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RETREAT OF COLUMBIA GLACIER, ALASKA - A PRELIMINARY PREDICTION

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Irreversible, drastic retreat of Columbia Glacier is inevitable, probably will begin in less than 20 years, and may already be in its early phase. This will cause an increase in iceberg discharge to about 6 km^3/y (a fourfold increase over the high 1977-78 level), more small icebergs may drift into Valdez Arm, and a 41-km long fiord will eventually be opened. Initial results of the analysis of Columbia Glacier field data, together with data from other calving glaciers, leads to these conclusions. Further analysis, which should be completed during the spring of 1980, will enable these statements to be refined, especially in regard to predicting the time of onset of rapid retreat. The following brief remarks summarize the pertinent observations and their implications. Documentation will follow. For more complete discussions of Columbia Glacier and calving-glacier stability, see Post (1975), Meier and others (1978), Sikonia and Post (1979), and Mayo and others (1979).

I. Current knowledge of Columbia Glacier and calving-glacier stability.

A. <u>The glacier terminus is on the back (upglacier) slope of a shoal.</u>

The terminus of Columbia Glacier has retreated only slightly from its location when first studied in 1899 (fig. 1). Virtually all of the terminus is now on the upglacier side of a terminal-moraine shoal with a submerged uphill slope of about 1 in 3. The configuration of the glacier bed has been determined by hydrographic soundings in embayments, radio-echo sounding through the ice, and calculations based on the equation of continuity. Much of the terminus is in water 50-150 m deep, but 1.5 km upglacier the bed is nearly

300 m below sea level (fig. 2). The glacier is in contact with its bed throughout its length and nowhere is it floating.

B. <u>In general, calving speed increases with increasing water depth at the terminus.</u>

Calving speed can be thought of as the calving flux (ice discharge) divided by the area of the vertical calving face. A study of 12 other calving glaciers indicates that the calving speed increases with water depth. The calving speed at the terminus of Columbia Glacier in 1978 was about 2000 m/y.

C. <u>Pronounced thinning has occurred over the lowest reach.</u>

During the 1977-78 measurement year, the glacier had a positive total balance (excess of accumulation over surface and internal ablation); an equal amount of calving would maintain constant mass. However, the calving flux for that year was far greater than that amount, and thus indicated an overall glacier thinning.

balance flux	0.41 km^3/y
thinning flux	.98 km^3/y
calving flux	1.39 km^3/y

Averaged over the entire area of the glacier, thinning in 1978 was 0.91 m/y. During the 1977-78 measurement year, thinning over the lowest reach ranged from about 4 m/y at km 56 to about 11 m/y at km 65.5 (see fig. 1 for explanation of these km coordinates); downglacier increase of thinning means that the glacier surface slope was also increasing. Over the lowest reach, 56 to 66 km, averaged 0.55 m/y from 1957 to 1974, but 3.20 m/y from 1974 to 1978 (Sikonia and Post, 1979). Thus the rate of thinning has also increased with time.

D. <u>The glacier speed over the lowest reach has increased with time.</u>

Glacier speed shows a pronounced seasonal variation, especially near the terminus (Sikonia and Post, 1979). After eliminating all variations having a period of 1 year, a long period increase remains. Analysis of speed at 62, 63, 64, 65, and 66 km (the present terminus is between 66 and 67 km) for the period July 26, 1976, to April 12, 1979, at 0.1 y-intervals (a total of 17), indicates a speed increase (acceleration) ranging from 66.4 m/y^2 (6 percent) at km 63, to 132 m/y^2 (7 percent) at km 66 (coefficients of determination r^2 = .33, .36, .55, .86, and .91 for km 62 to 66). There is also evidence that the speed in the early 1960's was appreciably lower than at the present time.

E. <u>The glacier has retreated slightly.</u>

The mean position of the terminus in late summer, averaged over a 3-km wide swath centered on the most active ice stream, has changed as follows:

Date	Position (km)	Retreat (km)
July 29, 1957	67.21	
		-.03
July 26, 1974	67.24	
		.13
October 1, 1976	67.13	
		.25
August 29, 1977	66.88	
		0
August 26, 1978	66.88	
		.27
October 20, 1979	66.61	

Large embayments have formed each recent year, usually in the period August to September. Therefore, the retreat from 1957 and 1974 to 1976 is probably somewhat less than given above. These embayments apparently did not form every year prior to 1975. Early investigators (1899 to 1935) made no mention of large embayments nor did their photographs show evidence of them, so these embayments must be considered as further evidence of present-day retreat. The large embayment of 1978 by mid-December had connected with Heather Bay, causing separation of the glacier from Heather Island for the first time since observations began, and greatly increasing the width of the calving ice face.

II. Implications of the present state of the glacier.

A. Further retreat of the terminus will further increase the calving speed.

This statement follows directly from I.A., terminus now on the backslope of the shoal; and from I.B., calving speed increases with water depth (fig. 2).

B. Slope increase due to thinning has caused flow acceleration which in part offsets increased calving.

This follows from I.C., thinning increasing with time and distance down-glacier; from I.B., flow acceleration; and from our present understanding of glacier flow, which is that internal deformation and basal sliding vary with slope raised to the poqer of about 3, and thickness raised to the power of about 4 (internal deformation) or 3 (basal sliding). Although thickness for the reach 56-66 km was reduced by 1.2 percent during the measurement year, slope increased by 3 percent. The increase in slope caused a greater change in speed than the decrease in thickness, and can account for the 6 to 7 percent speed increase.

C. Terminus retreat equals excess of calving speed over glacier speed.

This follows from continuity and the simple algebraic combination of flow vectors at the terminus (Meier and others, 1978).

D. <u>The glacier cannot accelerate indefinitely to keep up with increased calving speed</u>.

To maintain velocity as the thickness decreases, two different mechanisms may contribute: (1) The slope may steepen, and/or (2) The sliding component may increase, due to the reduction of the normal stress.

Presently unknown (because of difficulty measuring certain variables near the terminus and because more flow calculations are necessary) are: (1) How the second mechanism works generally, especially in regard to water pressure which may lower the effective basal normal stress, (2) the present relative roles of the two mechanisms, and (3) how long, as thickness decreases, the flow can continue to increase to match calving.

Numerical modeling, currently in progress, seeks to answer these three critical problems, especially the last. It is, however, apparent that flow acceleration to equal increased calving speed cannot be maintained for very many years. For instance, thinning at 65.5 km is currently proceeding at 10.8 m/y. At this location the glacier surface was only 115 m above sea level in late 1978. Characteristically, ice cliffs for large glaciers in deep water ar 80-100 m high above sea level. If thinning were to continue at the present rate, a typical ice cliff height of 90 m would be reached in 3 years; a 40-m height allowing the glacier to float off the bed would be reached in 7 years. Such a hypothetical thinning scenario is not likely, but is given only to illustrate that the time during which ice acceleration can match calving speed is measured in a few years, not decades or centuries. Another possibility must be considered. The Tyndall Glacier was undergoing a drastic retreat when, in 1963-64, the ice velocity increased suddenly from 360 m/y to about 3000 m/y, then rapidly dropped again. As a result, the retreat was interrupted by an advance and then by a pause, together lasting 2 years. After this, rapid retreat resumed and continues to the present. Contorted medial moraines indicate that Tyndall is capable of major surges. There is no evidence of major surges of Columbia Glacier. A surge of Columbia Glacier might slightly delay, but not prevent, drastic retreat.

E. <u>Irreversible, drastic retreat is inevitable.</u>

Once retreat from the shoal begins, the calving speed would immediately increase to about 3000 m/y, several times the maximum possible glacier speed for a non-surging glacier. Kinematic waves, in response to perturbations in thickness, would take several decades to move down from the present equilibrium line to the terminus. Thus a major increase in mass balance (excess of accumulation over ablation), even if prolonged, could not reverse the consequences of drastic retreat because the full effect of thickening would not occur at the terminus until after calving had reached a high speed. A surge, if it occurred, would be a temporary, short-lived phenomenon, and would leave the glacier thinner, and thus more precarious, than before. All of the major calving glaciers of Alaska except Columbia have already made drastic retreats from extended Neoglacial positions; nothing has been observed at Columbia to suggest that it should be an exception.

F. <u>Drastic retreat will begin in less than 20 years, and already may be in the early phase.</u>

This statement is a consequence of the observations listed above and conclusions given above, and the assumption that no surge occurs in this time limit. At no glacier has the initial stage of drastic retreat been observed carefully and measured, so the current state of Columbia Glacier cannot be compared with any other situation. Northwestern Glacier had retreated from about half of its moraine shoal in 1909, and drastic retreat was underway in 1928. Similarly, McCarty Glacier may have just started to retreat from part of its shoal in 1909, and drastic retreat was underway in 1925. Guyot Glacier terminated on a shoal in the Gulf of Alaska in 1904 but had retreated 6 km by 1911 to begin forming Icy Bay. Columbia Glacier has already retreated from almost all of its moraine shoal, to begin drastic retreat in less than 20 years.

III. Consequences of drastic retreat.

A. Iceberg production will increase about fourfold.

The calving flux for the lowest reach (56-66 km) can be estimated from the depth of the bed as about 6 ± 1 km^3/y. Although this is a large amount (16 million metric tons per day), it is only 4 times larger than the 1977-78 iceberg flux (1.4 km^3/y). It is still a larger increase over the iceberg flux of the 1960's, when the ice speed, and thus the calving speed, was appreciably less than that of 1978 (Post, 1975). The rate of iceberg discharge will vary greatly from week to week and year to year due to channel configuration, if the course of Columbia Glacier's recession is similar to that of other observed glaciers. Where wide, deep reaches open, rapid breakup of several cubic kilometers of ice may take place in a few months. Temporary slowdowns in recession and reduced discharge will result where the terminus is confined by narrows, islands, or sharp turns in the channel. The maximum shoal depth of 23 m (below lower low water) will limit exit of very large bergs, but a larger relative fraction of small bergs and bergy bits, small enough to float over the shoal but possibly hazardous to shipping, will be produced. This will result in greater frequency of icebergs entering Valdez Arm and northeastern

Prince William Sound, especially during the first 10 to 20 years after dr stic retreat commences. As the glacier retreats up the fiord, the number of dangerous icebergs reaching Valdez Arm is expected to diminish.

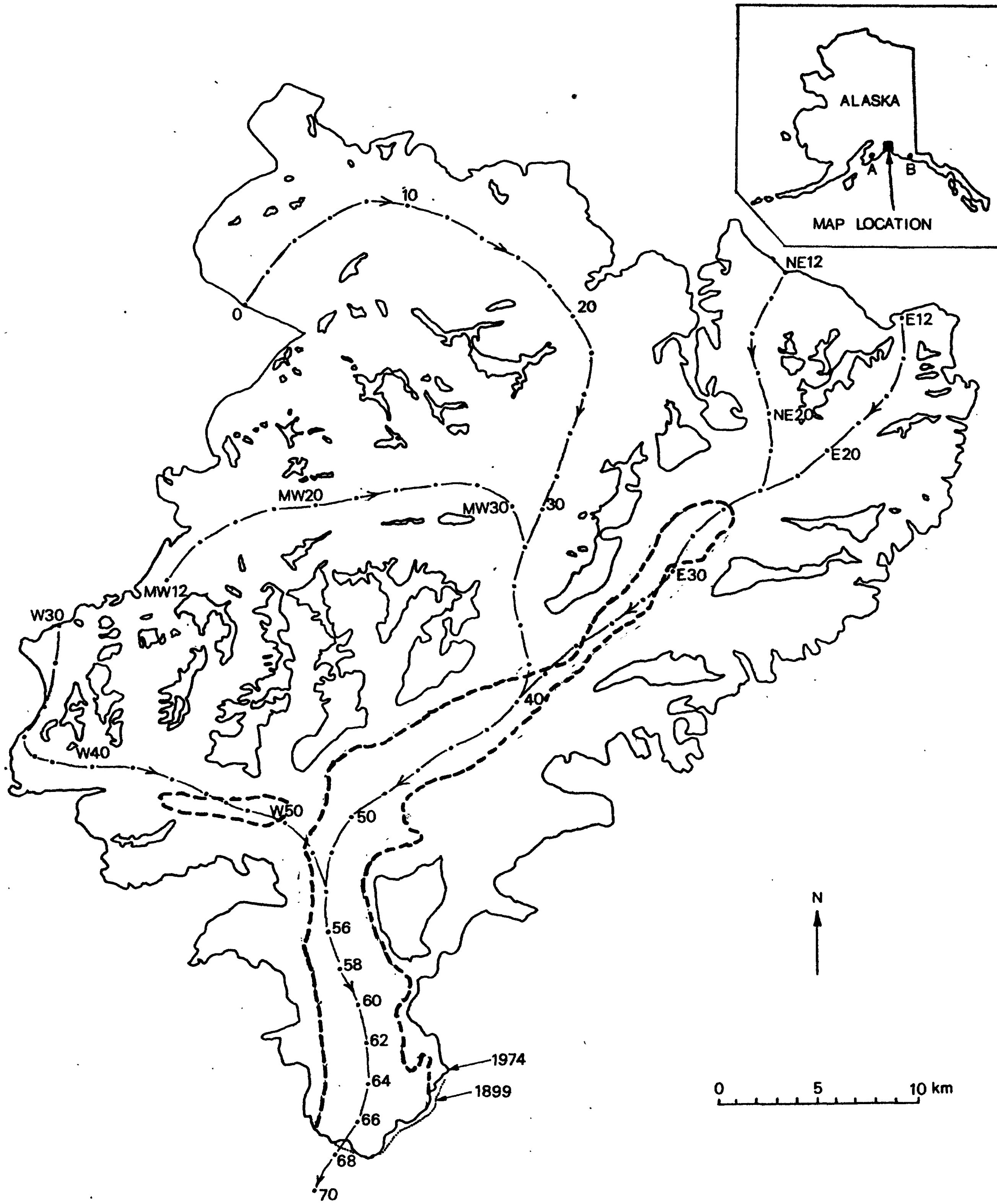
B. Retreat will continue until a large new fiord is opened.

The amount of retreat can be predicted from the bed contour map. Although the bed of the main stem reaches sea level at the 38 km point (fig. 1) below sea-level altitudes continue as far as the 26 km point on the East Branch. Thus, when drastic retreat is complete, the new fiord will be about 41 km long.

Based on observations of typical retreat rates at other glaciers, this is expected to take about 50 years. Numerical modeling now in progress should allow computation of retreat rates and calving flux as functions of time.

Figure 1. Columbia Glacier, showing longitudinal coordinates. This is a branching curvilinear system approximating the flow centerlines, with distances in kilometers from the head of the main ice stream (no letter), or from an arbitrary origin along each secondary branch (W = West Branch, E = East Branch, NE = Northeast Branch, MW = Middle West Branch), the origin being chosen so that the numbers match where the branch merges with the main ice stream. Dashed line shows limits of the sea level contour. In index map insert, "A" indicates location of McCarty and Northwestern Glaciers, "B", the Guyot Glacier.

Figure 2. Preliminary longitudinal surface and bed profiles (lower), and calving and glacier speed profiles (upper), for the 62-66.5 km reach of Columbia Glacier.



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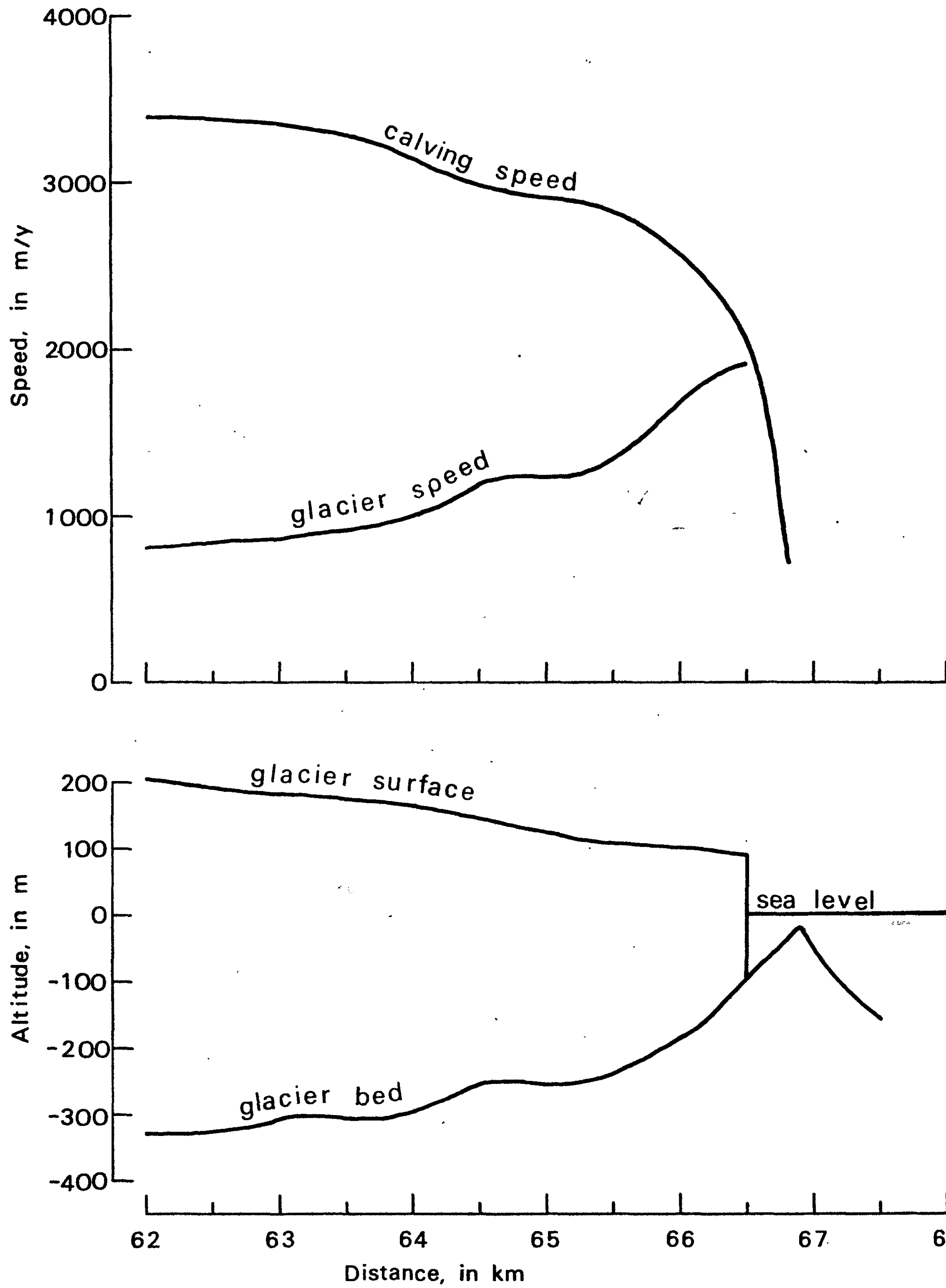

Figure 2. Preliminary results near terminus.

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