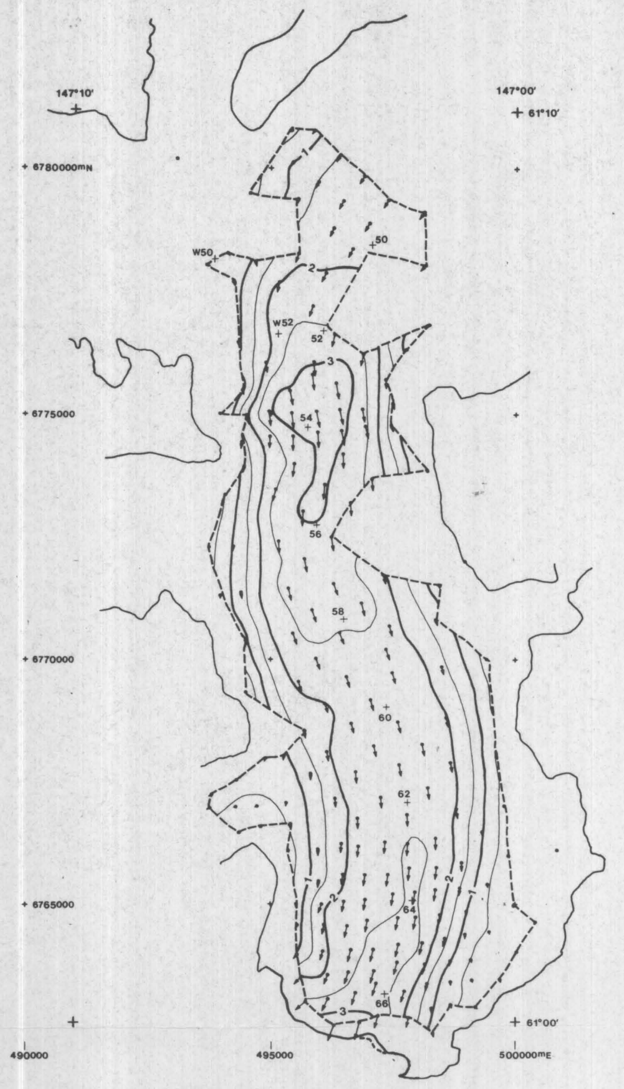
OPEN FILE REPORT 79-1265
SHEET 2 OF 3

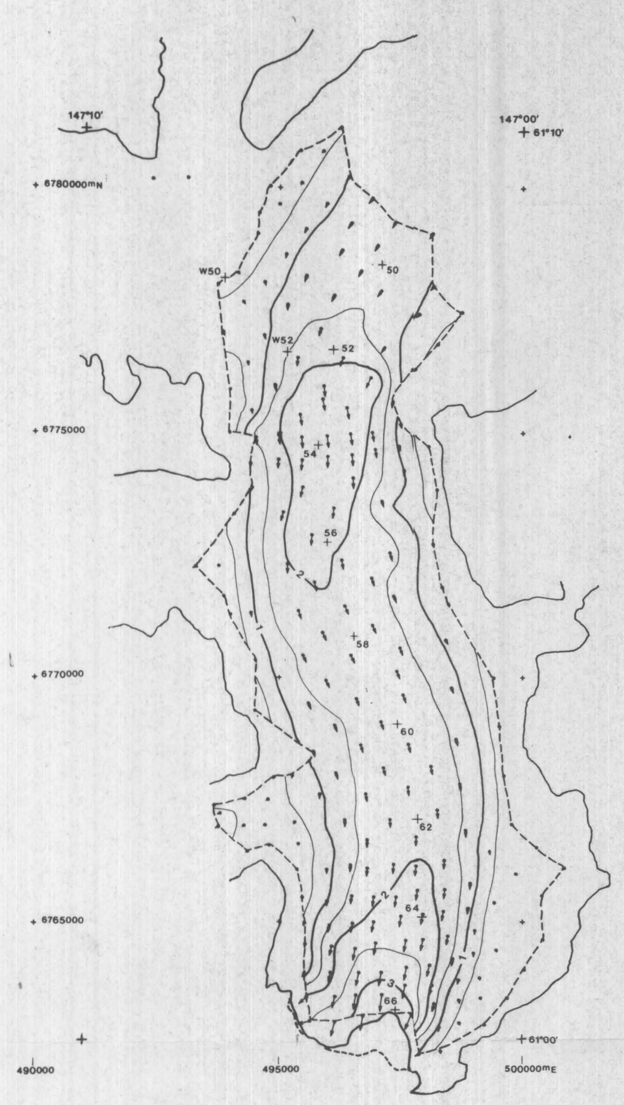
FIGURES 1 THROUGH 7
CONTOUR INTERVAL 0.5 METERS PER DAY

VELOCITY VECTOR SCALE
0 5 10 METERS PER DAY

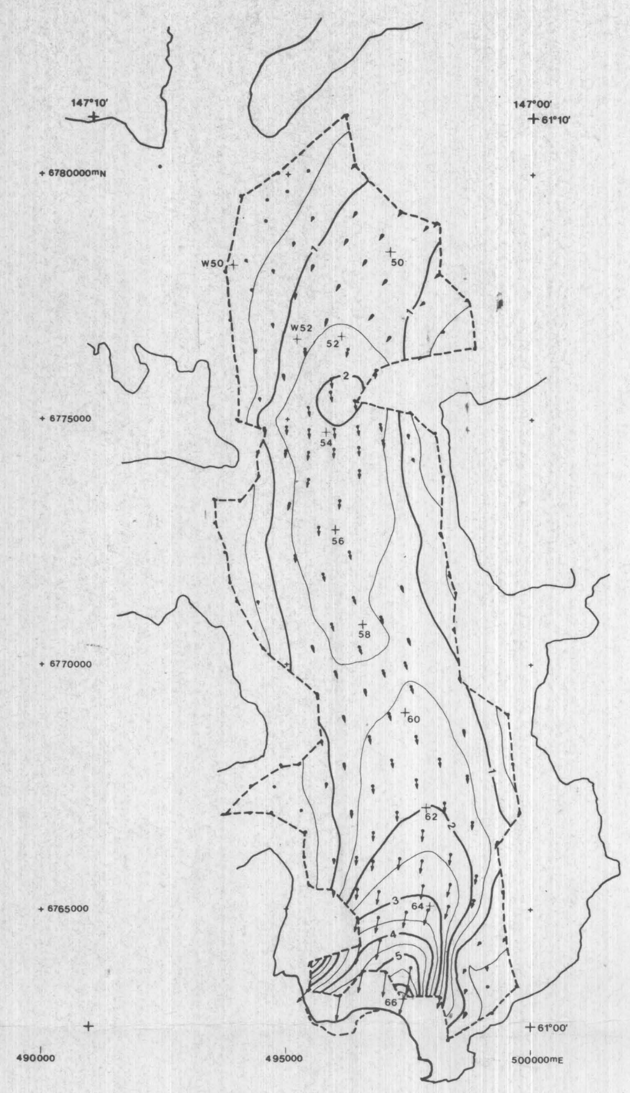
DISTANCE SCALE
1 0 1 2 3 4 5 KILOMETERS



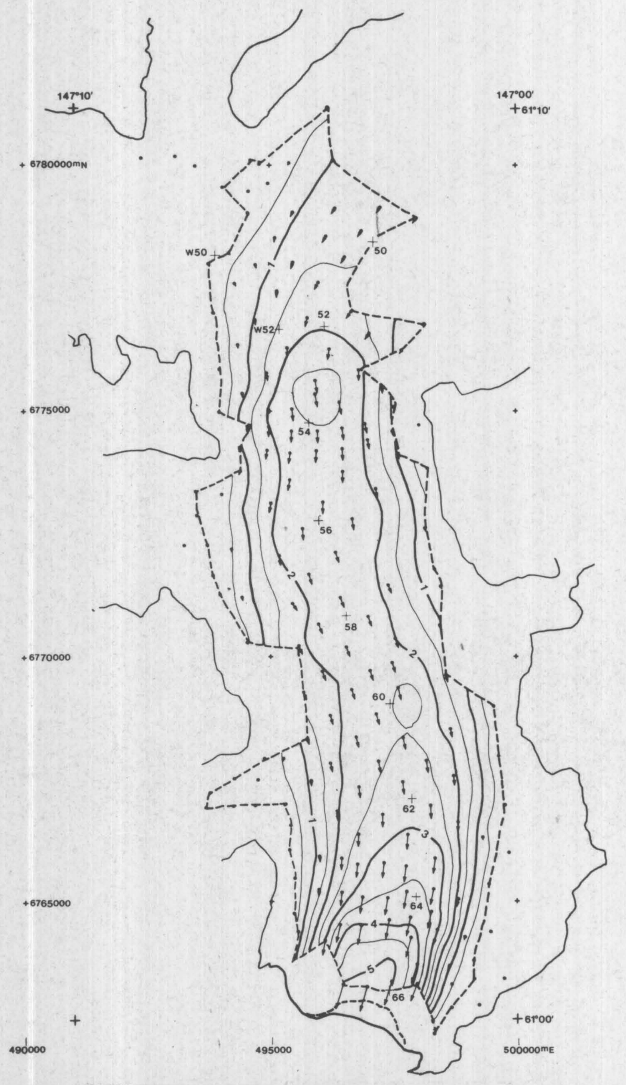
JUNE 2, 1977 TO JULY 7, 1977
Figure 1



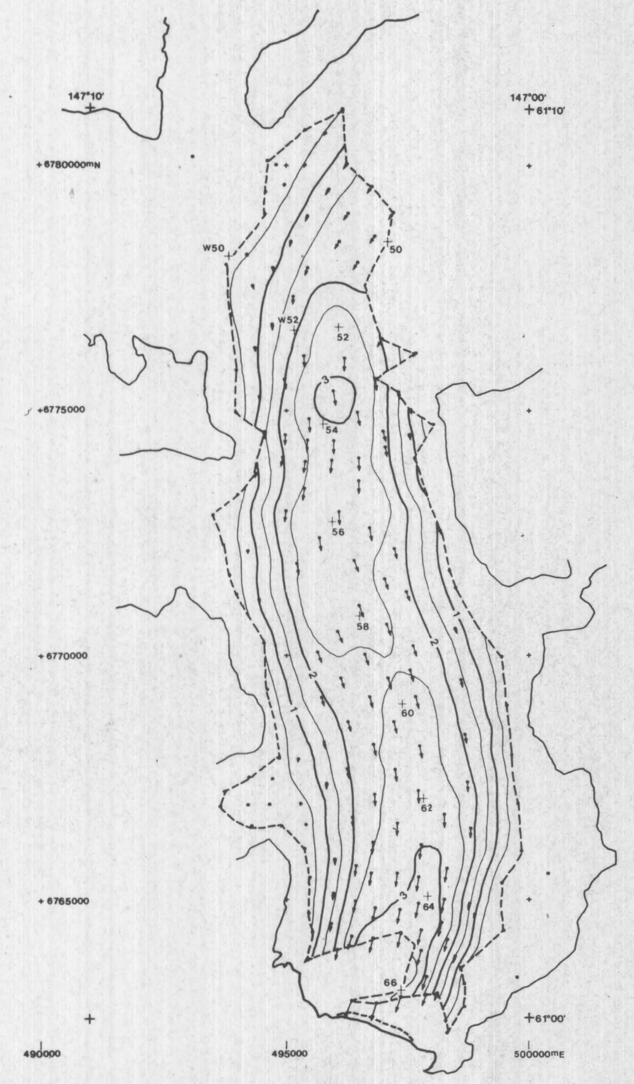
JULY 7, 1977 TO AUGUST 29, 1977
Figure 2



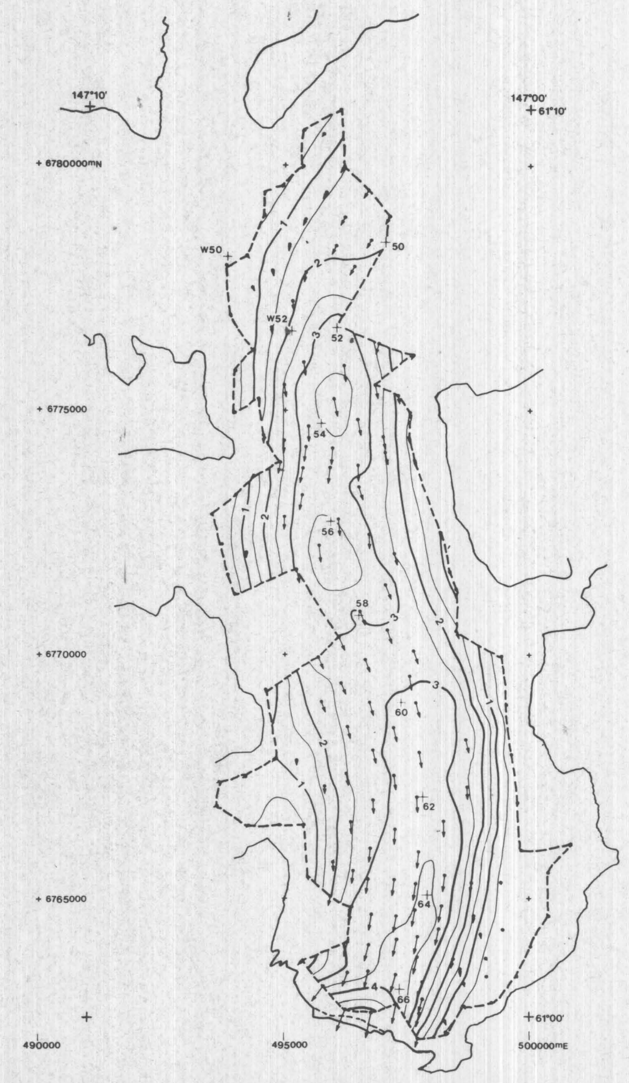
AUGUST 29, 1977 TO NOVEMBER 8, 1977
Figure 3



NOVEMBER 8, 1977 TO FEBRUARY 28, 1978
Figure 4



FEBRUARY 28, 1978 TO APRIL 19, 1978
Figure 5



APRIL 19, 1978 TO JUNE 11, 1978
Figure 6

JUNE 11, 1978 TO JULY 30, 1978
Figure 7

SURFACE VELOCITY AND CALVING 1976 TO 1978

Figures 1 through 7. Surface-velocity vectors and horizontal surface-speed contours for seven periods from June 2, 1977, to July 30, 1978, for the lower section of Columbia Glacier from about 50 km on the central profile to the terminus (sheet 1, figure 1). Data points consisting of identifiable glacier surface features were followed photogrammetrically from one photographic date to the next, thus allowing a determination of average velocity during the time intervals. Each vector has length representing an average day's movement during the time interval multiplied by a factor of 100, and a dot at its tail locates the midway point between the surface feature's location at the two photographic dates of the interval. The vectors have standard error of ±0.06 meters per day, and the associated speed contour map standard error of ±0.1 meter per day. The dashed curve inside the glacier boundary indicates the data area where surface features were followed. (Data points, sometimes only dots or near dots indicating low speed, occur at vertices of this data area boundary and at a few isolated points outside the data area.) The terminus position is indicated by a dashed curve for the earlier photographic date, and a solid curve for the later one (see also sheet 3). Centerline profile, UTM coordinates, and latitude-longitude ticks are shown (see also sheet 1, figure 1). Figure 7 also includes data from 24 to 37 km on the central profile. Note that pronounced velocity changes exist in the lower section of the glacier from season to season; these can be better understood with reference to figure 8.

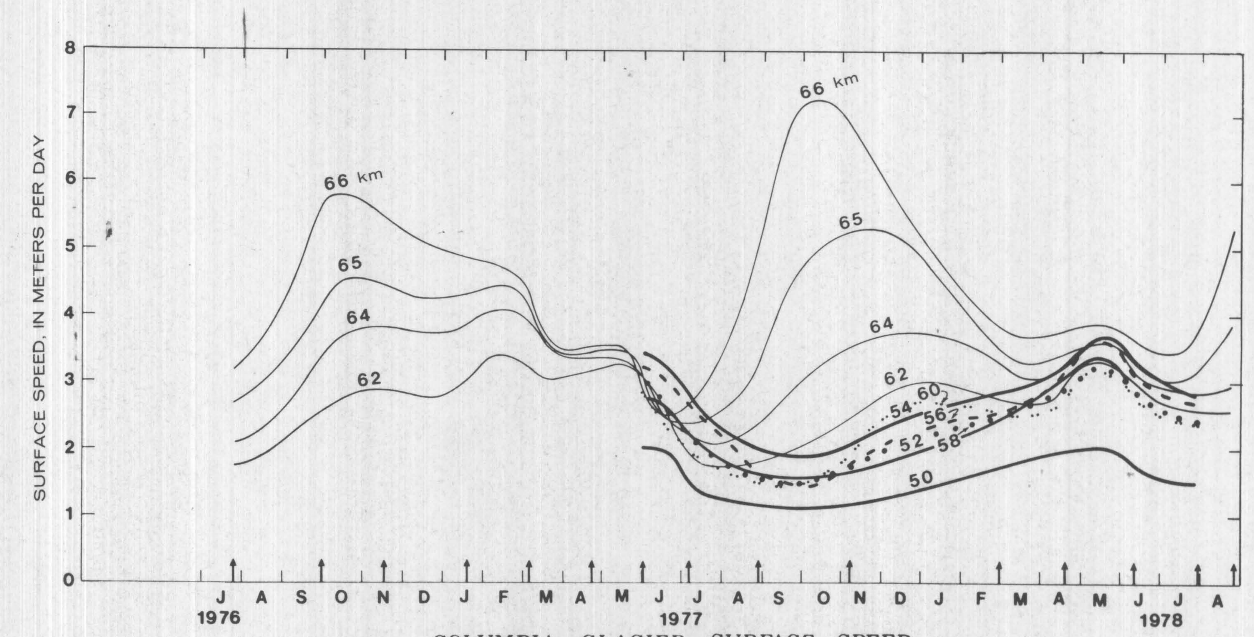
Figure 8. Surface speed curves expressed as functions of time at kilometer locations along the central profile from 50 to 66 km. These curves were constructed from the horizontal speed maps of figures 1 through 7, and seven maps from other photographic intervals. The dates of aerial photography are indicated by the arrows along the time axis. Each pair of photographic dates produces a maximum speed along a line transverse to the glacier flow through a central profile location, which is a time average for that interval with ± 0.1 m standard error. In figure 8 the smooth curves approximately yield the time average speed over each interval and, though nonunique, better picture the actual speed variation than do the averages (see also figure 9).

These speed curves show several features: the most striking effect is a very large seasonal speed increase close to the terminus (about 67 km on the central profile). This speed increase is in response to the formation of an embayment, a semicircular bay formed in the terminus by rapid iceberg calving (sheet 3; also this sheet, figures 1-7). The embayment results in a local increase in surface slope, producing a local speed increase. Notice that the speed increase first appears closest to the embayment, and then progresses upglacier, with the maximum speeds appearing later further from the terminus; note also that these embayment related speed maxima are felt strongly up to kilometer 60, that some effect is seen between kilometer 54 and 60, and that above kilometer 54 the effect is negligible.

In addition to the embayment-related speed variation, there is another seasonal variation which is synchronous from at least kilometer 50 to the terminus and shows a maximum speed in about May, and minimum in about October. From kilometer 54 to the terminus this variation and the embayment related variation are superimposed.

There are also longer term speed variations; surface speeds were measured by tracking surficial debris from about kilometer 62 to 62.6, from 1963 to 1968, and yielded an average 1.9 meters per day (Post, 1975, sheet 3). The same region averaged 2.7 meters per day between July 1977 and July 1978. Thus the glacier has responded to the mass loss of calving and thinning near the terminus by increasing surface gradient and hence flow into the area.

Figure 9. Calving and runoff. Field observations indicate that embayments are related to the position and discharge of subglacial water from the glacier basin. Since most of Columbia Glacier's runoff takes place under the glacier directly into Columbia Bay, measurement of runoff, at least by traditional methods, is impractical. As a workable alternative to using the runoff of Columbia Basin itself, figure 9 shows a smoothed hydrograph (U.S. Geological Survey, 1976, 1977, 1979) from the Knik River (sheet 1, location map), which drains a basin which is 54 percent glacierized in the Chugach Mountains. The gaging station is about 120 km northwest of the Columbia Glacier terminus. The calving speed for figure 9 is defined as the sum of the glacier surface speed plus the speed at which the ice cliff at the head of the embayment is retreating upglacier. Thus a steady terminus position occurs when calving speed equals surface speed, that is, when the head of the embayment is stationary. As in figure 8, a smooth curve is drawn through the measured average calving speeds. Linear regression of average calving speed against average runoff for the 14 measurement time intervals yielded a coefficient of determination r^2 of 0.93. The excellent correlation between the curves strongly reinforces the field observations that calving speed in the embayment is determined by the discharge of fresh water flowing under the glacier.



COLUMBIA GLACIER—SURFACE SPEED
AT KILOMETER LOCATIONS ALONG THE CENTRAL PROFILE
Figure 8

CALVING SPEED AT HEAD OF EMBAYMENT
COMPARED TO
DISCHARGE OF KNIK RIVER NEAR PALMER, ALASKA

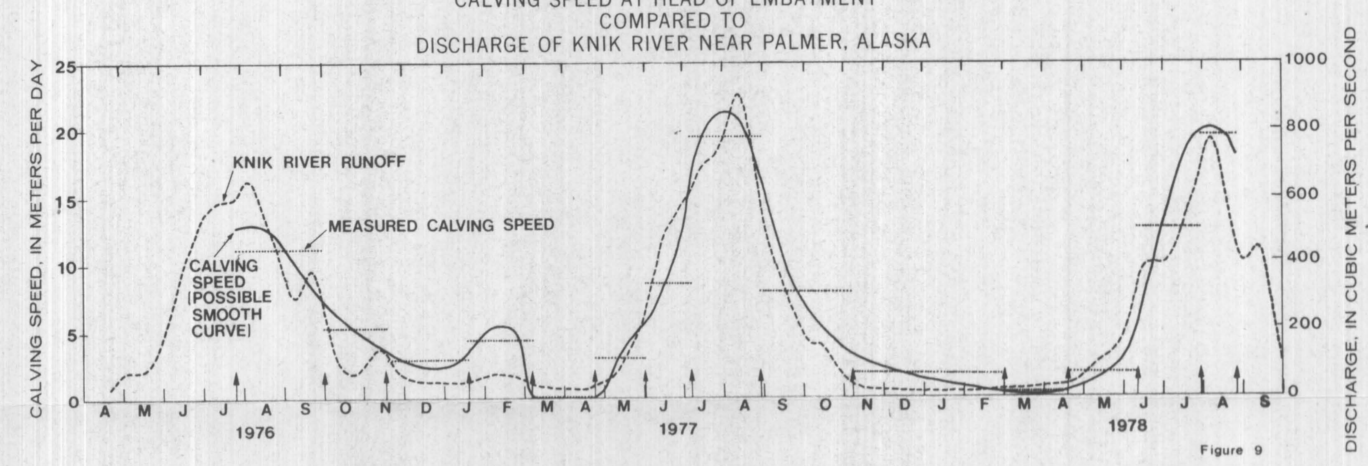


Figure 9

MAPS ON SHEET 3

Figure 1. Composite map showing annual changes July 4, 1971 - Jan. 6, 1979.

Figure 2. Maps showing seasonal terminal changes July 27, 1974 - Jan. 6, 1979.

How embayments are formed

Seasonal embayments have formed in all positions along the 4 km-long terminus discharging into Columbia Bay (Post, 1975, sheet 2). In 1963 the subglacial river discharged over outwash on Heather Island and no embayment was formed; except for this, embayments have occurred every year since 1960. Embayments increase in size both by a moderate, fairly continuous release of small icebergs at a similar calving rate to that at other points along the ice cliff, and by episodes of major calving lasting from a few minutes to an hour or more when the calving rate is orders of magnitude greater. These episodes appear to be related to exceptionally high rates of fresh-water release under the glacier or to points where release abruptly discharges from a different outlet. Between August 14 and 16, 1977, the greatest rate of iceberg calving yet recorded at Columbia Glacier rapidly enlarged a small embayment, resulting in a massive ice pack of brash and icebergs which completely filled the channel north of Glacier Island and extended 20 km or more into Prince William Sound both east and west of the island (sheet 1, figure 1). The calving during this event is believed to have been related to the sudden release of Kadin Lake, located 15 km upvalley (sheet 1, figure 1).

Until the seasonal runoff from ice melt and rainfall in the basin is reduced in early winter (this sheet, figure 9), an embayment increases rapidly in size, typically forming a deep, semicircular bay extending as much as 1 km into the terminal ice cliff (sheet 3; figure 1; figure 2, maps A, D, J, and O-Q).

Seasonal closure of embayments

The high ice cliff in the embayment is unstable, and due to visco-plastic deformation, the ice cliff height decreases, and surface slope, and therefore flow, increase toward the embayment. Since in the winter season the calving rate is drastically reduced (this sheet, figure 9), flow into the embayment predominates, and by late spring the bay is generally reduced to a shallow, broad bight (sheet 3, figure 2, maps D-I and L-N). This in turn may be completely filled before the next summer's episode of embayment formation begins.

Importance of embayments

Eighteen years of annual aerial reconnaissance disclose that embayments in other Alaskan tidal glaciers are quite rare and where found at all are generally small. Early observers did not report embayments in Columbia Glacier; it appears possible that the large embayments formed in recent years are, in part, related to the glacier's thinning and retreat from the crest of its terminal moraine (Post, 1978). Although data on the greatest extent of annual embayments prior to 1974 are lacking, embayments observed in the 1970's were generally larger than those observed previously. Since 1975, annual embayments have all been larger than any previously recorded. The size of embayments formed annually is apparently related to (1) the glacier's thickness and terminal position where the embayment forms, and (2) the location and nature of the seasonal subglacial discharge of water.

The embayment that formed during the summer of 1977 had a volume which represented about 30 percent of the total ice lost by calving; for the period April 1, 1977 to April 1, 1978, the total was about 1.0 cubic kilometers. In addition, there was increased ice flow into the region of the embayment (this sheet, figures 1-8) due to surface lowering from 54 km on the central profile to the terminus. The volume of ice lost in surface lowering during June 2, 1977, to November 8, 1977, excluding ablation (Mayo and others, 1979) accounts for about another 30 percent of the total ice loss by calving for the year's period. Thus a large part of the yearly calving flux is related directly to embayment formation.

As embayments increase in size, the water depth at the bay's head increases rapidly; when the bay extends 1 km into the glacier, the water depth may be 200 m or more (Post, 1978), and the top of the ice cliff may be 100 m or more above the water surface. During the melt season, under these conditions, large icebergs are released by a process of alternate collapse of the ice cliff above water and the rising of massive bergs from the bottom. In this situation calving can far exceed the annual ice and snow accumulation and ice supplied by flow from the upper glacier.

To remain stable near the narrow moraine bar where Columbia Glacier now terminates, the glacier must maintain some minimum thickness. Should the glacier's terminus increase in thickness, continued stability is assured. Should the glacier thin below some as yet unknown critical thickness, it will no longer advance to the shoal during the winter calving minumum, and embayments will continue to increase in size each year until the entire terminus ends in deep water. Very large icebergs would then be released, further depleting the ice reservoir upvalley and drastic retreat would commence.

Increasingly large embayments formed during the summer and fall of 1975, 1976, 1977, and 1978, and by January 1979 the glacier had retreated from Heather Island (sheet 3; figure 1; figure 2, map R), where, in June 1909, barometer readings checked at sea level showed that the height of the tidal ice cliff west of the island was at least 120 m (Grant and Higgins, 1913).

The data presented demonstrates that Columbia Glacier has been losing mass and that this rate of ice loss has been increasing in recent years; if continued, this will lead to drastic retreat. Current mass-balance and ice-flow dynamics studies seek to determine if the glacier can compensate for these mass losses, the greatest yet recorded for the glacier.

COLUMBIA GLACIER, ALASKA. RECENT ICE LOSS AND ITS RELATIONSHIP TO SEASONAL TERMINAL EMBAYMENTS, THINNING, AND GLACIER FLOW

by
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1979