INVENTORY OF TERMINAL POSITION CHANGES IN ALASKAN COASTAL GLACIERS SINCE THE 1750's

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THE PROGRAM OF REGIONAL GLACIER SURVEYS[1]

THE need for a systematic and up-to-date inventory of glacier positions in the cordilleran ranges of Southern Alaska first became apparent to me while participating in two glacial mapping expeditions to the Alaskan Panhandle in 1940 and 1941 (Miller, 1940, 1943). As a result, each summer from 1946 through 1953, I was fortunate enough to be able to undertake a program of ground and aerial surveys of termini and névé–line positions on Alaskan coastal glaciers (Miller, 1947, 1948, 1949, 1954). The project was further extended by selective photography and mapping carried out in 1954, 1955, 1958, and 1960 with the support of the Foundation for Glacier Research (Dudley and Miller, 1959; Miller, 1960; Miller, Jenkins and Elmore, 1963). In 1961 and 1962, with the aid of grants from the American Philosophical Society and the National Geographic Society, the survey of major coastal glaciers in Southeastern Alaska was brought up to date. A study of the behavior pattern of these termini over the past several centuries has been facilitated by the comparison of records obtained in this continuing field effort. Some results of the study are presented in this paper. Especially emphasized is the regional glacier fluctuation pattern since the 1750's.

In the assessment, more than 1,500 miles of coastline are considered, from Wrangell Narrows at Latitude 56°N. to Cook Inlet at Latitude 61°31′N. The overall region concerned is noted in figure 1. The routes of aerial and ground surveys are indicated on the map of figure 2. These surveys were made with locally chartered aircraft and small vessels provided by the U. S. Forest Service and the National Park Service. For the ground work, a mountain transit and a Wild T2 theodolite were used. For the photographic records at established control stations, a long-negative Zeiss-Ikon camera, a Speed Graphic or a Keystone F10 photogrammetric camera were employed. The aerial photographs were taken either with a 90 mm. German aerial Handkammer, a Fairchild 4 × 5-inch K-20 camera or the aforementioned F10. More than 2,700 oblique photographs and recorded observations on 174 major glaciers have been obtained.[2]

[1] With the support of a grant from the American Philosophical Society, 1961.

GLACIOLOGICAL PROVINCES IN SOUTH COASTAL ALASKA

For convenience, southeastern coastal Alaska is divided into seven glaciological provinces delineated on the map in figure 3. At least 80 per cent of the glaciers in Alaska are in these provinces. The main locations of concentrated land ice are shown in figure 1. Out of the total number of coastal glaciers in Alaska only those of the Kenai Peninsula and the Aleutian Islands are omitted from this grouping, since these were not involved in the 1914 Tarr and Martin study (1914) with which basic comparisons are made. Listed in geographical sequence from south to north the pertinent districts are:

A. Stikine District (Lat. 56°–58°N.)
B. Taku River District (Lat. 58°–59°30′N.)
C. Glacier Bay District (Lat. 58°–59°N.)
D. Chilkat District (Lat. 59°–59°30′N.)
E. Lituya Bay District (Lat. 58°–59°N.)
F. Mount St. Elias District (Lat. 59°–60°30′N.)
G. Prince William Sound and the Chugach Range (Lat. 60°–61°30′N.)

[2] Glaciers larger than eight square miles in area. The photographic record is on file at the Foundation for Glacier Research, Inc., Seattle, Washington, U. S. A. It is further noted that in 1940 aerial trimetrogon photographs of southeastern Alaska were taken for mapping purposes by the U. S. Army Air Corps. This was followed by U. S. Navy dimetrogon photography in 1948, with limited additional coverage in 1958 and 1962. This material is filed by the U. S. Geological Survey at the Denver Federal Center, Colorado.

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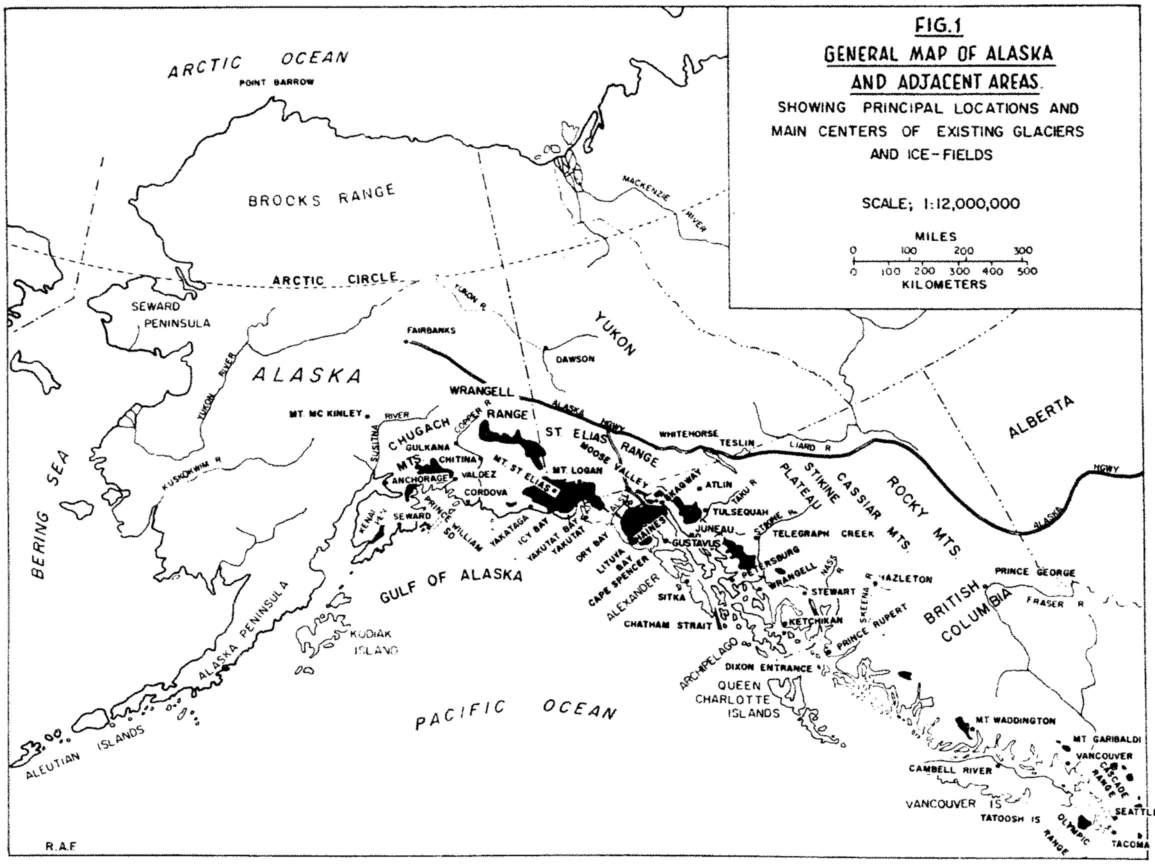

FIG. 1. General map of Alaska and adjacent areas.

Subdivisions of each district are given in table 1, which also summarizes the principal facts from the 1946–1962 surveys. In this table the terms "shrinking glaciers" and "expanding glaciers" are used to refer to changes in volume of the terminal sections as expressed by thinning or thickening rather than to observed changes of movement within the ice. When a glacier is described as "advancing" or "retreating" (receding) the connotation is still one of increase or decrease in volume; but the emphasis is on changes in lateral position of the termini. It is recognized that spasmodic and irregular lateral shifts in position are usually attended by velocity changes; but this cannot be evaluated without field measurement. The reference to "equilibrium glaciers" implies a static condition in which the factors controlling accumulation and wastage are more or less in balance. In this table, of course, the judgment has been made only from the observed behavior of termini.

In the following pages, the basic differences and similarities in regime pattern in each district are considered.

1. THE STIKINE DISTRICT

This region derives its name from the Stikine River, a large antecedent river draining from the interior of northern British Columbia and transecting the Alaskan-Canadian Coast Range to reach sea level at Wrangell. As shown by the limits of rectangle A in figure 3, all the glaciers between the Stikine River and the Taku Valley, 140 miles to the north, are grouped under this heading. The district is extremely mountainous and has all the characteristics of a coast line of submergence, with numerous inshore islands and deeply indented fiords. At sea level it is a region of heavy rain forests. Inland, the mountains are not as high as the ranges farther north, averaging only 5,000 feet; however, the terrain is rugged and there are local, heavily glaciated zones at high

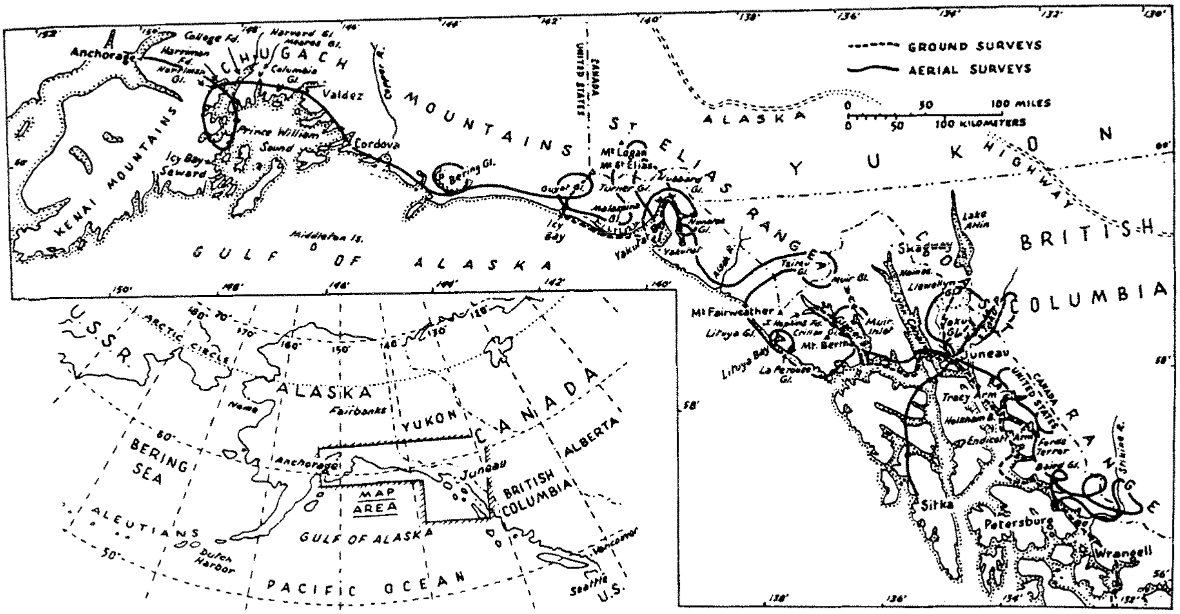

FIG. 2. Routes of regional glacier surveys in southeastern Alaska, 1946–1962.

elevation. The major glaciation at present is the Stikine Icefield, 30 miles northeast of Petersburg (figs. 1 and 3) where the range culminates in the summits of Devil's Thumb (9,077 ft.), Kates Needle (10,002 ft.) and Mount Ratz (10,290 ft.).

Some ten notable glaciers flow from the Stikine Icefield in an easterly and southerly direction. Eighteen major glaciers drain westward towards the coast. All were photographed in the regional survey; but for purposes of the present study, only the large valley glaciers on the west are considered. These reach low level and five of them debouch icebergs into the prominent fiords known as LeConte Bay, Tracy Arm, and Endicott Arm.

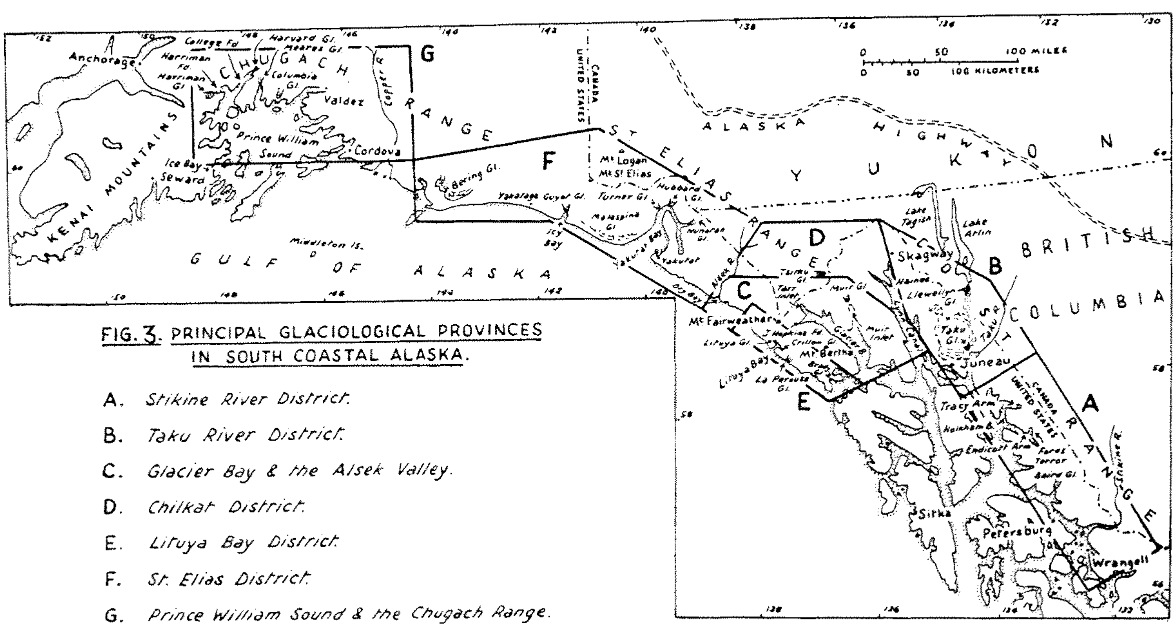

FIG. 3. Principal glaciological provinces in south coastal Alaska.

TABLE 1

REGIME STATISTICS FROM 1946-62 RECONNAISSANCE SURVEYS OF MAJOR GLACIERS IN SOUTH AND SOUTHEASTERN ALASKA

		REGIMEN PATTERN SINCE 1920'S					
	NUMBER OF GLACIERS OBSERVED	TERMINI DOMINANTLY SHRINKING	NEAR EQUILIBRIUM but GRADUALLY SHRINKING	IN EQUILIBRIUM	NEAR EQUILIBRIUM but GRADUALLY EXPANDING	STRONGLY OR RECENTLY ADVANCING AND NEAR POST-GLACIAL MAXIMUM	CLIMATIC CHARACTER OF NÉVÉ AREA **
A. STIKINE DISTRICT (a) *Stikine Valley*	10	5	3	2			COASTAL INTERIOR INT. & HIGH ELEV. SUB-CONTINENTAL
(b) *Forest Fiords to Speel River*	18	15	1		1	1 [*1]	INT. ELEV. MARITIME TO HIGH ELEV. SUB-CONTINENTAL
B. TAKU DISTRICT (a) *Taku-Llewellyn Glacier System and vicinity*	16	14	1			1 [2]	INT. ELEV. MARITIME AND HIGH ELEV. SUB-CONTINENTAL
(b) *East side Lynn Canal*	15	12	3				INT. ELEV. MARITIME
C. GLACIER BAY AND THE ALSEK RIVER	28	15	2	5	6		LOW & INT. ELEV. MARITIME
D. CHILKAT DISTRICT	22	7	5	6	4		INT. ELEV. SUB-CONTINENTAL
E. LITUYA BAY DISTRICT	7	1	1	1	1	3 [3,4,5]	INT. & HIGH ELEV MARITIME
F. ST. ELIAS DISTRICT (a) *Yakutat Bay & Brabazon Range*	29	24	3		1	1 [6]	LOW, INT & HIGH ELEV MARITIME WITH INTERIOR AS HIGH ELEV. SUB-CONTINENTAL
(b) *Icy Bay to Copper River Delta.*	12	10	2				LOW & INT. ELEV. MARITIME
G. PRINCE WILLIAM SOUND (a) *Valdez Icefield*	4				1	3 [7,8,9]	INT. & HIGH ELEV. MARITIME
(b) *West of College Fiord*	13	3	2	4	3	1 [10]	LOW, INT., & HIGH ELEV. MARITIME
TOTAL OBSERVED ON REGIONAL BASIS	174	106	23	18	17	10	

* 1, BAIRD GL. 2, TAKU 3, LA PEROUSE 4, CRILLON 5, LITUYA 6, HUBBARD 7, COLUMBIA 8, MEARES 9, HARVARD 10, HARRIMAN

** AS REFERRED TO IN THIS COLUMN:- LOW ELEVATION = 1-3000 Ft.
INTERMEDIATE ELEV. = 3-5000 Ft.
HIGH ELEVATION = 5000 Ft. and above

Infrequent observations on only a very few glaciers have been made in this district. From the scanty record and the information obtained in this survey, the apparent regime pattern covering the past thirty years has been deduced. Where estimates are necessary, the writer has been conservative and thus it is believed that the summary in table 1 represents the situation within reasonable limits. The dominant characteristic of these ice masses has been shrinkage with only a few of them near equilibrium. There is, however, one notable exception. This is the large ice stream known as Baird Glacier, lying east of Frederick Sound at the head of a small inlet called Thomas Bay. This glacier has experienced a significant and continuous advance over a period of many years. It is a trunk glacier with six tributary arms, the central one being 28 miles long and averaging 2 miles in width. It has a fairly consistent gradient of 3° and is nourished from a broad upland névé lying mainly between 4,000 and 5,000 feet. Parts of this névé extend into the summit area of the Stikine Icefield.

At the time of my first visit in 1941, the terminus rested on a gravel delta, with one mile of outwash separating it from the sea. The ice front was only a few feet from a forest trim-line marking a position attained about 1935. Judging from the mature nature of the forest and the large size of the trees with which the ice had come in contact, this was undoubtedly the most advanced position for some centuries and from the absence of outer moraines and other geomorphic evidence it is assumed to represent the post-Glacial maximum. By 1946 a 300-foot recession had taken place on the southeast margin, but the main section of the front was still well forward. Flights over the terminus in 1958 and 1960 showed that it was slightly farther back and somewhat thinner, but still within several hundred feet of the dense forest fringing the shores of Thomas Bay.

2. THE TAKU DISTRICT

This area lies at the northern end of the Alaskan-Canadian Coast Range and is bounded on the south by the valley of the Taku River and on the north by the Skagway River which flows from White Pass into the upper end of Lynn Canal. The boundaries which I have arbitrarily set for the district are shown in frame B, figure 3.

The most impressive geomorphic feature is the extensive network of glaciers comprising the Juneau Icefield, immediately north and east of the capital city of Alaska, Juneau. This icefield covers more than 1,500 square miles and is the most heavily glaciated sector along the axis of the Coast Range. The highland has the appearance of being ice-flooded with a much larger percentage of névé exposed than detached ridges and nunataks. The uppermost snowfields crest at 6,300 to 6,500 feet and the highest peaks reach elevations of over 8,000 feet (e.g., Devil's Paw, 8,584 ft. and Mount Nesselrode, 8,100 ft.). The southeastern half of the icefield consists mainly of the Taku-Llewellyn Glacier system which, at one point, stretches for a distance of 75 miles across the Coast Range.

All the major ice tongues descend to low levels from this upland and with one striking exception have been diminishing in size over the past three to four decades. As with the Stikine Icefield, the exception is the main trunk glacier, the Taku, which comprises a unit about 40 miles in length extending southward from the crestal névé or present high glacial center of the Juneau Icefield and which terminates at tide level in Taku Inlet. For some decades this glacier has been strongly and continuously pushing forward in a spectacular advance. An account by Captain George Vancouver indicates that another important advance occurred in historic times, as the upper end of Taku Inlet appears to have been blocked by ice when he visited it in 1794. He notes that there were "immense bodies of ice that reached perpendicularly to the surface of the water in the basin which admitted of no landing place for the boats" and so much floating ice, especially at the entrance of the inlet, that "a passage was with difficulty effected" (Vancouver, 1801: **3**: p. 278). This is quite unlike conditions today where very few icebergs are seen.

This not only suggests considerably more expansion than at present but also that the glacier was then suffering retreat from a maximum which had occurred sometime before. Since Vancouver mentions that this "basin" was about thirteen miles inland from the mouth of the inlet (1801: **6**: pp. 25–27), it would seem that the ice front at that time was somewhere near the place where the fiord narrows and then widens again due southeast of Norris Glacier (probably close to what is now called Taku Point). This is corroborated by local Thlingit accounts of an ice "barrier" which at a time "before white man came" prevented travel into the interior valley of the Taku River. That this barrier was removed by

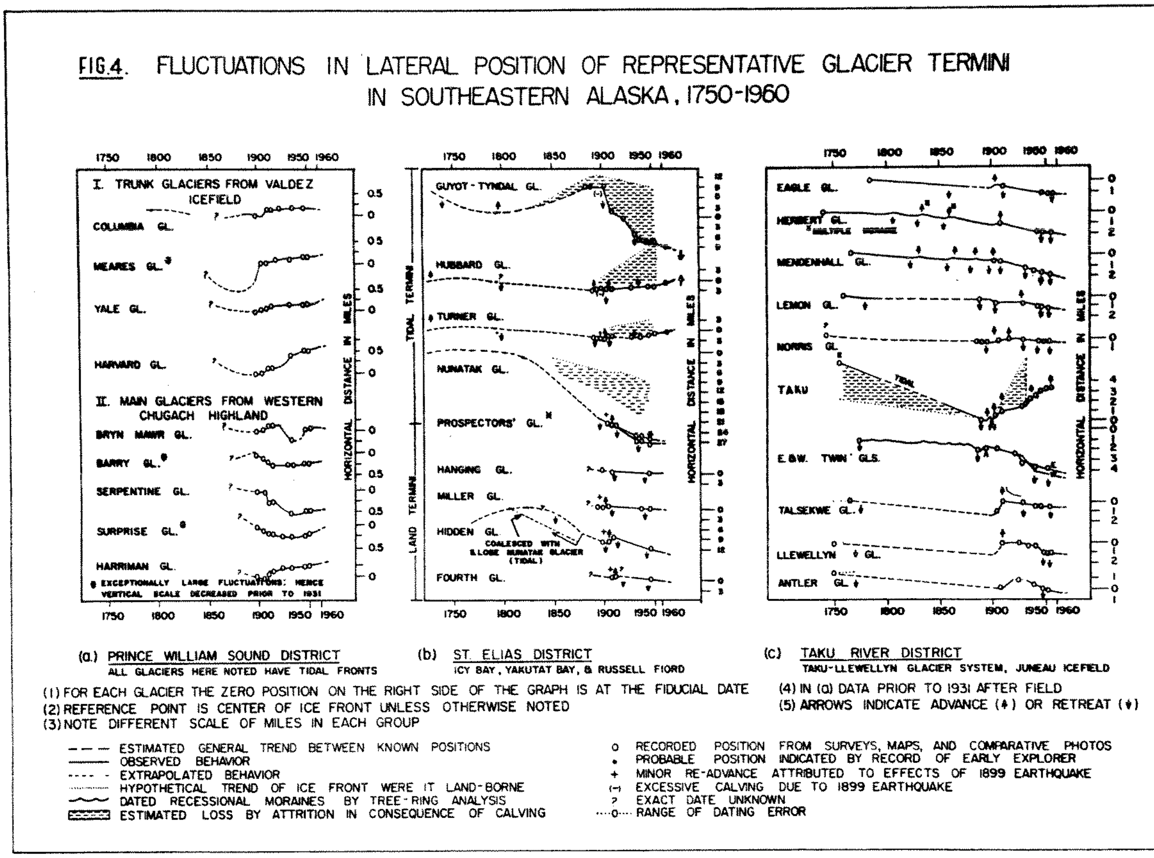

FIG. 4. Fluctuations in lateral position of representative glacier termini in southeastern Alaska, 1750–1960.

subsequent recession is certain, since during most of the nineteenth century Taku Inlet and its headward valley were used regularly by the natives to cross the Coast Range to the Atlin district. In the 1870's to 90's this famous old trail was also commonly used by prospectors until the discovery of Chilkoot Pass, in the vicinity of Skagway.

Dendrochronological studies show that this glacier reached such an advanced position in 1755 (Lawrence, 1950); but it is not certain whether the native account refers to this surge or to an even earlier one.

The variation of ten important glaciers in the Taku district are illustrated in figure 4. In this diagram, the present advance of the Taku Glacier is shown in comparison with the general pattern of retreat. Elsewhere in the district, all ice bodies which are not connected with the Juneau Icefield, such as Wright and Sittakanay Glaciers and others occupying cirques along the sides of the Taku River valley and Lynn Canal (Miller, 1961), have been experiencing consistent downwasting and lateral "shrinkage," especially since the decade of the 1920's.

3. GLACIER BAY DISTRICT

This district lies 100 miles due west of Juneau and is shown within frame C of figure 3. The waters of Glacier Bay now fill a broad palmate valley with two main channels, one of which is 60 and the other 90 miles long. In 1794, when Captain Vancouver first passed the mouth of Glacier Bay (1801: **5**: pp. 421–422), he observed that this great depression was filled with ice. The seaway to the south he named "Icy Strait" because of the countless bergs calving from the extensive glacial cliff which then blocked the entrance to the present bay. Now only infrequent bergs can be seen drifting out of the inner channels and fiords where but a few remnants of the former ice sheet are found.

The phenomenal disappeance of ice has brought many visitors to Glacier Bay in recent years, so that a number of records and photographs have been made since 1880, starting with those of Muir (1893), Wright (1887; 1891), and Reid (1892; 1896). I first visited the district in 1940 while on a survey expedition to the Brady Icefield at the southern end of the Fairweather Range. At that time this fiord, which is more than 2,000 feet deep, had experienced an unprecedented recession, losing nine miles of ice in the thirty-three years since 1907. Details of such staggering diminution of the whole Glacier Bay ice-sheet in the 1920's and 1930's, followed by the rapid encroachment of seed plants on the deglaciated terrain, were first presented in two papers by Cooper (1923; 1931). In a later paper (1937: pp. 47–48), he showed by ecological methods that the great Glacier Bay ice sheet reached its post-Glacial maximum, near the mouth of Glacier Bay, shortly after 1700 and that the major recessional trend set in sometime between 1735 and 1785. There was a marked slowing down in the recession between 1880 and 1899, the rate during this period being only half the average which had been in effect since 1794. The only known readvance was a short-lived one in the 1890's which was probably related to this "slowing down" period.

In 1941, together with W. O. Field on another mapping survey in Glacier Bay, we observed that shrinkage was still going on at a rapid rate on Muir Glacier in the eastern arm of the bay. We measured a total recession of 12 miles from this glacier's 1899 frontal position. (The map of this survey with an explanatory report has been published by the American Geographical Society, Field, 1947.) That the shrinkage continued in an accelerated fashion until 1946 has been verified by my ground records in that year.

My further aerial surveys in 1947, 1948, 1951, 1952 and most recently in 1961, show that over the past decade and a half a general slowing down of the recession rate of some of these glaciers, similar to that reported in the 90's, has again occurred. This conclusion was further verified by ground observations and photography while reoccupying some of our old photogrammetric stations in September, 1962.

In several instances there have been minor readvances. The advances are especially noted among a group of eleven hanging ice tongues which cling to the fiord wall of Johns Hopkins Inlet. Their source is a series of hanging valleys filled with firn at intermediate to high elevations. All appear sensitive to casual variations and each has a behavior quite out of phase with the others. This appears to bear relationship to the elevation distribution of these névés, since each is at a different level. Recent advances of some magnitude have also occurred on two large valley glaciers which reach tidewater in Tarr Inlet. These receive nourishment from tributaries at fair elevations in the vicinity of Mount Fairweather, which is the highest peak in the range. One is a lobe of Grand Pacific Glacier which came forward half a mile between 1941 and 1951 to a position from which it has only slightly fluctuated in the subsequent interval to 1962. The other is de Margerie Glacier which advanced a quarter mile in the period 1941–1951 and has similarly maintained this position without significant change over the last decade. It should also be mentioned that Carroll Glacier, in Queen Inlet, experienced thickening and advance in the decade 1941–1951, with slow thinning and retreat through 1962.

In this district I also include the glaciers of the Alsek River Valley. These have been dominated by shrinkage and retreat paralleling that in Glacier Bay. Several of the largest glaciers are transection types which connect through to the Muir and Grand Pacific icefields. The Alsek River joins the ocean at Dry Bay just north of the Fairweather Range, splitting it off from the main ramparts of the St. Elias Mountains (fig. 1). The existence of this valley permits maritime conditions to prevail far inland, reaching nearly to Glacier Bay on the inner side of the Fairweather peninsula. This orographical situation has helped greatly to accelerate the retreat of ice in both the Alsek and Glacier Bay sectors after the main nineteenth-century recessional trend was established.

4. THE CHILKAT DISTRICT

Northwest of Skagway lie the Chilkat Mountains from which we take the name of this district (frame D, fig. 3). Here there is a small icefield whose glaciers are thinning and in retreat, Forty miles to the southwest, however, along the southern boundary of this district are ten or more fair-sized glaciers which are close to equilibrium. Several of them have, in fact, expanded somewhat in the past fifteen years. These are ice tongues which flow northward from a serrated 7,000-foot range lying between Glacier Bay and Tsirku and Takhin River valleys. One of these is the Tsirku Glacier which has advanced more than a quarter of a mile since 1910. This glacier shares a névé with Carroll Glacier, mentioned above as one of the slightly resurgent glaciers of the Glacier Bay complex. Three other large ice tongues in the Tsirku valley have termini which up through the 1950's were well forward. Geological reports on this district and photographs taken by the Boundary Commission between 1905 and 1910 show that two of them, the Takhin and de Blondeau Glaciers, experienced strong enough advances just prior to 1905 to divert the upper 10 miles of the Takhin River into a tributary of the Chilkat River (U. S. Geological Survey, 1906: plate XXXVII). There has been very little change from these positions since then.

The pattern is again a paradox, with striking contrast to the contemporaneous shrinkage of glaciers in the nearby Chilkat Mountains, and especially to the situation which has been described in Muir Inlet lying only 10 miles south of the Tsirku valley.

5. LITUYA BAY DISTRICT

West of Glacier Bay rises the Fairweather Range on a narrow southward trending peninsula 90 miles long and 30 miles across. These ice-clad mountains are among the most precipitous in Alaska. They average 10,000 feet in elevation and culminate in the great ice pyramid of Mount Fairweather, whose summit is 15,300 feet in elevation yet stands only 9 miles from the ocean. I refer to the western flank of this massive range as the Lituya Bay district because this is the name of the only inlet which breaks the line of the outer coast. The district is outlined in rectangle E, figure 3, and includes all the glaciers for 100 miles north of Taylor Bay, at the entrance to Cross Sound, to Dry Bay at the delta of the Alsek River.

In the north, the mountains are lower and the main glaciers have been gradually shrinking or close to equilibrium. From Lituya Bay southward, however, a different pattern occurs. These southern glaciers were considerably receded at the end of the eighteenth century while the Glacier Bay ice sheet was at its maximum. In the 1890's, however, they were expanding and advancing vigorously when the Glacier Bay ice was just as vigorously disappearing (Klotz, 1899). In 1946 and 1947 I observed that they were still well forward with, in some cases, further advances in progress. This trend persisted up to the time of our survey flights in 1952 and 1953. The aerial photographic records in 1958 and again the photographs obtained during our survey of 1961, however, reveal a slight reversal in trend on several major tongues.

A few details of this pattern are important. The most southerly ice tongue is the Brady Glacier, which finds its source in the Brady plateau at the southern tip of the peninsula. The Brady Glacier was first sighted by Captain Vancouver on his cruise of exploration in 1794 (Vancouver, 1801: p. 417). He described its terminus in that year as "an immense body of compact perpendicular ice extending from shore to shore," a short distance north of a deserted Indian village. This is important, because a position for 1893 noted on the Canadian Boundary Survey map (1895: Sheet 15) shows that the glacier had advanced 6 miles in the intervening century and that the Indian village was covered by upwards of 1,000 feet of ice (Klotz, 1899: p. 528). A further survey in 1907 by the International Boundary Commission (1923: Sheet No. 1) shows that the front moved ahead another mile in the fourteen-year interval. From then until 1947 it remained close to the 1907 position indicating that for the previous forty years it was more or less in equilibrium at a point close to its early twentieth-century maximum. Between 1948 and 1958 slight downwasting occurred in the terminal zone, but with a static lateral position close to the 1947 frontal limit in evidence up through the 1961 survey.

The healthy condition of this glacier system in the present century appears related to the following. The largest névé area lies between the 2,000- and 3,000-foot contours; but there is a large amphitheatre on the northwestern side of the plateau which receives much snowfall at elevations of 3,000 and 6,000 feet. This highland basin is hemmed in by the flanks of Mount Bertha (10,147 ft.) and Mount La Perouse (10,750 ft.) which serve as high-level extensions of the amphitheatre's catchment. It is from this sector that the main south-flowing current of the Brady Glacier is supplied. Other glacier currents, which descend eastward into Glacier Bay, do not receive their main supply from this cirque-headed valley but from lower névés of the ice field. In this appears to lie the answer to the differences in regime between their termini and that of the main Brady Glacier lobe.

La Perouse Glacier, 30 miles up the coast, is the only Alaskan ice front in contact with the open ocean and which calves bergs directly into the surf. For the better part of sixty years, this bulging lobe has oscillated within a few hundred feet of a forest trim-line established in 1895. The same type of variation has characterized a large unnamed piedmont tongue which reaches sea level three miles south of La Perouse Glacier. This, too, attained its most advanced position in 1899 and now, after another sixty-two years, is still only a few hundred feet from the frontal moraine. At the time of the 1947 survey, noticeable thinning had occurred, apparently the result of slightly negative regime conditions since the 1930's. Between 1947 and 1958 further retraction within a few hundred feet of the 1899 position was observed, a condition continuing to persist through 1961.

Special mention is also made of Crillon and Lituya glaciers, at the head of Lituya Bay. These are large valley glaciers with tidal fronts at the inner ends of this T-shaped fiord. From a map made by the La Perouse expedition, which in 1786 discovered the bay (map reproduced in Klotz, 1899), the late eighteenth-century positions are known. Comparing these with the 1893 positions indicated on the Canadian Boundary Survey map (1895: Sheet 16), it is seen that each of these glaciers came forward no less than 2.5 miles in the intervening century. It is reported that much of this advance occurred after 1874 (Dall, in Reid, 1899: p. 225). In the decade between 1895 and 1906, the Lituya glacier advanced another half mile (Wright, F. E. and C. W., 1908: p. 53). My aerial photographs from 1947 and 1948 and again in 1958 and 1961 show that it continued to advance, the net gain being at least another one-third of a mile in the preceding half-century. Crillon glacier has also advanced but not to such an extent. At the time of the Lituya Bay earthquake in July, 1958, it appeared to be in an equilibrium position, though by 1961 a slight resurgence seemed to be underway. Although these glaciers are similar in size, the reported differences in magnitude of advance suggest relationship to areal and elevation differences in their névés. The superimposed effect, if any, of avalanche shaking during the diastrophism of 1958 is not yet clear, but some effect may be expected since the epicenter of the quake was in inner Lituya Bay (Miller, D. J., 1960). Both glaciers receive nourishment at elevations well above 5,000 feet. Since much of it is in the form of avalanche snow off the western cliffs of Mount Lituya (11,750 ft.) and Mount Crillon (13,200 ft.), some increased forward movement may become evident during this present decade.

Attention is also drawn to the behavior of a medium-sized cirque glacier, which on the La Perouse map is shown to reach the sea in the western arm of Lituya Bay.[3] In 1907 the Boundary Commission mapped its terminus at the 1,000-foot contour to which it had receded. In 1948 (U. S. Geological Survey Map 1951–53), the front had retreated to the 1,600-foot contour at least three-quarters of a mile back from the sea. This behavior is completely opposite to that described for the neighboring Lituya and Crillon glaciers. This is especially significant when it is realized that the regime pattern of this glacier parallels that of a number of ice lobes east of the Fairweather Range and which, at the end of the eighteenth century, also descended to sea level from névés at the same elevation as this cirque, i.e., between 3,000 and 4,000 feet. That climatic conditions in the middle decades of the nineteenth century were conducive to shrinkage on these lower glaciers is corroborated by the existence of a 400-foot floodwater trim-line in the forest near the mouth of Lituya Bay. Although the direct effects of previous earthquakes in this region are not ruled out, this appears to have resulted from the breakout of a vast quantity of ice-impounded water, held in by one of the large glaciers at the head of the bay. A study of vegetation along the trim-line has shown that the flood occurred in 1856 (D. J. Miller, personal communication). This was an event of extraordinary magnitude and is worth noting because of the lack of climatological information about Lituya Bay during the middle of the last century. It suggests that a period of excessive melting had occurred, probably as the result of accelerated thinning and retreat of the low-level glaciers in the decade or two before 1856. This inference is supported by the report of a second but much smaller flood in 1936, a year without any reported diastrophic event and following a period of ten years of accelerated ablation and recession on many of the low-level ice tongues in adjacent districts.

6. THE ST. ELIAS DISTRICT

The St. Elias Range borders the eastern shore of the Gulf of Alaska from Dry Bay to the Copper River. The district, as indicated by

[3] Because of the historical record, the variations of this glacier are of additional significance. For future reference, I have suggested naming it de Langle Glacier, after the chief of one of La Perouse's barges which explored this arm of the bay in 1786.

Frame F, figure 4, is a region covered by upwards of 10,000 square miles of ice. As in the Lituya district, this coast is devoid of fiords and inlets with the exception of Yakutat Bay and Icy Bay (fig. 2), where the largest valley glaciers reach the sea. Two of these glaciers drain from the most extensive névés on the North American continent.

No previous investigations had been made in Icy Bay prior to our ground studies of 1946 and none in Yakutat Bay since Tarr and Martin's monumental field work in 1913 (Miller, 1948). In 1948 and 1951 and again in 1961 and 1962, we were able to supplement the observations with additional ground and aerial material. From this information, the regime graph in figure 4 has been drawn.

In this figure a representative group of glaciers in this district is considered. The extensive Guyot Glacier, which is comparable in its catchment area to the former Muir Ice Field of Glacier Bay, is seen to have suffered excessive shrinkage and retreat from a maximum position reached about 1888. At that time there was no Icy Bay. But between 1904 and 1909 recession began which, continuing to 1951, caused fifteen miles of bay to open up and more than 1,500 feet of thinning to take place at the combined terminus of the Guyot and Tyndall glaciers. In the decade to 1961, continuing and vigorous retreat produced another four miles of open water at the Guyot terminus; with separation of the Tyndall Glacier taking place about 1953. By the summer of 1963, the Guyot Glacier terminus had further separated into two tidal arms, the easternmost front lying nearly one mile back from the late 1961 position noted in figure 5*a*. By the end of 1963 the tidal terminus at the western arm of the Guyot Glacier was about six miles farther back than the position of 1938 shown in the figure (also Miller *et al.*, 1963). This means that Icy Bay is today about twenty miles long, with its inner reaches rimmed by three spectacular ice cliffs instead of one composite tidal front with which it has been characterized since the turn of the century. The effect has been the most catastrophic of any recent glacier retreat in Alaska. It is comparable to the phenomenal disappearance of ice in Glacier Bay except that the opening of Icy Bay began a century later and has been contemporaneous with the remarkable advance of the Hubbard Glacier, as described below.

The presence of two crescentic submarine ridges having the appearance of moraines and lying respectively one and three miles offshore from the present mouth of Icy Bay relates to glacial maxima in recent times. The inner one is an extension of Icy Point on the western side of the entrance and is at the glacier's observed 1888–1904 position. It probably represents the latest maximum, while the outer moraine would appear to have been built by an earlier and stronger advance. From the foregoing, it seems probable that the retreat from the earlier advance coincided with the nineteenth-century recession of Muir Glacier and others in Glacier Bay. This is given credence by the records of early explorers and details of native history from this area. Tebenkof (1848 and 1852), a Russian cartographer, made a chart in 1848 based on log books of Russian navigators who explored this coast between 1788 and 1807. His chart shows a deep wedge-shaped re-entrant east of present-day Icy Cape. Here was definitely a bay, five miles wide and extending northward about eight miles, with the water on its western shore lapping against a lengthy ice front, the outermost end of which reached all the way out to the mouth of the bay. Behind the bay and the ice front a tree-covered surface is indicated. On the opposite shore trees are shown on the chart, some of them growing close to another large glacier farther inland toward the east. This fact was substantiated by observations in 1946 along the inner shores of the Bay where we found tree trunks *in situ* being exhumed from glacial gravel only recently uncovered by the thinned and receding Guyot ice sheet. The presence of a forest here agrees with the native account mentioned below and shows the contrast to the conditions shown on Topham's sketch map of 1888 and on the larger map of I. C. Russell in 1891. Each of these indicates only a solid front of ice. Yet, only a half-century before, the British explorer Sir Edward Belcher (1843: pp. 79–80) reported that an ice-rimmed bay did exist at this site. An advance must therefore have been underway at that date to culminate in the 1880's and '90's, as already noted.

That there was an earlier advance in historic times is supported by the following account from Thlingit tribal history given to me in 1946 by B. A. Jack, a ninety-year old native in Yakutat. His interpreter, an educated and highly respected tribal princess, who appeared reliable in her translation, stated that he was the last direct descendent of a branch of interior Copper River Athapascans who had migrated southward and intermingled

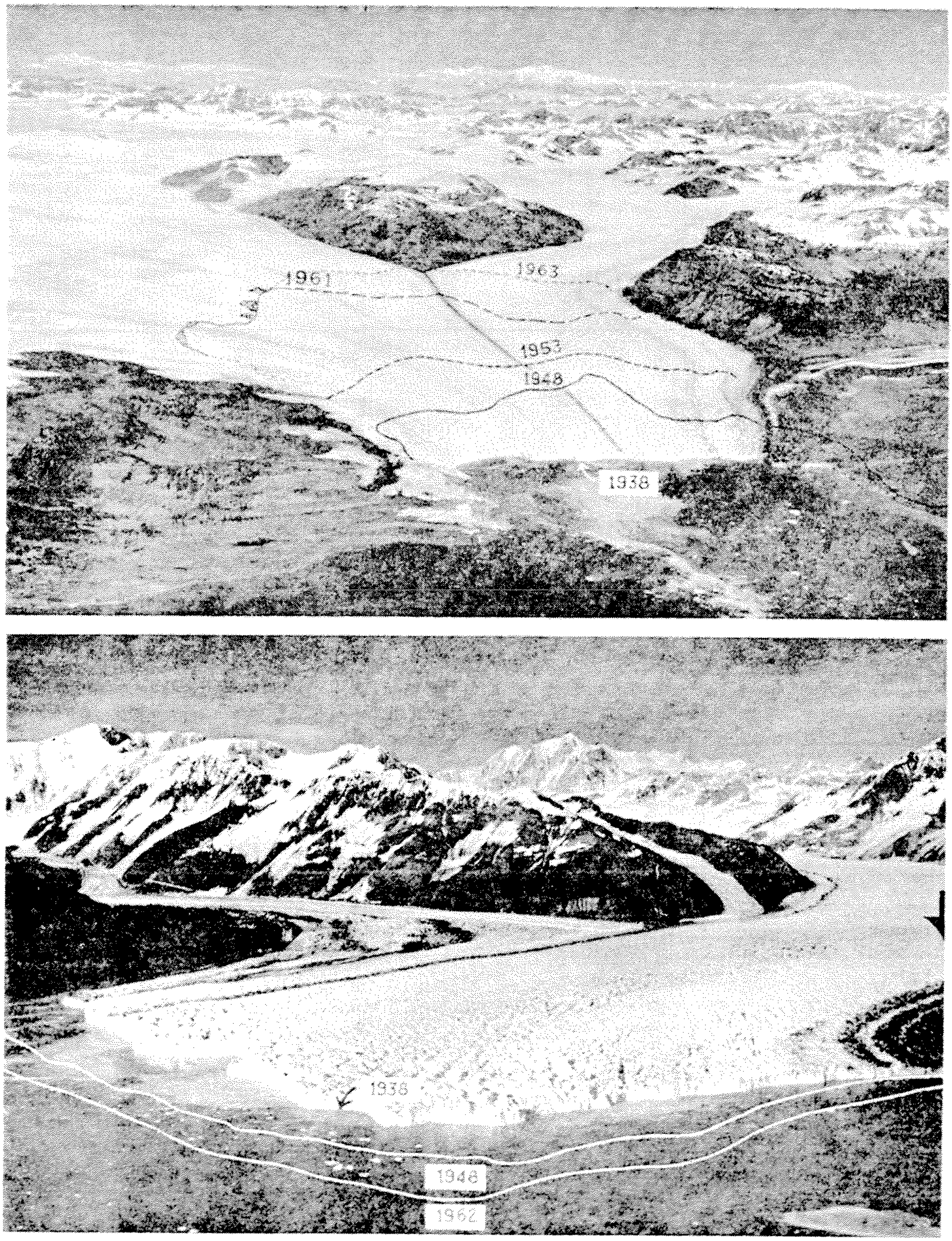

FIG. 5. Two views of simultaneously advancing and retreating glaciers in the St. Elias District. (a) *Upper*: Guyot Glacier. Six miles of recession has occurred at center of this ice front in the 25-year interval noted. The debris-filled ice on the right is from the Tyndall Glacier. (b) *Lower*: Hubbard Glacier. Left background, Mount Vancouver (15,820′) and Mounts Hubbard and Alverstone (center background, *ca.* 15,000′). An advance of three-quarters of a mile has occurred on the left front in the interval noted. Photographs by H. B. Washburn (1938).

with the coastal Thlingits some years before white men came. The account came from his people and described how they had established a settlement on the then green shores of Icy Bay. He told of a catastrophic advance of ice down the bay which had threatened the village and forced his forebears to flee. This report is in every way similar to that given to Topham by George, the second Chief of the Yakutats in 1888 (Tarr and Martin, 1914: p. 47).

This is pertinent corroboration in spite of the scepticism with which one normally views details of native-told history. The report that this fluctuation was before "white men came" would place the advance before the time of the concentrated Russian colonization along this coast in the 1790's and indeed probably well before it, since the first explorer reached this coast in 1741. The ice cliff in contact with the "forested" west shore of Icy Bay on Tebenkof's map was observed sometime after the advance and was most likely a diminishing remnant of the western lobe of the Guyot which had destroyed the village. If this assumption is correct, it was observed during a recessional stage and the forest on the Tebenkof chart was interstadial. Eighty to ninety years would have been required for such a growth to seed and develop into trees large enough to warrant mention by the Russian cartographer. From this I estimate that the Guyot ice sheet began to recede no later than 1700. Thus the first advance would have been in progress in the early or middle seventeenth century, since the native account certainly refers to its initial stage. This is consistent with the available information on the regional growth of glaciers which we know was well underway in the late seventeenth century. The story of the sudden forward motion of the Guyot front may be an exaggeration in the native account; but it could well be an example of catastrophic movement such as occurred in the Alaska Range in 1936 when the Black Rapids Glacier slid forward three miles in five months at an average speed of 115 feet per day (Hance, 1937).

In passing it should be mentioned that the source névé of the Guyot ice sheet covers some hundreds of square miles and is essentially low-level, lying mainly between 2,000 and 4,500 feet.[4] Its broad western section is relatively unbroken by rock ridges and nunataks, such as characterize the higher snow fields and névés of the main part of the range toward the southeast.

[4] Fig. 5*a*, and also Bering Glacier map sheet, scale 1:250,000. Alaska Reconnaissance Topographic Series, U. S. Geological Survey, 1951.

Practically all of the other twenty-eight glaciers observed in this district have been shrinking rapidly in the past forty years. Only the Hubbard Glacier and Turner Glacier in Yakutat Bay are exceptions. Turner Glacier receives its main supply of ice at elevations above 5,000 feet in a steep-walled valley reaching to high levels on the heavily-glaciated and avalanche-riven slopes of Mount Cook (13,760 ft.). From the variations in recorded tidal positions of this terminus from 1909 until my 1946 through 1951 surveys it appeared to be in equilibrium; however, if we allow for the effects of tidal action, from the regime standpoint it has been undergoing a slow but persistent advance. Such an advance, in fact, is corroborated by the slightly expanded position revealed by comparison of the 1946–1951 photos and those obtained in 1961 and 1962. The relationship is illustrated in figure 4*b*.

The Hubbard Glacier, at the head of inner Yakutat Bay (fig. 5*b*), exhibits the strongest departure from the district pattern. This is a wide valley glacier with a spectacular frontal ice cliff which is one of the largest and most impressive in North America. Since about 1890 it has been experiencing a continuous and steady advance, which as of 1962 began to threaten closure of the entrance to Russell Fiord. In fact, today the terminus is but a scant 500 yards from Osier Point in inner Disenchantment Bay (Miller, Jenkins and Elmore, 1963). In net value, the advance has been one and one quarter miles from 1899 through 1958, both years in which severe earthquakes took place. That in 1899 caused massive losses from the terminus. This earthquake had its epicenter in Yakutat Bay and has been cited by Tarr and Martin (1914: Ch. 10) as the essential cause of the resurgence observed on most of the glaciers in Yakutat Bay between 1899 and 1910.[5] It is my conviction that the Hubbard Glacier's persistent growth cannot be attributed to this diastrophism (Miller, 1958). It is significant that the nine glaciers which were described as having spectacular resurgences in the eleven years after 1899 (Tarr and Martin, *op. cit.*, p. 172) owing to earthquakes are all glaciers with the greatest part of their catchment areas at low or intermediate

[5] The 1958 earthquake had its epicenter, as previously noted, in Lituya Bay, 100 miles down the coast, with effects of the seismic ground wave causing a portion of the coast to disintegrate and slump into the sea near the village of Yakutat.

elevations (i.e., 2,500–4,000 feet) and all have suffered the most severe shrinkage since 1910. Of more importance is that the Hubbard Glacier, like the Taku, is the main outlet from the highest névés in the St. Elias Range. These form an exceedingly extensive source area embracing more than 14,000 square miles between Mount Logan (19,820 ft.), Mount Vancouver (15,820 ft.), and Mounts Hubbard (14,950 ft.) and Alverstone (14,500 ft.). The latter three summits are also shown in the photograph of figure 5*b*.

Although since the turn of the century an advance of only one and a quarter miles is noted for the Hubbard Glacier, a far more significant advance is actually represented when we consider what the pattern would be if this terminus were landborne. Special considerations are, therefore, necessary when interpreting the regimen of a glacier on the basis of variations of termini discharging into the sea. Such, as we shall see, is especially germane in the case of the Taku Glacier on the Juneau Icefield. Of course, not only must advancing glaciers with tidal termini be critically examined, but those fiord-head glaciers with receding fronts as well. Two examples of the accelerated and catastrophic wastage on tidal glaciers compared with normal ablation losses of a land terminus are shown graphically for Nunatak Glacier and Guyot Glacier (previously discussed) in the curves of figure 4*b*. In addition to accelerated ablation by warmer wind and rain at sea level, there is the combined effect of wave action, ocean currents, and diurnal fluctuations of tide. The process is abetted by the natural buoyancy of a floating ice-foot which makes the rise and fall of the tide a more effective agent in causing huge pieces to break off and drift away.[6]

On retreating fronts the tidal influence increases the rate of shrinkage and on expanding glaciers it tends to reduce the rate of advance. Although this makes it difficult to judge the significance of glacier fluctuations influenced by these factors, an estimate of relative rates of lateral advance and retreat can be made from study of the average quantity of free and floating ice in the fiord and from comparisons with the fluctuations of nearby land glaciers of comparable size and extent. I have attempted to do this for the four main tidal glaciers in the St. Elias district and have indicated the estimates by dotted line in figure 4*b*. The recessional rates on four typical west and south-facing land termini are also compared. On a qualitative basis the stippled portions of the figure, indicated between observed tidal rates and rates postulated for land-borne termini, represent the indeterminate increments of loss due to calving.

7. PRINCE WILLIAM SOUND AND THE CHUGACH RANGE

The last glaciological province to be considered is in the Chugach Mountains on the northern shore of the Gulf of Alaska. It has not yet been possible to obtain adequate aerial coverage of the glaciers at the eastern end of this range, near the Copper River delta; therefore, reference is made only to the more heavily glaciated region farther west. This sector lies between Valdez and Seward and includes the extensive fiord system and interior bays of Prince William Sound (Rectangle G, fig. 3).

The most complete summary of early observations in this district has been given by Martin (Tarr and Martin, *op. cit.*: chapters 12–23). Subsequent observations have been made by Field (1932) and Brown (1952), to which my 1949–1951 and S. Chapman's 1958 aerial observations are but a supplement. A 1960 aerial photographic record by A. Post and 1961 observations by W. O. Field (personal communication) should be useful for comparative analyses.

The Chugach Range is still little known from the glaciological standpoint. It rises in a great tectonic arc extending from the St. Elias district to the mountains of the Kenai Peninsula on the west. Much of it has not been mapped in detail, but we know that these glaciers rise in an icefield as large as, or larger than, the Juneau Icefield and that some of their névés reach to greater heights. The physiography of the region combines the precipitous nature and elevations of the mountains of the Fairweather Range with the broad and interconnected nature of the highland glaciers in the Boundary Range of the Taku and Stikine districts. Even the loftiest peaks rise close to the sea and attain elevations between 9,000 and 13,000 feet. The precipitation is the heaviest in Alaska, with an annual mean snowfall of

[6] This has been the prime mechanism of the rapid wastage along the receding ice fronts of Glacier Bay, where recession has in some cases averaged one to two miles a year. As an example of the devastating influence of this situation, in one twenty-minute period in August, 1941, I observed a gigantic embayment open upon the frontal cliff of Muir Glacier. This enclave was ¼ mile across and ½ mile deep and was produced by the sudden removal of two massive floating pieces, each no less than 400 feet long and 600 to 1,000 feet thick.

266 inches at Valdez. As much as 671 inches of snow have been reported in one season (1902–1903) at Fort Liscum, five miles southwest of Valdez and close to the northeast shore of Prince William Sound (U. S. Weather Bureau, 1922: p. 10). The regional snow-line and mean névé-line are much lower in this district than elsewhere along the coast.

Many of the smaller glaciers are in retreat. Significantly, however, over the past sixty years a larger proportion has been advancing than in the other districts described. In fact, all of the trunk glaciers are now well forward. Each has a tidal terminus, so the position records underestimate the magnitude of their general advance. The most persistently advancing glaciers come from the Valdez Icefield on an inner peninsula of the Sound, framed between two large northward-trending channels called Valdez Arm and College Fiord. This peninsula is subjected to strong maritime influences tending towards a high degree of cloudiness and frequent storms throughout the year. The pattern of fluctuations on the four major glaciers having their sources in this icefield is shown in the chart of figure 4*a* (early position points on this chart from Field, 1932).

The strong advances of Meares Glacier and Harvard Glacier have been especially persistent since 1900. These are again comparable to the advance of the Taku Glacier in the Juneau area. Yale Glacier and Columbia Glacier appear to be near equilibrium; but since the main currents of these glaciers calve into the sea their regime trend is one of gradual expansion. Columbia Glacier has the largest tidal front in Alaska, with a lobate terminus seven miles across. To the present there have been many minor fluctuations within a quarter of a mile of the point reached by the center of the front in 1935, a position not greatly different from that shown on Captain Vancouver's map of 1794 (Vancouver, 1801). Ring counts on tilted trees at the end moraine prove that the 1935 position was as far advanced as any attained in at least five hundred years (Cooper, 1942: p. 9).[7]

The variations of five major glaciers flowing into the western side of College Fiord are also shown in the graphs of 4*a*. These ice tongues arise in the mountains of the western Chugach Range and show a different kind of pattern. Recession has been the rule since the 1890's, although in the last ten years a strong resurgence has been indicated. Of this group, only the Harriman Glacier has experienced a continuous advance (since 1910). This is a large glacier with a catchment area comparable in elevation to that of the advancing ice streams of the Valdez sector. Again, we see the situation of simultaneous advance and retreat in adjacent ice masses . . . a pattern which has been repeated in every district from the Stikine River northwards along more than 1,000 miles of the Alaskan coast, and one which is particularly typified by the Taku Glacier system near Juneau.

THE REGIONAL PATTERN AND ITS COMPARISON WITH OTHER AREAS

Ideally, regime comparisons should be made between glaciers of similar size, form and gradient and ones on which the respective névés and termini are at comparable elevations. The extremely mountainous character of these Alaskan districts, however, provides such a diversity of morphological factors influencing glaciers that not many direct comparisons are possible. On the other hand, since the survey embraces about 90 per cent of the important glaciers in south coastal Alaska, it may be concluded that a sufficient number has been dealt with for the regional pattern to be clear. The general trend between the 1920's and 1960's is shown by the following summary statistics, calculated from the data in table 1.

Noteworthy in this tabulation is the consistency of pattern in Districts A, B, and F, and the similarity between Districts E and G. This appears to be due, in part, to similarities in geographical position of the prime source névés of the Alaskan-Canadian Coast Range and the inner St. Elias Mountains. Certainly the most heavily glaciated highlands of these two areas are 50 to 100 miles farther inland than the Fairweather and Chugach Ranges and are thus more continental in their climate than the icefields which nourish the Lituya Bay and Prince William Sound glaciers.[8] (This important difference based on maritime versus continental climatic tendencies is referenced

[7] This relationship may be extremely significant since, as in the case of Baird Glacier in the Stikine District (table 1), this present glacial position probably represents the post-Glacial maximum . . . i.e., since ±8000 B.P.

[8] In such considerations, it should also be mentioned that the Fairweather and Chugach Ranges lie astride a tectonically-sensitive "earthquake belt," as previously noted for the maritime sector of the St. Elias District. This further begs the question of the occasional effects of diastrophism on the behavior of certain glaciers such as in Lituya Bay and Prince William Sound. These effects need, of course, to be differentiated from those which are climatologically controlled.

TABLE 2

REGIME STATISTICS FROM 1946–62 RECONNAISSANCE SURVEYS OF MAJOR GLACIERS IN SOUTH AND SOUTHEASTERN ALASKA

	No. of Glaciers Observed	Percentage of Termini		
		Dominant Shrinkage	Near Equilibrium*	Persistent Advance**
District A (Stikine)	28	70%	26%	4%
District B (Taku)	21	84	13	3
District C (Glacier Bay)	28	54	46	0
District D (Chilkat)	22	32	68	0
District E (Lituya)	7	14	57	29
District F (St. Elias)	41	82	15	3
District G (Chugach)	17	18	59	23
All Districts	174	61%	33%	6%

* Including termini close to equilibrium but still showing fluctuations either towards shrinkage or gradual expansion.
** Glaciers also near to their post-Glacial maximum.

in the right hand column of table 1). The significance of this factor in explaining the larger proportion of advancing glaciers in these latter districts is corroborated by the fact that the outer maritime provinces receive from 80 to 100 per cent more precipitation annually than the inner maritime and sub-continental areas, and as much as 800 per cent more than the continental areas lying close behind the coast ranges. Likewise, the sea-level stations at Cordova and Yakutat often receive 200 to 300 per cent more snowfall than the sea-level station at Juneau. The rainfall patterns at the mouth of Glacier Bay (Gustavus) and in the Chilkat District (Haines) appear as gradational between the continental and maritime extremes.

To sum up the regional pattern, in spite of marked differences in the geographical factors affecting glacier nourishment, the dominant characteristic throughout Southeastern Alaska during the past fifty years has been shrinkage. The recessional rate on many glaciers, especially those having source névés at low elevation, became much accelerated in the 1920's. For many of those with high névés, a slower retreat took place in the 1920's and '30's, while a few have experienced spasmodic readvances between 1938 and the present. The only persistently strong departures from the general trend have been on large trunk glaciers. For each such case of significant advance, however, there has been a marked and contemporaneous retreat of another valley glacier of comparable size. Invariably, this opposite behavior has been on glaciers coming from the same or adjoining névés.

Simultaneous advance and retreat in adjacent glaciers has been reported in parts of Iceland (Thorarinsson, 1940: p. 135) and Patagonia (Nichols and Miller, 1952). Periodic reports on French, Swiss, Italian, and Austrian glaciers (e.g., see Mercanton, 1948, and *Journal of Glaciology* listings through 1960) also show that over the past thirty years while 91 to 96 per cent of the Alpine glaciers have been retreating, about 2 per cent have remained stationary and from 2 to 5 per cent have advanced. However, the proportion of equilibrium and advancing glaciers in Alaska is much higher than in any comparable region in the world; and nowhere else has the contrast been so pronounced nor has it been seen on such a large scale. The pattern has also been so consistent over such a wide range of latitude (56° to 62°N.) that a causal factor must be involved which is of broad regional proportion and of fundamental global importance.

SUMMARY COMMENT

Although from the information given it has been possible to formulate the basic regional pattern of coastal glacier oscillations over the past two centuries, the picture is complex and many details remain unclarified. Mere consideration of changing terminal positions of glaciers without concern for related orographical and meteorological factors in their catchment areas can only result in partial answers to the critical questions concerning cause of the advance and retreat. A full understanding of the regime of these Alaskan ice masses, both in terms of the larger relationship of Pleistocene Cordilleran glaciations and to the fluctuating climatic events following the Thermal Maximum, requires a thorough, long-term glaciological and geophysical investigation of selected ice masses from termini to source area and in three dimensions as well. Where possible, such research should be concentrated on prototypical glacier systems having characteristics of the larger regional pattern.

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