate that most of the eskers developed in supraglacial or englacial streams.

Since the Casement Glacier began to terminate on land in 1907, it has retreated a maximum of four miles to its 1963 position. From Reid's plane-table map of the Muir Inlet Region in 1890-92, it is possible to calculate that in one locality ice 800 feet thick wasted away in 39 years. This is an average of approximately 20 feet per year, a figure comparable to the wastage of 18 feet per year determined by comparing a photograph taken in 1948 with the conditions in 1962.

The construction of maps from the 1946 and 1948 aerial photographs enabled a detailed analysis of the morphological changes that have taken place near the ice margin between 1946 and 1963. Since 1946 glaciofluvial erosion, rather than glaciofluvial deposition, has been dominant.

ACKNOWLEDGMENTS

This study of the proglacial deposits of the Casement Glacier has been financed by the National Science Foundation, Grant No. G-24149, and has been administered by the Ohio State University Research Foundation as Project No. 1496.

Field parties from the Institute of Polar Studies have studied glacial geology in the Glacier Bay Area for four summers since 1958. These studies, coupled with earlier photographic coverage of the area, have shown the existence of varied land forms (meltwater channels, eskers, and kames) produced by the ice wastage. These studies are the basis for the present work.

This study would not have been possible without the initial planning and strong encouragement of Dr. Richard P. Goldthwait. The advice and help of Dr. William O. Field of the American Geographical Society is much appreciated.

The National Park Service provided the field party with transportation and radio communication, and delivered supplies. Mr. L. J. Mitchell, superintendent of Glacier Bay National Monument, Chief Ranger Fisher, Ranger Butts, and Captain J. Sanders of the <u>M.V. Nunatak</u>, were all most cooperative and helpful.

Mr. Steven Calmer and Mr. Roy Welch were field assistants. They were particularly helpful in carrying out survey work, analysis of glacial and glaciofluvial sediments, and mapping.

The manuscript was read by Dr. R. P. Goldthwait, Dr. R. L. Cameron, and Dr. A. Mirsky of the Institute of Polar Studies, and Dr. Pitts of the University of Oregon. Their suggestions for its improvement are gratefully acknowledged.

This report was written when the author was assistant professor of geography at the University of Oregon.

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Area

The Casement Glacier is within Glacier Bay National Monument in Southeast Alaska (Fig. 1). The Glacier has an area of 50-60 square miles with extensive firn basins between 3000 and 5000 feet and has numerous tributary glaciers. It is connected across a divide to Davidson Glacier which flows eastward to Lynn Canal.

The Glacier Bay fjord system separates two mountain ranges, the Fairweather on the west and the Chilkat on the east. Muir Inlet is the northern arm of Glacier Bay, and the present snout of the Casement Glacier is four miles inland of the east shore of the inlet. Since 1899, the Casement Glacier has retreated from the edge of Muir Inlet where it coalesced with the Muir Glacier and from Adams Inlet where it joined the Adams Inlet Glacier. The 15 square mile area exposed by the retreating ice, and the subject of this report, is delimited by the Klotz Hills in the south, Forest Creek in the north, and the edge of the glacier to the northeast.

A thick gravel deposit, Hypsithermal in age (Goldthwait, 1963), forms a steep scarp behind a series of gravel fans along the east shore of Muir Inlet. This steep scarp which is between 30 and 60 feet high is backed by a more gentle slope rising to a north-south ridge between 200 and 300 feet in altitude. To the east of this ridge the topography is irregular but has a general slope down to an altitude of 130 feet at the present ice margin. Several large channels have been cut through the main north-south ridge. Except for the most northerly of the channels, now occupied by a small stream named Forest Creek, the channels are not occupied throughout most of their lengths by streams. All the meltwater flowing off the southeastern part of the Casement Glacier now enters Seal Inlet, an arm of Adams Inlet.

Climate

The climate is maritime and summer temperatures are relatively high for a glacier environment. The mean monthly temperature was 51.1°F. in July and 50.1°F. in August. Across the Muir Inlet in the vicinity of the Burroughs Glacier, Taylor (1962, p. 6) recorded in the summer of 1960 a mean monthly temperature of 50.0°F. in July and 49.5°F. in August. He also recorded nearly 8 inches of rain in August. In this area the high summer temperatures accompanied by rain seem to be responsible for the rapid ablation of the glaciers.

Revegetation of areas exposed by retreating ice is rapid. In the area studied alder now covers the Klotz Hills and the slope to the north of Forest Creek. The alder extends from the gravel bluff overlooking Muir Inlet across the ridge to within one and a half miles of the present ice margin. Small spruce are scattered throughout.

Problem

Two distinct problems are considered here: (a) the history of the deglaciation of the area between Muir Inlet, Adams Inlet and the present margin of the Casement Glacier; and (b) the processes involved in the development of land forms produced by glaciofluvial erosion and deposition.

Methods

A vertical aerial photograph (S.E.A. 72,033) on the scale of approximately 1:13,000 was used to prepare a base map on which were drawn distinctive features, such as eskers, kames, and meltwater channels. Stream sections were cleaned and studied to determine the composition and depositional environment of the deposits. Stone counts and stone orientations were also made.

Plane table maps of two esker systems were made using a Kern self-reducing telescopic alidade. Altitudes were determined using an aneroid barometer. A cairn built near high-water mark on the beach near the base camp was used as a reference. Relative rather than absolute altitudes were important.

The author visited the American Geographical Society to examine photographs and maps of the area. Dr. W. O. Field, of the Society, has collected an impressive series of photographs which record the wastage of ice in the Muir Inlet region since 1894.

DEGLACIATION OF THE MUIR INLET REGION

The earliest recorded observation of the glaciers of Glacier Bay was made by Vancouver (1801) who described the appearance of the bay in 1794. From that description it is impossible to locate the exact position of the terminus, but at that time Glacier Bay was entirely filled with ice (Fig. 1).

In 1880, when John Muir (1915) visited Glacier Bay, the ice had retreated into Reid Inlet and Muir Inlet. Muir Glacier had a 2 mile-wide front just south of Mount Wright.

The first plane table map of the Muir Inlet region was made by H. F. Reid (1896) in 1890 and 1892 (Fig. 2). This map shows the front of Muir Glacier still blocking Adams Inlet. In his report Reid estimated that the greatest advance of Muir Glacier had occurred 100-150 years earlier, in other words before Vancouver's visit. Reid had seen the large terminal moraine at Bartlett Cove (Fig. 1) and concluded that it represented the greatest extension of the glaciers in Glacier Bay. Spruce stumps found in the moraine described by Reid have subsequently been dated. Radiocarbon dating (Lawrence 1958) and tree-ring analysis (Goldthwait, 1963) indicate that the spruce stumps are between 120 and 125 years old. If 50 years are allowed for spruce seedlings to become established, the date of this moraine is probably about 175 years B. P. (Goldthwait, 1963). Reid's estimate was therefore fairly accurate, and this period of glacial advance is generally called part of the Little Ice Age.

Papers by Cooper (1937), Field (1954), Lawrence (1958), and Goldthwait (1963) all document the retreat of the glaciers in Muir Inlet, Adams Inlet, and Wachusett Inlet. Using 36 radiocarbon dates made available by IGY surveys and earlier botanical studies in the fjords of Glacier Bay, Goldthwait (1963) was able to date the deposits accumulated during the Hypsithermal episode and the events of the Little Ice Age glaciation. He established that by 7,500 years B. P. the Wisconsin Age glaciers had withdrawn farther than those existing at the present time. He also stated that gravel and lacustrine deposits filled the upper bays to present sea level about 7,000 years ago and reached 100 meters above present sea level 1,700 to 2,500 years ago. The southward expansion of glaciers (the Little Ice Age) began as early as 2,735 B. P. These advancing glaciers eroded the outwash that accumulated during the Hypsithermal period, removing most of it from the middle of the valleys and streamlining those deposits that occurred in protected localities. During this period of glacier expansion a silty gray till was laid down on top of the Hypsithermal deposits to a depth of 1 to 100 feet. The Little Ice Age Glaciers reached their maximum extent in Glacier Bay between 200 and 300 years ago, and since that time there has been rapid retreat. Detailed discussion of the retreat of Casement Glacier will be based on the author's interpretation of photographs provided by Dr. W. O. Field of the American Geographical Society. Positions of the ice terminus are given in Figure 3.

The earliest photograph studied (Brabazon, 1894) shows the Casement Glacier confluent with the Muir and Adams Inlet Glaciers and the tops of the Klotz Hills standing above the ice as small nunataks. This is the condition which most closely approximates Reid's 1894 plane table map. At that time there was approximately 1000 feet of ice over the camp site occupied in 1962 (Fig. 4,location 13).

A map of the Muir Inlet region prepared in 1907 by the International Boundary Commission and a photograph (Fig. 5) taken from Mt. Wright (Boundary Survey 1907) show a remarkable change in the extent of glacier ice in both Muir and Adams Inlets. Between 1894 and 1907 Muir Glacier retreated 8 miles, but a line on the 1907 map showing the position of the Muir ice front in 1903 indicates that Muir Glacier retreated 6 miles in a four year period.

By 1903 the Muir and Adams Inlet Glaciers were no longer confluent, and the rate of retreat of the ice front up Adams Inlet was much slower than that up Muir Inlet. This is due possibly to more rapid calving in the deeper water of Muir Inlet. It is possible that by 1907 the Casement Glacier may have ended on land; it was definitely ending on land in 1911 as shown by a photograph taken by L. Martin. The photograph shows ice resting on gravels with a subglacial stream emerging at the ice front.

A series of vertical aerial photographs, taken by the United States Navy in 1929 for the U. S. Geological Survey, shows the position of the margin of Casement Glacier. Between 1911 and 1929 the Casement Glacier had retreated only one mile from the east shore of Muir Inlet and was still confluent with the Adams Inlet Glacier.

The position of the ice margin in 1931 was determined from photographs taken by C. W. Wright and its position in 1935 determined from an aerial photograph taken by W. O. Field. By 1941 the Casement and Adams Inlet Glaciers were almost separated except for a strip of buried ice along the north shore of Seal Inlet.

In 1946 the U. S. Coast and Geodetic survey took a 9-lens photograph of the Casement Glacier and its outwash area. This is the first large-scale photograph which can be used to locate the ice margin and associated land forms accurately. It is not easy to distinguish between gravel and morainal material on the one hand and ice, covered with ablation moraine, on the other; therefore in some localities the position of the ice margin is only approximated.

The Glacier Bay area was photographed again in 1948 and stereoscopic pairs of photographs are available for the area discussed in this report. The changes that took place in the position of the margin of the ice, and the morphology of the area close to the ice margin between 1946 and 1948 and between 1948 and 1963 are discussed in detail later in this report.

GLACIAL STRATIGRAPHY

Two cross sections of the glacial stratigraphy in front of the Casement Glacier, A-B and C-D, are shown in Figure 6 and can be located in Figure 3. The stratigraphic units represented are:

5. Ablation Moraine

4. Upper Gravels

3. Upper Till

2. Lower Gravels

1. Basal Till

Basal Till

There is only one good exposure of this deposit in the area being considered. On the north side of the rock gorge presently occupied by Forest Creek the following section was measured (Fig. 4, Exp. I):

Little Ice Age gravels	2 ft.
Clay with weathered angular stones	2 ft.
Closely-packed angular stones	4 ft.
Weathered angular stones in sandy matrix	20 ft.
Dark gray clay with numerous marine shell fragments	10 ft.
Bedrock	

This section presents several problems. The dark gray clay with shell fragments occurs beneath 20 feet of till consisting of angular stones (many are weathered) in a sandy matrix. The four feet of closely packed angular stones above the till appear to be a solifluction deposit which probably moved down from the rock cliffs to the north at the beginning of the Hypsithermal period. There is no evidence of Hypsithermal gravels in this section; they may have been washed out by the predecessor of Forest Creek or they may never have been deposited because of obstruction by solifluction material.

The basal till in Exposure I is probably of Wisconsin age. Although there are no Hypsithermal gravels present above the basal till in this exposure, the great thickness of the Hypsithermal gravels (100 feet) on the south side of Forest Creek and above the elevation of the basal till suggests that this till is older than the Hypsithermal gravels.

The dark gray clay at the base of Exposure I contains numerous shell fragments which suggest a marine environment for the clays. These clays now have a maximum upper limit of 60 feet above present-day sea level; this suggests a minimum displacement relative to present sea level of 60 feet.

Lower Gravels

Beneath these gravels at Exposure II on the northwest side of the Klotz Hills are between 10 and 20 feet of dark gray silts, clays, and sands. Several bands of gray clay about 2 inches thick were examined closely and were seen to contain light and dark layers approximately 1/10 inch thick. These alternating layers are probably varves. No similar deposit was seen in the area being considered, but when the author visited the coastal sections 1/2 mile southeast of Goose Cove, 2 miles north of Forest Creek, a similar deposit 20 feet thick was discovered. Goldthwait (1963, p.5) described similar deposits, interbedded with the fine upper parts of the Hypsithermal outwash, in more than a dozen localities in Glacier Bay. He accounted for these lake deposits as follows: "It is not clear whether small lakes were ponded in side valleys and/or the main outwash by local fans after outwash building abated, or whether the readvance of ice down the main Glacier Bay blocked these valleys, both to the northeast and the southwest, to create large common ice-dammed lakes. One indication that the latter may have occurred is that all dates just under silts indicate that these lakes existed after 1,400 B. C."

Throughout most of the area being considered the gravels are the oldest deposits to be seen. As observed on the south bank of Forest Creek, they are well-stratified deposits having an almost horizontal stratification. In Forest Creek these gravels are over 100 feet thick, and in meltwater channels to the south there are bluffs where over 50 feet of the same gravels are exposed. A pebble count taken at Exposure IX (Fig. 4) showed that the gravels consist of 25% granites, 23% syenites, 8% diorites, and 35% metamorphic rocks (quartzite, hornfels, slate, marble). Twenty-three percent of the pebbles were round, 42% sub-round, and 35% sub-angular. Pebble sizes ranged from less than one inch to over six inches, and there were some well-rounded cobbles up to 12 inches in diameter.

Similar gravels were observed at 12 exposures (II, III, IV, V, VI, VII, VIII, IX, X, XII, XIII, and XIV). The thickness of these gravel deposits ranged from 20 feet to 100 feet, and they were all, with the exception of Exposures II and VI, topped by a till. A study of the shape of the pebbles found in nine of the exposures is summarized in Table I.

Table I. The Shape of Pebbles Based on Samples of 100

Exposure No. (Fig. 4)	Description	Angular	Subangular	Subround	Round
II	gravel	15	51	27	7
III	till	30	51	19	0
	gravel	4	41	36	19
IV	gravel	2	45	45	8
	till	23	55	21	1
	gravel	2	52	24	22
V	gravel	6	40	40	14
	till	23	50	16	11
	gravel	1	49	33	17
VI	gravel	1	43	34	22
VII	till	39	44	16	1
	silty clay	0	0	0	0
	gravel	4	33	44	19
IX	gravel	0	35	42	23
	till	16	34	30	20
	gravel	0	30	48	22
XV	till	23	50	19	8
	gravel	0	55	38	7
XVI	till	15	54	21	10
	gravel	3	45	42	10

These gravels belong to a stratigraphic unit occurring throughout the Glacier Bay area which has been dated by the analysis of the tree trunks that the gravels buried. The gravels were laid down during the Hypsithermal period and are 1,700-7,500 years old.

Upper Till

Throughout most of the area studied, the Hypsithermal gravels are overlain by a till ranging in thickness from 2 to 30 feet. It is not always easy to distinguish the till from the Hypsithermal gravels on the basis of content, texture, or structure. The rock types found in the till are similar to those found in the gravel, and the till also contains many rounded pebbles and cobbles. The matrix of the till is also very sandy. The character of the till is very similar to that of the Hypsithermal gravels and probably was derived from them. Analysis of pebble shapes in each of these deposits confirmed the difference between them; the suspected tills contained between 13% and 39% angular pebbles, and from 0-25% rounded pebbles. The gravels, on the other hand, contained between 0-4% angular pebbles and 17-19% rounded pebbles (Table I).

The till described above was deposited by the Casement Glacier when it advanced during the Little Ice Age. Stone orientations measured with a Brunton Compass at Exposures IX and XV (Fig. 7) show a dominant northeast and north trend, respectively, and indicate that the Casement Glacier deposited the till.

Upper Gravels

Throughout large parts of the area, resting either on Hypsithermal gravels (Exposures II and XII) or on Little Ice Age till, are gravels varying in thickness from a matter of a few inches to 70 feet. These gravels form either an extensive sheet or mounds and ridges 5 to 70 feet high. These mounds and ridges will be discussed later. The upper gravels were laid down by meltwaters associated with the most recent wastage of the Casement Glacier.

Ablation Moraine

Angular rock fragments ranging in size from a few inches to five feet across were scattered amongst and on top of the Little Ice Age gravels. In certain areas these angular fragments occurred in such profusion that the underlying gravels were completely obscured.

A traverse of the present surface of the Casement Glacier indicated large areas of ablation moraine almost obscuring the ice beneath it (Figs. 8 and 9). Aerial photographs of the Casement Glacier show these concentrations of ablation moraine extending up the glacier in relatively narrow strips in the form of medial moraines. The concentration of ablation moraine near the present ice margin appears to be the result of the contortion of these medial moraines so that they merge and form extensive spreads. The large areas of concentrated ablation moraine to the west of the present ice margin were formed presumably in the same manner.

Moraines

The accumulation of large moraine ridges has not been a feature of the wastage of the Casement Glacier. Only in one locality was ther a large, linear ridge made up of angular blocks arranged in a haphazard manner. This ridge (4) consists of three segments more or less in line, and consisting of angular blocks, 1 to 5 feet across, forming a ridge 6 to 20 feet high (Figs. 4 and 10). There is no fine matrix between these blocks. Since the linear ridge trends northwest, it possibly represents the last junction between the Casement and Muir Glaciers.

To the west of Seal Inlet, two major ridges 30 feet high, consisting of angular and rounded material, may also be moraines. The trend of these features, almost parallel to the probable direction of ice movement, suggests that they may be moraines associated with an ice lobe.

Within a mile of the present ice front are several low but distinct ridges, one to three feet high, consisting of angular and rounded fragments with a clayey matrix. They range in length from 10 to 150 feet and have two dominant trends, one parallel with, and the other at right angles to, the present ice margin. No attempt was made to map these forms or to study the orientation of the rock fragments in these low ridges. Their origin may be related to structures within the wasting ice-mass or they may be ice-pressed forms (Gravenor and Kupsch, 1959).

GLACIOFLUVIAL EROSION

Period 1907-1946

The wastage of the Casement Glacier since it began to terminate on land about 1907 has been, and still is, accompanied by large volumes of meltwater. The meltwater routes have varied considerably, and now there are many deserted meltwater channels. The mapping and description of these channels make possible the reconstruction of the pattern of ice wastage.

Meltwater channels in the area range in size from one 100 feet deep, 1/4 mile wide, and 3 miles long to smaller but important channels only 6 feet deep, 30 feet wide, and 100 feet long. Most of the channels are cut in till and gravel, but Forest Creek (Fig. 4, location 1), which still carries melt-waters from the Casement Glacier, has cut to bedrock in which it has carved a 30 feet deep gorge. Other meltwater channels cut through solid rock occur at ten localities northwest and south of the present ice margin.

Northern edge of the area. To the northwest of the present ice margin, near Forest Creek, bedrock is exposed. In this rock several distinct melt-water channels have been cut. They range from 20 to 40 feet in depth, with steep rock walls. At the mouths of the lower channels, gravel terraces indicate a depositional phase of the meltwater streams that cut the channels. It is suggested that these channels were cut at or beneath the margin of the ice when the Casement Glacier occupied the Forest Creek Area.

North-south ridge. It is significant that Forest Creek and two other large channels (11 and 14) leading to Muir Inlet are deepest where they cut through the north-south ridge of Hypsithermal gravels. Although there are small channels (3 and 9) cutting through the north-south ridge, each of these channels becomes larger as it descends the west-facing slope (Fig. 14). The fact that Forest Creek and the two other large channels (11 and 14) each cut through the north-south ridge suggests that the courses of these three melt-water streams were established before the ice front of the Casement Glacier had receded to the crest of the north-south ridge. As the ice continued to waste eastward these routeways were sufficiently well-established to be maintained, and the channels became incised in the north-south ridge. It is possible that all these major meltwater channels functioned subglacially during the early stages of ice wastage in a manner similar to those observed at the Burroughs Glacier in 1961 (Taylor and Goldthwait, personal communication). It is not necessary to postulate a 1/4 mile wide subglacial valley, which, it might be argued, could not exist because of lack of support for the ice-roof. The original subglacial channel was probably much narrower than the present channel, the much wider channel being produced by the meandering of a proglacial stream at a late date (Fig. 15). The floors of each of the three large meltwater channels show lateral cutting in the form of numerous distinct terraces at a number of levels.

The three minor channels (3 and 9) which are 20 to 50 feet deep and 150 to 1,500 feet wide were each initiated when the ice front rested on the west-facing slope or at the ridge crest. Although each of these channels just cuts through the north-south ridge crest, each becomes much smaller to the east of the ridge crest. Small distributary channels, ranging in depth from 6 to 12 feet, which link small areas of lake sediment on the east-facing slope to the heads of the three channels, indicate that each channel acted as an outlet for comparatively small lakes. The distributary channels leading from the lakes to the heads of the channels are not large enough to be outlets of principal glacial drainage. In other words, the channels were probably initiated by subglacial streams and later used by waters flowing from locally-fed lakes.

The approximate position of the ice margin in 1935 is shown on Figure 3. It was parallel to the shores of the westernmost proglacial lakes and cut across channels 11 and 14, possibly in the vicinity of the one north-sloping channel (12). It appears that this was a critical stage in the ice wastage. Once the ice margin started to descend the east-facing slope, most of the meltwaters moved either to Forest Creek or along the two major east-west channels (11 and 14).

An interesting feature of the connected lakes near the ridge crest is that there are numerous angular blocks of their floors. Lake sediments do not cover these blocks at present, and it is tempting to suggest that the lakes were formed beneath the ice and that the angular blocks represent ablation moraine. However, it is probable that the blocks were originally covered by a thin veneer of lake silts that has subsequently been removed by rain. Similar angular blocks were observed on the floor of another lake farther east. This lake was proglacial, as seen on an aerial photograph taken in 1948.

The development of channels 11 and 14 continued during the retreat of the ice front from the 1935 position. These two channels probably functioned simultaneously and may represent the continuation of two major subglacial streams. Esker systems (15 and 17) at the head of each of these channels represent a depositional phase of these same subglacial or englacial streams. Extensive lake sediments and former shore lines at the eastern ends of the large channels do not imply that these major channels were cut by overflows from those lakes, because the outlets leading from each of these lakes into the channels are relatively small, about 6 feet deep and from 30 to 50 feet wide.

One meltwater channel that has an unusual location (12) deserves some comment. It begins in an area of well rounded gravels as a shallow depression very near to the north side of channel 14. It drops northward and enters channel 11 as a 50 feet deep, 300 feet wide channel. The fact that the channels are accordant suggests that they were cut at the same time. The tributary channel may have originated as a marginal drainage channel and was possibly fed by a subglacial stream.

The next stage of glaciofluvial erosion resulted in the abandonment of both the large channels (11 and 14) leading to Muir Inlet in favor of a southward movement of meltwaters to Adams Inlet. Three major channels were cut during this stage. Channel 18 is a steep-sided trough, 60 feet deep and one quarter mile wide, cut through gravels and till. It swings in an arc across the head of channel 14. Meltwaters that had previously flowed down channel 14 began to escape southward and eventually cut the floor of channel 18 below that of channel 14. Meltwater flowing down channel 18 at first continued southward down channel 19 but later, presumably because of further retreat of the ice margin, abandoned this route in favor of a more direct route to sea level at the head of Seal Inlet. The reconstruction of the above sequence is based on the orientation of small channels at the head of channel 19 which indicate that the waters that moved down it flowed from the north. The south bank of channel 18 truncates the head of channel 19, and its floor is approximately 40 feet below the floor of channel 19.

The large north-south drainage channel (19) leading to Adams Inlet was formed when the ice margin lay across this area (1930 to 1940), and the short channels on its western side were formed along the ice margin during successive stages of retreat.

The most recent phase (post 1948) has been the complete abandonment of channel 18 and the establishment of the present drainage system. During the last 15 years the meltwaters moving off the southern part of the Casement Glacier have established a marginal stream parallel to the ice front which has destroyed eskers and ice-contact deposits clearly indicated on the 1948 aerial photographs.

The Klotz Hills. The north side of the Klotz Hills is thickly covered by alders and therefore difficult to map. The features produced by meltwater erosion on these north-facing slopes generally trend east-west. All the channels are cut in glacial and glaciofluvial deposits; bedrock appears in the bottom of one channel.

Just north of the Klotz Hills are two minor drainage channels which carried meltwater to Muir Inlet. To the east of the Klotz Hills is a major north-south drainage channel (19) formed as the ice retreated northward from Adams Inlet. This north-south channel has a number of tributaries entering from the west side; there are none on the east side. As the ice margin retreated toward the north, subglacial drainage flowed out along the main channel, and marginal drainage entered from the west as the gravel area sloped toward the ice and to the east. The tributary channels, successively abandoned as the ice margin retreated, have been left hanging as the main channel continued to develop. The southernmost tributary is over 20 feet above the floor of the main channel, the next is about 20 feet above, the next is 8 feet above, and the last is 3 feet above the main channel. The northernmost channel is connected to a series of small lakes (now dry) which were probably ice-dammed.

Period 1946-1963

The area to the east of the present major meltwater stream has been the most recent to be uncovered by the retreat of the Casement Glacier. Large masses of buried ice still exist (Fig. 16). Although the evidence of meltwater erosion in this part of the area is very clear, it was difficult to map these features in the field because, as the 1948 aerial photograph showed, all this part of the area was covered with ice.

With the exception of a large channel, 40 feet deep, cut through gravels (21), all the late meltwater channels in this area are cut through ridges of metamorphic rock that trend northwest. The bedrock channel that runs along the southeast side of the rock knob (19 B) is 150 feet wide and 80 feet deep. The upper parts of each side of this channel are formed by gravels, and the rest is cut through rock. The longitudinal profile of this channel has a steep gradient with a drop of nearly 100 feet. This channel, apparently the highest in altitude of the group, was probably the first to be cut and the first to be abandoned. When it ceased to function, the meltwater flowed to the southeast and cut another channel which is a rock gorge 10 feet deep and 30 feet wide. There is evidence of water erosion on the col in which this channel is located at least 40 feet above the floor of the main channel. The meltwaters then proceeded via a right-angle bend down a channel which is a sinuous rock gorge, 20 to 40 feet deep, that is in some parts very narrow. The fact that this channel cuts through a rock ridge suggests that it is a superimposed channel, its course having been determined by the former presence of ice (Price 1960).

The meltwater stream presently bordering the ice margin flows through a braided channel one half mile wide. It is destroying eskers and ice-cored gravel ridges and mounds on both sides of its channel as it flows south and east to Seal Inlet. Throughout the summer of 1962 the various parts of the stream were seen frequently changing course and sweeping along large boulders.

At the northwest edge of the Casement Glacier another much smaller meltwater stream parallels the northern ice margin, descends a 150 foot waterfall, and is joined by a subglacial stream that emerges at the bottom of a deep marginal hole surrounded by deep crevasses. Both of these streams reenter the ice and reappear to feed Forest Creek.

Summary

Until the Casement Glacier had retreated to its 1946 position, most of the glaciofluvial erosion was concentrated in the cutting of proglacial meltwater channels by streams that probably had subglacial or englacial origins. Throughout the period between 1929 and 1946 the Casement Glacier was retreating down a "reverse slope," and it is suggested that at least the lower layers of the ice near the snout were stagnant. The main evidence for this conclusion is furnished by numerous eskers formed during this period which will be described later. Although the glacier was retreating down a reverse slope the major meltwater channels were well established, and they were able to maintain their courses by eroding rapidly and causing the drainage divide to migrate northeastward. However, it eventually became easier for meltwaters to proceed to sea level at Seal Inlet and, except for Forest Creek, meltwater channels leading to Muir Inlet were abandoned.

GLACIOFLUVIAL DEPOSITION

Outwash Fans and Integral Deposits

The dominant deposit of the deglaciated area in front of the Casement Glacier is the widespread glaciofluvial gravels ranging in age from the Hypsithermal period to the present day.

Along the east shore of Muir Inlet, from the northern side of Forest Creek to the northern edge of the Klotz Hills, there is a series of five outwash fans. These fans are formed of well-rounded pebbles, cobbles, and boulders with some sand, and each is located at the mouth of a meltwater channel. The largest outwash fan is associated with the two major east-west meltwater channels (11 and 14); it has a radius of three-quarters of a mile and a maximum width of one mile. The slope of the undissected part of this fan is approximately 100 feet per mile, and this part of the fan forms a distinct terrace that separates the two main channels. Shallow, braided channels on the surface of the terrace indicate that waters once flowed across the surface of the fan from the lower part of channel 14 toward the lower part of channel 11. Presumably these fans began to develop when the Casement Glacier started to end on land, in 1907. They continued to develop so long as the meltwaters moved down channels leading from the Casement Glacier to Muir Inlet. The fan at location 5 is similar to the others, except that on its upslope end there is a series of gravel ridges that lead into the fan from the floor of a channel. The gravel ridges are generally sharp-crested and sinuous, 10 to 20 feet high, and consist of well rounded gravels, cobbles, and boulders. Several angular blocks were observed on the top and sides of these gravel ridges. The form and content of these ridges indicate that they are eskers, and the occurrence of angular blocks on their surfaces suggests that they were formed beneath the ice. If the subglacial origin of these eskers is accepted it is probable that the fan was formed as an ice-contact feature at the ice front. This hypothesis is strengthened by the indented nature and steep slope of the upslope end of the fan and by the presence of small kettle holes, 5-10 feet deep, on the surface of the fan near its eastern edge.

It is most likely that meltwater flowed down the channel in a subglacial tunnel that led to the fan, as the only channel cut through the fan is only 10 feet deep and 30 feet wide and is presently occupied by a small stream. Another small gully which parallels the ice-contact face of the fan carried relatively small amounts of water around the southern edge. If large amounts of meltwater had descended the main channel after the fan and eskers were formed, presumably the fan would have been dissected and the eskers destroyed.

Three small areas of lake sediments were observed east of the fan. It appears that small lakes were impounded between the esker ridges and the ice-contact face of the fan at a later date.

Early Esker Ridges and Associated Deposits

Between Forest Creek and channel 11 there are several gravel ridges that trend northeast. The longest ridge (8) is between 10 and 30 feet high and consists of well-rounded gravels, cobbles, and boulders. This ridge descends a west-facing slope for 400 yards before crossing the floor of a lake and ascending the east-facing slope of the main north-south rise. This small gravel ridge is absent over the crest of the rise but reappears on the west-facing slope to Muir Inlet. Here it has been cut through by a channel, leaving a small segment south of the channel. A subparallel ridge similar in form has also been cut through by the channel. A third gravel ridge occurs only on the east-facing slope of the rise one quarter of a mile south of ridge 8; it is 10 to 15 feet high and consists of well-rounded gravels, cobbles, and boulders with several angular boulders, three to four feet across, on or near its crest.

Several other small ridges are about ten feet high. One crosses the floor of a small lake and bifurcates around several depressions six feet deep and ten feet in diameter. Another (7) is covered by large angular blocks and its western end is cut by a channel.

South of channel 9 thick alder vegetation made field mapping difficult. A distinct sinuous ridge (10) observed on the 1948 aerial photographs was found to be between 20 and 30 feet high. A group of similar but smaller ridges occurs on the higher ground on the north side of channel 11.

This system of gravel ridges or eskers represents deposition in a subglacial or englacial drainage system that functioned at the time when the Casement Glacier covered the north-south ridge crest. As seen, some eskers were deposited before the cutting of channels; others, topped by lake silts, must have been deposited before the formation of lakes. Since the general direction of meltwater drainage was from northeast to southwest, it is postulated that "up-hill" sections of eskers were either deposited by waters flowing under hydrostatic pressure or by englacial, or supraglacial, streams which were subsequently let down onto the reverse slopes. It is presumed that these eskers were formed during the early stages of the wastage of the Casement Glacier, possibly even before it broke away from the ice occupying Muir Inlet (probably 1900 to 1920).

Apart from the early eskers described above, later glaciofluvial deposition in the area between the north-south rise and the present ice front consisted primarily of irregular deposits spread over the surface of the Little Ice Age till as the Casement Glacier retreated down the east-facing slope. The outwash deposits consist of well-rounded gravels, cobbles, and boulders. They form an irregular topography with a local relief generally between 6 and 12 feet but with a few mounds 30 feet high. These deposits have been cut into in several places by small channels showing a general movement of meltwaters toward nearby lakes.

Thick vegetation precluded any detailed mapping of depositional forms on the northern slopes of the Klotz Hills. A few mounds and short ridges of coarse gravel, with occasional angular blocks scattered on their slopes, were observed. The ridges are short and sinuous, between 10 and 30 feet high and about 100 feet long. The mounds range in diameter from 20 to 40 feet and are about 20 feet high. This area has shallow depressions containing lakes. East of the Klotz Hills near the southernmost tributary to channel 19 is a complex system of sand and gravel ridges and mounds, 10 to 30 feet high and covered by large angular blocks. The slope on which these forms stand descends toward the east, but the ridges have a definite north-south trend.

These ridges and mounds appear to be small-scale kames and eskers. The fact that they are covered by ablation moraine suggests that they were formed subglacially, and if such small forms survived the adjacent ice must have been stagnant when they were formed.

Proglacial Lakes Ponded on the East-facing Slope

Many small lakes developed on the east side of the north-south rise as the ice lay against it. The former shorelines are clearly marked, and small bodies of water still occupy some of these lake basins. The form of these lake basins, particularly their steep sides, suggests that they were formed by the wastage of buried ice blocks. The old lake floors are covered by dark gray silts on top of which are numerous rounded and angular boulders. The angular boulders on the lake floors and on the surface of the outwash gravels suggest a subglacial environment for the deposition of both the lake silts and the outwash gravels. As an alternative hypothesis, the writer believes that the lakes and the outwash gravels were laid down primarily in front of a "normal" retreating ice front. The angular blocks on the lake floors were placed there either by dropping off the retreating ice front or by rafting by icebergs.

The origin of the small lakes inland of the minor north-south rise could also be related to irregularities in the Hypsithermal gravel surface. The form of these lake basins and the fact that a considerable amount of water still stands in two lakes indicate that they were not just ice-dammed lakes. Two former lakes were ice-dammed, however, as indicated by the sediments and as seen on the 1948 aerial photograph. There is no bank of gravel on the east side of these old lake beds; the ice front presumably acted as the dam. Other lake systems, now represented by relatively small areas of lake sediments occurring in shallow depressions 10 to 15 feet deep, were probably frontal lakes at one time but do not owe their existence to the presence of the ice dam.

Gravel Ridges at Location 15

General description: A complex system of anastomosing ridges formed of gravels and cobbles occurs at the eastern end of channel 11 (Figs. 4, 20, and 21). They are spread over an area of one mile from northeast to southwest and half a mile from north to south. Most of the ridges are between 20 and 40 feet high; the highest is 60 feet above the adjacent lake floor. The material that forms the ridges ranges in size from sand to large boulders, but most of it is coarse gravel and cobbles. All the material is well rounded and unconsolidated. There were no good sections in the ridges that revealed evidence of stratification, and attempts to cut deep sections in the coarse, unconsolidated material to study its structure proved fruitless.

It is possible to distinguish three main types of ridges in this complex: linear ridges, closed ridges, and flat-topped ridges.

Linear ridges: There are three main linear ridges in the esker system, marked in figure 20. These ridges are peripheral to the system. Two have continuous crest lines; the third has a complex crisscrossing relationship with other ridges, and it is possible that it is not a single linear feature. These ridges, ranging in height from 10 to 50 feet, are sinuous and the crest lines uneven. The elevation along the crest of the linear ridge along the southeast side of the system ranges from 178 feet at the northeast end successively south westward to 194 feet, 178 feet, and 205 feet. The linear ridge at the extreme northwest edge of the complex also has a ridge crest that increases in elevation to the southwest. The maximum elevation of all three ridge crests is at the southwest end of the ridge.

There are minor linear ridges besides the ones just described: those that are nearly parallel to the major ridges and those at right angles to the major ridges. In general the ridges of both these categories are shorter, smaller in cross-sectional area, and lower in elevation in their central sections than the main ridges.

There are three minor gravel ridges running roughly east-west which join the major linear ridge on the southeast side of the esker system but which are still smaller and simpler linear ridges. These ridges are 10 to 15 feet high and 20 to 40 feet wide; their crest lines rise in elevation from east to west. Each ridge has its highest elevation where it is confluent with the main ridge. The nature of the junctions between the major and minor ridges is of interest. Generally the junction angle is between 30° and 70° and the crest lines of the minor ridges rise in elevation to join the major ridge.

Closed ridges: In the central and northern parts of the esker system is a series of depressions surrounded by ridges. The floor of the depressions are from 30 to 60 feet below the surrounding ridges. The highest elevations recorded in the ridge system (highest, 212 feet) are on the crests of these closed ridges which are linked to the main linear ridges and some short linear ridges.

Flat-topped ridges: Near the southcentral part of the ridge system there are some well-developed flat-topped ridges which have a common elevation of approximately 185 feet. The only other flat-topped area has an elevation of 203 feet, and there are several other highs in the northeast part that have elevations ranging from 195 to 209 feet. This may indicate a more continuous flat-topped surface before the depressions between the closed ridges were formed.

Lake development: A well-marked shoreline was observed at 172 feet on the northwest side of the main esker system. The presence of shoreline features on the sides of the gravel ridges in the southwest half of the system indicates that the ridges were formed prior to the drainage of the lake. Other field evidence for the former existence of a lake is the veneer of dark gray lake sediments observed on the floors of the depressions and small channels that have been cut through some of the gravel ridges. Most channels are 6 to 12 feet deep, 30 to 50 feet wide, and about 100 feet long. It appears that as the general lake level was lowered the various ridges emerged above the surface and a stage was reached when several separate lakes existed enclosed by gravel ridges. The levels of these small lakes were not the same, and waters moved from one lake basin to another by cutting the channels just described.

There was no one outlet for the large lake that continued to function for a long period of time. The channel in the south that drained the lake for awhile is 6 feet deep and is at an elevation of 160 feet. When water fell from 172 feet to below 160 feet this channel ceased its outlet role.

The 1946 and 1948 aerial photographs show clearly the existence of this lake in the southwest half of the esker system. At that time the south outlet was functioning, and all the ridges with crests below 172 feet were still submerged. It appears that the lake was dammed by the margin of the Casement Glacier.

Origin of the ridges: The form of the linear ridges in this system suggests that they represent the courses of former meltwater streams The three main linear ridges are approximately parallel to the direction of former ice movement, and it seems likely that these ridges are true eskers. If only the pattern presented by the ridge crests is considered and all height relationships are ignored, it seems reasonable that this pattern could have been produced by an anastomosing meltwater stream system.

There can be little doubt that the meltwaters flowed southwestward. This is indicated by the occurrence of acute angle junctions between ridges and by the general pattern of meltwater channels in the vicinity of the esker system. It is likely that the same meltwaters that deposited the gravels which make up the ridge system also cut channel 11. No stratification with imbricate structure was observed that would have indicated the direction of water movement.

The gradients of the ridge crests seem to be unrelated to the direction of flow of the meltwaters that deposited the gravels which now form the ridges. The elevations recorded along the crest lines of the various ridges have a wide range. For example, one ridge near the center of the system has an altitude of 193 feet at its junction with a minor ridge, but it drops down to 169 feet before rising again to 198 feet at its southwestern end. Similarly, another ridge is 140 feet at its northeast end and rises steadily to 214 feet at its southwest end.

The origin of the linear ridges appears to be related to the movement of meltwaters to the southwest, but whether these waters moved through subglacial, englacial, or supraglacial channels is difficult to determine. It could be argued that, since some of the gravel ridges end higher up than they began, they must have been deposited under hydrostatic pressure in subglacial tunnels. On the other hand, the same gravels could have been deposited in channels with a normal gradient either within or on top of the ice and subsequently were let down by the wastage of the underlying ice to their present position.

However, a close examination of the 1948 aerial photograph indicates that the gravel ridges extended east of the ice margin so that they were bounded by ice on either side. It seems likely that these gravel ridges were also underlain by ice. Twelve feet of buried ice lay beneath one gravel ridge at the extreme northeastern end of the esker system in 1962, and some ice was seen underlying other gravel ridges to the east of the major meltwater stream (20, 22).

It is significant that all the gravel ridges of this system observed in the 1948 photograph have a dominantly linear form. The complex system of closed ridges is not discernible, but two continuous ridges are seen extending up on to the ice surface. It is concluded that the closed ridges and their associated depressions have been produced by the melting out of ice from between and beneath the ridges seen in the 1948 photograph.

Whether the deposits were laid down in tunnels within the ice or in open channels in the ice surface is not known. Angular blocks and fragments that probably represent ablation moraine occur on some of the gravel ridges. The presence of such angular material lying on top of glaciofluvial deposits has been interpreted by many writers as indicating that the glaciofluvial deposits had been laid down beneath the ice surface. However, observation of the activity that takes place along the banks of a meltwater stream which is flowing between ice walls suggests that angular blocks of material often slide down from the ice surface and are incorporated within, or rest on top of, the glaciofluvial deposits. The fact that high gravel ridges are seen on the ice surface in the 1948 photograph favors the supraglacial hypothesis for the formation of this esker system.

The favorite hypothesis of formation of this esker system is as follows. The melting of the ice from the sides of the gravel deposits occurred first and produced the typical sharp ridge crest and steep slopes that form the majority of the esker ridges at present. The subsequent melting out of the ice from beneath the gravel ridges produced the uneven crest lines. The formation of the proglacial lake seen in the 1948 aerial photograph must have been subsequent to the melting out of the ice beneath and at the sides of the gravel ridges; otherwise the shorelines clearly seen on some ridges could not have been formed or have survived the disturbances produced by the melting out of the ice beneath the ridges. Although the supraglacial hypothesis is favored here for the eskers of this system, it should be pointed out that the evidence is not conclusive.

Gravel Ridges East of the Major Meltwater Stream

On the east side of the major meltwater stream there is a series of gravel ridges from 15 to 120 feet high that consist of well-rounded gravels, cobbles, and boulders, and have steep sides and sharp crests. The present drainage is undercutting one ice-cored gravel ridge (22) to form an ice cliff approximately 60 feet high. This ridge has a gravel core only 5 feet thick (Fig. 16).

Two major problems are encountered in interpreting these gravel ridges. There appears to be no relationship between the cutting of early meltwater channels and the deposition of the gravel ridges. It is not possible to determine how much of the gravel ridges was destroyed during the cutting of channel 21 and the development of the present meltwater stream leading to Seal Inlet. On the 1946 and 1948 aerial photographs there is no evidence of gravel ridges or supraglacial meltwater streams in the localities where ridges were found in 1962. However, the orientation of some of these ridges suggests that they were probably linked with gravel ridges on the west side of the valley train before meltwaters started moving towards Seal Inlet.

It seems likely that these ridges were formed englacially or subglacially in ice that became isolated and stagnant to the south of the rock knob (19 B). The other ridges farther to the southeast were probably produced by the melting out of blocks of buried ice. There are no channels which feed into these ridges, and two of the ridges encircle a depression, while two others form the banks of a lake. The position of these ridges between two high rock ridges suggests that this was a locality where a mass of stagnant ice, covered by thick gravels, wasted away to produce the four ridges and the two depressions.

Gravel Ridges at the Eastern End of Channel 14

This small gravel ridge system appears to be a remnant of a larger system that has been destroyed by the cutting of channel 18. The gravel ridges are 10 to 40 feet high, consist of well-rounded gravels, cobbles, and boulders, and have sharp crests. The crest lines of these ridges are irregular. Scattered over the surface of these gravel ridges there are numerous angular blocks, some of them 6 feet across. Between the major ridges are depressions with irregular hummocky floors with scattered patches of fine sediment. Even within the main gravel ridges there are a few depressions 3 to 10 feet deep which suggest the former presence of buried ice blocks.

Gravel Ridges at the Northern End of Channel 18

A plane table map on the scale of 1:2,000 was made of these ridges (Fig. 22). The longest ridge is one quarter of a mile long, and the altitude of its crest ranges from 163 feet at its northern end to 191 feet where it is joined by another ridge and then falls to 153 feet at its southern end. The tributary ridge also rises in elevation from 156 feet at its northern end toward its junction with the main ridge. Most remarkable is the location of this system of gravel ridges on the floor of channel 18; the ridges are generally at least 40 feet below the ridge system to the southwest (17).

There are two types of ridges in this system. All of the ridges are formed of well-rounded gravels, cobbles, and boulders, and all are sharp-crested except for one long ridge which has a flat top 15 to 30 feet wide. On the surface of this flat-topped ridge there is evidence of stream erosion, and one channel oriented east-west suggests that water moved across the top. The presence of flat-topped and sharp-crested ridges in the same group poses certain problems.

Examination of the 1946 aerial photograph shows the easternmost ridge in existence with a meltwater stream flowing approximately parallel to it on its southeast side. It is possible that at that time gravels underlain by ice lay to the northwest of this ridge and that the westernmost ridge was produced by the wastage of this ice. This hypothesis is supported by the fact that the surface immediately to the north and west is pitted with depressions 5 to 15 feet deep.

At a locality at the northeastern end of the ridge system, a mass of buried ice at least 12 feet thick was exposed in the core of a gravel ridge. This supports the hypothesis that much of the ridge system was developed on top of ice. The position of the ridge system on the floor, but at the northern end, of a major meltwater channel (18) demonstrates that the ridges themselves developed during a depositional phase of the meltwater streams as they flowed southwestward in or on the ice but before they cut channel 18. The linear form of these ridges and the fact that they represent the former course of a meltwater stream permit them to be called eskers.

Summary

The main problem in the interpretation of the glaciofluvial deposits described above is to determine the nature of the environment in which deposition took place. The outwash fans, outwash spreads, and lake sediments were almost certainly proglacial. The eskers, on the other hand, are not so easily interpreted. The major lines of evidence are their form and position, their composition and stratigraphy, their relationship with each other and with meltwater channels, and the presence or absence, either in 1962 or earlier, of ice in or beneath the ridges.

The linear form, the nature of the tributary junctions between ridges, and their sorted, rounded composition suggest that the material was deposited by meltwater streams. The general movement of meltwaters, based on old photographs and glacier slopes in the area being considered, was from northeast to southwest; but some eskers rise in elevation to the southwest. There are two possible hypotheses. The eskers could have been deposited in subglacial tunnels and the uphill sections deposited under hydrostatic pressure, or the eskers were deposited in englacial tunnels or supraglacial channels and were subsequently let down onto the underlying topography. The presence of ice-cored ridges near the present ice margin, the irregular crest lines of the ridges, and the existence of kettles in the ridges and the outwash spreads around the ridges, all favor the second hypothesis. The fact that large gravel ridges can be seen, in the 1946 and 1948 aerial photographs, extending onto the ice surface demonstrates again the supraglacial rather than englacial environment for at least most of the ridges.

It has been argued that gravel ridges established on or within an ice mass will be destroyed when the ice melts out. In his paper on the supraglacial debris on the Wolf Creek Glacier, R. P. Sharp (1949) indicates that the differential melting of the ice beneath the debris produces a constant redistribution of the material with the consequent destruction of specific forms. However, in a later paper (Sharp, 1953), he points out that the wastage of ice beneath the spruce trees that have grown along the stagnant margin of the Malaspina Glacier must have been sufficiently uniform so that no marked tilting of the trees or serious damage to their roots has resulted. He further states (p. 879) that: "Preservation of supraglacial eskers underlain by no more than 10 to 20 feet of ice appears to be within the realm of possibilty under favorable conditions."

In the marginal portions of the Casement Glacier it would be necessary to postulate the preservation of eskers that developed on ice approximately 50 feet thick to explain "uphill" sections of certain eskers. With uniform melting beneath a thick gravel covering in some localities at least 50 feet thick, this hypothesis seems reasonable.

ICE WASTAGE AND MORPHOLOGICAL CHANGES BETWEEN 1946 and 1963

Aerial photographs taken in 1946 (U. S. Coast and Geodetic Survey), 1948 (U. S. Geological Survey), 1956 and 1958 (K. Loken, A. G. S. collection) allow a detailed analysis of the changes in the location of the ice margin, the wastage of buried ice, and the routes followed by meltwater streams. The information gathered from the photographs enables a better understanding of the forms and deposits mapped in 1962.

The 1946 and 1948 photographs are of excellent quality, and it was hoped that it would be possible to draw detailed maps from each photograph and compare them. However, the 1946 photograph was taken with a 9-lens camera and there is considerable distortion in the vicinity of the glacier terminus. The map of conditions in 1946 is therefore a sketch map using the less distorted 1948 vertical aerial photograph as the base. Figure 23 indicates the conditions in 1946, 1948, and 1963.

In 1946 the Casement ice front was acting as a dam for a large lake adjacent to the main esker system (15). Streams fed by the overflow of waters from the lake still flowed down channel 11 to the west. The channel and eskers had formed before this. In 1946 some of the eskers on the floor of the large lake (15) were beneath the water surface but several clearly extend behind the ice front and onto the ice surface.

The position of the ice margin in the area between locations 15 and 16 is difficult to determine. It is probable that this area was occupied by buried ice. A second proglacial lake near the head of channel 18 is in evidence and was drained by streams that flowed to Seal Inlet. These streams were confluent with a meltwater stream that emerged from beneath the ice to the northeast. To the northwest of this meltwater stream there was a large, sinuous esker, which at least in its northeast part extended onto the ice surface.

In 1946 at the head of channel 18 the esker system (16) was represented by only one ridge. To the north of this ridge there appears to have been buried ice. East of channel 18 there was a relatively high ridge of ice becoming progressively thinner and more dirty to the south. A tongue of ice also underlies some well-developed eskers on the north side of Seal Inlet; these cannot now be found. An outwash fan extended into Seal Inlet at the end of channel 18.

The major change between 1946 and 1948 was the abandonment of channel 18 by meltwaters supplied by the drainage of a proglacial lake and a major stream emerging from the Casement Glacier. The meltwater stream from the glacier cut through the ice ridge east of channel 18 and followed a more direct route to Seal Inlet. During the change the eskers on the north side of Seal Inlet were destroyed.

The eskers just west of the major meltwater stream from the ice were still present on the ice surface in 1948, and since stereoscopic pairs of photographs are available the heights of these gravel ridges can be estimated. Measurements made by Roy Welch indicate that the gravel ridges were approximately 130 feet high and approximately 100 feet wide at the base. All that can be interpreted from Loken's photographs of 1956 and 1958 is that these eskers were still in existence. The main meltwater stream followed a southerly course similar to that of 1948. By 1962 the eskers had been completely destroyed. Early marginal lakes had been drained, and a major meltwater stream, half a mile wide, was actively destroying the major esker system.

The ice margin in 1962 was readily located, and only small patches of buried ice were observed south and west of the rock knob. Since that rock knob, approximately 260 feet high, was covered with ice in 1948, it can be stated that at least 250 feet of ice had been removed in 14 years. This ice wastage has been the result of ablation and meltwater stream activity to the south, and finally north, of the rock knob.

The author visited the area in June, 1963 to determine what morphological and drainage changes had taken place during the past year. Photo station 19B was re-occupied and a panoramic photograph of the Casement Glacier taken. When this photograph was compared with one taken from the same station in 1962, it was seen that considerable thinning of the ice near the margin of the glacier had taken place but there had been no measureable, horizontal retreat of the ice margin. No morphological or drainage changes of any significance had occurred along the ice margin although there was noticeably less water in the major meltwater stream than in August 1962.

Between 1946 and 1963 the proglacial environment near the margin of the Casement Glacier became increasingly one in which glaciofluvial erosion was dominant. The Casement Glacier now appears to be retreating up its valley rather than down a reverse slope, as it had done prior to 1946.

CONCLUSIONS

In the area between Casement Glacier and Adams and Muir Inlets one important factor that usually complicates the interpretation of any land form was controlled. The excellent collection of photographs of the Casement Glacier dating from 1894 made it possible to establish chronological relationships.

Since the Casement Glacier began to end on land in 1907 it has retreated a maximum of 4 miles to its 1963 position. In the same period the Muir Glacier, the snout of which is still located in the fjord, has retreated 9 miles. From Reid's plane table map (Fig. 2) of the Muir Inlet region (1890-92), on which he shows contours on the surface of the Casement Glacier, and the U. S.

Geological Survey topographic sheet Juneau D-6, it can be seen that nearly 800 feet of ice wasted away during 39 years. This is an average of 20 feet per year, a figure comparable to that determined for the area near the bedrock hill near the present ice edge during the years 1948-1962 (18 feet/year) or by John Muir long ago (1915).

The retreat of the glacier down a reverse slope has obviously played an important part in the development of both meltwater channels and depositional features between 1907 and 1946. The deglaciated area near the Casement Glacier shows that depositional features, such as eskers, can develop in association with a retreating valley glacier as long as the meltwater streams in the proglacial area follow restricted courses. However, when glaciofluvial erosion becomes dominant along the whole length of the ice margin, as has happened since 1946 near the Casement Glacier, depositional forms are destroyed.

The meltwaters from the Casement Glacier first escaped westward to Muir Inlet and then southeastward to Adams Inlet. As the ice thinned over the north-south ridge, the major east-west channels were cut at first under, and then later in front of, the ice through Little Ice Age till and Hypsithermal gravels. Large outwash fans developed at the west end of each of the channels leading to Muir Inlet. Groups of eskers, developed in or on top of the ice, represent depositional phases of the meltwater streams that also cut the major east-west channels. The existence in 1962 of some ice-cored eskers, the irregular crest lines of the eskers, and associated kettle holes within the esker systems suggested a supraglacial or englacial origin for most of the eskers. The occurrence of eskers near the terminus but actually on the surface of the Casement Glacier was indicated by air photographs taken in 1946 and 1948. This evidence supports the englacial or supraglacial hypothesis.

As the terminus of the Casement Glacier retreated down a reverse slope, numerous small proglacial lakes developed. Eventually the main meltwater drainage ceased to move towards Muir Inlet but followed a more direct route to sea level in Adams Inlet. This stage of the wastage of the Casement Glacier has been characterized by the destruction of glaciofluvial deposits laid down at an earlier stage.

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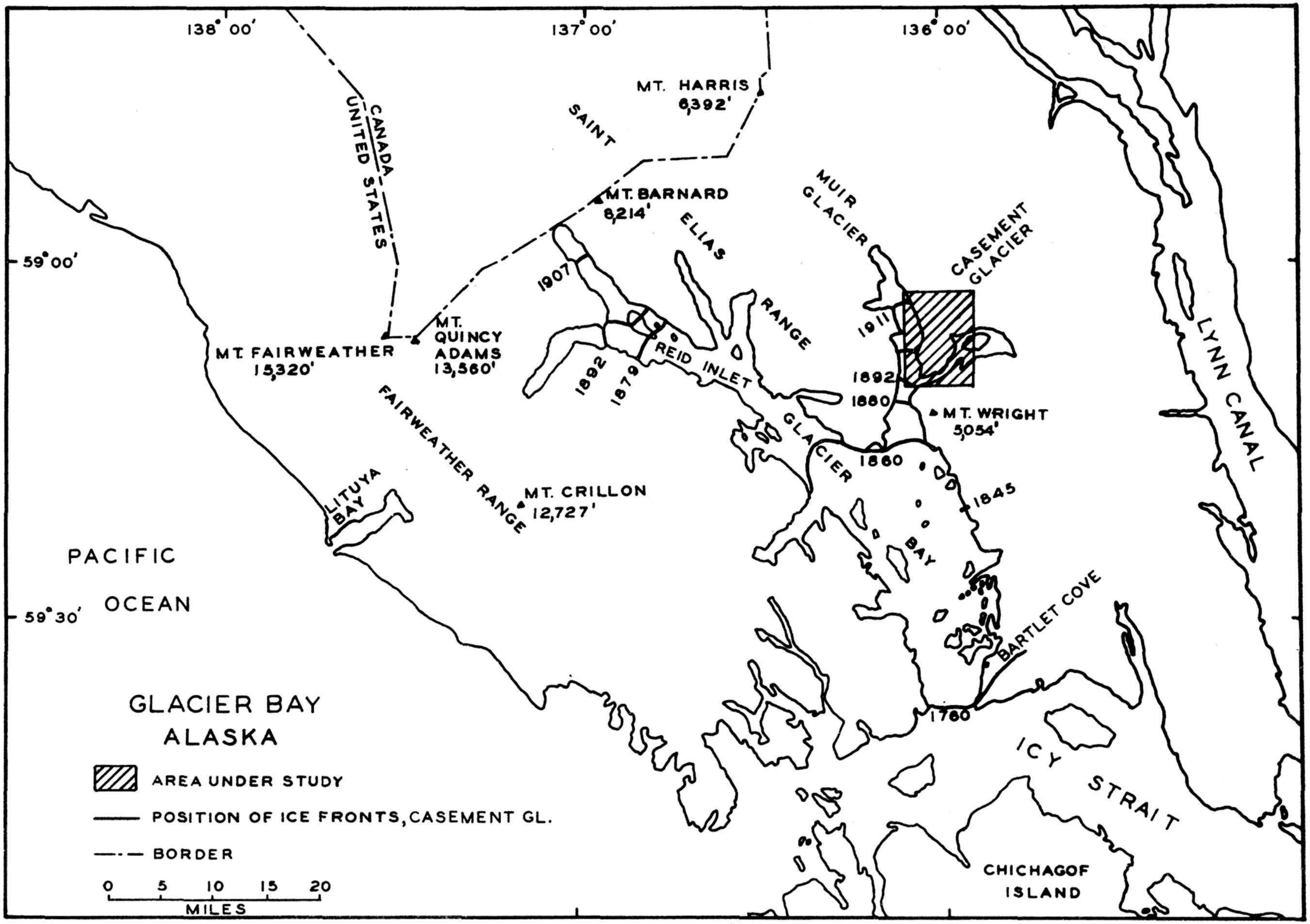

Fig. 1. Location map.

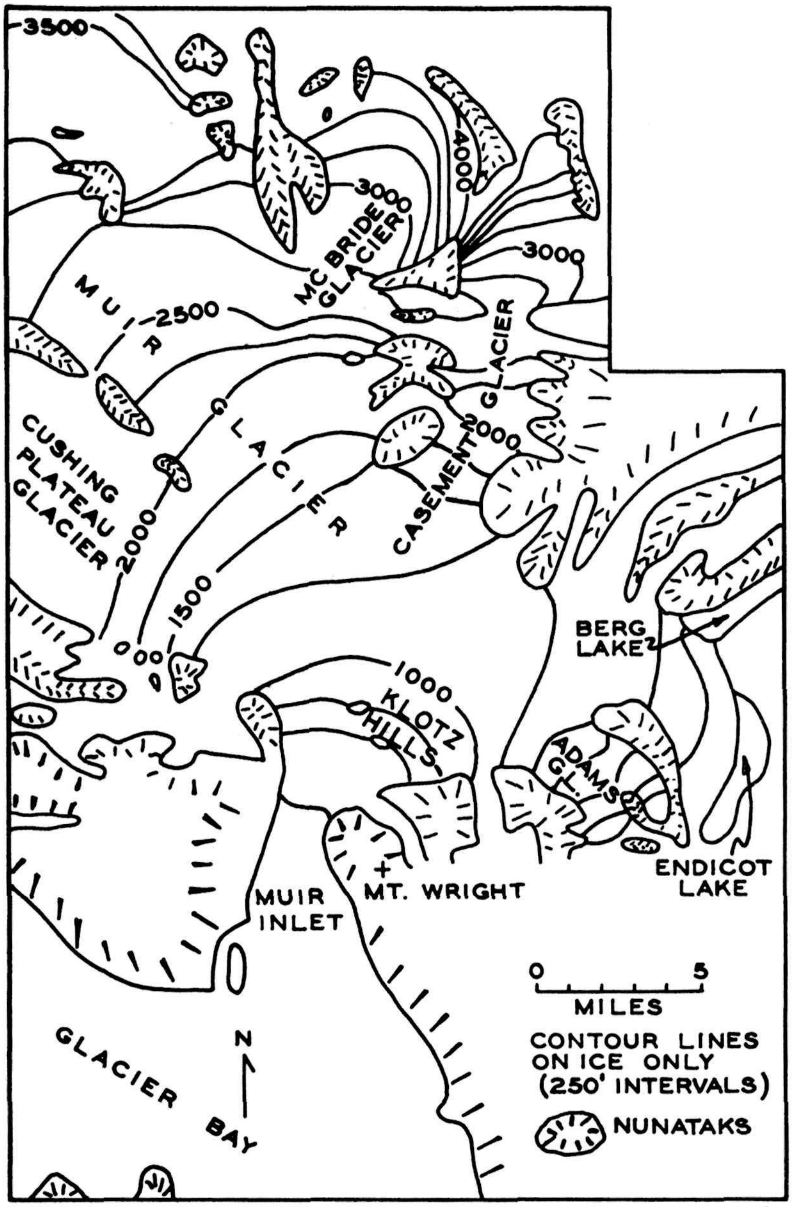

Fig. 2. Muir Glacier system as surveyed in 1890 and 1892 by H. F. Reid.

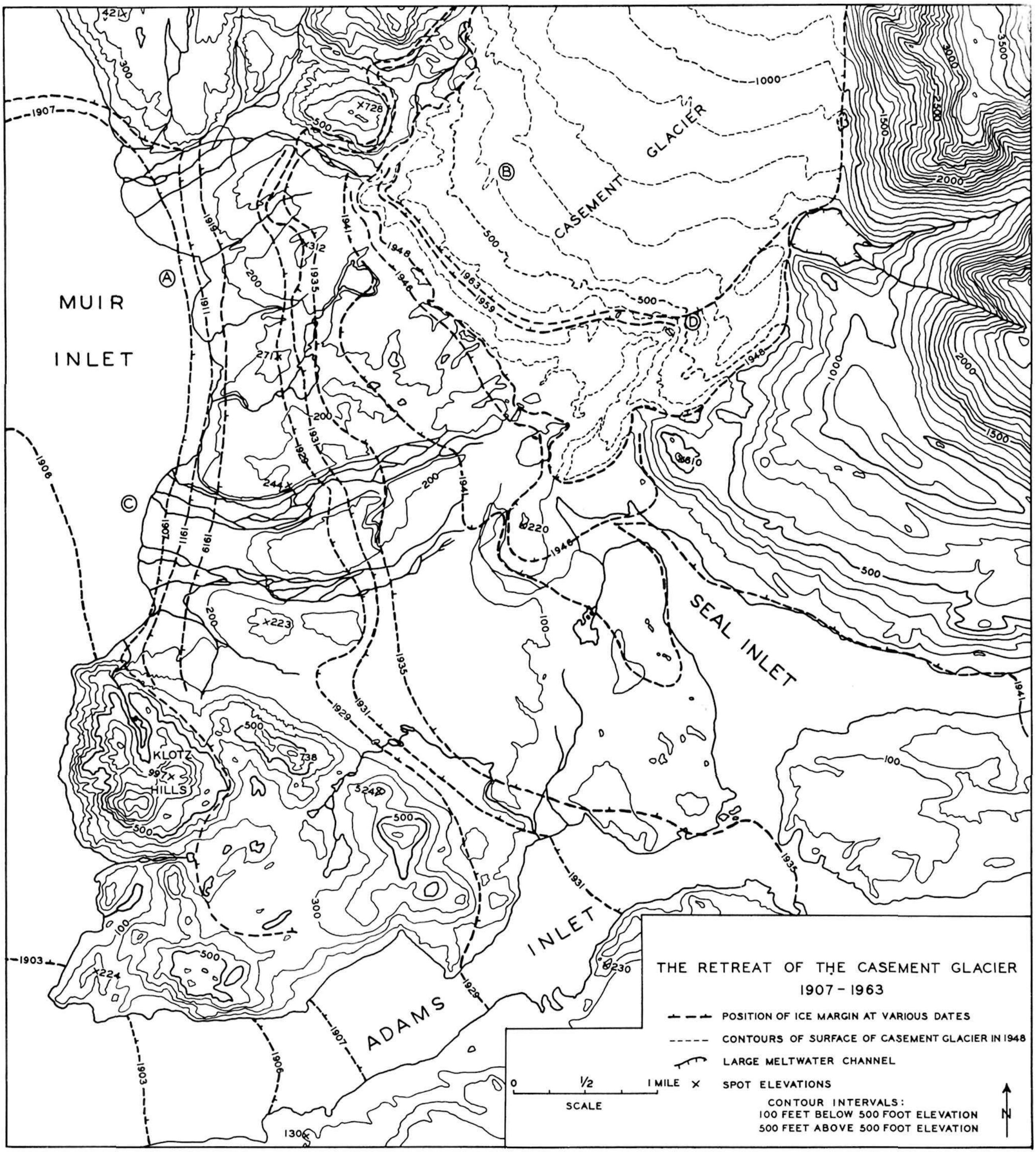

Fig. 3. Retreat of the Casement Glacier terminus, 1907-1963.

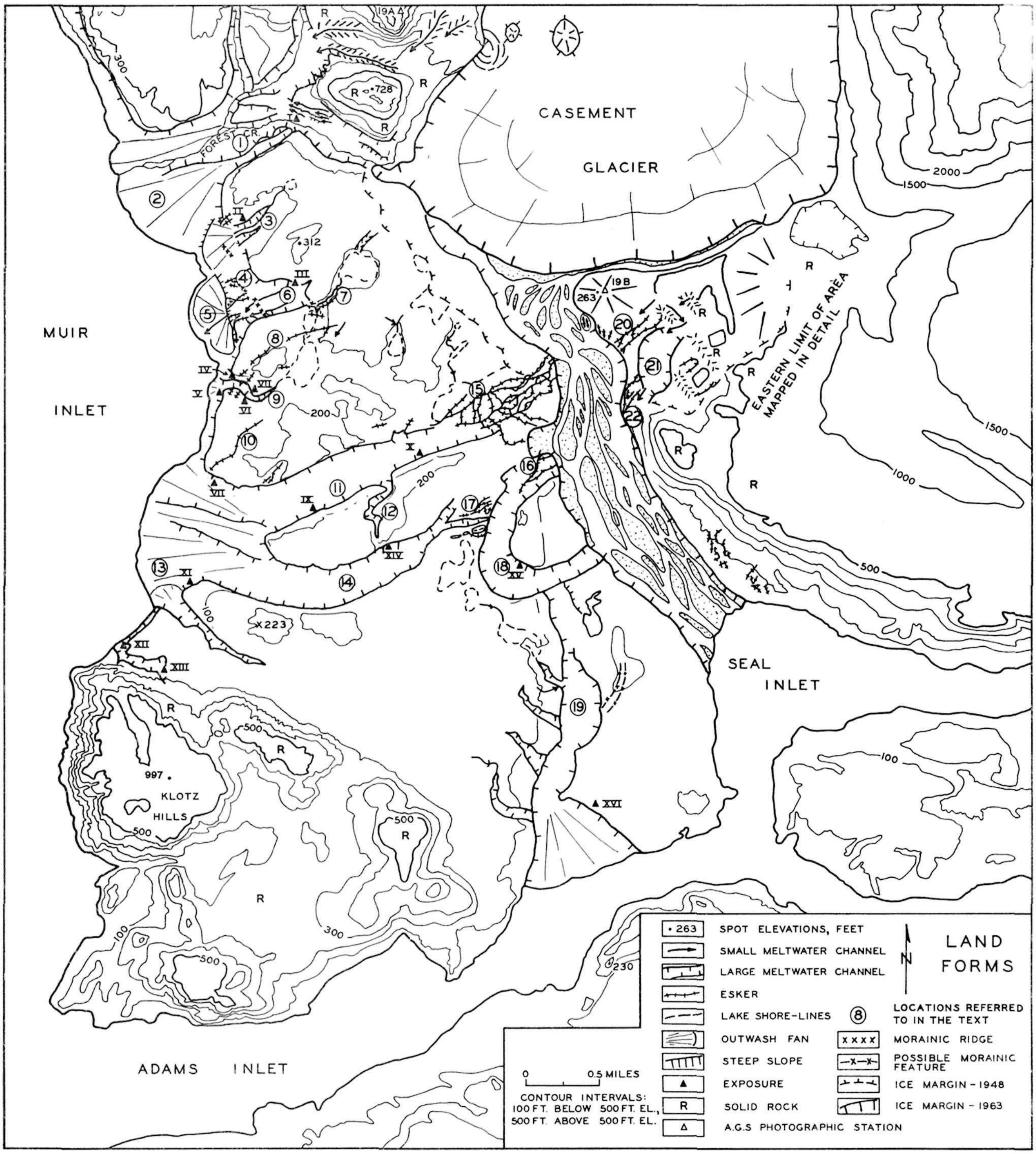

Fig. 4. Glacial land forms, depositional and erosional, in front of the Casement Glacier.

Fig. 5. Casement and Muir Glaciers from Mt. Wright, 1907.

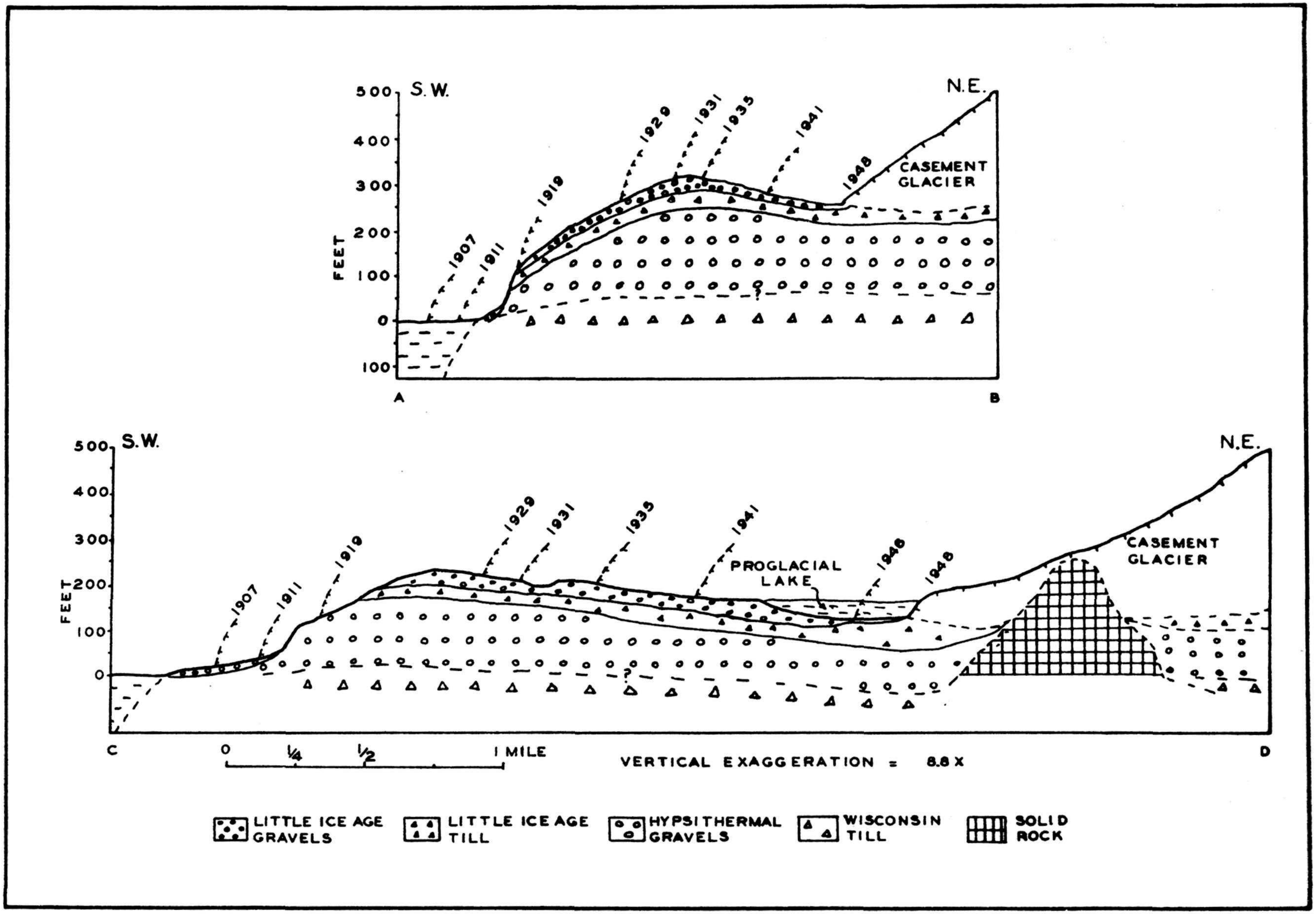

Fig. 6. Cross profiles of the Casement Glacier proglacial area based on 1948 U. S. Geological Survey maps.

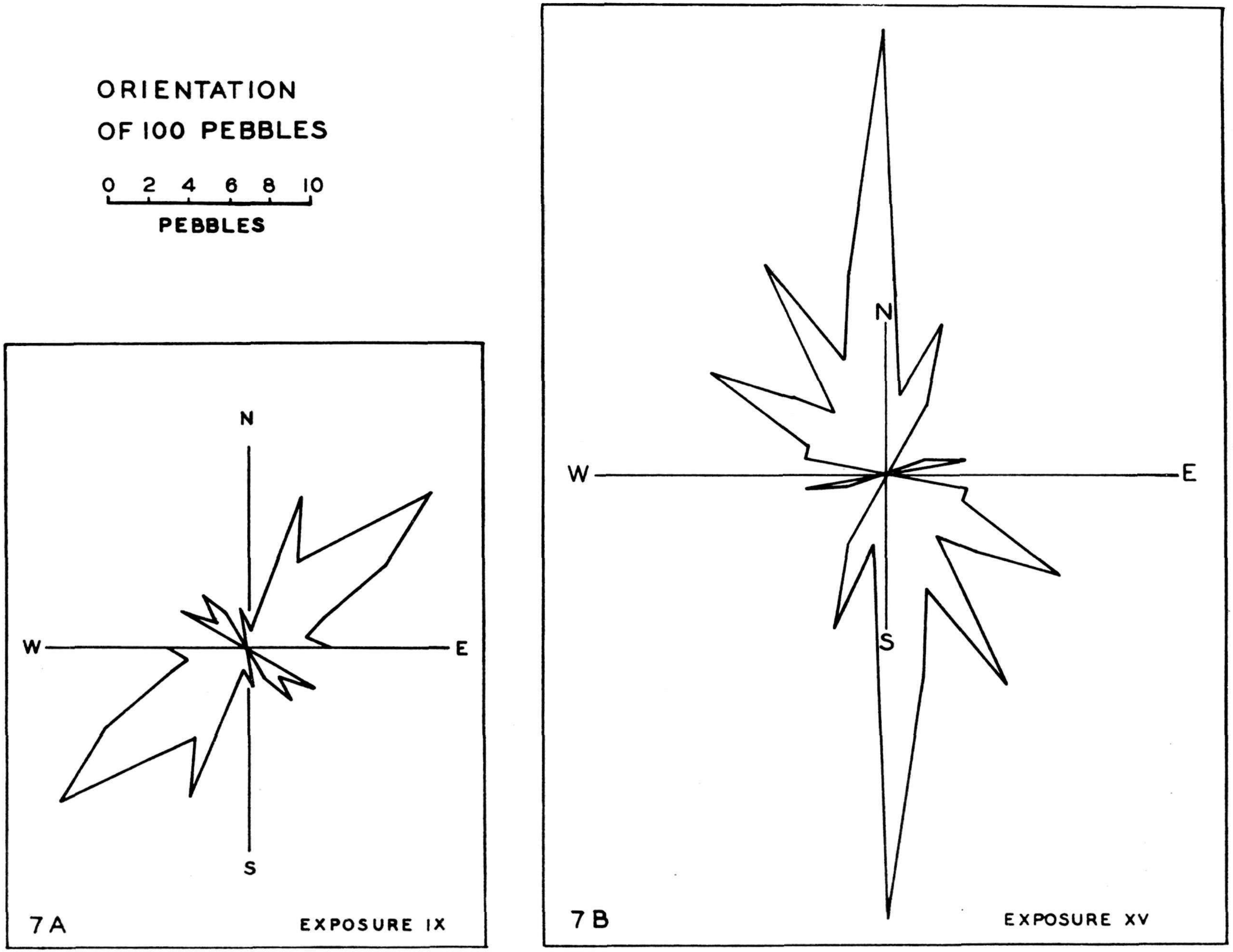

Fig. 7. Pebble orientation in till near Casement Glacier.

Fig. 8. Aerial view of Casement Glacier and part of proglacial area.

Fig. 9. Ablation moraine on Casement Glacier.

Fig. 10. Moraine parallel to Muir Inlet and west of the north-south ridge.

Fig. 11. Looking northwest up Forest Creek from near its southeastern end.

Fig. 12. Aerial view of the two major channels draining into Muir Inlet.

Fig. 13. Esker system in upper part of the northernmost major channel draining into Muir Inlet.

Fig. 14. Minor channel which drains into Muir Inlet.

Fig. 15. Aerial view taken in 1929, showing the Casement Glacier and a subglacial stream emerging from the terminus.

Fig. 16. Ice-cored gravel ridges on the east bank of the Seal Inlet valley train.

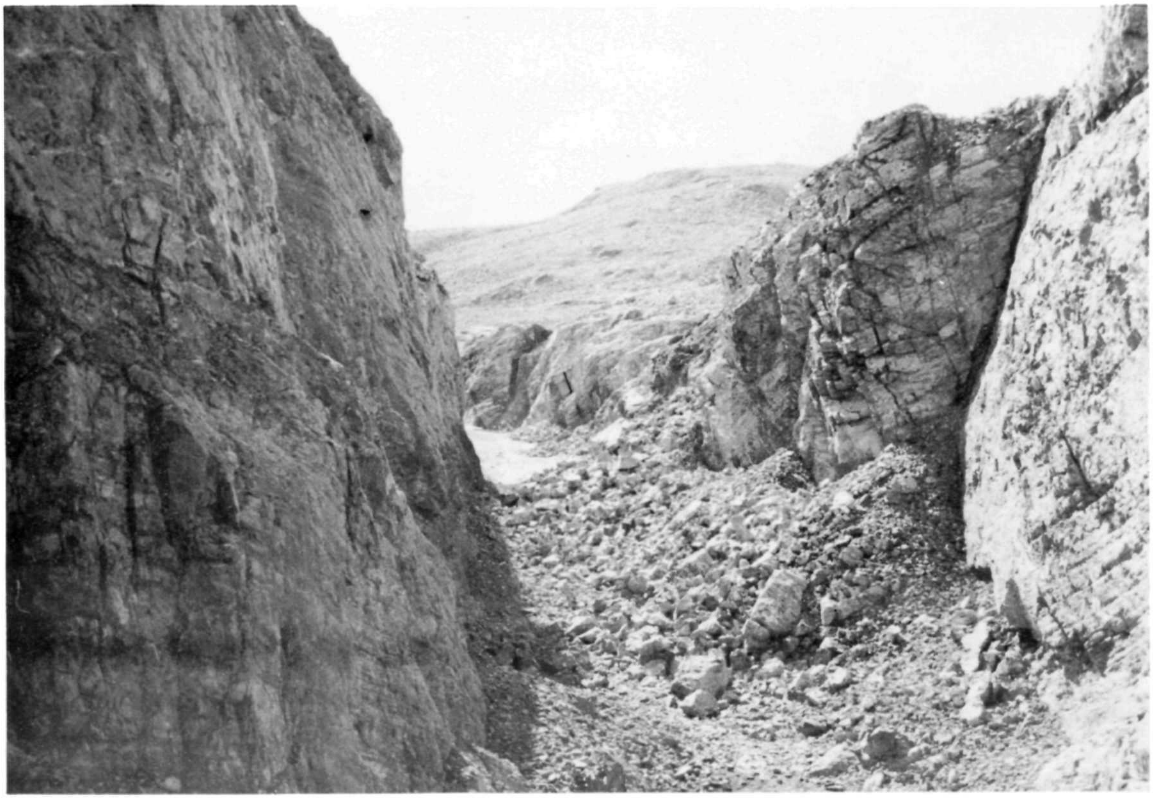

Fig. 17. Channel cut in bedrock near present margin of Casement Glacier.

Fig. 18. Subglacial stream emerging from Casement Glacier.

Fig. 19. Esker leading to a fan on Muir Inlet.

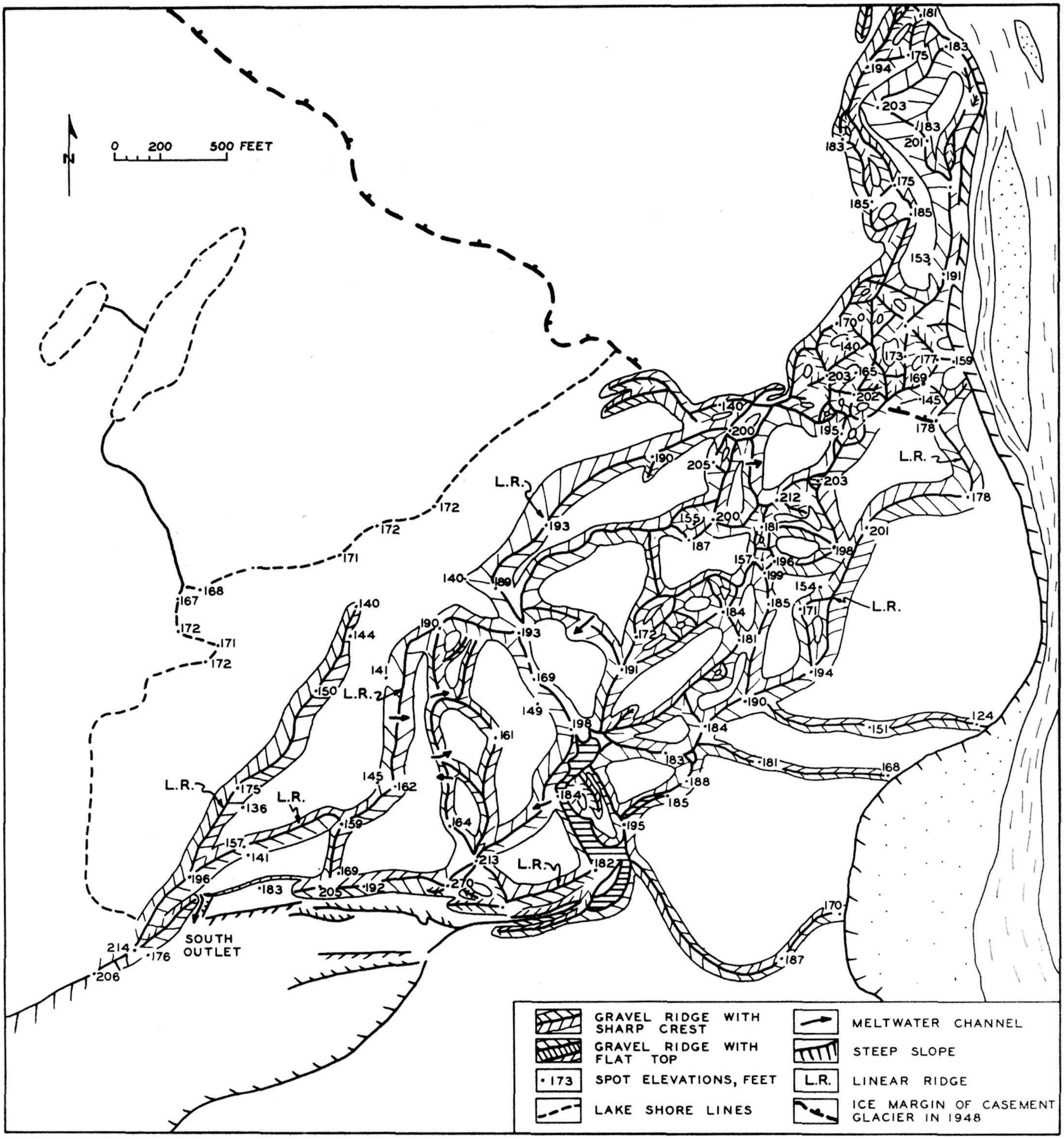

Fig. 20. Plane table map of major esker system in area between locations 15 and 16 (see Fig. 4).

Fig. 21. Aerial view of major esker system.

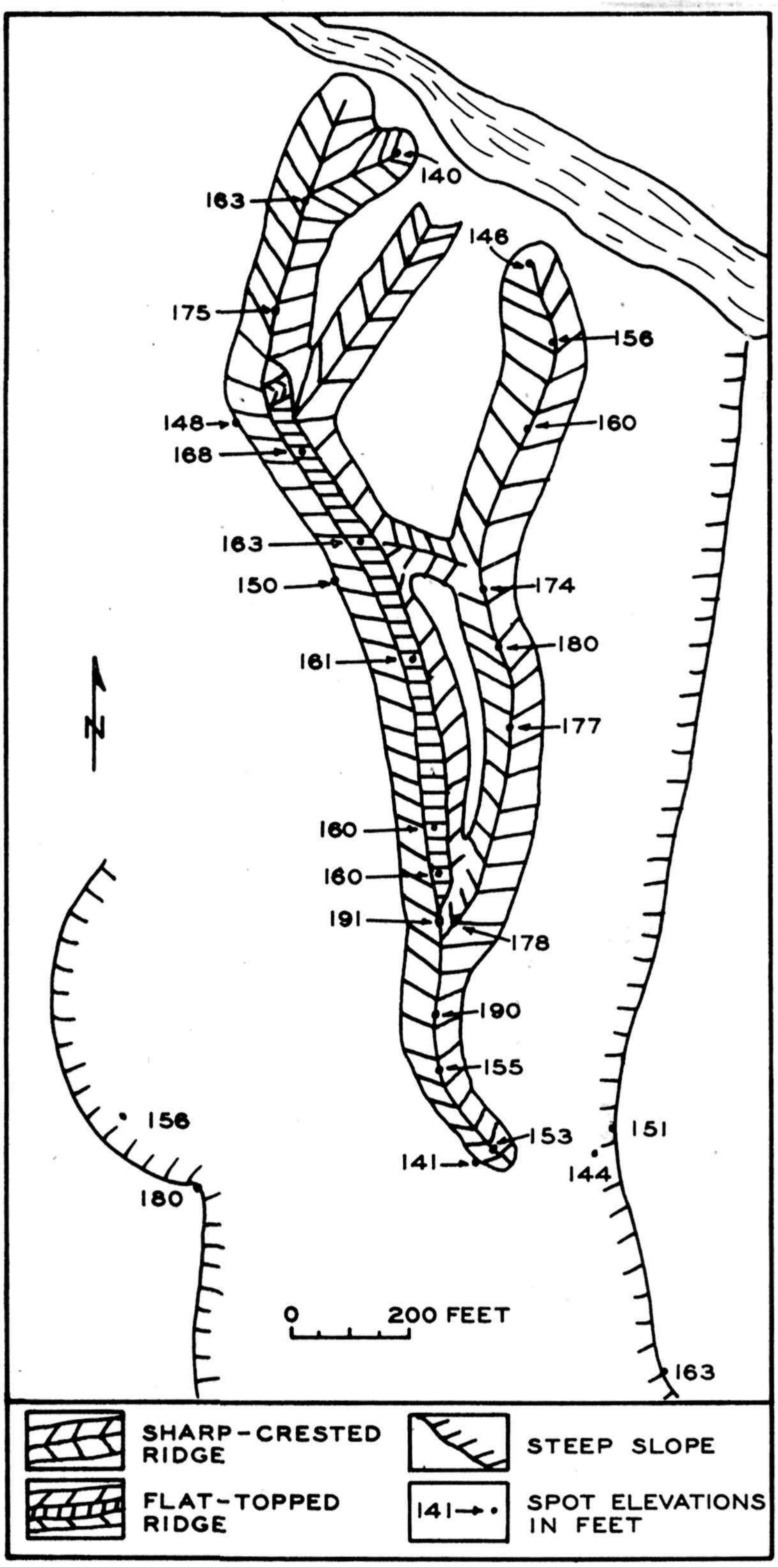

Fig. 22. Plane table map of eskers at location 16 in the arcuate meltwater channel (see Fig. 4).

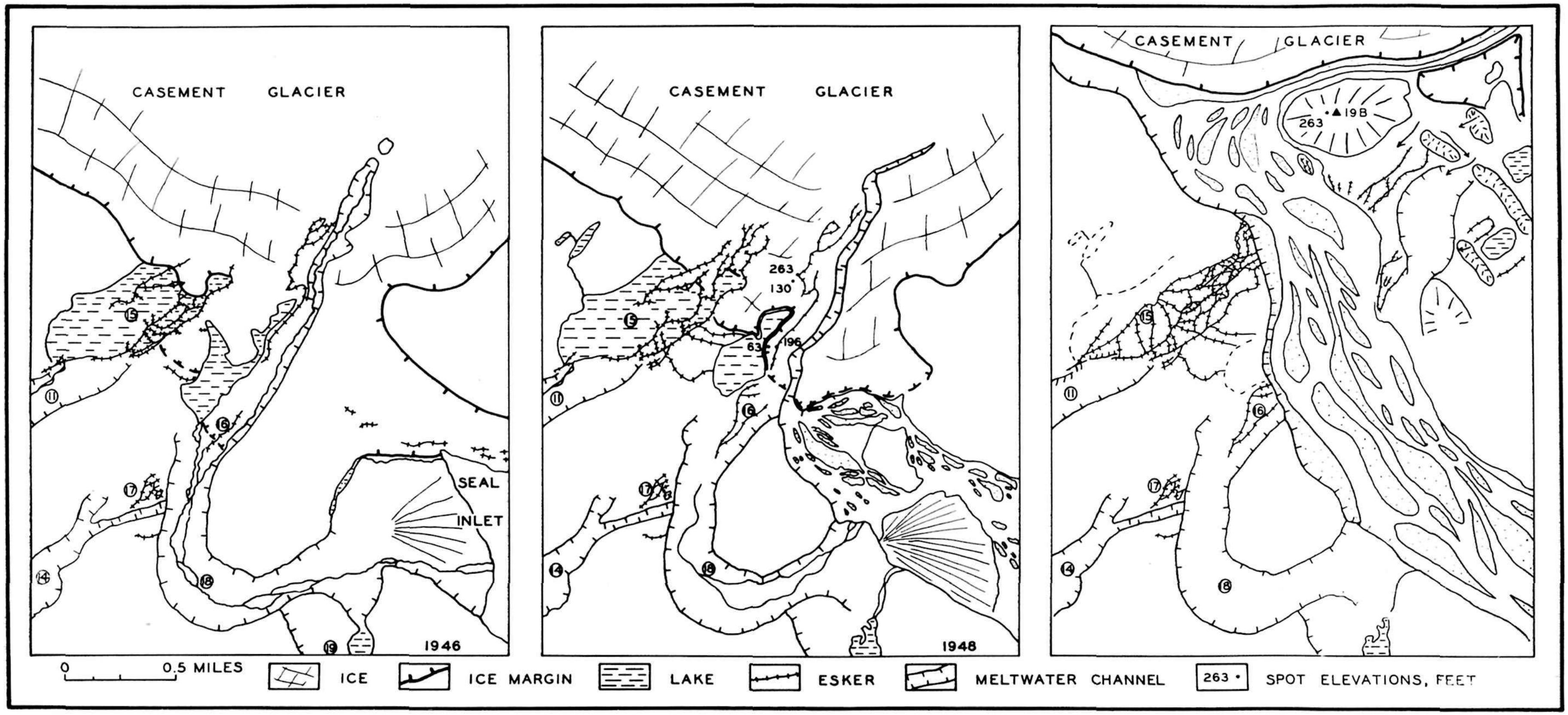

Fig. 23. Proglacial conditions in 1946, 1948, and 1963.