A PRELIMINARY FORECAST OF THE ADVANCE OF HUBBARD GLACIER AND ITS INFLUENCE ON RUSSELL FIORD, ALASKA

by Dennis C. Trabant, Robert M. Krimmel, and Austin Post

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ILLUSTRATIONS

CONVERSION FACTORS AND VERTICAL DATUM

Multiply	By	To obtain
millimeter (mm)	0.03937	inch
meter (m)	3.281	foot
kilometer (km)	0.6214	mile
square kilometer (km^2)	0.3861	square mile
cubic kilometer (km^3)	0.2399	cubic mile
cubic kilometer per year (km^3/yr)	0.2399	cubic mile per year
meter per day (m/d)	3.281	foot per day
meter per year (m/yr)	3.281	foot per year
cubic meter per second (m^3/s)	35.31	cubic foot per second
degree Celsius (°C)	°F = (1.8 x °C) + 32	degree Fahrenheit (°F)

Sea level:

In this report "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)--a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called Sea Level Datum of 1929.

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ABSTRACT

The persistent advance of Hubbard Glacier near Yakutat, Alaska, since about 1895 has generally accelerated during the 20th century. The advancing ice and push moraine blocked the entrance to Russell Fiord for the first time this century between May and October 1986. Following closure, fresh-water inflow filled Russell Fiord until the dam failed. If a dam does not fail or is not overtopped, water will overflow into the Situk River. Analysis of recent glacier behavior and current conditions indicates that a closure that will eventually result in overflow into the Situk is likely to occur within a decade. Because Hubbard Glacier is in the strongly advancing phase of the calving glacier cycle, the current advance is likely to continue regardless of climate variations. Furthermore, the gradual increase in both annual precipitation and temperature recorded at Yakutat since 1950 favors glacier growth. The advance is sustained by an accumulation-area to total-glacier-area ratio of 0.95 and a terminal moraine shoal that controls calving losses. The estimated mass flux out of the accumulation area is 6.8 cubic-kilometers water equivalent per year. Calving losses now account for about 95 percent of this flux. About 4 percent of the total flux is lost to melting and 1 percent goes into storage as the ablation area is extended and becomes thicker. Ice speeds--measured from aerial photography, by satellite relay, and with radio beacons--are about 3 kilometers per year near the terminus and vary seasonally. Speed pulses affect the entire lower glacier. Seasonal advance and retreat of the calving terminus has been measured from aerial and terrestrial time-lapse photography. Terminus advance is directly related to ice speed and the rate at which the terminal moraine is moved and indirectly related to water depth at the terminus. The closure forecast is based on an understanding of the generalized calving glacier cycle, assessment of Hubbard Glacier's current status in that cycle, and observations that indicate how seasonal speed changes, speed pulses, fiord bathymetry, and tidal fluxes near the damming point may affect future closures. A closure is most likely to coincide with the seasonal terminus advances in April, May, and June. The possibility of a closure of sufficient duration to produce overflow into the Situk River is increasingly likely with time. Episodic formation and failure of the dam would result in intermittent overflow into the Situk River.

INTRODUCTION

A slow but persistent advance of Hubbard Glacier in southeast Alaska (fig. 1) has been observed since about 1895. Post and Mayo (1971) predicted that the advancing glacier would dam Russell Fiord (fig. 1) by about 1990. After a closure, runoff from glaciers and adjacent areas causes the level in "Russell Lake" to rise until the ice dam fails or a former overflow channel at the south end of the fiord is reached at 39.96 m altitude (Paul, 1988). Overflow on the south end of the fiord will enter the upper reaches of Old Situk Creek, a tributary to the Situk River. Overflow is expected to increase the average discharge of the Situk River by tenfold (Paul, 1988). The physical, social, and economic impacts of such a change in the flow of the Situk River prompted an evaluation of the activity of Hubbard Glacier with regard to possible closure of Russell Fiord. To address these concerns, this U.S. Geological Survey study was made in cooperation with the U.S. Department of Agriculture, Forest Service and the National Park Service.

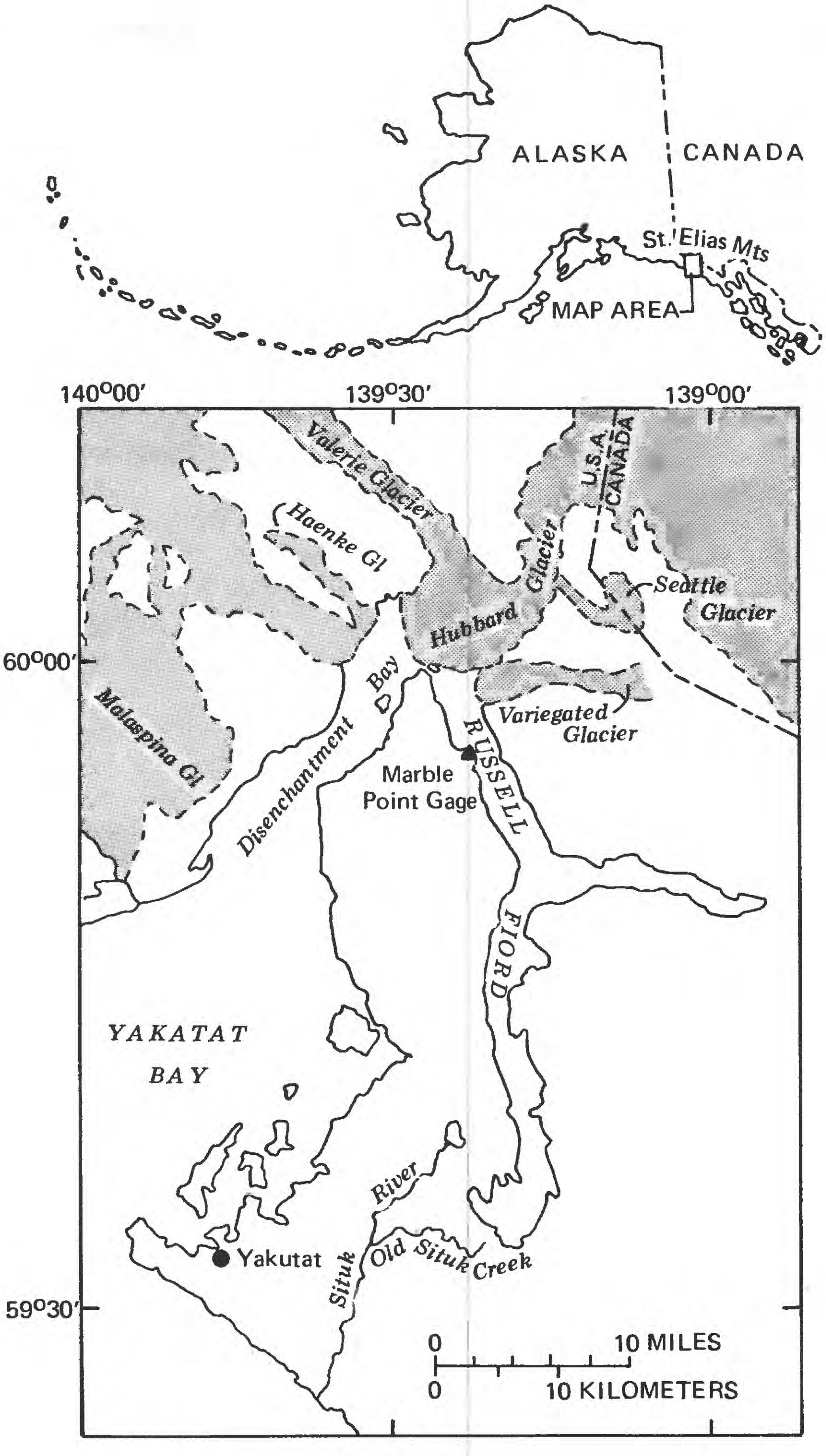

Figure 1a.--Location of study area.

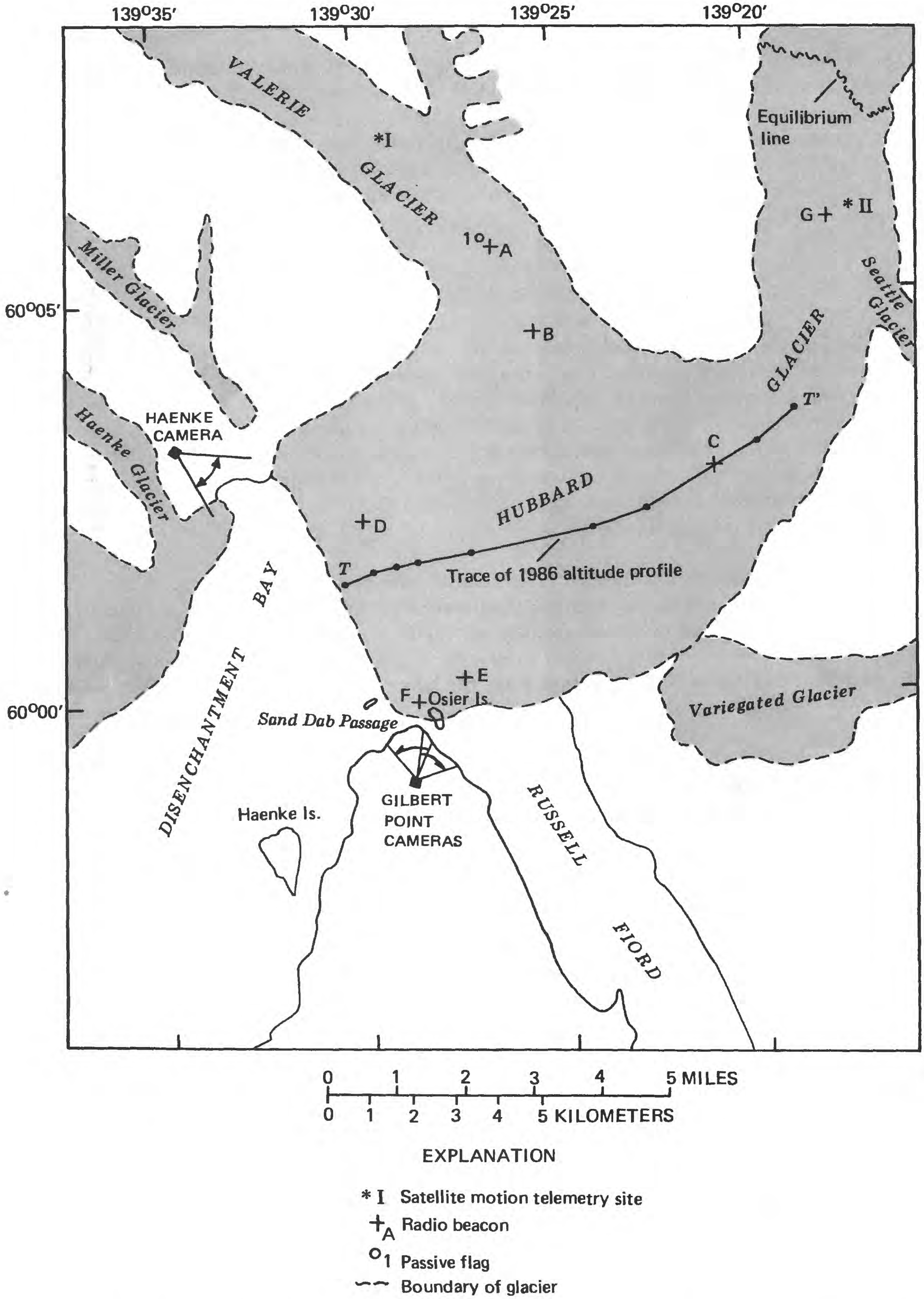

Figure 1b.--Location of study area and data-measurement sites [see fig. 6 for section T-T'].

The first closure in the 20th century occurred in late May 1986. When the glacier dam failed in early October 1986, the water level in Russell Fiord had risen 25.5 m.

The purpose of this report is to present a description of current (1990) conditions and ongoing changes at Hubbard Glacier that are the physical basis for a forecast of possible future closures of Russell Fiord. The data needed to update these predictions and provide warnings of possible closures are also evaluated.

THE ADVANCE AND RETREAT OF CALVING GLACIERS

Various ideas have been proposed to explain the advance of Hubbard Glacier. Tarr and Martin (1914) postulated that earthquake-induced snow and ice avalanching caused advances of many glaciers of Yakutat Bay, including the Hubbard Glacier. Miller (1966, 1967, and 1975) suggested sunspot activity affecting storm paths with related changes in the levels of maximum snow accumulation as the cause. The current understanding of processes that control the behavior of tidal glaciers was published (Post, 1975) in conjunction with the U.S. Geological Survey's ongoing investigation of Columbia Glacier, which began in 1974. Columbia Glacier is on the south coast of Alaska, about 430 km west-northwest of Hubbard Glacier.

The authors consider Hubbard Glacier's present advance to be the latest phase of large-scale, alternating slow advances and drastic retreats which have been taking place during the middle and late Holocene in practically all of Alaska's iceberg calving glaciers [1] (Post, 1975, 1980a,b,c, and d). That these changes are not directly related to climate changes is shown by their asynchronous behavior and by the fact that similar changes have not taken place in nearby glaciers that end on land.

The primary influence on the stability of calving glaciers was identified by Post (1975) as the water depth at the calving face; calving speed is related directly to water depth--slow in shallow water and faster in deep water. Advancing calving glaciers end on a terminal moraine shoal, unconsolidated material that nearly fills the fiord at the glacier front (fig. 2b). Measured water depths near the calving faces of stable and advancing glaciers have been found to be generally less than about 80 m, compared with several hundred meters of water in the fiord beyond the shoal (Brown and others, 1982).

Calving Glacier Dynamics

On a time scale of hundreds of years, calving glaciers advance by "moving" their terminal moraines down the fiord (fig. 2). The moraine generally is not simply pushed; the moraine advances by glacier erosion of material on the upstream side and re-deposition of that material on the fiord side. The deposition produces a series of foreset beds. Foreset bedding was recorded in Columbia Glacier's terminal moraine by sub-bottom sounder profiling (Meier and others, 1978), which confirms this theory of moraine advance. The rate of advance of the terminal moraine is slow (rarely more than a few meters per year) in deep fiords and is controlled by the amount of moraine material that must be moved to maintain relatively shallow water at the calving face.

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1 The term "calving glacier" as used in this report refers to a glacier that ends in tidewater, discharges icebergs, and is in contact with its bed throughout its length (not floating).

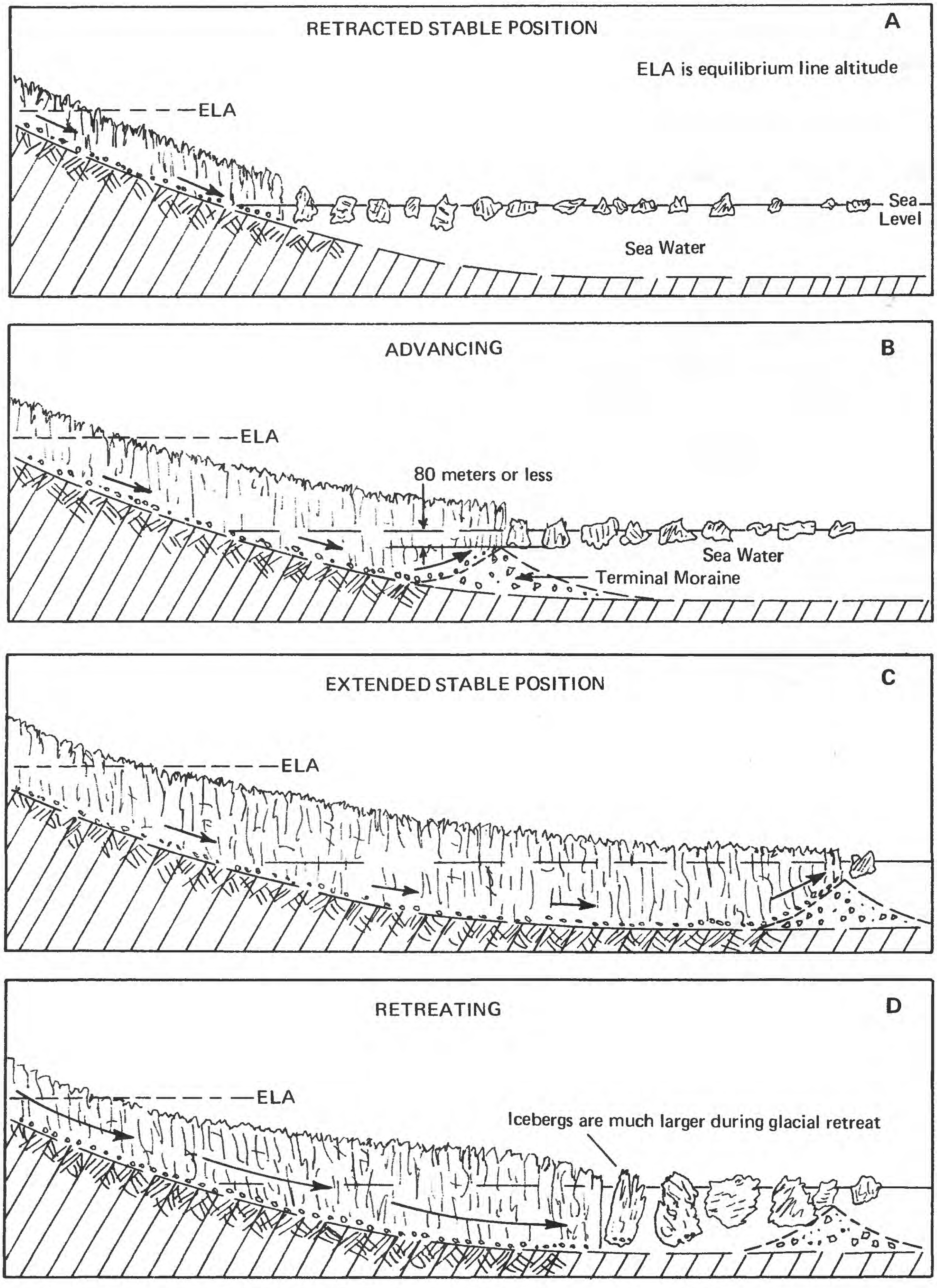

Figure 2.--The tidal glacier cycle.

An advance will generally continue until the area that receives more snow each year than melts (the accumulation area) is reduced to approximately 0.6 to 0.7 of the total area of the glacier. The ratio of accumulation area to total glacier area is reduced when an advancing glacier increases its area by expansion at lower altitudes (Mercer, 1961). A glacier on land that is neither advancing nor retreating typically has an accumulation area ratio (AAR) between 0.5 and 0.8 (Meier and Post, 1962). When the AAR of a calving glacier falls below 0.7, the glacier becomes increasing sensitive to external influences, including climate variations, that may cause it to retreat from its moraine shoal. The drastic retreat of Columbia Glacier, began at an AAR of 0.66.

Drastic retreat of a calving glacier normally begins when a small recession from the shoal results in the terminus receding into deeper water upstream from the terminal moraine crest (fig. 2d). Because calving speed is directly related to the water depth at the terminus (Brown and others, 1982), a retreat into deeper water stimulates an increase in calving speed. Instability develops when the calving speed becomes greater than the ice speed and the retreating calving front moves into even deeper water. Onset of the drastic retreat of Columbia Glacier is an example (Meier and others, 1984). Drastic retreat ends when the terminus recedes into shallow water, usually at the head of the fiord (fig. 2a). The rate of retreat can be a kilometer or more per year -- many times faster than the rate of advance (Brown and others, 1982).

In most cases as calving glaciers drastically retreat, the AAR increases as the ice in the ablation area is discharged as icebergs. Thus calving glaciers ending near the heads of fiords frequently have high AAR's, whether they are advancing or retreating (Meier and others, 1980).

Re-advance, following a drastic retreat, begins when there is enough morainal material at the calving face to maintain a terminal moraine shoal as the calving face advances into deeper parts of the fiord (fig. 2b). Calving speed is then less than the ice flow speed.

Seasonal Changes

Annual advances and retreats of the termini of calving glaciers of a few hundred meters are superimposed on the longer term changes discussed above and are influenced by seasonal changes in glacier ice speed and subglacial runoff. At Columbia Glacier, late-summer/autumn retreat of the terminus is caused by an increase in the calving speed that is associated with seasonally increased runoff from melt and rain; the late-winter/spring advance is a response to seasonally increased ice speed and decreased runoff (Sikonia and Post, 1980). The seasonal advances and retreats of Columbia Glacier's terminus continue to occur, even as drastic retreat is ongoing (Krimmel, 1987). Seasonal advances and retreats generally have little direct effect on the longer term advance or retreat of calving glaciers.

STATUS OF HUBBARD GLACIER AND CURRENT OBSERVATIONS

Hubbard Glacier generally has been advancing since it was first mapped by the International Boundary Commission in 1895 (Davidson, 1903). Comparison of maps and vertical aerial photographs of the glacier's terminus shows that the average rate of advance has accelerated during the 20th century (fig. 3). The average rate of advance into Disenchantment Bay has been as follows:

Period	Average rate (meters per year)
1895 to 1948	16
1948 to 1962	18
1962 to 1972	30
1972 to 1983	38
1983 to 1988	47

Accumulation Area Ratio

The flow of Hubbard Glacier is regulated by its mass balance, which is largely controlled by the local climate and calving losses. Year-to-year changes of the accumulation area ratio (AAR) are an index to the climatically controlled accumulation and ablation components of mass balance. For many years since 1963, observations of the glacier near the end of the melt season show that the line separating the accumulation area from the ablation area (the equilibrium line) is normally at about 1,000 m altitude (A. Post and R.M. Krimmel photography available from the Ice and Climate Project Office of the U.S. Geological Survey, Tacoma, Washington). The AAR for a near-equilibrium glacier is between 0.5 and 0.8 (Meier and Post, 1962); with an equilibrium line altitude (ELA) of 1,000 m, Hubbard Glacier has an AAR of 0.95. This AAR demonstrates that the glacier's mass balance is extremely positive and that Hubbard Glacier can easily sustain its calving and melt losses while advancing the terminus and increasing its thickness by moving the terminal moraine further into Disenchantment Bay.

Climatic Sensitivity

Hubbard Glacier is not currently sensitive to small climate changes. In addition to having a very high AAR, Hubbard Glacier is relatively insensitive to climate-induced changes in the regional ELA because the equilibrium line lies on a steep, narrow part of the ice stream (fig. 1b) where ELA changes have little influence on the AAR. For example, a climate-induced ELA rise of 200 m would decrease the accumulation area and reduce the AAR by only about 4 percent, to 0.91. If the ELA were lowered by 200 m, the accumulation area would become larger, but would result in an increase in the AAR of only about 1 percent.

Natural changes in the ELA have likely been smaller than ±200 m for decades. For instance, the 1987-88 balance year resulted in a 50-m lowering of the ELA as shown on the late August and September 1988 aerial photography. This relatively small change was the response to winter precipitation (September 1987 through March 1988) that was about twice the 1951-80 normal amount, followed by a summer (May through August) that had near-normal temperatures, which

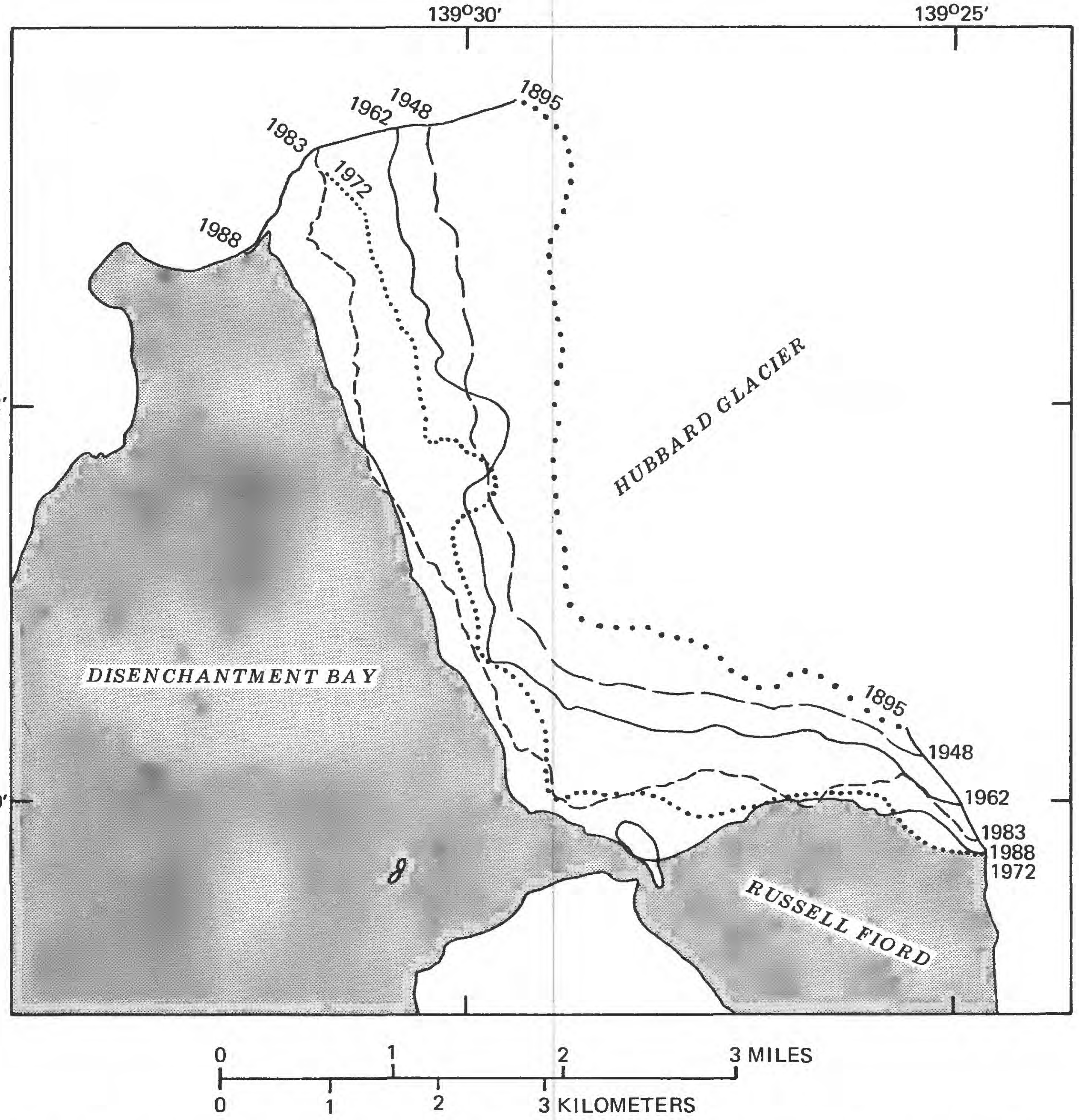

Figure 3.--Hubbard Glacier terminus positions: 1895, June 1948, October 1962, September 1972, June 1983, May 1988.

suggests near-normal melting. Therefore, the exceptionally heavy snowfall of the 1987-88 winter had a relatively small effect on the 1987-88 ELA on Hubbard Glacier.

Calving glaciers become sensitive to climate when the AAR approaches 0.7. On the present-day Hubbard Glacier, the reduction of its AAR to 0.7 would require raising the ELA by 1,000 m. Such a dramatic rise of the ELA would have to be sustained for a decade or more before the climate-induced changes would slow the advance of the Hubbard Glacier terminus.

Estimated Mass Flux Through the Lower Glacier Area

It could be argued that a glacier with an AAR of 0.95 is so healthy, there is little doubt about its future. Nevertheless, an estimate of the mass-balance driven ice flux is useful for assessing the relative importance of losses due to melting, and the ability of the glacier to sustain calving while increasing the ice storage (thickening) in the lower glacier.

The total accumulation and ablation on Hubbard Glacier have not been measured, but can be estimated by using data collected at nearby Variegated Glacier (fig. 1). Measurements on Variegated Glacier (C.F. Raymond, University of Washington, written commun., 1980 and 1981) indicate that the mass balance, as expressed by the ELA in late summer, correlates well with the inverse of winter precipitation at Yakutat (fig. 4). The correlation indicates increasing amounts of snow accumulation in the Hubbard Glacier basin. Furthermore, gradual changes in the climate seem to favor continued glacier growth. The annual precipitation at Yakutat has been generally increasing since 1950, as has the mean annual air temperature since the weather observation station was moved in 1964 (fig. 5).

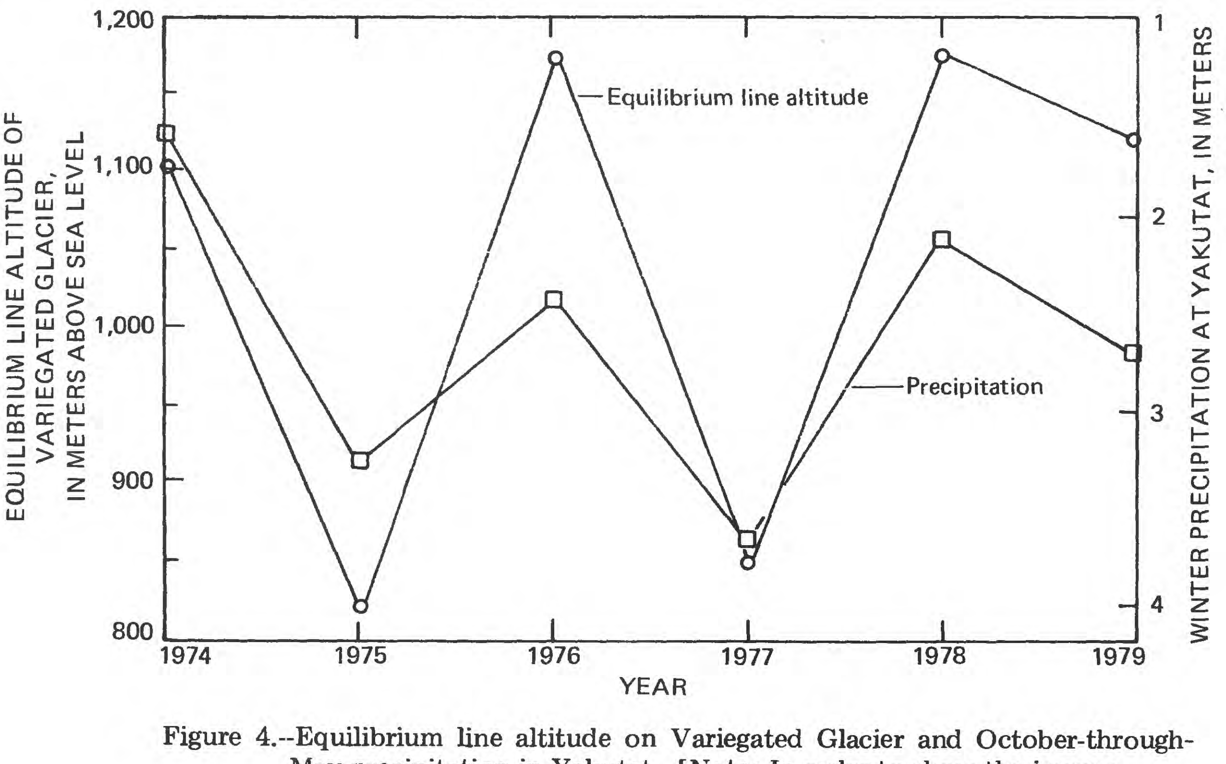

Figure 4.--Equilibrium line altitude on Variegated Glacier and October-through-May precipitation in Yakutat. [Note: In order to show the inverse relationship clearly, the precipitation axis is inverted, that is, decreases toward the top. The equilibrium line altitude was estimated using the measured net balance on Variegated Glacier (C.Raymond, University of Washington, written commun., 1980 and 1981).]

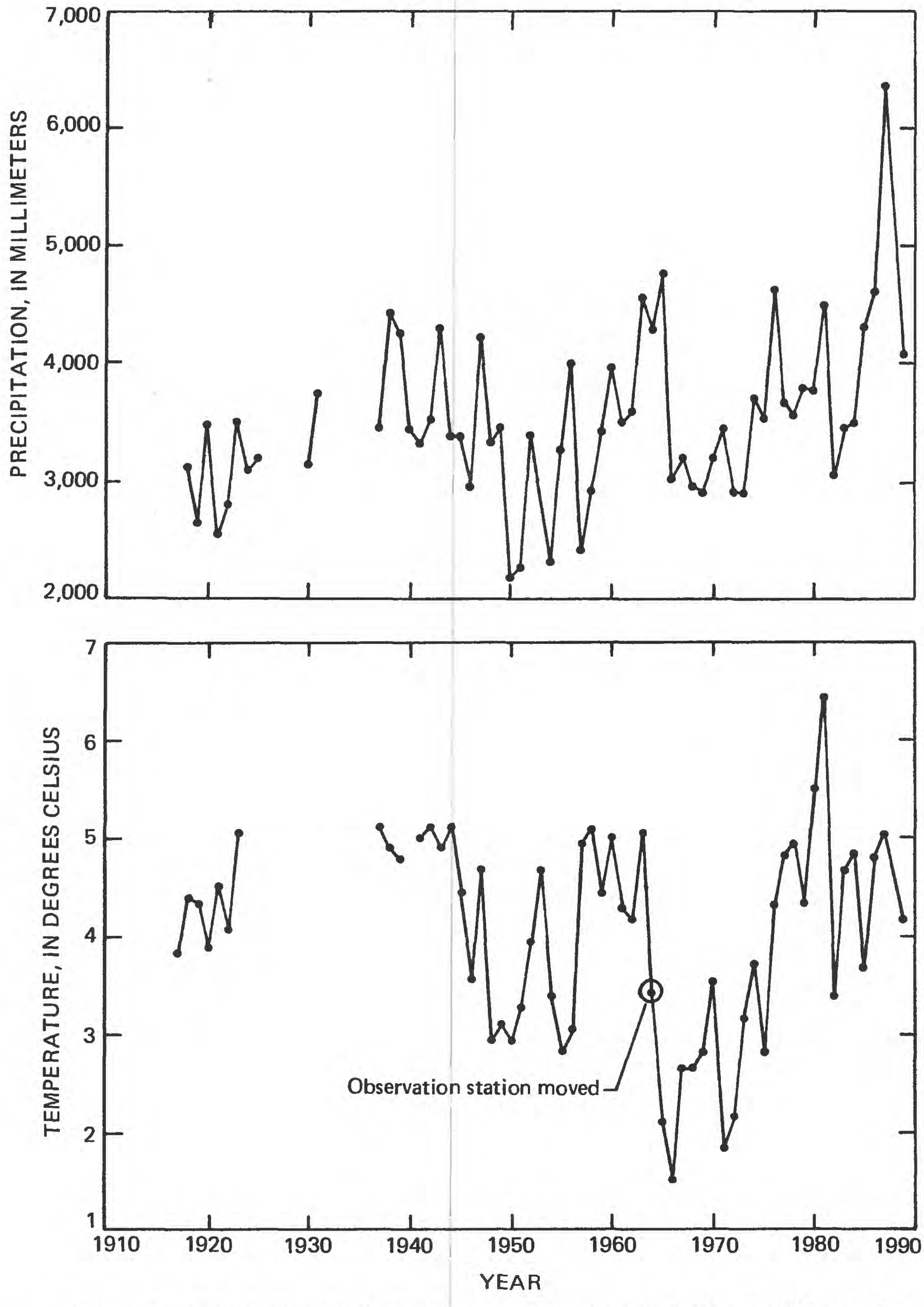

Figure 5.--Annual precipitation and mean annual temperature at Yakutat for the period of record. [Data from National Oceanic and Atmospheric Administration; local climatological data for Yakutat, Alaska.]

An estimated annual average accumulation of 2.0 m water equivalent occurs on Hubbard Glacier. This estimate is based on observations from (1) Variegated Glacier, where an average of 2.8 m water equivalent of snow remained at the end of the melt season at 1,500 m altitude for the period 1974 to 1979, and (2) a 1965 traverse from the Seward to Kaskawalsh Glaciers (across the upper Hubbard), when accumulation was found to decrease inland from about 2.0 m to 0.5 m (Marcus and Ragle, 1970). Multiplying the 2.0 m water equivalent estimate by the accumulation area of Hubbard Glacier (3,400 km^2) yields an equilibrium mass flux out of the accumulation area of about 6.8 km^3/yr water equivalent.

Estimated Ice Melt on the Lower Glacier

Ice melt losses can be estimated from observations at Variegated Glacier (C. Raymond, University of Washington, written commun., 1980 and 1981). Average water equivalent ice ablation rate at 500 m altitude from 1974 to 1979 was 3.2 m/yr. Assuming that this value is representative of the 95 km^2 ablation area of Hubbard Glacier, the annual volume of ice melt on the glacier is about 0.3 km^3, or about 4 percent of the ice flux into the ablation area. Most of the rest of the ice is lost by calving or goes into thickening the glacier. Even though the uncertainties in this estimate are large, the assessment demonstrates that melt losses are not a significant factor in Hubbard Glacier's mass balance.

Thickness Increases of the Lower Glacier

As the terminus of Hubbard Glacier advances down the fiord, the ice behind the calving face must thicken if the advance is to be sustained. This is a consequence of the geometry of the underlying terminal moraine, an almost constant average height of the calving face, and the ice surface slope toward the calving face. A comparison of surface longitudinal profiles of the glacier for 1959 and 1986 (fig. 6), which shows that the lower part of the glacier has thickened, again supports the concept that the glacier is healthy and able to sustain its advance down the fiord. An average annual rate of 0.5 m/yr net thickening in the lower glacier was estimated from the surface altitude profiles. At that rate, the volume of ice that goes into storage annually in the 95 km^2 of the lower glacier is about 0.05 km^3, or less than 1 percent of the ice equivalent volume balance flux into the area. Therefore, melt losses and thickening currently amount to less than 5 percent of the estimated balance flux, leaving about 95 percent of the balance flux to be lost by calving. In spite of significant uncertainties in the estimation of mass flux, the largest part of the ice flux supports continued advance, calving, and thickening of the glacier.

Ice Thickness

Measurements of ice thickness on Hubbard Glacier have been made using a surface-based, pulsed-radar system with a frequency of about 1.7 MHz using previously described methods (Mayo and Trabant, 1982). The maximum ice thickness below the junction with Valerie Glacier is thought to be about 700 m. This means that the bed of the glacier at that point is about 400 m below sea level. The glacier bed maps presented in Mayo (1988a) show a generalized bottom configuration. The ice-thickness measurements to date are shown on a map with a revised glacier bed estimate (fig. 7).

Glacier Speed

Surface ice speeds on Hubbard Glacier have been measured by repeated surveys of markers left on the surface, from satellite location telemetry units, and from analysis of periodic aerial photography. Surface speeds up to about 3,000 m/yr below the junction of the Hubbard and Valerie Glaciers have been measured (Krimmel and Sikonia, 1986).

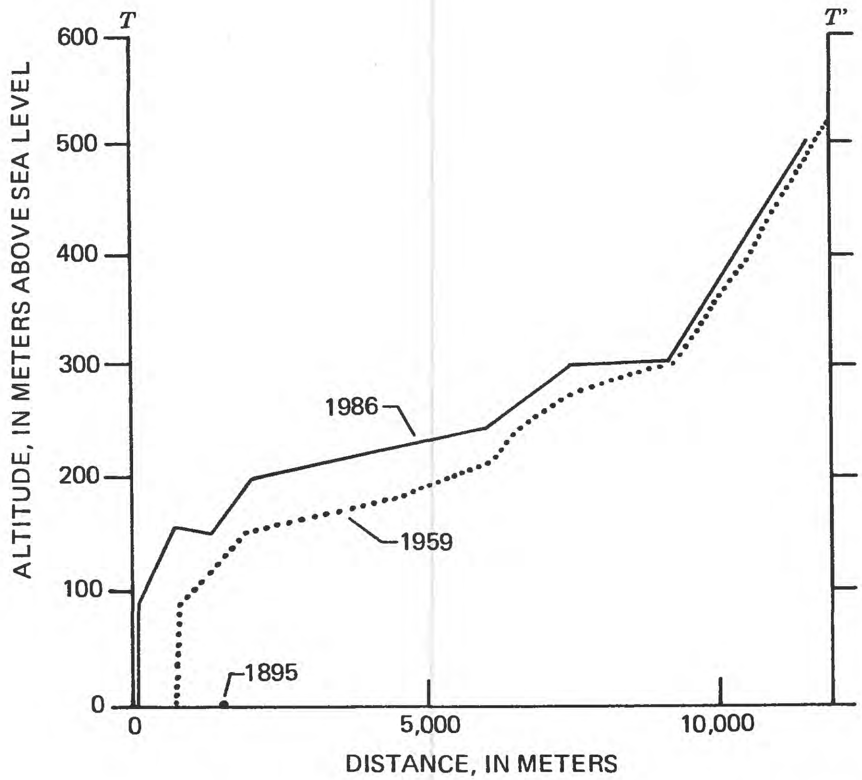

Figure 6.--Profile of glacier surface altitude of lower Hubbard Glacier and position of the 1895 terminus. [Trace of profile *T-T'* shown on figure 1b.]

Passive and Active Markers

Markers deployed at surveyed positions on the surface of Hubbard Glacier (fig. 1b) were re-surveyed when recovered later. The difference in position is due to glacier flow (fig. 8). Markers were used from June 1986 until 1988. The first markers were simply high-visibility flags that were recovered by searching from a helicopter. Because flags are lost when covered by snow, radio beacons were deployed: three in July 1986, two more in June 1987, and one in May 1989 (fig. 1b). The radio beacons have a life expectancy of 3 years and can be recovered by helicopter-supported searching using a directional antenna and receiver. When the beacons are covered by snow, a refined location is determined by searching with a signal processor that analyzes signal strength. The resolution of the horizontal coordinates of the beacons are determined to about ±20 m with the signal processor. Beacon markers are recovered (when possible) each summer and relocated up-glacier so that the following year's data can be obtained in the same area.

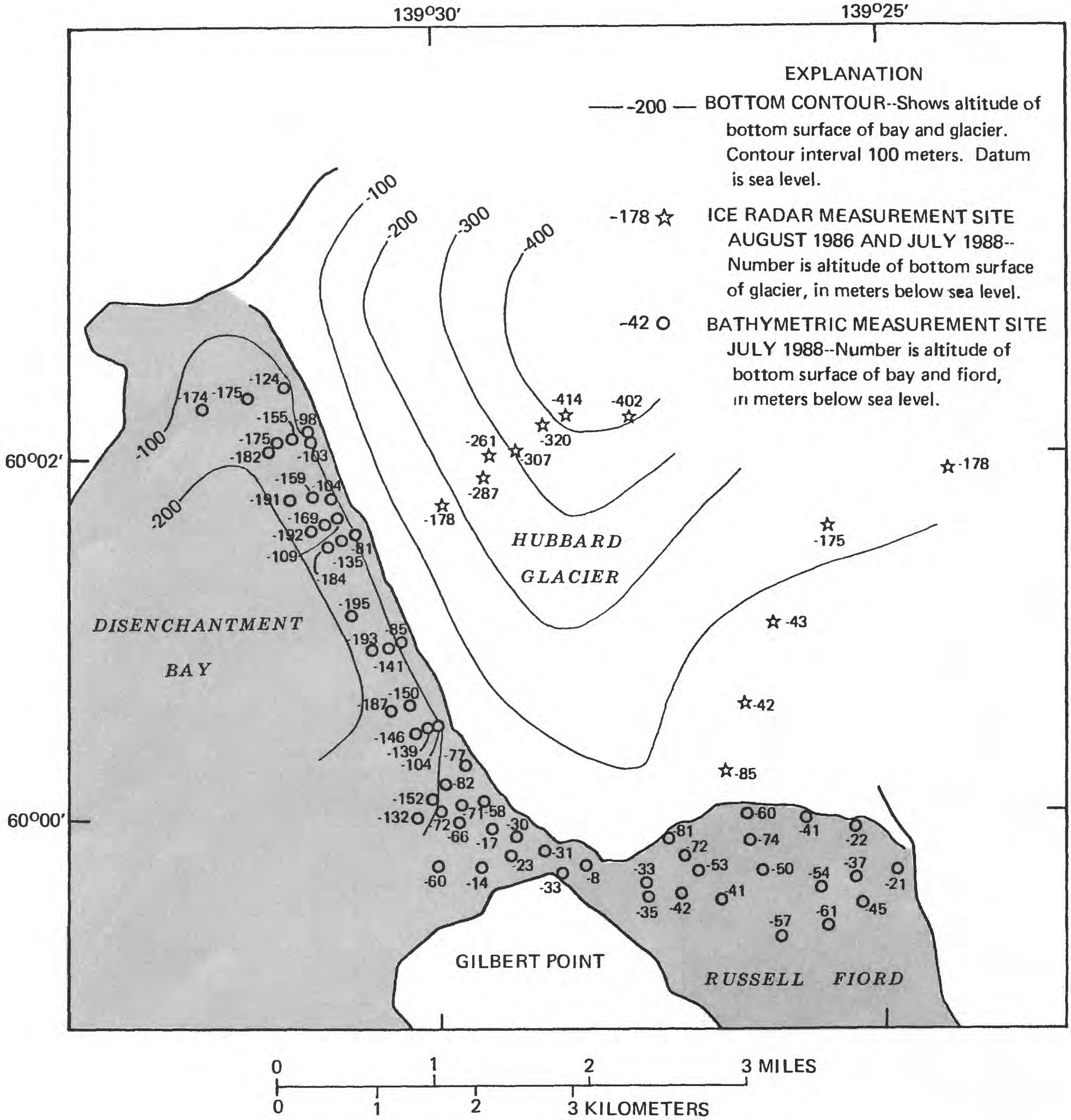

Figure 7.--Bottom map of Hubbard Glacier and Disenchantment Bay near the calving terminus.

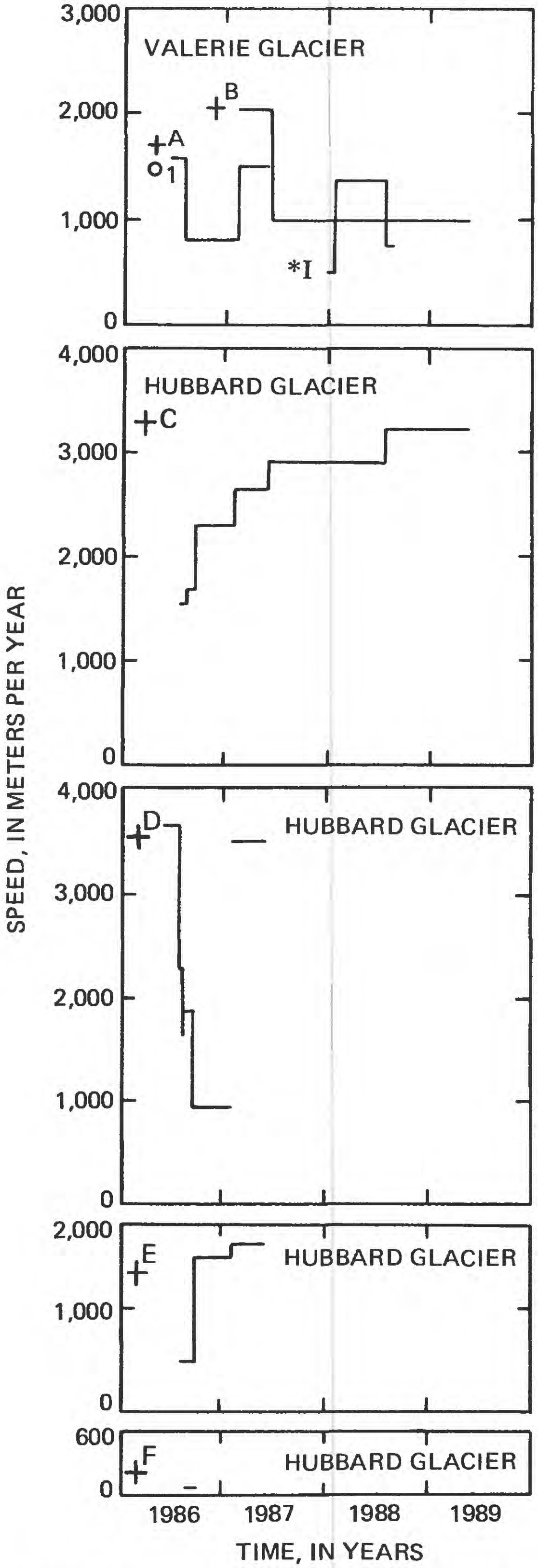

Figure 8.--Glacier speeds measured by flags, radio beacons, and satellite motion telemetry systems on Hubbard and Valerie Glaciers. [The identifying letters, numbers, and symbols are the same as on figure 1b.]

Figure 9.--A satellite motion telemetry unit. [Unit moves with ice and reports changes in position that are interpreted as glacier motion.]

Satellite Location and Telemetry

Four satellite receiver and relay systems were on Hubbard Glacier in December 1987. The intent was to have a near-real-time, all-weather capability of sensing and relaying glacier speeds for detecting unstable flow events, and to increase the understanding of seasonal speed changes. The system consists of a marine navigation receiver and a satellite data telemetry transmitter, and has a horizontal resolution of ±50 m. One system operated successfully from the Valerie Glacier surface beginning on December 22, 1987 (figs. 1b and 9). Speed data derived from the two periods of directly reported position changes are shown in figures 8 and 10. The satellite data in figure 8 show a strong seasonal change in glacier speed and no unusual speed events.

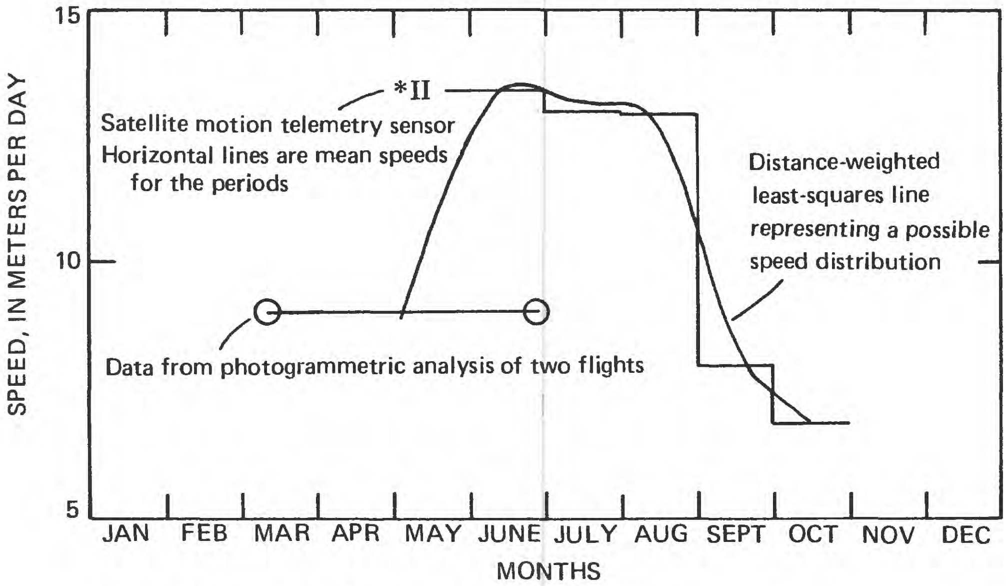

Figure 10.--Surface ice speeds near the equilibrium line on Hubbard Glacier during the spring 1989 pulse.

In May 1989, a system was placed on the main Hubbard ice stream (fig. 1b) where the ice speed was expected to be higher than on the Valerie tributary. The navigation unit was removed from the system to increase system reliability and reduce operating costs, but its removal reduced the system's spatial resolution to about ±150 m. However, the higher ice speed on the main Hubbard Glacier ice stream somewhat compensates for the loss in resolution and results in useful surface ice speed data. The monthly average speed data (fig. 10) show that relatively high speeds of about 13 m/d were sustained from the time of installation in late May, to late August, and decreased to about 8 m/d in September.

Aerial Photography

Photogrammetric determination of ice surface speed and altitude changes on large, highly crevassed glaciers was demonstrated at Columbia Glacier by Meier and others (1985). The velocity and surface altitude of the lower Hubbard Glacier were similarly analyzed by Krimmel and Sikonia (1986) for the period July 30 to August 23, 1978. Following the 1986 closure of Russell Fiord, renewed interest in the speed of Hubbard Glacier, its seasonal changes, and relation of speed to calving front location prompted the beginning of a new series of aerial photographs. Photographs were obtained on August 24, 1987; January 28, May 25, and September 8, 1988; and March 12, April 7, May 21, and June 28, 1989. For this report, the photographs were used to: document ice speeds (fig. 10), determine terminus positions (figs. 11 and 12), evaluate the effects of speed pulses (fig. 13), determine the equilibrium line altitude, and document the general activity of the main branch of Hubbard Glacier and its lower tributaries.

Surges and Pulses

Many of the glaciers surrounding Hubbard exhibit strong, non-seasonal, flow irregularities first reported by Tarr and Martin (1914). Surging glaciers tend to be geographically clustered (Post, 1969). In the vicinity of Hubbard Glacier, Variegated Glacier (fig. 1) is a typical surging glacier with a well-documented surge history. It moves slowly for 18 to 20 years, then for 1 to 2 years moves at

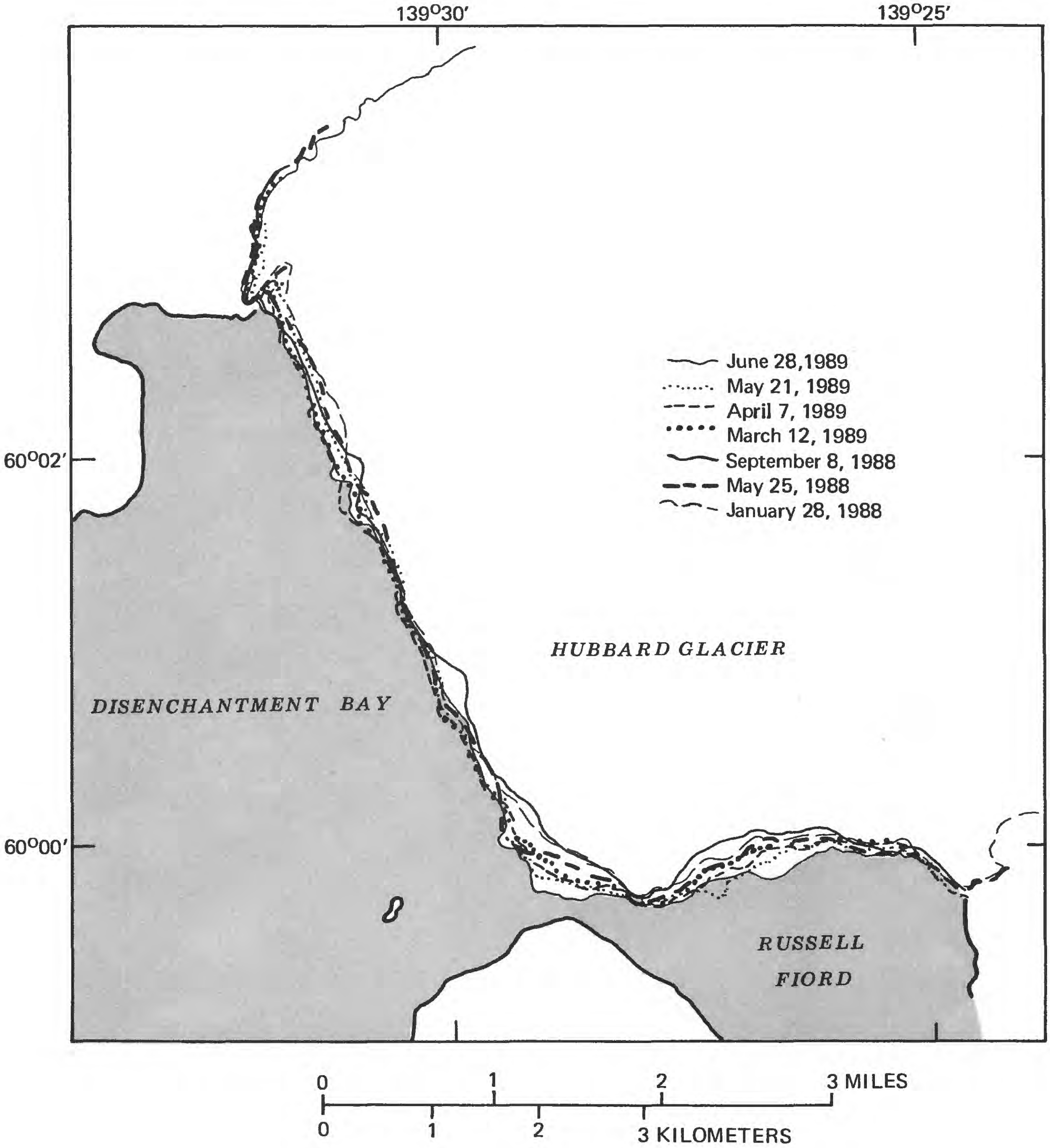

Figure 11.--Seasonal changes in the Hubbard Glacier terminus.

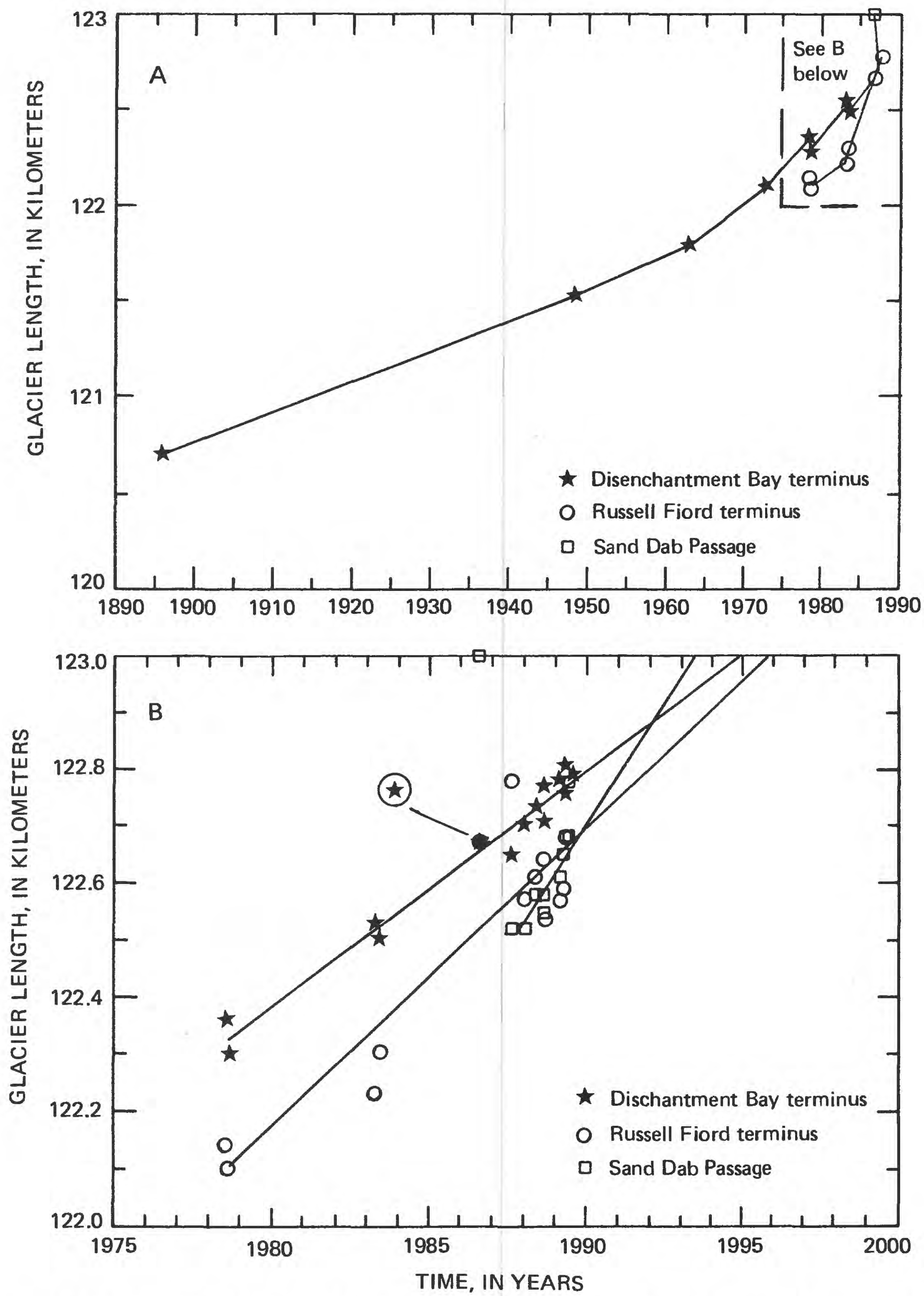

Figure 12.--Advance of Hubbard Glacier into Disenchantment Bay, Russell Fiord, and Sand Dab Passage. A, data points through the closure in 1986. B, least squares fitted linear extension of terminus advances on expanded time scale. [Glacier-length changes for Disenchantment Bay and Russell Fiord are width averages. Glacier length at Sand Dab Passage is width of narrowest part of passage subtracted from 123 km, which is defined as the point of closure. Closure is expected when the glacier length reaches 123 km. Linear extrapolation for Sand Dab Passage excludes the data points representing the 1986 closure and glacier-pulse-induced advance in June 1989.]

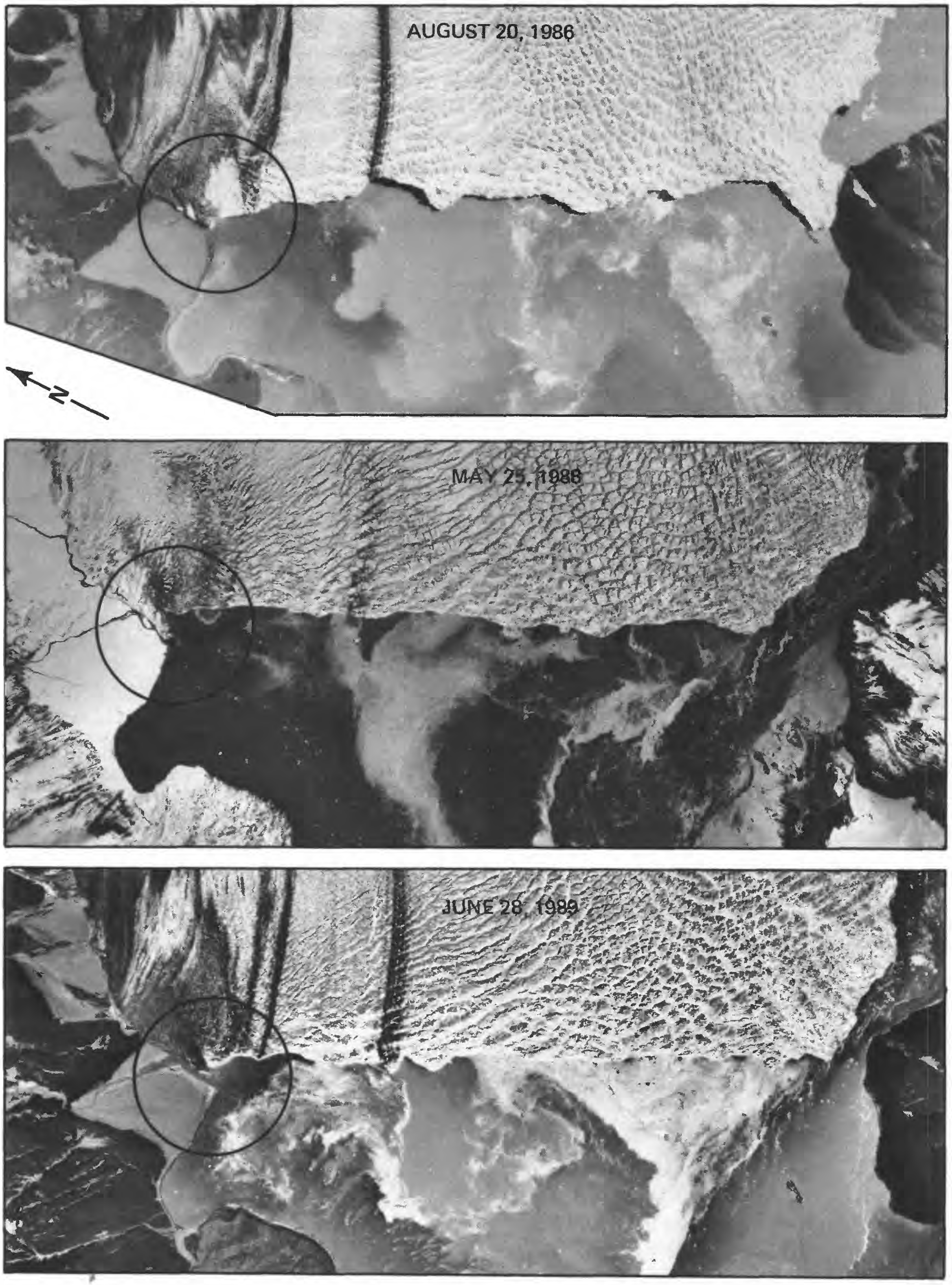

Figure 13.--Vertical aerial photographs of Hubbard Glacier: August 20, 1986; May 25, 1988; and June 28, 1989. [August 1986 photo shows ice dam in place and advanced position of terminus along north shore (circled). May 1988 photo shows an abandoned "tusk" of ice on north shore (circled) left by slight recession of terminus following spring 1986 pulse of Hubbard Glacier and a 350-m opening at Sand Dab Passage. June 1989 photo shows that the spring 1989 glacier pulse recovered the 1986 advanced position and did not block Russell Fiord, but closed Sand Dab Passage to 220 m.] (August photo by U.S.D.A. Forest Service.)

speeds 10 to 100 times as fast as during its quiescent phase (Kamb and others, 1985). Haenke Glacier (fig. 1b) advanced 2 to 3 km in less than a year beginning in late 1986. Malaspina Glacier (fig. 1a) experienced a surge on its east side in 1986, during which ice advanced about 5 km into Malaspina Lake. The "Seattle Glacier" [2] (fig. 1), a small tributary on the east side of the lower part of Hubbard Glacier, surged in 1971. Mayo (1988a) reported that the Valerie Glacier tributary of the Hubbard had a speed of 36 m/d measured over a 21.6-hour period in June 1986.

Brief, rapid accelerations in glacier flow intermediate between surges and normal flow have been termed "pulses" (Mayo, 1978). Pulses in glaciers that end on land are more easily recognized than those in calving glaciers. No full-scale surge activity of the main Hubbard Glacier has been observed yet, but apparently brief accelerations, which are referred to as "pulses" in this paper, do occur.

On Hubbard Glacier, several observations suggest that a pulse occurred prior to the 1986 closure. However, because no ice-speed measurements are available, there is no direct evidence that Hubbard Glacier moved faster than the high of 8 m/d measured on its lower part, and the 12.5 m/d measured near the equilibrium line between July 30 and August 23, 1978 (Krimmel and Sikonia, 1986). Increased crevassing and a relatively high surface speed measured on Valerie Glacier (Mayo, 1989) may have been associated with a general speed increase of Hubbard Glacier. In August 1986, the authors observed fresh marginal shearing and lowering of the adjacent Hubbard Glacier surface in the lower ice-fall region just above the confluence with the Valerie Glacier. At nearly the same time, there was about 150 m of advance along the north shore that culminated between June and August 1986 (fig. 13). In addition, an abnormally large amount of glacier ice in Disenchantment Bay in June 1986 indicated that the calving rate had increased. Because the terminus did not retreat in concert with increased calving, the large amount of floating ice suggests that the calving rate increased in response to increased glacier speed. All these observations indicate that a fairly strong pulse occurred in the lower Hubbard Glacier during the spring of 1986.

Seasonal Terminus Changes

Seasonal variation of the ice front complicates determination of the general pattern of change for short periods of measurement. Seasonal changes observed on Columbia Glacier have included minor advances during late winter or early spring and terminal retreats during fall (Krimmel and Vaughn, 1987). Changes in the terminus position of Hubbard Glacier are recorded by field surveys, time-lapse photography (fig. 14a,b), and vertical aerial photography (fig. 13). The field survey method determines the position and height of the calving face by measuring an azimuth and vertical angle to the intersection of the ice face with the sea surface and top of the ice face, at 30 to 50 points.

Time-lapse photographs are also used to map the terminus of Hubbard Glacier. These photographs are obtained every 2 days from 2 locations (fig. 1b). As many as three cameras have been operated intermittently since November 1987. The photographs show the terminus in its seasonally advanced position in July 1988 (fig. 14a). The seasonal advance results in a somewhat rounded upper surface profile near the calving face and a slightly reduced height of the terminus ice cliff. This observation indicates that the ice moves beyond the shallowest part of the moraine shoal into deeper water on the fiord side of the moraine crest (fig. 2b). Seasonal retreat culminates in September, leaving the calving face at its maximum height (fig. 14b); this suggests that the fall calving face is near or possibly slightly behind the top of the shoal. The photo series from the Haenke

[2] Unofficial geographic name.

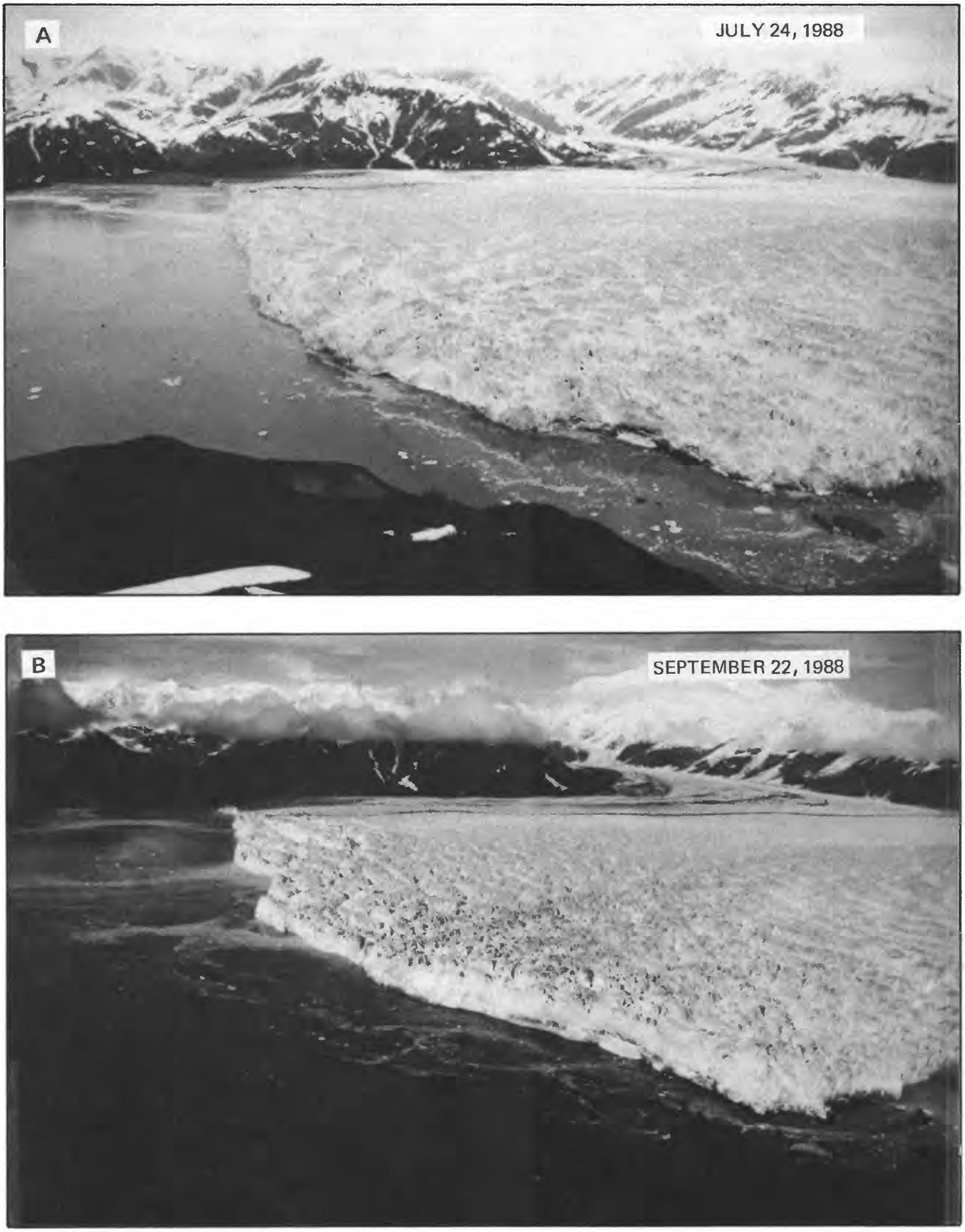

Figure 14.--Hubbard Glacier terminus from the time-lapse camera station on Gilbert Point (fig. 1b). [A, terminus in its seasonally advanced position with a lower terminus ice cliff and more rounded surface profile just above the calving face. B, terminus in its seasonally retreated position with a taller calving face and less rounded surface profile near the terminus.]

camera (fig. 1b) shows a slow advance of the Disenchantment Bay terminus from November 1987 to July 1988 and a retreat from July to September 1988. The Gilbert Point camera (fig. 1b) shows continuous retreat of the ice cliff from July through September 1988, with the highest rate of retreat occurring after September 9.

The photographs from the time-lapse cameras also show the development of embayments and ice projections along the calving face of Hubbard Glacier. Embayments are short-lived (1 to 3 months), localized recessions of the calving face to positions behind the crest of the moraine shoal. They are most common during the summer and fall and seldom exceed a few hundred meters in width or depth. Embayments were mapped near the center of the Disenchantment Bay terminus in 1962 and 1972 (fig. 3). Ice projections--the opposite of embayments--are short-lived, localized (fig. 3). Ice projections--the opposite of embayments--are short-lived, localized advances that seldom exceed a few hundred meters in width or extension. They are most common in the winter and spring and are presumably advances of ice beyond the general crest of the moraine.

Because the short-term spatial variability of terminus changes (fig. 11) masks the longer term pattern of advance and retreat, an "average terminus position" is determined for each terminus photograph or survey. The width average is found by dividing the area of a polygon (whose variable side is the glacier terminus) by the width (fig. 15). This is done separately for the Disenchantment Bay and Russell Fiord terminus sectors. The series of averaged terminus positions (fig. 12) clearly show a continuing general advance into Disenchantment Bay. The small, late summer recession is evident only where the data are closely spaced in time. The averaged advance rate was 120 m/yr for the period August 1987 to March 1989; this is considerably higher than the 29 m/yr rate calculated for the 1983 to 1988 period. The higher advance rate calculated for this relatively short period is a result of the pulse noted above, and demonstrates the variability of seasonal and annual advance speeds on Hubbard Glacier. The terminus in Russell Fiord receded during the same period, at an average rate of 145 m/yr.

Bathymetry

Recent helicopter-borne bathymetry has recorded the position of the terminal moraine in Disenchantment Bay and changes in "Sand Dab Passage"[3] (fig. 1b). Positions for the bathymetric sounding are determined either by a dual ranging microwave system or by optical surveying. Recent soundings near the terminus of Hubbard Glacier (fig. 7) show that the terminal moraine has advanced into positions where several hundred meters of water were sounded in 1978 (National Oceanic and Atmospheric Administration, 1978). The annual advance of the terminal moraine has been too small to be detected by repetitive bathymetric sounding. In the 1960's, a tide flat and spit made a low tide connection between Osier Island and the mainland (A. Post photograph No. F7-61-126 available from the Ice and Climate Project Office of the U.S. Geological Survey, Tacoma, Washington). The connecting spit was breached by 1971 (A. Post photograph No. 7711-88) as the tidal activity became concentrated in that area by the advance of Hubbard Glacier. During the 1986 closure, some of the unconsolidated marine and glacial sediments at the terminus were pushed above sea level by the advancing ice, forming the leading edge of the dam that blocked Russell Fiord. The ice-pushed sediments also formed a series of islands on the Disenchantment Bay side of the ice dam (figs. 13 and 16). Much, if not all, of this moraine was removed by the October 1986 outburst.

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[3] Unofficial geographic name.

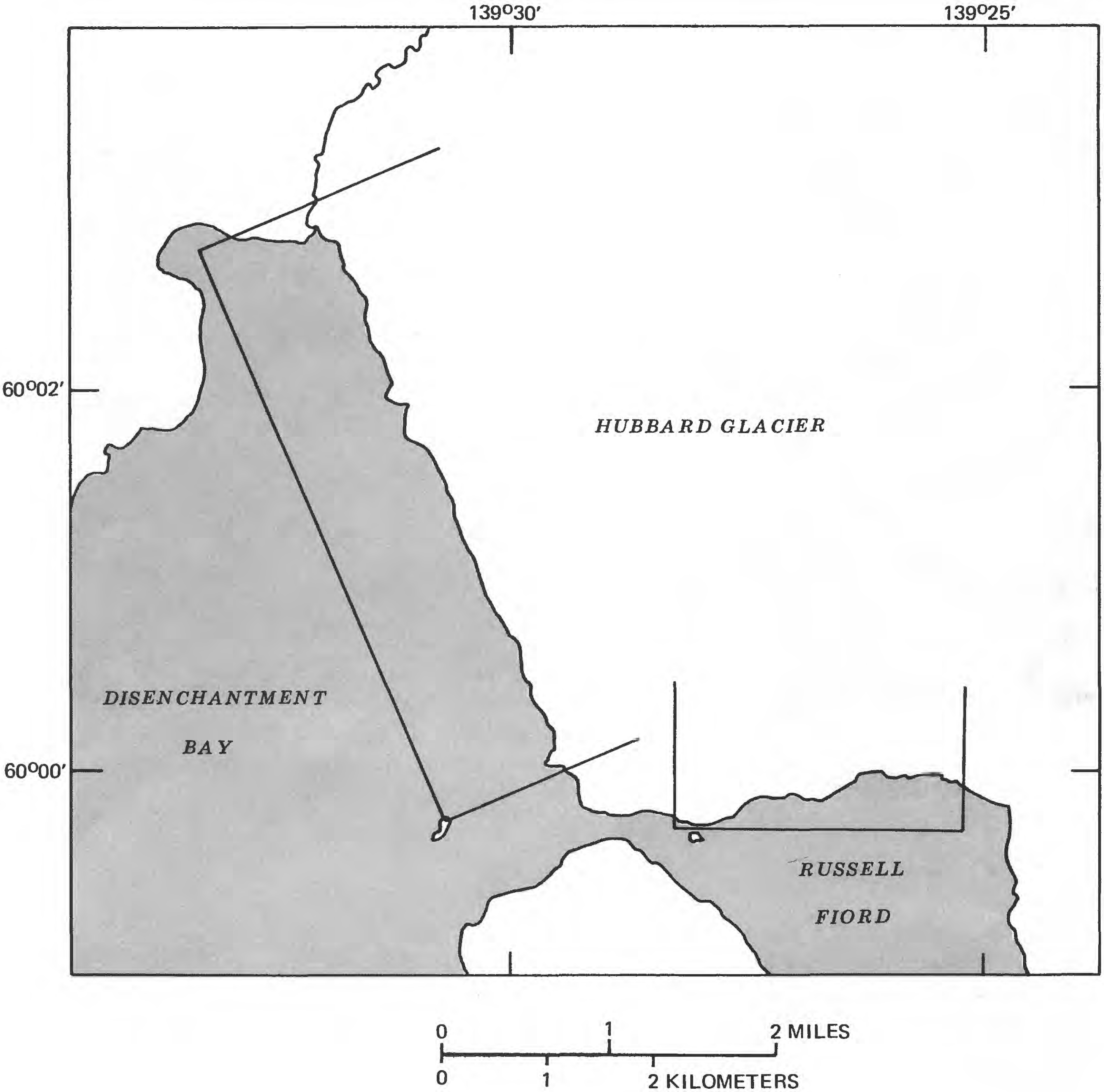

Figure 15.--The width-averaging polygons used for the Disenchantment Bay and Russell Fiord termini. [Polygons are bounded by three fixed sides and part of the glacier terminus. The longest side is perpendicular to the 1980's centerline flow direction at 123-km glacier length for each terminus. Width average is found by dividing polygon area by fixed width and subtracting quotient from 123 km.]

Figure 16.--Dam showing moraine seal and moraine islands in Disenchantment Bay (left center), August 24, 1986.

Tidal Observations

The Marble Point water-level gage (fig. 1a), installed on October 5, 1986 (Seitz and others, 1986), began recording the level of Russell Lake 2 days before the dam failed and the lake drained. Since that time, the gage's satellite telemetry has reported the upper part of the tide cycle in Russell Fiord. Because the gage data are being reported through a real-time data network, it is possible to monitor changes in the tidal communication between Disenchantment Bay and Russell Fiord by comparing the tidal signal from within Russell Fiord to the tidal signal reported by the tidal benchmark at Yakutat (fig. 17). It is anticipated that the tide range in Russell Fiord will decrease, the general level will rise, and the time lag will increase as the opening at Sand Dab Passage, which connects the fiord to Disenchantment Bay, is restricted. The tide data are a continuous, real-time monitor -- not hindered by darkness and unfavorable weather -- of the critical conditions at Hubbard Glacier.

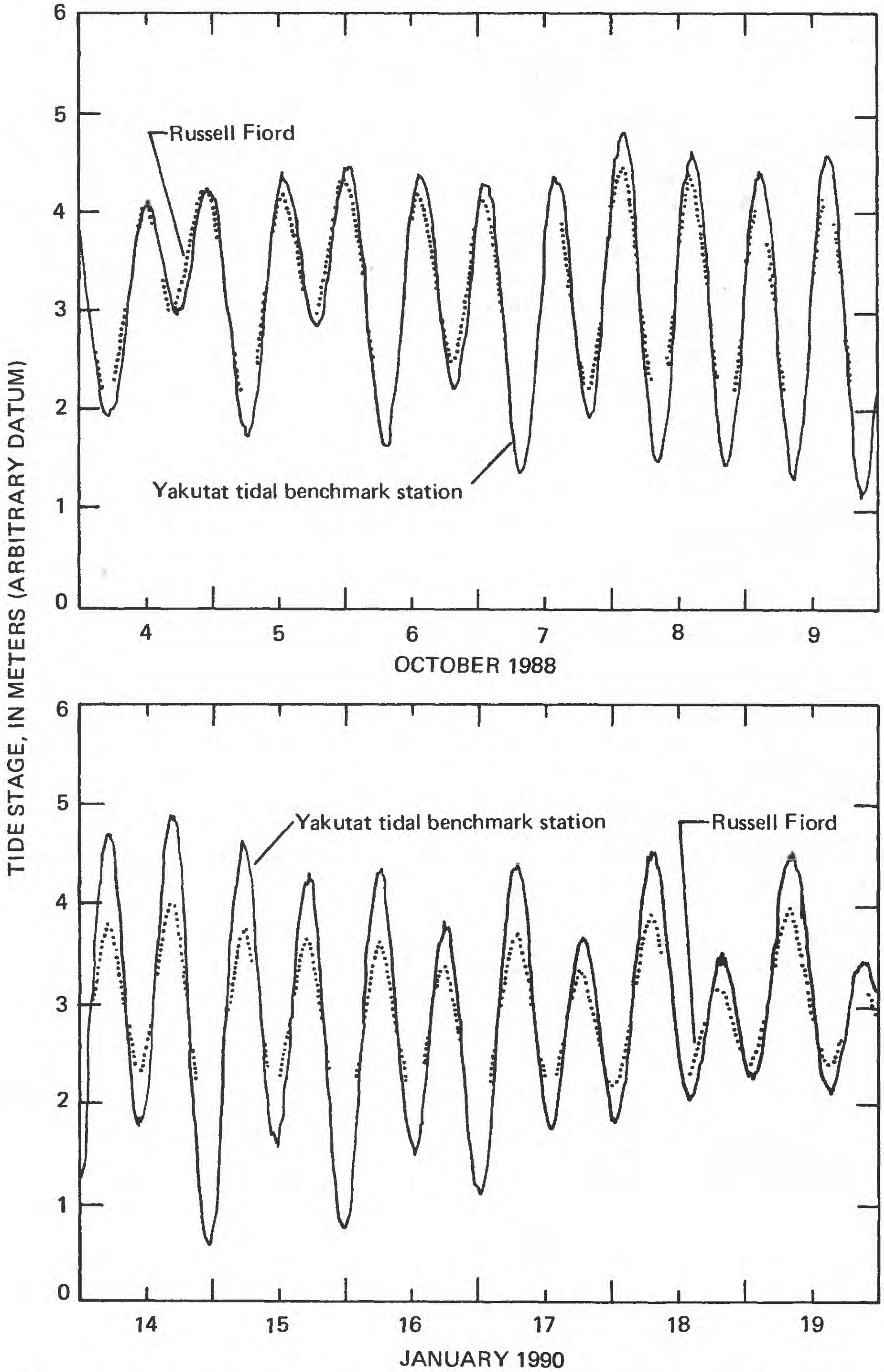

Figure 17.--Tidal data from the Yakutat tidal benchmark station (solid line) and Russell Fiord (dotted line) for October 1988 and January 1990. [Gradual constriction of Sand Dab Passage is indicated by reduced tidal amplitude in Russell Fiord compared with tides at Yakutat.]

THE 1986 DAM AND 1989 PULSE

Oblique aerial photographs taken by Yakutat residents in April and May 1986 show Hubbard Glacier advancing rapidly along a relatively narrow part of its terminus toward Gilbert Point (fig. 1b). One photo by C. Rayson (U.S. Forest Service, Yakutat) shows a bar above sea level in front of the most rapidly advancing ice front. The bar protected about 600 m of the calving glacier face from direct contact with the sea, effectively stopping calving along that reach (Mayo, 1989). The protected ice face advanced at nearly the rate of glacier flow. Between August 1985 and late May 1986 (the time of closure) this part of the Hubbard Glacier terminus advanced about 800 m at an average rate of about 2.7 m/d (Mayo, 1988b).

The advancing ice and push moraine closed the entrance to Russell Fiord near the end of May 1986 (fig. 18). The level of Russell Fiord began to rise immediately because of fresh-water inflow from Hubbard Glacier itself and glaciers and non-glacier areas surrounding the fiord. The average rate of rise was 0.18 m/d, with a maximum rate of about 0.30 m/d during a rainy period in late July and early August (Seitz and others, 1986). A series of measurements of the position of the dam (fig. 18) shows that after the initial closure, an increase in the width of the dam and a continued advance of the terminus toward Gilbert Point took place. The dam width increased from about 450 m on June 12, to about 600 m on August 7. At the same time, the calving front northwest of the dam on Disenchantment Bay receded (fig. 18). After early August, the dam lost width principally by calving from the Disenchantment Bay face. The September ice-front survey shows an embayment forming on the Disenchantment Bay side of the dam near Gilbert Point. The last measurements prior to the outburst were the incomplete October 5 outline and an ice-dam width measurement of 165 m on the same date (fig. 18). At this time, the narrow dam supported a lake level about 25 m above sea level (Seitz and others, 1986). During the last days of September and first week of October 1986 preceding the outburst, a subglacial discharge of sediment-laden water from under the dam was reported by Seitz and others (1986). They also reported that the dam failed catastrophically between 2300 and 2400 hours on October 7. The 1986 closure did not cause overflow into the Situk River drainage, which would have required the lake level to reach about 40 m above sea level.

The outburst flood swept away the ice and moraine dam and most of the loose sediments that had nearly connected Osier Island with the mainland; a 480-m wide gap opened between the calving ice front and Gilbert Point (fig. 12). The width-averaged Disenchantment Bay terminus receded after the outburst; the Russell Fiord terminus continued its strong advance during the year following the outburst before receding 210 m between August 1987 and January 1988. After the outburst, the rate of advance of the Disenchantment Bay terminus was reduced for about 2 years, but the overall rate has since recovered (fig. 12). Approximately 1 year after the outburst, the Sand Dab Passage opening started to slowly close again with superimposed seasonal changes that parallel the width-averaged Disenchantment Bay and Russell Fiord parts of the terminus (fig. 12).

During the spring of 1989, a pulse in Hubbard Glacier was observed in both aerial photographic and satellite telemetry data (fig. 10). Between April 7 and June 28, the glacier advanced, closing the distance to Gilbert Point from 350 m to 220 m (figs. 11 and 12). The closure rate was 2.6 m/d (similar to the average 1986 closure rate of 2.7 m/d). The increased tidal restriction produced no statistically significant change in the tidal signal reported from Russell Fiord. During this time, Hubbard ice advancing along the north shore of Disenchantment Bay reactivated the ice left by the 1986 event (figs. 11 and 13). The cover photograph shows Hubbard Glacier on June 28, 1989, at its closest approach to closure since 1986.

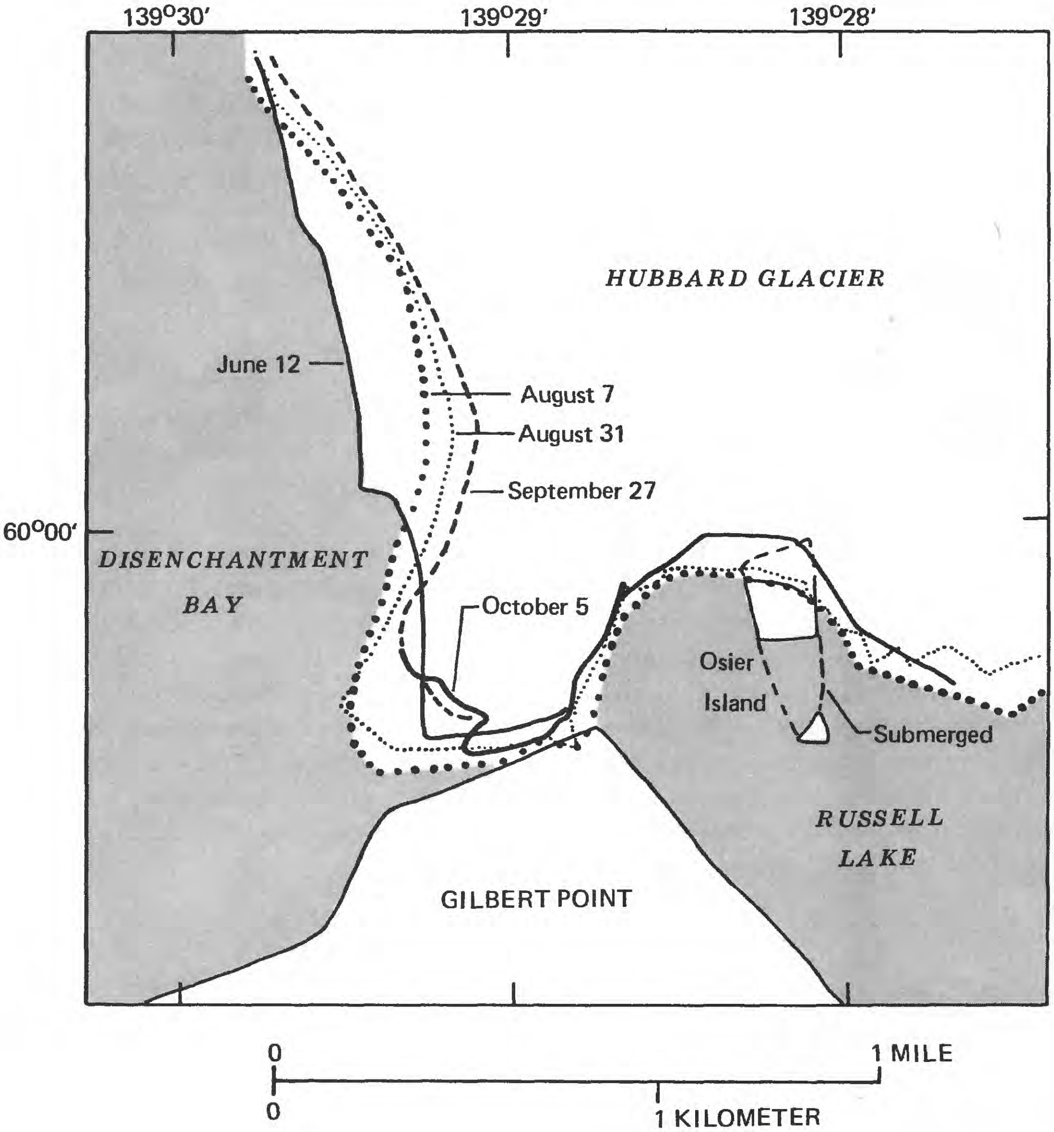

Figure 18.--Changes of the 1986 dam.

The glacier-speed and terminus-advance event of spring 1989 is judged to be similar in magnitude to the 1986 event that resulted in the damming of Russell Fiord. However, the 1989 event did not result in a closure because the loose materials that had formed the protective moraine that reduced calving in 1986 had been washed away by the outburst flood.

THE FUTURE

Hubbard Glacier is expected to continue its slow advance into Disenchantment Bay and Russell Fiord. At the present rate of advance, the terminus at Sand Dab Passage will reach Gilbert Point in about 1993 (fig. 12); however, unpredictable events make such a simple forecast unreliable. Unknown factors such as the recurrence interval of pulses, the formation of above-water terminal moraines, terminal embayments, terminal projections, and the effect of tidal currents on the rate of calving are critical to the timing of the next closure and the durability of the next dam.

It is unlikely that the combination of processes that resulted in the formation of the 1986 closure will be repeated, because the sediment that formed the protective bar that stopped calving is no longer in place. Most of it was removed during the outburst of Russell Lake. As a result, the March to June 1989 pulse in Hubbard Glacier, which was similar in strength to the 1986 event, reduced the width of Sand Dab Passage by only about one-third and did not culminate in a closure.

In the dam-forming area near Gilbert Point, the glacier's width-averaged advance rate will be influenced by two opposing processes. The localized rate of advance is expected to increase because of the relatively shallow water (30 m) in Sand Dab Passage. However, as the width of the connection between Russell Fiord and Disenchantment Bay decreases, the erosive power of the tidal currents will increase, resulting in increased calving as the ice face is exposed to more rapidly moving water. For an average tide change of 2.7 m in Russell Fiord every 6 hours, the average discharge is about 24,000 m^3/s; however, because the water stops and changes direction every 6 hours, the peak discharge each half cycle is even larger. The relative influence of both water depth and flow speed will change with time; tidal current velocities will first increase, then decrease as the closure progresses and the lake level begins to rise.

A Forecast

On the basis of the observations and data presented above, the next closure of Russell Fiord by Hubbard Glacier is estimated to have a:

Very probable chance of closure within 10 years,
Better than 50-50 chance of closure within 5 years,
50-50 chance of closure within 3 years, and
Less than 50-50 chance of closure within 1.5 years.

A closure is considered to be an event of sufficient duration to produce overflow into the Situk River.

The stability as well as the potential for failure of the dam is complexly related to the nature of the ice advance that results in dam formation, the time of year a dam forms, the number of years before a dam forms, the physical dimensions of the dam, and the rate of water rise in Russell Fiord. If the closure is due to a progressive advance, as opposed to a pulse, the closure is more likely to result in long-term overflow into the Situk drainage. A closure is most likely to occur during April, May, and June, when the seasonal terminus advances are most rapid. However, a spring closure will be subjected to the most rapid water-level rise as both melt and rain runoff fill Russell Fiord, a rapid rise of the lake could outpace the thickening and widening of the dam due to ice flow, and thus increase the likelihood of dam failure. In addition, the more time that passes before the next closure, the more likely the closure will last long enough to produce an overflow into the Situk River drainage. As time passes, the general advance of the entire Hubbard Glacier terminus will result in a stronger dam because there will be a greater thickness of ice in the dam that is emplaced. Considering the complex interaction of dam formation and failure processes, it is likely that overflow into the Situk drainage may be episodic at first, as dams form and fail. However, once a stable dam is in place, it is likely to be sustained for many hundreds of years as Hubbard Glacier slowly advances down Disenchantment and Yakutat Bays during the advance phase of the tidal glacier cycle.

There is a small chance that a closure will not occur in the next 10 years, and an even smaller chance that a closure may be forestalled for decades. For instance, it is possible that the advance into Disenchantment Bay will partly bypass Gilbert Point, and a tidal channel will be maintained, or reform periodically, until the thickness of ice and rate of flow overwhelm calving losses in the channel. Less likely, the closure could be forestalled by a calving retreat of Hubbard Glacier. This retreat could be brought on by an instability in the Russell Lake ice front triggered by a rising lake level or outburst flood from Russell Lake that would form an embayment in Hubbard Glacier large enough to initiate drastic retreat.

This prediction may be modified and updated as new information becomes available. Most likely, data derived from ongoing observations of new events will make more reliable predictions possible.

A numerical simulation of the glacier system was considered at the outset of the investigation. It was concluded, however, that using numerical simulation for the purpose of predicting dam formation by Hubbard Glacier would probably be unsuccessful for several reasons. At this time, there are no adequate simulations of some fundamental processes such as: basal sliding, submarine moraine advance, ice deformation in the vicinity of a submarine moraine, calving, seasonal ice speed changes, pulses, and the effect of strong tidal currents at a calving face. Without available process simulations to incorporate in a model, considerable time and effort would be needed for basic research in these areas. Furthermore, it was realized that combining these elements into a predictive model that would be required to simulate response of the small part of the terminus in the dam-forming area would probably be unsuccessful. The conclusion was that although progress in this area would be of significant scientific value, the work was not likely to produce a useful predictive tool for Hubbard Glacier.

Overflow Timing

The filling rate during the 1986 closure indicates that Russell Lake would fill and overflow in a minimum of 7 and maximum of 14 months, and produce an average overflow of 560 m^3/s, with peak flows of approximately 1,400 m^3/s (Paul, 1988). The earlier in the spring a closure forms, the more likely the overflow will occur in the minimum amount of time (7 months).

RESEARCH BEYOND 1990

Continued measurements on Hubbard Glacier are necessary to predict fiord closure as accurately and early as possible. Early detection of a closure is critical to assess closure stability and predict overflow into the Situk River drainage. The stability of an ice dam is directly related to the following factors: whether the closure is caused by a glacier pulse or progressive closure, the physical dimensions of the dam, the seasonal time of emplacement, and the rate of rise and total depth of water it impounds.

Continuing data-collection activities on Hubbard Glacier that would allow refinement of closure predictions include:

1. Vertical aerial photography to document, in detail, the changes in the Hubbard Glacier. When obtained several times a year, it provides data on the glacier's advance and changes in ice speed, ice thickness, and calving speed. It can also be used to distinguish seasonal advances and retreats from the long-term changes.

2. Land-based time-lapse photography to record the rapid formation of embayments, ice projections, ice thickness, and terminal position changes, and to define the seasonal amplitude of terminus position changes.

3. Optical surveys of terminus positions during field visits to instrumentation sites. These quantitative additions to the glacier terminus position data set include a measurement of the height of the calving face.

4. Annual bathymetric monitoring near the Hubbard Glacier terminus to record changes in water depth.

5. Operation of two real-time measurement systems to relay the water levels in Russell Fiord and the glacier ice-flow speeds in Hubbard Glacier. These systems, described below, can detect significant changes even when local weather or lighting conditions thwart field access:

   a) Data from the Marble Point water-level gage (fig. 1a) constitute a real-time closure detection system and will verify the rate of Russell Lake rise following a closure. The nature of the events following closure will be critical to evaluating the possibility of dam failure and to predicting the time of overflow into the Situk River.

   b) A single satellite motion telemetry system on the main Hubbard Glacier ice stream (operating in low resolution mode to reduce costs) will refine the understanding of seasonal speed changes and detect large changes in ice speed, such as that in the spring of 1989. Early detection of changes in ice speed will alert observers to critical changes in the glacier system, and the association of an unusual ice speed event with the formation of an ice dam may be critical to assessing its stability.

SUMMARY

1. Hubbard Glacier has been undergoing a steady advance since the late 19th century.

2. At the present rate of progressive advance, Hubbard Glacier will close Russell Fiord before the end of this decade.

3. The present advance is not sensitive to climatic variations.

4. A seasonal cycle of ice speed, calving rate, and terminus position occurs.

5. Pulses in Hubbard Glacier can last for months and are not currently predictable.

6. Embayments in the terminal ice cliff form and disappear in a period of days or weeks. As yet, none have been observed to be large enough to jeopardize the glacier's stability.

7. The 1986 dam was formed by the combination of a pulse in Hubbard Glacier and the formation of an above-water moraine along part of the terminus, which stopped calving in that sector. Ice flow speeds in 1989 were similar to those in 1986, but no protective moraine formed and continued calving prevented a new dam from forming.

8. A relatively narrow dam (about 300 m) is sufficient to restrain a 40-m head of water, which will cause overflow into the Situk River drainage.

9. Several dams at Gilbert Point that cause overflow into the Situk River and subsequently fail may be expected before a stable dam is emplaced.

The anticipated result of the current understanding of conditions at Hubbard Glacier and Russell Fiord is that possibly the largest drainage change of this century could occur during the 1990's, when Hubbard Glacier blocks Russell Fiord. Should the blockage occur, the former fiord will be filled by fresh-water inflow until it overflows into the Situk River. After a series of dams and failures, the glacier blockage of Russell Fiord is expected to be stable for hundreds of years and increase the average flow of the Situk River by at least 10 times.

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