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COLUMBIA GLACIER PROGRESS REPORT--DECEMBER 1977

by The Columbia Glacier Team

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ABSTRACT

Columbia Glacier may become unstable and retreat rapidly, causing an increase in the calving of icebergs. A program was begun to determine the glacier's stability and to predict its future behavior. Hydrographic soundings show that the glacier terminates against a compact moraine; water depths over this shoal do not exceed 23 meters at low tide. In late summer, several unusually large episodes of calving occurred during the formation of a 1- by 2-kilometer embayment in the terminus. Icebergs up to 68,000 metric tons were measured in Columbia Bay. Two wave instruments and four wind instruments were installed to aid in studies of iceberg breakoff and drift. In order to model the future iceflow at the terminus, observations of mass balance, velocity, and surface altitude were made throughout the length of the glacier but were concentrated near the terminus. Fifteen new geodetic survey stations were established and new survey procedures devised. The 1976-77 mass balance is estimated at +6 meters of water equivalent, but about 11 meters of thinning occurred during this year near the terminus. A method was devised using aerial photography to map ice velocity on the lower glacier. The velocity near the terminus increased to 6 meters per day in October, 1976, then decreased to 3 meters per day in May, 1977. Development of an airborne, radio-echo sounding system to measure ice thickness was begun. Estimates of ice thickness, velocity, and discharge were used in a preliminary 1-dimensional model which was run until steady-state was achieved. The Columbia Glacier estimated data do not agree with the steady-state thickness distribution. A simple stability model for the terminus was devised, and development of more complex and realistic models was begun.

INTRODUCTION

Possible Instability of Columbia Glacier

by Austin Post

Nearly all calving* glaciers in Alaska and other parts of the world which end in the oceans have experienced large scale asynchronous advances and retreats. This behavior is apparently not directly related to climatic variations. A very critical factor in the stability of these glaciers is the water depth at the glacier terminus. Instability results when such a glacier retreats even a short distance into a deep, broad basin. The glacier may then retreat irreversibly many kilometers per year as innumerable icebergs, some of immense size, break away from the glacier.

Since first mapped in 1794, nine Alaskan calving glaciers have made large-scale drastic retreats. The 100-km retreat of ice in Glacier Bay is probably the greatest retreat in historic time in the world. Columbia Glacier (fig. 1), 1,100 km^2 in area and the largest glacier ending in Prince William Sound, is now the only calving glacier remaining on the North American Continent which is still in an extended Neoglacial position.

The terminus of Columbia Glacier has been in a state of near equilibrium (Post, 1975) since its position was first recorded in 1794. Even under these conditions, icebergs occasionally drift into the shipping lanes in northern Prince William Sound and the approaches to Port Valdez, the southern terminal of the new Trans-Alaska Pipeline (Post, 1977). Drastic retreat of the glacier would increase iceberg hazards to shipping, especially to large, unwieldy vessels such as oil tankers.

Preliminary hydrographic profiles and radio-echo soundings conducted in 1973 and 1974 disclosed that (1) Columbia Glacier terminates in shallow water, (2) the shoals at the terminus do not continue far under the ice, (3) for at least 30 km upglacier from the terminus, much of the bottom is far below sea level, and (4) the bed of the glacier lies as much as 700 m below sea level in some areas. Thus the potential for rapid, large-scale, irreversible retreat does exist.

Observations of iceberg plumes by officers of the Alaska State Ferry E. L. Bartlett indicate that iceberg discharge in 1975 and 1976 was greater than normal. Aerial photography of the terminus shows that unusually large embayments formed in 1975 and 1976. The altitude of the ice surface near the terminus decreased by more than 10 m from 1974 to 1976. These indications suggest that drastic retreat may be imminent.

*The term calving glacier as used in this report refers to a glacier which ends in water and discharges icebergs, but which is grounded (not floating).

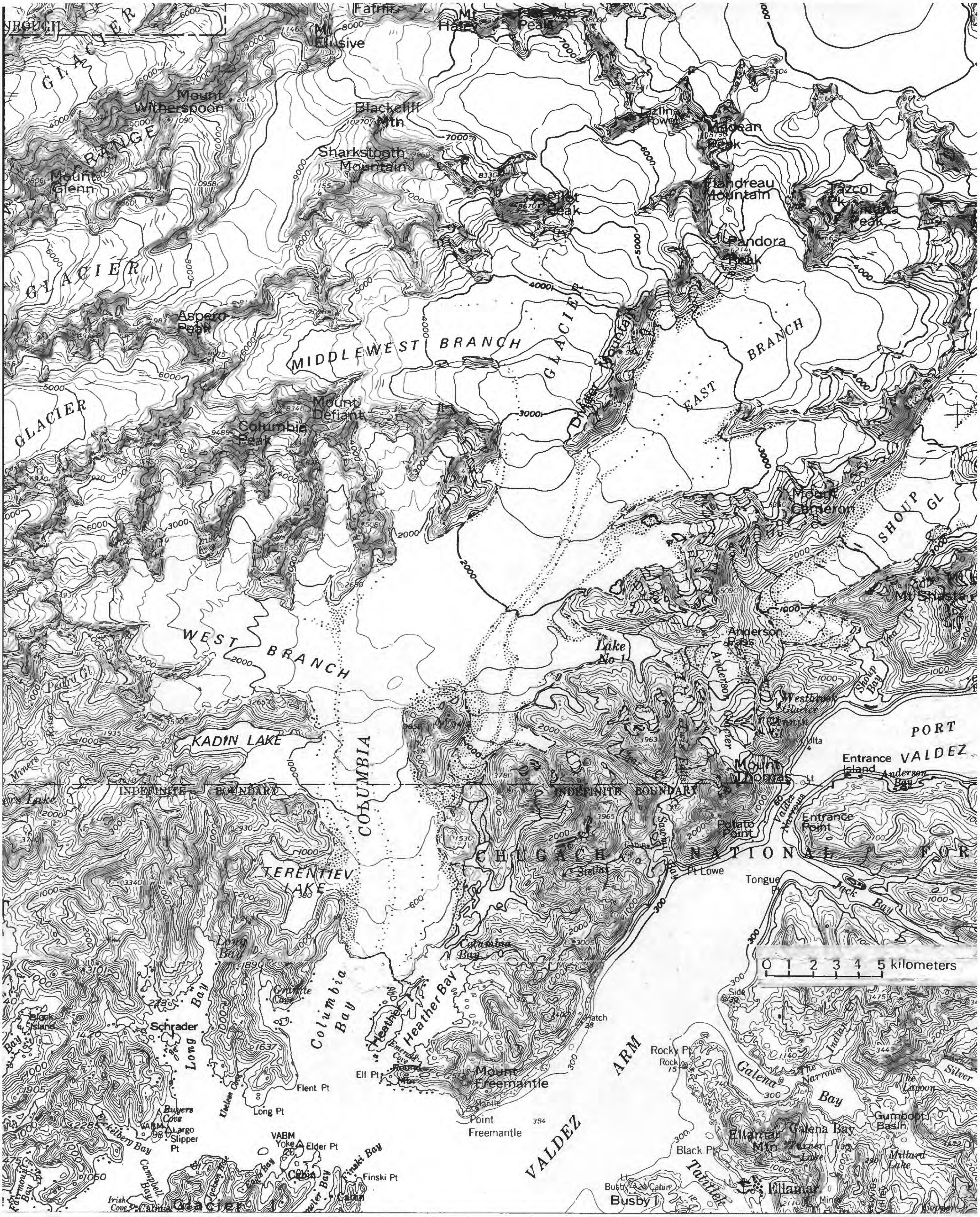

Figure 1. Map of Columbia Glacier and environs, Alaska. Scale 1:250,000.

The Scientific Program

by Mark F. Meier

As Columbia Glacier has the potential for going into rapid, large-scale, irreversible retreat, the principal questions are: Is this retreat imminent and, if so, when will it begin and what will happen? Answers to these questions require the solution of two scientific problems. These two problems can be seen by examining the equation for the advance or retreat of a claving glacier:

$$\dot{X}(t) = U(X,t) - C(X,t)$$

where X is the terminus position, $\dot{X}$ is the rate of change (advance or retreat) of the terminus in the longitudinal direction, U is the rate of ice flow forward at the terminus, C is the rate of calving at the terminus, and t is the time ($\dot{X}$, U, and C have dimensions LT^{-1}). Possible instability results from the fact that U and perhaps C can be functions of x. The main problem is the prediction of $\dot{X}(t)$; which requires prediction of both U(X,t) and C(X,t). These two terms require two different kinds of studies, which must then be put together to make the prediction about possible retreat and the resulting flux of icebergs.

Modeling of U(X,t), the ice flow at the terminus, is a standard problem in glacier dynamics. It requires data on those variables which control flow--such as mass balance, bedrock configuration, etc.--and a numerical analysis to model the flow and to predict its future change. Unfortunately, no three-dimensional*, time-dependent model of glacier flow has yet been devised; no theory of sliding at the bed has yet been established and verified. Thus several models will be used to look at different aspects of this ice-dynamics problem, and then these models will be joined to produce a prediction. In order to confirm the validity of these procedures, a large amount of data on flow and thickness of the glacier in its current state will be collected.

The second scientific problem, modeling of the calving rate C(X,t), may be more difficult. Little if any work has been done on this problem. A knowledge of a calving law would greatly aid in the assessment of the current and future stability of the terminus as well as aid in the prediction of the future iceberg production of Columbia Glacier. Empirical studies will attempt to relate calving rate to such parameters as water depth, ice cliff height, degree of extending flow, and rate of flow by measurements at many other calving glaciers. However, it may suffice just to know the present calving rate at Columbia Glacier in order to obtain a reasonable minimum estimate of future increased iceberg discharge, as the variation of calving rate with water depth, etc., may not be as large as the possible variation of calving flux due to changes in glacier thickness.

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* In this report we define the dimensionality of a model as the number of independent spatial dimensions considered. Thus the model of Rasmussen and Campbell (1973) is considered to be 2-dimensional.

Once U(X,t) and C(X,t) are known, the future iceberg calving flux C*(t) can be determined (C* has dimensions L^3T^{-1}). The terminus location X at time t is

$$X_t = \int_0^t \dot{X} dt = \int_0^t (U-C)dt$$

The equation $C^* = \int_S C ds$ is then evaluated over the cross-sectional area S of the terminus at $X = X_t$.

An observational program was begun in 1977 to provide in early 1979 estimates of the future calving flux based on models of calving and flow. In order to learn about the dynamics of iceberg calving, a small research vessel, the RV Growler was outfitted in Tacoma and sent to Alaska. Many hydrographic sounding lines were made in the vicinity of Columbia Glacier by the crew of the Growler during the period June-October 1977, and two sub-bottom profiling experiments were conducted. Soundings were carried right to the calving ice face by means of a small radio equipped launch, the Bergy Bit. The RV Growler served as a base for recording waves produced by (and thus times of) iceberg breakoffs, measuring and tagging icebergs, mapping iceberg plumes, and obtaining wind data to aid in the prediction of iceberg size distributions, trajectories, and lifetimes. These data, together with data on water currents obtained by the National Ocean Survey, will be used by the Coast Guard in modeling iceberg drift and hazard. The Growler also served as a base for other field studies which could be done from sea level access, such as some control surveys and ablation stake measurements.

In order to understand the dynamics of the flow of Columbia Glacier a series of numerical models were investigated and a field program was designed to obtain the necessary data for these models. The models selected for use include the Rasmussen-Campbell two-dimensional, time-dependent model (which uses a non-linear flow law but assumes no sliding at the bed); a one-dimensional, time-dependent model similar to those developed by Nye, Bindschadler, and Budd; and two-dimensional, finite-element, non-time-dependent models developed by Schmidt and Raymond to cope with complex boundary conditions at the terminus of a glacier.

These models require, either for input or for verification, data on elevation of bed, thickness of ice and its rate of change, slope of the ice surface and its change with time, width, ice velocity, and ice discharge. We therefore designed a field measurement program that would obtain all othe necessary data, with special emphasis on the difficult problem of obtaining sufficiently accurate values for ice thickness and discharge, and bed elevation. Discharge Q_i at $x = x_i$ can be measured in two different ways:

$$Q_i = \int_0^{x_i} (b - \dot{h})\, w dx \quad \text{and}$$

$$Q_i = f_i u_i h_i w_i$$

where b is the annual balance in units of ice-equivalent per year, h is the thickness and $\dot{h}$ the rate of change of thickness, w the width, u is the centerline surface speed of flow, and f is a factor relating the centerline surface speed to the average speed in a cross-section for a given shape of a cross-section. Sufficient data will be obtained to determine Q by both methods, with a sensitivity analysis already made to determine accuracy requirements. The measurement program involves both aerial photography and helicopter-supported field studies on the surface of the glacier. In 1978 an airborne radio-echo sounder will be used for ice thickness measurements. Developmental work began in 1977 on adapting for airborne use a radio-echo sounder which was designed and used successfully for work on the ice surface.

The data-collection program was designed to be most accurate, complete, and frequent near the terminus; less accurate, complete, and frequent data are required farther upstream (fig. 2). The reach from 52 to 67 km* (the lowest 14 km) is considered to be the most essential flow-dynamics unit, as the state of flow in this reach determines reactions at the terminus in the very near future (kinematic waves go through this reach in about 4 years). The reach from 35to 53 km is treated as another important unit, as it influences behavior of the terminus over longer time spans (kinematic waves originating in this reach probably arrive at the terminus 5 to 20 years later, depending on point of origin). Measurements also are being made farther upglacier in order to perform a complete mass balance and dynamic analysis, to initiate the really "long-term" studies (i.e., 20-100-year response time), and to confirm models, but these data are somewhat less important for calculations of the behavior of the immediate terminus; unpredictable (but somewhat more important to long-term predictions) changes in climate may have a large effect on the discharge during the time in which flow perturbations are traveling from these reaches down to the terminus.

A total of 62 stakes was set along the length of Columbia Glacier and its main tributaries during the late summer of 1977 (fig. 2). At each of these stakes provision was made to measure ice velocity (horizontal and vertical components), change in thickness, and annual mass balance. In order to obtain data a resurvey of the stakes will be required in 1978. This ambitious field data-collection program required development of a number of new survey and field operation techniques. Fortunately, in spite of the innovations and the complexity of the job, no problems were encountered and all data required in the 1977 program were obtained.

The lowest part of the glacier is virtually impassable even with helicopter support. A method was devised to obtain velocity and thickness change data using aerial photography which turned out to be extremely successful. The velocity field was mapped on the surface of the lower glacier about every 6 weeks beginning July 25, 1976. Completion of the project field studies is planned for September of 1978.

The following discussion of activities in 1977 is arranged by type of field or office activity. Each segment of the discussion was prepared by the team member who had principle responsibility for the design and operation of that particular activity. Much tabular data (such as coordinate locations) is also presented because of its widespread use by team members. Only results which were available by November 30, 1977, are included, and many of these are tentative or incomplete. These results are given here mainly to present a sketch or impression of the type of accomplishments which will be forthcoming at the conclusion of the study. The principal final result, prediction of the posssible drastic retreat of Columbia Glacier and the ensuing iceberg discharge, cannot be discussed until all of the parts of the puzzle fall into place.

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* A curvilinear coordinate system was established along the approximate centerline of the main trunk glacier, with 0 at the head and with the terminus between 66 and 68 km. Distances were also defined along the principle tributaries (fig. 3).

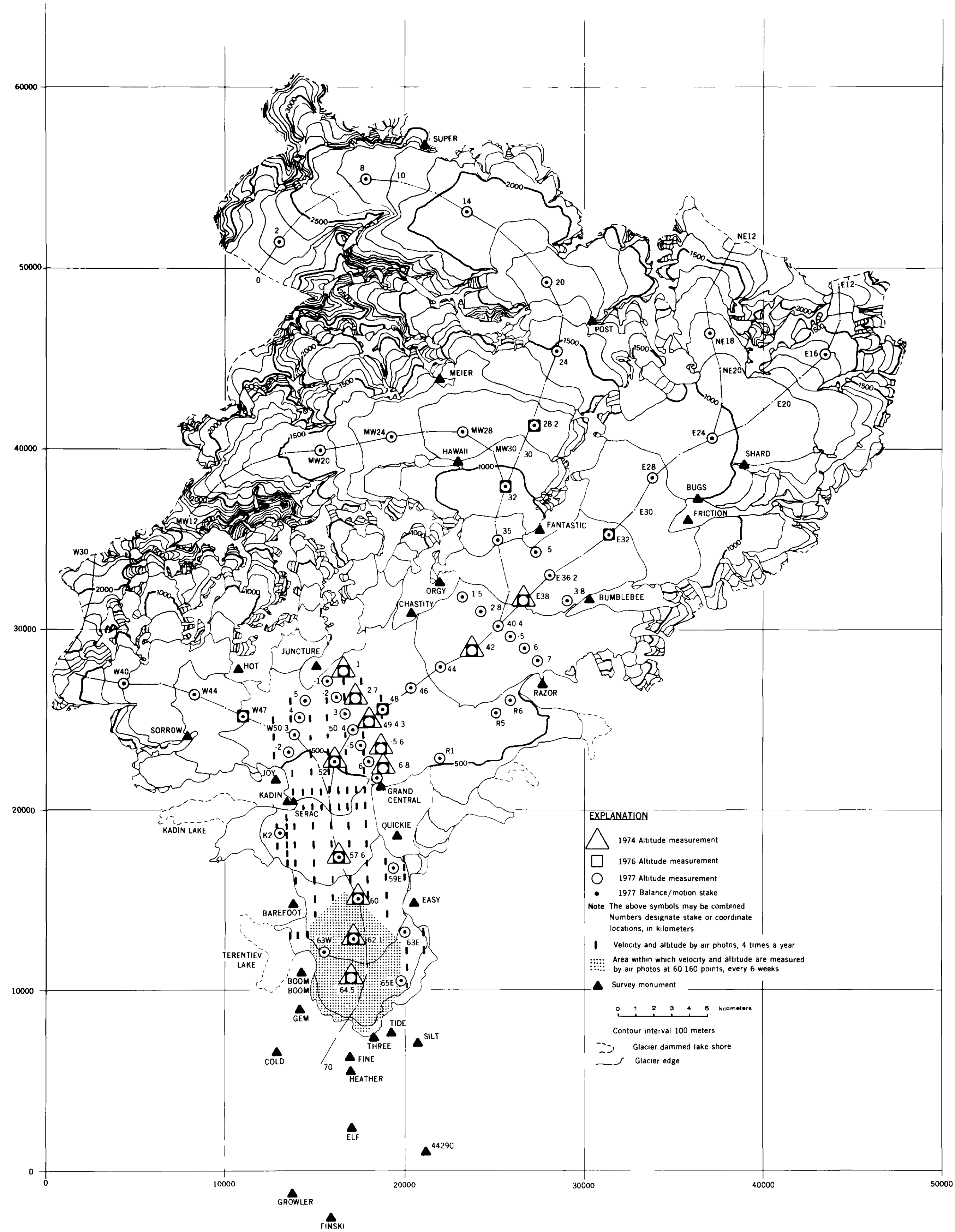

Figure 2. Map showing coordinate systems, survey stations, stakes and measurement locations. The square grid represents the local sea level coordinate system in meters. The longitudinal profile coordinate system is shown by dots every 2 km connected by lines, drawn along the centerline of the trunk glacier and main tributaries; values are in kilometers.

Acknowledgments

The Office of Marine Safety, U. S. Coast Guard, Valdez, Alaska, as well as their 17th Coast Guard District Headquarters in Juneau, provided excellent cooperation and assistance during the field season, including communication services, dockage and storage space for the RV Growler and research equipment; this support is gratefully acknowledged. A temporary field storage shed was erected in Emerald Cove near Columbia Glacier, and survey stations and wind instruments were located at strategic points so that iceberg drift could be plotted, survey control established, and hydrography of the area completed. The Tatitlek Corp., Chugach Natives Inc., and the U. S. Forest Service are thanked for their cooperation in permitting these activities and the installation of these temporary structures. The Western Marine Center, National Ocean Survey of the National Oceanographic and Atmospheric Administration, Seattle, provided many items of scientific equipment which materially aided the research.

SHIP-BASED RESEARCH

RV Growler

by Austin Post

A 12-m utility boat was obtained as excess property from the U. S. Navy. It was extensively modified by the U. S. Geological Survey in Tacoma, Washington, by strengthening the hull for work in floating glacier ice, adding enclosed scientific and marine equipment and living space for up to six research personnel, equipping the vessel with gear to house and deploy various scientific instruments, and installing precision water depth recorders; it was named the RV Growler (fig. 3). In addition, a 3 m unmanned, radio-controlled battery-powered launch (the RV Bergy Bit) was constructed and equipped with a precision depth recorder to obtain hydrographic data in the extremely hazardous areas directly under terminal ice cliffs of calving glaciers. The RV Growler proceeded to Alaska in April 1977 and worked in cooperation with the Office of Marine Geology, Geologic Division, U. S. Geological Survey, in the Gulf of Alaska and in Yakutat and Icy Bays through May 30, 1977. On June 18, 1977, the vessel and the radio-controlled launch began operations at Columbia Glacier and continued collecting data there until October 25, 1977.

Hydrographic Surveys

by Austin Post

Few of the waterways surrounding Columbia Glacier have been previously sounded in detail. Thus reconnaissance soundings were run during the course of other work where future observation of icebergs was anticipated. Most of the waters between Glacier Island, Point Freemantle, and Unakwik Inlet were briefly examined. A number of dangerous, uncharted rocks and shoals were located; when plotted, these data will be forwarded to the National Ocean Survey for use in updating navigation charts and Coast Pilot publications. Once survey markers were emplaced and their locations determined (fig. 4), detailed hydrographic surveys were made in Columbia Bay (fig. 5) and Heather Bay. This work, particulary in Columbia Bay, was hampered by extremely thick brash and icebergs calved by the glacier all through the field season.

Figure 3. Research vessel Growler running sounding lines in the large embayment which formed in the terminus of Columbia Glacier in August 1977. The radio-controlled launch Bergy Bit (hanging from the stern davits) is used to obtain data in the highly hazardous areas directly under the 50- to 100-m-high terminal ice cliffs. This photograph was taken from a height of 8 m on a 40-m-long iceberg stranded in 20 m of water near the crest of the terminal moraine shoal. The iceberg broke up and drifted out of the embayment a few hours later.

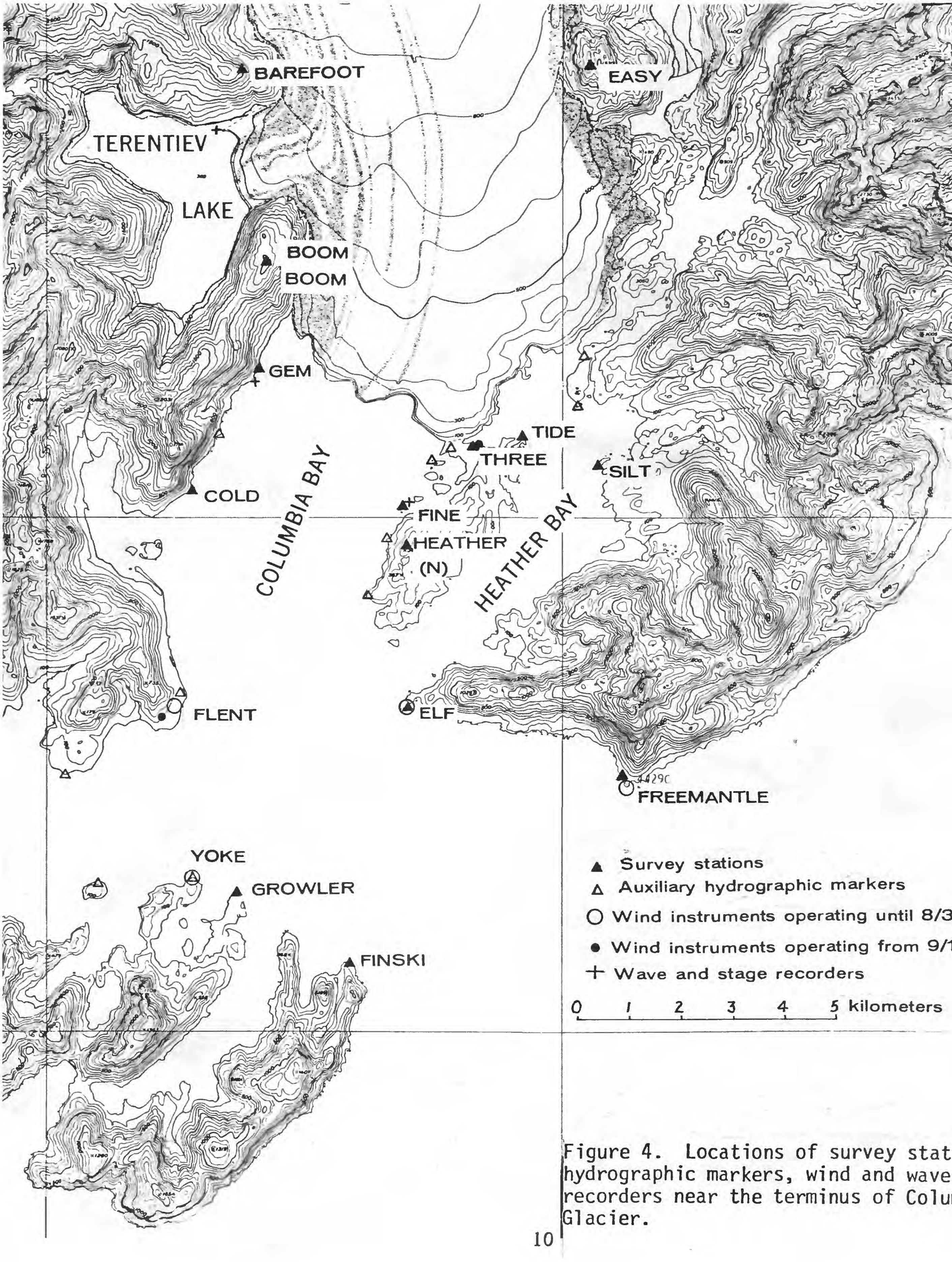

Figure 4. Locations of survey stations, hydrographic markers, wind and wave recorders near the terminus of Columbia Glacier.

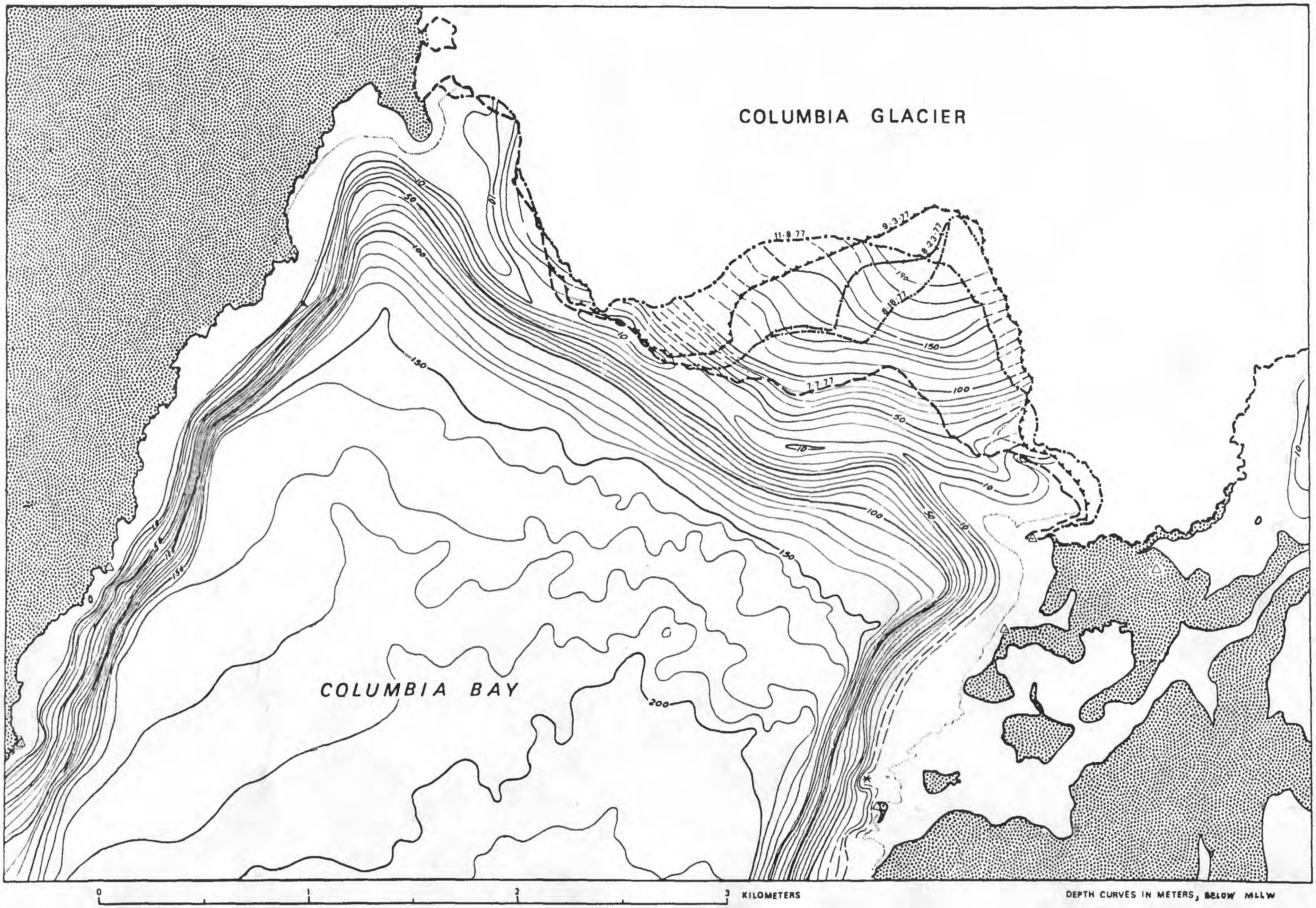

Figure 5. Preliminary chart of terminal moraine shoal, Columbia Bay, Alaska. The moraine forms a barrier crossing Columbia Bay. The growth and changes of the 1977 embayment are shown from July 7 through November 8. The maximum water depth measured was 193 m at the head of the embayment in early September.

In October two technicians from the Office of Marine Geology, Geologic Division, installed Mini-Sparker* gear aboard the RV Growler, and about 100 km of detailed sub-bottom profiles were obtained of upper Columbia and Heather Bays, of the terminal moraine shoal (fig. 6a), and within a large embayment formed in the glacier terminus by drastic calving during the summer. Meares Glacier was also visited, and about 50 km of Mini-Sparker profiles were run in and on the approach to Unakwik Inlet. Later in October a technician from Shannon and Wilson, Inc., installed a Lister Boomer system aboard the vessel, and about 50 km of lines were run in Columbia and Heather Bays. Excellent records were obtained (fig. 6b).

The major finding of the hydrographic surveys and the Boomer and Sparker profiles is that the terminal-moraine shoal is composed of compact rock debris with little or no buried ice. Although dangerously large icebergs frequently do enter the shipping lanes, the maximum water depth over the moraine is about 23 m at lower low water. Thus the moraine acts as a dam which prevents extremely large icebergs from escaping. From the point of view of ship safety, this has both advantages and disadvantages. Very large bergs are most easily detected and avoided by vessels but would drift greater distances before melting. Due to the moraine barrier, these large bergs will break up, before escaping, into smaller bergs that are harder to detect, thus presenting the more serious menace of smaller and more numerous icebergs in a more limited area. This local hazard will be greatly increased should Columbia Glacier drastically retreat. Large icebergs trapped by the moraine could be expected to break up over periods of months, with dangerous icebergs escaping during each tide cycle. On the other hand, should the glacier--and the hazardous ice cliff--retreat far back from the shoal, it might be possible to erect artificial barriers on the moraine crest to prevent the escape of dangerous icebergs from Columbia Bay. As long as the glacier terminates on or near this barrier, such efforts are hardly practical.

Iceberg Calving

by Austin Post

Periodic visual observations of average calving were maintained on a nearly daily basis during the summer and fall of 1977 in an effort to determine what relationship existed between calving and such variables as (a) state of tide, (b) time of day, (c) clear or rainy weather and wind conditions, (d) water depth, (e) configuration of the terminal ice cliff, and (f) subglacial fresh water runoff. When not within visual range, calving was noted by a loud, thundering sound, audible over a great distance. Study of these observations disclosed that major calving does not appear to be predictable. Constantly heavy calvings, however, did appear to be associated with abnormal release of subglacial fresh water. Columbia Glacier's subglacial river discharge varies from day to day or even hour to hour, both in location and volume of water released. Particularly during August, when major calving was most frequent, nearly all of Columbia Bay was discolored by a surface layer of fresh water laden with glacier flour. These fresh-water currents, up to 2 knots or more and frequently in the form of a fairly narrow stream, would flow over the terminal moraine bar and extend several kilometers into the bay. This heavy discharge was not constant in position or volume.

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* Use of brand names or model numbers in this report does not imply endorsement by the U. S. Geological Survey.

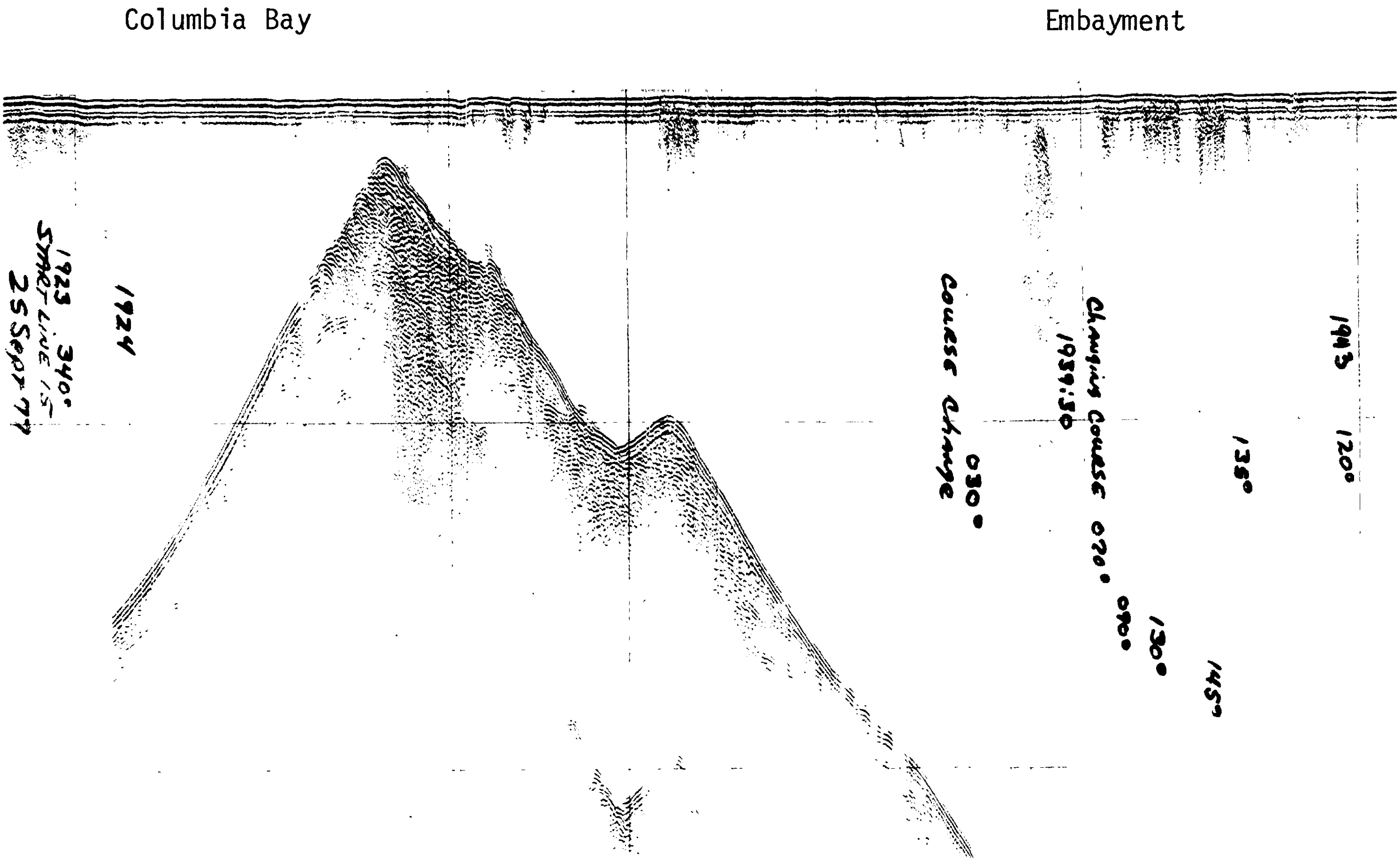


Figure 6a. Mini-Sparker profile across the terminal-moraine shoal, with embayment and glacier on the right. The hard, ringing reflection from the moraine surface and lack of penetration is typical of Sparker profiles of compact glacier moraines.

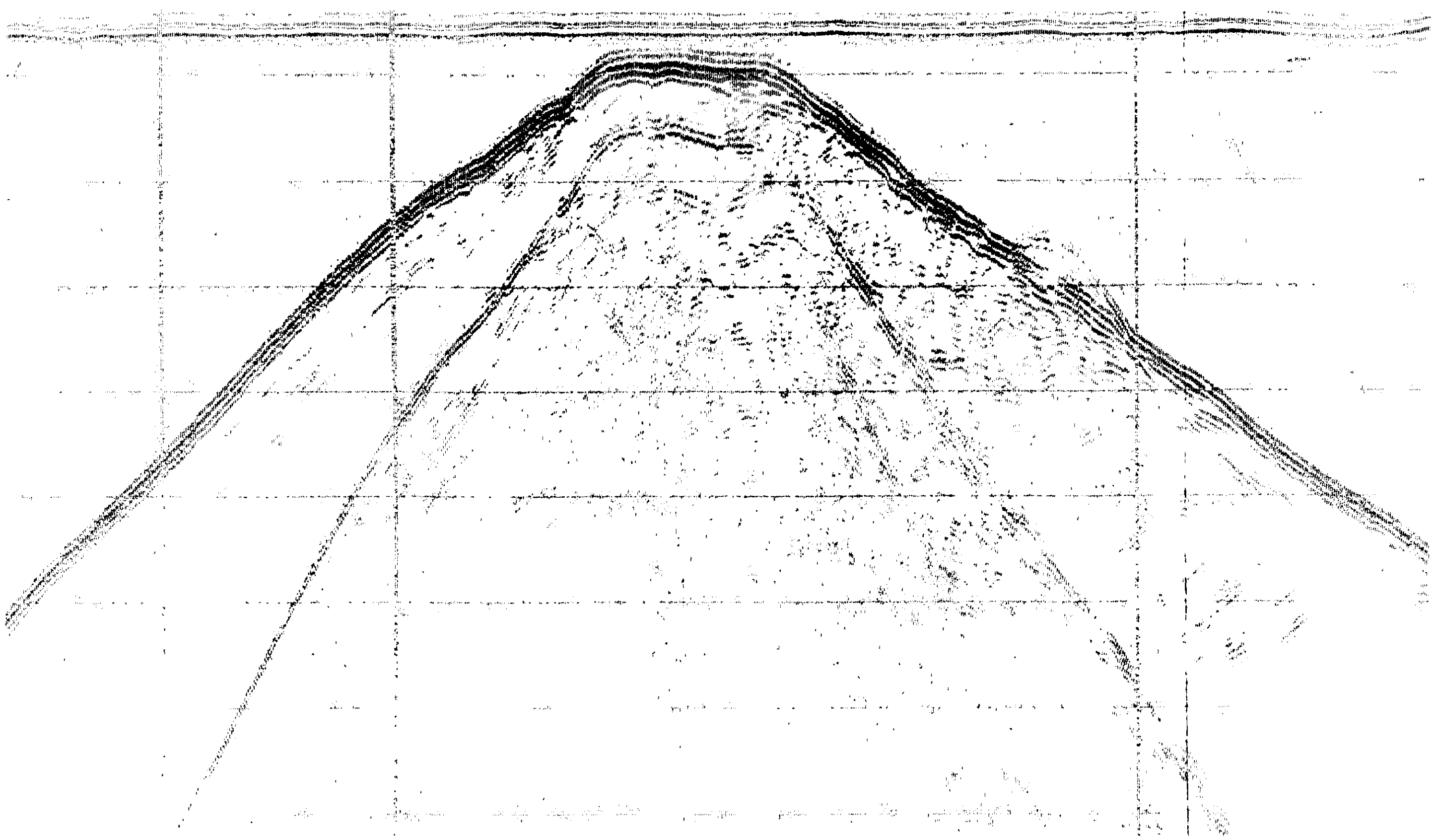


Figure 6b. Lister Boomer profile across the terminal-moraine shoal, with embayment and glacier on the right. Note traces of foreset bedding in bottom right. The dip of these beds is similar to that of the downstream side of the moraine (left) and the angle of repose, and is consistent with the hypothesis that the submarine terminal moraine is being shifted slowly downvalley by erosion on the upstream side and deposition on the downstream side. Neither profile (6a or 6b) (or any other) provides evidence of any buried glacier ice in the moraine.

On at least three occasions in 1977, only one of which was witnessed, very large-scale calving of enormous icebergs occurred, involving quantities of ice orders of magnitude above that normally observed. The largest of these calvings may have been related to the August 1977 dumping of ice-dammed Kadin Lake, 11 km upglacier. A very deep, narrow embayment in the glacier's terminus (fig. 5) with a large tunnel visible at its head was observed on August 19, following the largest known discharge of icebergs from the glacier, on or about August 15. Although these major calving events appear to be associated with fresh-water release, notable increase in volume of water released was not observed during the event witnessed.

Late in the season, the rate of calving declined at the head of the embayment formed by the earlier events, and the glacier began advancing in this portion of the terminus faster than ice was being released. The most rapid advance took place where water depths of over 190 m had been previously recorded (fig. 5). From mid-September on, little or no subglacial water was observed being released from this part of the glacier; on the western side of the embayment, where the subglacial river was then situated, considerable calving was still in progress. As a result, the embayment continued to increase in width, and the glacier was still experiencing a slight loss in area when the field observations ended on November 8.

Judging from past years, the embayment can be expected to close more or less completely by the glacier's advancing into it during the winter and spring. Should the glacier fail to close the embayment by next June, it appears possible that the glacier could begin a large-scale retreat in 1978. Even if the embayment is closed, the glacier ice thickness in the terminal area will again be considerably lowered by flow into the embayment. The ice surface has been successively lowered in this way each year since detailed observations started in 1974. If continued, such thinning will almost certainly cause the glacier to drastically retreat many kilometers from the moraine in a few years.

Wind Instruments

by C. S. Brown

During the summer of 1977 the U. S. Geological Survey maintained four weather stations near Columbia Bay, Alaska, to determine wind speed and direction in the area useful for modeling iceberg drift. Figure 4 shows their approximate locations, as well as the locations of the two stations installed in early September for operation during the fall and winter months.

Two of the stations were MRI (Meteorological Research Inc.) Mechanical Weather Stations, and two were ESI's (Electric Speed Indicators) assembled and interfaced with recorders. The MRI is a self-contained unit mounted on one metal pole approximately 1.5 m high. The ESI is a 4-component system. The anemometer cups and the wind vane are on separate poles approximately 1.5 m high and 1 to 2 m apart, with the power source and recorder placed on the ground.

The wind direction was measured in degrees, with 0^{o} being true north; the wind speed was measured in kilometers per hour.

Six-hour averages have been calculated from 30-minute readings for all four stations from the time they were established in late June-early July until August 31. The averages have been supplied to the U. S. Coast Guard. As the wind was found to be quite light and variable during the summer months, wind roses have also been drawn to better illustrate wind direction. Average values of speed and direction are given in table 1.

Table 1. Average wind speed and direction

from date of installation through August 31, 1977

Station	Direction	Speed
Flent	N to NE	8 km h^{-1}
Yoke	N to NE	3 km h^{-1}
Freemantle	no prevailing direction	4 km h^{-1}
Elf	N	8 km h^{-1}

Iceberg and Terminus Ablation Studies

by E. A. Senear

The volume of each of approximately 25 icebergs was calculated from above-water dimensions. The above-water volume was usually assumed to be that of half of a triaxial ellipsoid. The average water density, calculated from temperature and salinity profiles run in the upper 10 to 13 m of the sea water in front of glacier (table 2), was 1.018. The density of the ice was assumed to be 0.90. The size of the icebergs ranged from 20 to 36,000 m^3 in volume, or 18 to 32,000 Mg (metric tons) in mass. Late in the season, U. S. Coast Guard personnel measured 27 additional bergs ranging from 1,529 to 68,461 Mg in size (Kollmeyer, and others 1977).

The distribution of icebergs was mapped once or twice daily during the course of other work by the crew of the Growler. Mapping was done on forms similar to those completed by officers of the Glacier Queen and the Bartlett in 1976 (Post, 1977); an example is shown in figure 7. Iceberg distribution data were also obtained by officers of the Bartlett in 1977.

Two sets of ablation stakes were maintained on the ice above Heather Bay. One set of 4 stakes was located on the crest of the ice above Heather Island and was maintained from July 25 to October 6. In setting the set of stakes on the ice up from the east side of Heather Bay, an attempt was made to place them in areas with varying amounts of debris on the ice to see what effect debris had on ablation. The stakes were revisited every 2-3 weeks. For a short period on the ice above Heather Island, small stakes were set in crevasse walls and slopes of various orientations to investigate the effect of crevassing on ice melt.

Table 2. Temperature and salinity profiles

in near-surface water off Columbia Glacier terminus

[All profiles were taken in mid-Columbia Bay from 0.5 to 2 km south of the moraine crest, August 2-5, 1977]

Depth (m)	Temperature (°C) avg.	Temperature (°C) s[1]	Salinity (ppt[2]) avg.	Salinity (ppt[2]) s[1]	Number of readings
Surface	6.53	2.20	15.06	1.66	17
1	7.31	1.54	15.80	1.53	17
2	7.83	1.05	16.87	1.05	16
3	8.26	0.94	17.26	1.15	16
4	8.84	0.80	17.60	1.29	16
5	9.23	0.87	18.41	0.73	17
6	9.97	1.07	18.94	0.80	16
7	10.07	1.40	19.20	0.81	16
8	10.42	1.63	19.38	0.94	17
9	10.92	1.89	19.58	1.05	17
10	11.42	1.95	19.85	1.01	18
11	11.91	1.89	20.19	0.87	17
12	12.89	1.76	20.28	0.60	12
13	13.13	1.77	20.85	0.80	3

[1] standard deviation
[2] parts per thousand

Wave and Stage Recorders

by David Frank

Wave recorders were constructed in Tacoma and established at 2 sites in Columbia Bay: beginning June 26, 1977, near station Gem on the west shore about 1 km from the glacier terminus; and beginning June 25, 1977, near station Fine on the east shore about 2 km from the terminus (fig. 4). The distinctive wave-trains generated by calving ice are detected by pressure transducers set offshore on the sea bottom. The resultant electrical signal is transmitted by cable and recorded on small strip-chart recorders. The system will record fluctuations in water level to a depth of 7 m. Tide fluctuations and individual waves as small as 20 cm at Fine and 50 cm at Gem can be read from the record. Both recorders operated the end of August. The Fine recorder was restarted on October 12; part of the Gem system was removed for repair on October 13.

On July 24, 1977, a similar system was established to record the stage at the margin of ice-dammed Terentiev Lake. At the time of the last observation on November 16, 1977, the lake had not dumped. The recorder should continue to operate through the winter, or until Terentiev Lake empties.

Columbia Bay Survey and Survey Stations

by W. G. Sikonia

The survey net established in 1974 by the Project Office - Glaciology was tied to the National Geodetic Survey network by additional surveying in 1977, establishing solid control for the entire network of survey stations along the glacier. The triangulation stations near Columbia and Heather Bays were resurveyed, and then the entire survey net was readjusted using the "Three-Dimensional Geodetic Survey Adjustment" (Sikonia, 1978) computer program (table 3). Calcomp plots of the survey stations, including UTM (Universal Transverse Mercator) coordinates and latitude-longitude ticks, were then made and transferred to maps of Columbia Glacier at scales of 1:100,000, 1:50,000, 1:20,000, and 1:10,000. Elevation control for the entire net is based on the NOAA tide station 945-4429C near Point Freemantle. The stations were also used for locating temporary navigation and positioning marks (fig. 4).

Figure 7. Iceberg distribution form filled out August 23, 1977. Crosses represent icebergs up to 5 m; stars 5 to 10 m across; squares more than 10 m. Special features, such as unusual calving, embayment changes, river discharge, and other observations are noted on each form, which were generally filled out at least once each day from June 18 to October 25. Similar forms were filled out by officers aboard the Alaska State Ferry <u>E. L. Bartlett</u> during summer months.

SURFACE STUDIES OF ICE BALANCE AND DYNAMICS

by L. R. Mayo and D. C. Trabant

Resume of Field Operations

The purpose of this part of the project is to measure the balance and dynamics of Columbia Glacier using stakes installed in the glacier together with precision surveying of the glacier surface altitude at predetermined or previously measured locations.

A geodetic surveying net was established on ridges overlooking the ablation zone of the glacier in July 1974 by the Project Office - Glaciology, Tacoma, and the Alaska Glaciology Unit, Fairbanks. At the same time a number of surveys was made to the glacier surface, along with radar and gravimeter measurements of the ice thickness. The altitude of the glacier surface was remeasured at a number of these points in July 1976 (fig. 2), and additional first-time measurements of the ice surface were made in the accumulation zone of the glacier.

The intensive work of 1977 required three field trips. The first trip in July was necessary to repair 1974 survey monuments, establish new monuments in the rest of the glacier basin, and resurvey the altitude control (fig. 8). The purpose of the second trip in August and September, was to install and survey stakes throughout the glacier, concentrating on the centerline profiles of the four largest tributaries and the main ice stream as well as a number of cross-sections (fig. 2). The beginning of the intensive measurement year was chosen to be September 1, 1977. On the third trip, November 16, the purpose was to measure the snow and ice balance to date and to service balance/motion stakes on the glacier.

Survey programs and methods

Over the past two years, we have developed a completely integrated system for rapid geodetic surveying in the field and complete data reduction in the field or office. This system includes:

1. Complete data reduction using a pocket programmable calculator (HP-67) so that results are available in the field.

2. Fully three-dimensional calculations over the curved earth surface referenced to either UTM coordinates or locally defined coordinates at sea level.

3. Measurement of the combined effects of earth curvature and atmospheric refraction of light between theodolites for net surveying, by observing a known point from another known point during data surveys or as a part of the solution when observations to three monuments are used to calculate an instrument's positions.

4. Occupation of any desired survey point, either over an established monument or simply in view of three monuments.

5. Location of any desired XYZ coordinate position by predicting the horizontal and vertical theodolite readings to the desired location under any light curvature conditions. The distance along the ray is calculated and when a distance

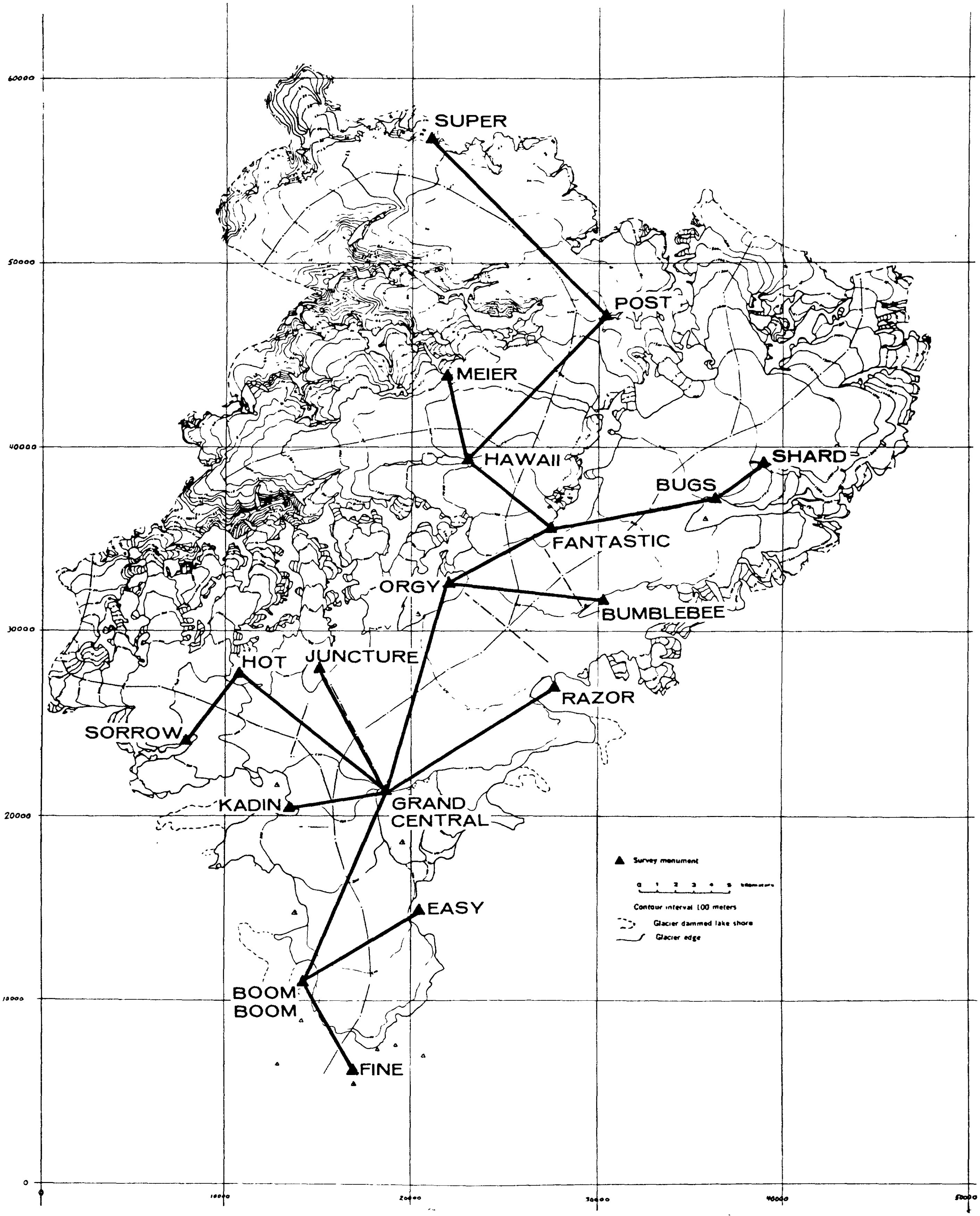


Figure 8. Altitude control of the survey net was surveyed in 1977 along these lines by two theodolites, one at each end of the line, to measure earth curvature and atmospheric refraction. Seven of these monuments were established in 1974 and eleven were established in 1977.

measurement is made, the move necessary to correct the position is calculated. Precise location is necessary for all measurements of change in altitude of the glacier surface.

6. Calculation of all motion and balance parameters at the surface of the glacier including magnitude, azimuth, and vertical angle of ice velocity, stake slippage surface slope and slope azimuth, altitude at any desired index point in the area of the stake, and altitude change, balance, and emergence for a fixed index position.

7. If bed geometry is known, possible calculation of such things as vertical and horizontal strain rates, and the moving wedge effect of the ice on the change in altitude of the glacier.

The surveying net at Columbia Glacier is planned to have as few points in the net as possible, but enough points to allow surveys with distances less than 10 km. Each primary survey point must have a second monument located for easy azimuth and refraction observations. The azimuth/refraction reference points are located in the direction of intended glacier surveys.

All survey monuments are permanent and visible from other monuments and from the glacier surface. The monuments at Columbia Glacier are cement-filled steel pipes grouted into 0.5 m-deep holes in bedrock. The pipes are about 0.8 m high and have the monument name stamped in an aluminum plug cemented into the pipe top. The survey monument is thus at the pipe top. Bright yellow sheet-metal cones have been placed around several of the pipes to increase visibility. Most monuments include a temporary air photo marker.

The horizontal, vertical, and distance control surveys between net points were carried out independently. A sufficient number of horizontal direct and inverted angles was measured from an azimuth reference to a new monument to define the angle within $\pm 0.0002^g$, a definition of about $\pm$ 0.03 m at 10 km distance. The slope distance was measured several times with a tellurometer corrected for air density, giving results accurate to 10 ppm or $\pm$ 0.10 m at 10km distance.

The vertical control originated at NOAA tidal station 945-4429C at Point Freemantle (fig. 4). The vertical survey was accomplished by simultaneously measuring vertical angles between two theodolite axes. The difference between the vertical angles is a measurement of the combined curvature and refraction between the theodolites at that time. This simultaneous backsight/foresight technique allows altitude measurements to be made over long distances, quickly, and with relatively small errors--about $\pm$ 5 ppm vertical error compared with slope distance, or less than 0.5 m error over the 67-km-long glacier.

The field time required to survey the net involved two people for about 1 hour for each survey point. This time included travel by helicopter and instrument setup time. Approximately 15 minutes of observation time is required for each point. The location of the survey points at Columbia Glacier and the path of the survey control are shown on figure 8.

Calculations can be made most simply at any glacier location if a sea level scale coordinate system is used. The origin of a local sea level coordinate system for Columbia Glacier is the intersection of UTM coordinates X = 480,000, Y = 6,754,000 m. At Columbia Glacier the scale change from UTM to sea level involves dividing UTM distances

Table 3. Columbia Glacier surveying monuments

[Coordinates in meters]

Monument		UTM zone 6 Easting	Northing	Local Sea Level X	Y	Altitude Z	To*
Finski	1947	495896.45	6751353.84	15902.81	-2647.22	2.42 3.94	m, b p
Growler	1972	493711.15	6752742.27	13716.63	-1258.23	5.78 7.31	m, b p
4429C	1976	501186.26	6755010.62	21194.74	1011.03	4.06 5.59	m, b p
Elf	1947	497038.91	6756350.63	17045.73	2351.57	4.53 6.06	m, b p
Flent	1977[1]	492727.4	6756555.2	12732.5	2556.2	-	-
Heather (N)	1974	497011.67	6759469.50	17018.48	5471.69	110.11 110.10 111.63	m[2] b p
Fine	1974	496930.62	6760236.55	16937.39	6239.05	3.02 3.00 4.52	m b p
Fire	1974[1]	496605.7	6759554.5	16612.3	5556.7	-	-
Cold	1947	492840.77	6760544.47	12845.91	6547.09	2.75 4.28	m, b p
Silt	1951	500708.42	6761023.12	20716.70	7025.93	3.25 4.78	m, b p
One	1974[1]	497554.7	6761084.6	17561.7	7087.4	-	-

[1]auxiliary hydrographic marker surveyed by sextant in 1977

[2]rock bolt is about 24 cm below surrounding turf level

Table 3. Columbia Glacier surveying monuments--continued

[Coordinates in meters]

Monument		UTM zone 6 Easting	UTM zone 6 Northing	Local Sea Level X	Local Sea Level Y	Altitude Z	To*
Berg	1974[1]	493256.3	6761382.7	13261.7	7385.6	-	-
Three	1974	498275.57	6761367.30	18282.88	7370.25	26.60	m[3]
						26.56	b
						28.08	p
Tide	1974	499235.16	6761585.34	19242.86	7588.38	2.24	m, b
						3.77	p
Gem	1974	494144.95	6762903.63	14150.61	8907.19	6.64	m
						6.63	b
						8.15	p
Boom-Boom	1974	494279.36	6764969.04	14285.08	10973.43	506.02	m
						506.00	b
						507.50	p
						506.0	a[4]
Photo marker near Boom-Boom	1974	494288.4	6764986.1	14294.1	10990.5	501.4	b, a
Barefoot	1974	493787.25	6768724.92	13792.76	14730.81	486.69	m
						486.66	b
						488.20	p
						486.7	a[4]
Easy	1977	500538.57	6768801.08	20546.79	14807.00	461.13	m, p
						460.18	b
						460.83	c
						460.2	a
Quickie	1974	499479.21	6772557.27	19487.00	18564.69	710.65	m, b
Serac	1974	493736.21	6774410.22	13741.70	20418.39	509.30	m, b
						510.82	p[5]
						509.3	a[5]
Kadin	1977	493460.54	6774439.99	13465.93	20448.17	545.32	m, p
						544.28	b
						544.95	c
						544.3	a

[3] monument at Three is top of a 3/4" pipe set in concrete

[4] installed July 1977

[5] removed 1977

Table 3. Columbia Glacier surveying monuments--continued

[Coordinates in meters]

Monument		UTM zone 6 Easting	UTM zone 6 Northing	Local Sea Level X	Local Sea Level Y	Altitude Z	To*
Photo marker near Grand Central	1977	498591.5	6775245.5	18598.9	21254.0	637.2	b, a
Photo marker near Grand Central	1974	498609.2	6775246.9	18616.7	21255.4	640.0	b, a
Grand Central	1974	498596.60	6775250.41	18604.04	21258.91	638.60	m[5]
						638.57	b[5]
						640.09	p[5]
	1977[6]					639.64	m
						638.62	b
						639.63	p
Joy	1974	492765.46	6775663.94	12770.57	21672.61	935.41	m
						935.38	b
						936.90	p
						935.4	a[7]
Sorrow	1977	487850.94	6778046.28	7854.08	24055.90	785.30	c
						784.59	b
Razor	1974[8]	507576.04	6780993.23	27587.07	27004.03	822.69	m
						822.66	b
						824.18	p[4]
						822.7	a[4]
Photo marker near Juncture	1974	494727.1	6781406.6	14733.0	27417.6	721.0	b, a
Hot	1977	490752.06	6781735.96	10756.36	27747.06	906.99	m, p
						906.01	b
Juncture	1974	495024.29	6781928.55	15030.30	27939.73	828.77	m
						828.76	b
						830.28	p[4]
						828.8	a[4]
Chastity	1974	500233.03	6784912.23	20241.12	30924.60	919.83	m
						919.80	b
						921.32	p

[6] same horizontal location as 1974--monument changed July 1977

[7] removed July 1976

[8] 1977 survey indicates altitudes at Razor 0.38 m lower than the 1974 survey--the altitudes given correspond to the 1977 survey

Table 3. Columbia Glacier surveying monuments--continued

[Coordinates in meters]

Monument		U T M zone 6 Easting	Northing	Local Sea Level X	Y	Altitude Z	To*
Bumblebee	1974	510148.08	6785684.98	30160.14	31697.66	807.11	m[5]
						807.08	b
						808.60	p[5]
						807.1	a
	1977[6]					808.07	m, p
						807.1	b
						807.68	c
						807.1	a
Orgy	1977	501938.08	6786579.54	21991.88	32592.58	1072.14	m, p
						1071.09	b
						1071.85	c
						1071.1	a
Fantastic	1974	507404.60	6789531.50	27415.57	35545.71	1074.37	m[5]
						1074.33	b
						1075.85	p[5]
	1977[6]					1075.27	m, p
						1074.33	b
Friction	1974	515663.79	6790107.36	35678.06	36121.81	1124.59	m
						1124.56	b
						1126.08	p
Bugs	1977	516340.45	6791259.25	36354.99	37274.16	1027.35	c
						1026.65	b
Shard	1977	518542.57	6793194.93	38557.99	39210.61	1059.59	m, p
Hawaii	1977	502992.78	6793296.08	23001.98	39311.80	1230.67	c
						1229.97	b
Meier	1977	501857.87	6797844.12	21866.62	43861.66	1431.26	m, p
Post	1977	510402.03	6801042.85	30414.20	47061.67	1831.91	p
						1830.6	b
						1831.62	c[10]
Super	1977	50113.92	6810738.69	21122.37	56761.39	2511.87	m, p
						2510.92	b

[9] pipe down

[10] no reference

Legend:

a - Air photo marker (same as b if marker at monument location)
b - Rock or concrete base in which monument set
c - Cone top
m - Monument (brass or aluminum disk, top of rock bolt, etc.--always the the highest point of the monument marker)
p - Top of pipe or EMT (of 1977)

by 0.999600. UTM coordinates may be obtained from sea level net coordinates by

$$XUTM = (.999600)\,X_o + 480{,}000$$
$$YUTM = (.999600)\,Y_o + 6{,}754{,}000$$

UTM and sea level coordinates of survey points are presented in table 3.

The third coordinate system, the longitudinal profile, originates at the highest ice divide on the main stream of Columbia Glacier and progresses downstream at 2-km intervals along the curvilinear longitudinal axes of the main ice stream and its more important branches, and is defined in terms of UTM coordinates (table 4). It is a right-handed system which also defines transverse profiles. This is a convenient system for rapid location referencing and serves well for arraying results along the length of the glacier.

Data surveys proceed somewhat differently from the net surveys. The theodolite is set up over a known point with a tellumometer nearby. Two HP-67 programs handle all of the field-data input and calculations as the surveying is being done.

All parts of the field survey are carefully controlled to insure accuracy. This includes frequent azimuth referencing, measurement of the combined effect of curvature and refraction, and measurement of the air temperature for correction of distance measurements. All interim results of the survey are calculated as the survey proceeds and the coordinates of each measured point are calculated and recorded during the survey. This allows complete checking of the results and a resurvey can be made if any fault becomes apparent. This field calculation and verification procedure adds to fieldwork time, but results in much larger savings of office time. Moreover, most of the pesky problems that usually crop up during data calculation have been elimiated in the field.

Surface Altitude Changes of Columbia Glacier

Measurement of altitude changes of the surface provides one method of monitoring the regime (health) and stability of a glacier. From July 1974 to July 1976, Columbia Glacier thinned throughout the lower 30-km reach (fig. 9). During this two-year period, Columbia Glacier lost more ice from melting and calving near the terminus than it gained from ice flow into the area. Therefore the stability of the Columbia Glacier terminus has decreased and the likelihood for calving instability occurrring in the future has increased.

From July 1976 to August 1977 the thinning of the lower 20 km of the glacier continued, and at an increased rate at most measurement points. For example, at the point closest to the terminus (64.5 km) the rate of thinning in 1974-76 was approximately 6 m yr^{-1}, and for 1976-77 it increased to 12 m yr^{-1}. A positive feedback system now appears to be operating. The thinning near the terminus increases the likelihood that large embayments will form and the large embayments cause further thinning of the terminus area. Therefore, the glacier may be entering a period of calving instability.

Comparing the 1976-77 altitude change for the 42 to 60-km and 47 to 64.5-km reaches, gives average slope increases of about 0.7 m km^{-1} and 1.7 m km^{-1} respectively. Increased slope tends to increase ice velocity, whereas decreased thickness tends to decrease velocity. It is not yet known which effect is the more important here. Increased ice velocity, a negative feedback system, would serve to stabilize the glacier, but had not done so near the terminus from 1974 to 1977.

Table 4a. Columbia Glacier longitudinal profile

[Coordinates in meters]

1. Main Glacier

Longitudinal coordinate (km)	U T M zone 6 Easting	Northing	Local sea level X	Y
0	491,875.0	6,803,825.0	11,879.8	49,844.9
2	493,022.4	6,805,463.1	13,027.6	51,483.7
4	494,309.4	6,806,994.1	14,315.1	53,015.3
6	495,986.1	6,808,084.2	15,992.5	54,105.9
8	497,798.4	6,808,930.1	17,805.6	54,952.1
10	499,789.6	6,808,741.9	19,797.5	54,763.8
12	501,691.7	6,808,123.8	21,700.4	54,145.5
14	503,4289	6,807,132.9	23,438.3	53,154.2
16	505,150.4	6,806,114.8	25,160.5	52,135.7
18	506,671.2	6,804,815.9	26,681.9	50,836.3
20	507,897.1	6,803,235.6	27,908.2	49,255.3
22	508,748.6	6,801,426.0	28,760.1	47,445.0
24	508,435.7	6,799,460.6	28,447.1	45,468.8
26	507,728.8	6,797,577.7	27,739.9	43,597.2
28	507,110.8	6,795,677.6	27,121.6	41,694.3
30	506,345.4	6,793,829.8	26,355.9	39,845.8
32	505,609.1	6,791,970.3	26,619.4	37,985.5
34	504,991.1	6,790,068.2	25,001.1	36,082.6
35	505,147.6	6,789,080.5	25,157.6	35,094.5
36	505,364.0	6,788,092.8	25,314.1	34,106.4
38	505,770.9	6,786,148.1	25,781.2	32,160.9
40	505,152.8	6,784,246.0	25,162.9	30,258.1
42	503,738.6	6,782,831.7	23,748.1	28,843.3
44	501,956.6	6,781,923.8	21,965.4	27,934.9
46	500,338.6	6,780,748.2	20,346.7	26,758.9
48	498,702.3	6,779,598.2	18,709.8	25,608.4
50	497,066.0	6,778,4482	17,072.8	24,457.9

Table 4a. Columbia Glacier longitudinal profile--Continued

[Coordinates in meters]

Longitudinal coordinate (km)	U T M zone 6 Easting	Northing	Local sea level X	Y
52	496,075.1	6,776,710.9	16,081.5	22,720.0
54	495,762.2	6,774,735.5	15,768.5	20,743.8
56	495,950.4	6,772,744.4	15,956.8	18,751.9
58	496,508.4	6,770,823.8	16,515.0	16,830.5
60	497,388.3	6,769,027.8	17,395.2	15,033.8
62	497,824.6	6,767,075.9	17,831.7	13,081.2
64	497,918.8	6,765,078.1	17,925.9	11,082.6
66	497,360.8	6,763,157.6	17,367.7	9,161.2
68	496,262.7	6,761,486.9	16,269.2	7,488.9
70	495,244.7	6,759,764.5	15,250.8	5,766.8

2. East Branch

Longitudinal coordinate (km)	Easting	Northing	X	Y
E38	506,544.6	6,785,682.3	26,555.2	31,694.9
E36	508,065.4	6,786,981.1	28,076.7	32,994.3
E34	509,737.1	6,788,079.2	29,749.0	34,092.8
E32	511,355.1	6,789,254.8	31,367.6	35,268.9
E30	512,769.3	6,790,669.0	32,782.4	36,683.7
E28	513,760.2	6,792,406.2	33,773.7	38,421.6
E26	515,281.0	6,793,705.1	35,295.1	39,721.0
E24	517,077.1	6,794,585.0	37,091.9	40,601.3
E22	518,924.8	6,795,350.4	38,940.4	41,366.9
E20	520,465.9	6,796,625.2	40,482.1	42,642.3
E18	521,986.7	6,797,924.1	42,003.5	43,941.7
E16	523,465.9	6,799,270.2	43,483.3	45,288.3
E14	524,231.3	6,801,117.9	44,249.0	47,136.8
E12	524,168.5	6,803,116.9	44,186.2	49,136.6

Table 4a. Columbia Glacier longitudinal profile--Continued

[Coordinates in meters]

3. West Branch

Longitudinal coordinate (km)	U T M zone 6 Easting	U T M zone 6 Northing	Local sea level X	Local sea level Y
W52	495,144.2	6,776,637.6	15,150.2	22,646.7
W50	493,845.3	6,778,158.4	13,850.8	24,168.1
W48	491,943.2	6,778,776.5	11,947.9	24,786.4
W47	491,019.3	6,779,159.1	11,023.7	25,169.2
W46	490,128.3	6,779,613.1	10,132.3	25,623.4
W44	488,280.5	6,780,378.5	8,283.8	26,389.1
W42	486,378.4	6,780,996.5	6,381.0	27,007.3
W40	484,378.4	6,780,996.5	4,380.2	27,007.3
W38	482,403.0	6,781,309.4	2,404.0	27,320.3
W37	481,452.0	6,781,618.4	1,452.5	27,629.5
W36	480,998.0	6,782,509.4	998.4	28,520.8
W34	481,906.0	6,784,291.4	1,906.4	30,303.6
W32	482,524.0	6,786,193.6	2,525.0	32,206.4
W30	482,680.9	6,788,187.4	2,682.0	34,201.1

4. Middle West Branch

Longitudinal coordinate (km)	U T M zone 6 Easting	U T M zone 6 Northing	Local sea level X	Local sea level Y
MW30	504,902.2	6,793,841.2	24,912.1	39,825.1
MW28	503,213.9	6,794,912.8	23,222.8	40,929.2
MW26	501,214.5	6,794,975.7	21,223.0	40,992.1
MW24	499,239.1	6,794,662.8	19,246.8	40,679.1
MW22	497,287.3	6,794,226.5	17,294.2	40,242.6
MW20	495,317.1	6,793,882.6	15,323.2	39,898.6
MW18	493,325.9	6,793,694.4	13,331.3	39,710.3
MW16	491,405.3	6,793,136.5	11,409.9	39,152.1
MW14	489,668.1	6,792,145.5	9,672.0	38,160.8
MW12	488,322.1	6,790,666.3	8,325.4	36,681.0
MW11.45	487,951.9	6,790,259.5	7,955.1	36,274.0

Table 4a. Columbia Glacier longitudinal profile--Continued

[Coordinates in meters]

5. North East Branch

Longitudinal coordinate (km)	U T M zone 6 Easting	Northing	Local sea level X	Y
NE22	517,665.2	6,796,4966	37,680.3	42,513.6
NE20	517,571.0	6,798,494.4	37,586.0	44,512.2
NE18	516,982.9	6,800,406.0	36,997.7	46,424.5
NE16	516,701.1	6,802,386.0	36,715.8	48,405.4
NE14	517,692.0	6,804,123.3	37,707.1	50,143.3
NE12.55	518,410.4	6,805,382.8	38,425.8	51,403.3

Table 4b. Columbia Glacier transverse profile

[Coordinates in meters]

E 36-km profile, azimuth -64^g

Profile station (km)	U T M zone 6 Easting	U T M zone 6 Northing	Local sea level X	Local sea level Y
E36-0	506,993.7	6,788,669.8	27,004.5	34,683.6
E36-.5	507,261.7	6,788,247.6	27,272.6	34,261.3
E36-1	507,529.6	6,787,825.4	27,540.6	33,838.9
E36-2	508,065.4	6,786,981.1	28,076.6	32,994.3
E36-3	508,601.2	6,786,136.8	28,612.6	32,149.7
E36-3.8	509,029.9	6,785,461.3	29,041.5	31,473.9

Bumblebee profile, azimuth 82^g

Profile station (km)	Easting	Northing	X	Y
B0	508,138.7	6,781,539.0	28,150.0	27,550.0
B1	508,417.7	6,782,499.3	28,429.1	28,510.7
B2	508,696.7	6,783,459.6	28,708.2	29,471.4
B3	508,975.7	6,784,419.9	28,987.3	30,432.1

40-km profile, azimuth -46^g

Profile station (km)	Easting	Northing	X	Y
40-1	502,902.5	6,786,229.9	22,911.7	32,242.8
40-1.6	503,277.6	6,785,899.2	23,286.9	31,912.0
40-2	503,652.7	6,785,568.5	23,662.2	31,581.1
40-2.8	504,252.8	6,785,039.5	24,262.5	31,051.9
40-3	504,402.8	6,784,907.2	24,412.6	30,919.6
40-4	505,152.8	6,784,246.0	25,162.9	30,258.1
40-5	505,902.9	6,783,584.7	25,913.3	29,596.5
40-5.2	506,052.9	6,783,452.4	26,063.3	29,464.2
40-6	506,653.0	6,782,923.4	26,663.7	28,935.0
40-6.8	507,253.1	6,782,394.4	27,264.0	28,405.8
40-7	507,403.1	6,782,262.1	27,414.1	28,273.4

Table 4b. Columbia Glacier transverse profile--Continued

[Coordinates in meters]

Razor profile, azimuth 43^g

Profile station (km)	U T M zone 6 Easting	U T M zone 6 Northing	Local sea level X	Local sea level Y
R0	501,191.5	6,766,295.1	21,200.0	12,300.0
R1	501,971.9	6,766,920.3	21,980.7	12,925.5
R2	502,752.3	6,767,545.5	22,761.4	13,550.9
R3	503,532.7	6,768,170.7	23,542.1	14,176.4
R4	504,313.1	6,768,795.9	24,322.8	14,801.8
R5	505,093.5	6,769,421.1	25,103.5	15,427.3
R6	505,873.9	6,770,046.3	25,884.3	16,052.7

50-km profile, azimuth -70^g

Profile station (km)	Easting	Northing	X	Y
50-1	495,704.0	6,781,121.2	15,710.3	27,132.1
50-2	496,158.0	6,780,230.2	16,164.5	26,240.7
50-3	496,612.0	6,779,339.2	16,618.6	25,349.3
50-4	497,066.0	6,778,448.2	17,072.8	24,457.9
50-5	497,520.0	6,777,557.2	17,527.0	23,566.6
50-6	497,974.0	6,776,666.2	17,981.2	22,675.3
50-7	498,428.0	6,775,775.2	18,435.4	21,783.9

West 50-km profile, azimuth 80^g

Profile station (km)	Easting	Northing	X	Y
W50-1	493,227.3	6,776,256.3	13,232.6	22,265.2
W50-2	493,536.3	6,777,207.4	13,541.7	23,216.7
W50-3	493,845.3	6,778,158.4	13,850.8	24,168.1
W50-4	494,154.3	6,779,109.5	14,160.0	25,119.5
W50-5	494,463.3	6,780,060.6	14,469.1	26,071.0

54-km profile, azimuth 13^g

Profile station (km)	Easting	Northing	X	Y
54-1	494,783.0	6,774,532.7	14,788.9	20,540.9
54-2	495,762.2	6,774,735.5	15,768.5	20,743.8
54-3	496,741.4	6,774,938.3	16,748.1	20,946.7
54-4	497,720.6	6,775,141.1	17,727.7	21,149.6

Kadin profile, azimuth -109^g

Profile station (km)	Easting	Northing	X	Y
K0	493,394.6	6,764,695.7	13,400.0	10,700.0
K1	493,253.7	6,763,705.7	13,259.0	9709.6
K2	493,112.8	6,762,715.7	13,118.0	8719.2

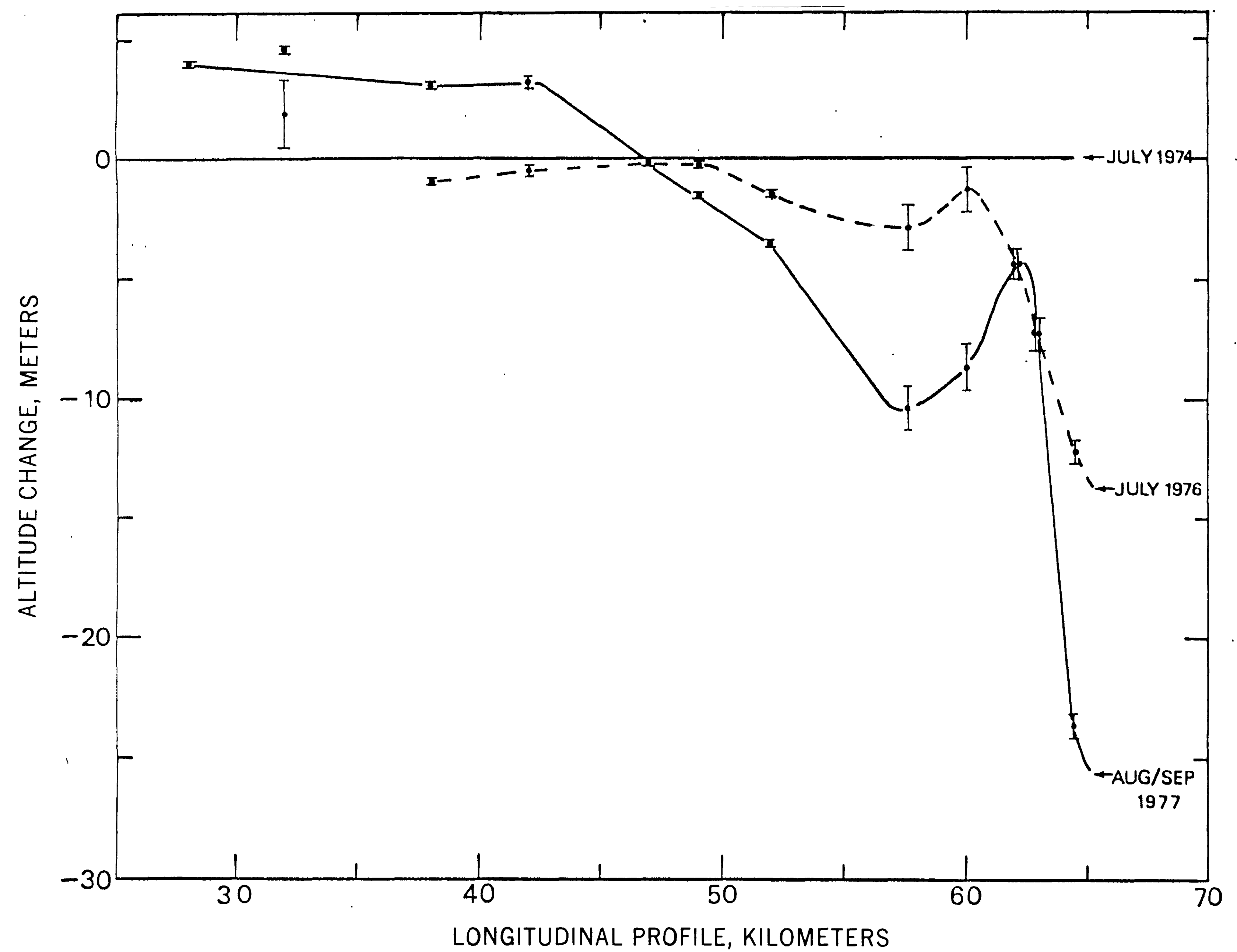


Figure 9. Altitude changes measured along the centerline of Columbia Glacier from July 1974 to July 1976 and to September 1977. Errors bars (vertical lines) include errors of measurement and errors due to difficulty in estimating local mean altitude of a rough surface.

Glacier thickening of 4 to 6 m above the 47-km point is undoubtedly due to the record-breaking deep 1976-77 winter snowpack (U. S. Geological Survey, 1977). At Wolverine Glacier, a U. S. Geological Survey research basin 100 km southwest of Columbia Glacier (Meier and others, 1971), the 1976-77 winter snowpack was about 10 percent greater than the previous high value (1969-70) in twelve years of record, and about twice the average snow accumulation. The measured snow balance at Wolverine Glacier in June 1977 was 4.6 m water equivalent. Aprroximately 6 m water equivalent of snow averaged over the glacier appears to have accumulated on Columbia Glacier during the 1976-77 winter.

In order to estimate the annual balance of Columbia Glacier averaged over longer periods than the 1977-78 measurement year, a search was made for earlier air photography showing equilibrium line conditions. Snowlines or equilibrium lines were plotted from this photography by E. A. Senear or Austin Post for the following dates: 8/2/50, 7/3/54, 7/9/57, 8/12/61, 8/26/63, 8/24/64, 8/25/65, 9/3/66, 8/24/68, 8/25/69, 9/1/70, 9/3/71, 9/10/72, 9/3/73, 9/3/74, and 9/6/75. These data will be compared with mass-balance data and equilibrium lines from other Alaskan glaciers.

AIRBORNE STUDIES

Aerial Photography Program

by David Frank and David Hirst

High- and low-altitude vertical photographs and low-altitude oblique photographs were taken of Columbia Glacier (table 5) and 20 other calving glaciers (table 6) during October 1976 through September 1977. These aerial photographs are being used to map changes and ice velocity in the terminus areas of many calving glaciers and to calculate the ice velocity and changes of thickness in the lower part of Columbia Glacier.

Surface Ice Velocity Using Aerial Photography

by M. F. Meier and W. G. Sikonia

Surface velocity and thickness change of the lower Columbia Glacier are essential data for any modeling of behavior of the glacier in the immediate future. The lowest part of the glacier flows with surface speeds ranging between about 2 and 6 $m\ d^{-1}$ and is an area of rapidly extending flow, thus the ice is very heavily crevassed. The rapid motion and the high degree of crevassing permit remote measurements of surface velocity and thickness change using aerial photography. It is possible to select recognizable points (normally the distinctive angle and pattern of crevasse intersections) on two or more sets of aerial photographs. By measuring the change of position of these particular features on the surface, displacements and thus velocities during that period can be measured. This method does not rely on debris patches or surface markings, and therefore is usable both in summer and in winter.

The method was first attempted using transparencies on a light table in the office. Aerial photographs from missions flown in July, October, and November of 1976 were enlarged on transparent mylar to a scale of 1:20,000 by matching the shorelines around Columbia Bay shown on a map to that scale. By laying one enlargement on another and

Table 5. Aerial photography of Columbia Glacier through November 8, 1977

[v=vertical; o=oblique. Flight altitudes are given in meters for vertical photographs]

LOCATION	DATE										
	10/1/76	11/17/76	1/19/77	3/7/77	4/23/77	6/2/77	7/7/77	7/15/77	8/30/77	9/3/77	11/8/77
Terminus	v	v	v	v	v			v, o		v, o	
	5500	5500	5500	5500	5500			3100		3000	
Lower 14 km						v	v		v		v
						5500	7000		7000		7000
Middle Glacier											v
											8200*
West Lakes								v, o		v, o	v
								3100		3000	7000

*Only partial coverage

Table 6. Aerial photography of calving glaciers other than Columbia Glacier

[v=vertical; o=oblique. Flight altitudes are given in meters for vertical photographs]

GLACIER	DATE (all are 1977)									
	7/12	7/15	7/16	7/17	8/20	8/30	8/31	9/1	9/2	9/3	10/1
Portage		v, o 2000						v 2600		v 1700	
Harvard		v, o 3800								v, o 12-2600	
Yale										v, o 12-2600	
Meares		v, o 3800								v 8-2600	
Tsaa			o		v 8500		v, o 3300		o		
Guyot			o		v 8500		v, o 3300		o		
Yahtse			o		v 8500		v, o 3300		o		
Tyndall			o		v 8500		v, o 3300		o		
Turner	o		o		v 8500		v, o 2100		o		v 8500
Hubbard	o 17-2200		o	8500	v		v		o		v
Grand Pacific				v, o 1700				v, o 3000	o		
Margerie				v, o 2700				v, o 3000			
Johns Hopkins				v, o 2600				v, o 2900	o		
Muir				v, o 2800			v 2700	v 2900	v 7000		
Brady			o					v, o 3000			
Taku	v, o 4400					v, o 4500		v, o			
Sawyer	v, o 2600					v, o 2600					
S. Sawyer	v, o 2600					v, o 2600					
Dawes	v, o 1700					v, o 1700					
LeConte	v, o 22-2600					v, o 2200					

then shifting it relative to the other it was possible to superimpose crevasse intersections in a local region of glacier. The relative displacement of one image relative to the other, based on the fixed shoreline points, gave a measure of the displacement of the ice during this period of time. Several variations on this method were tried, including the use of a positive transparency of one date and a negative transparency of another date. All methods worked, and in fact it was not difficult to derive useful velocity values using this simple office procedure. Thus, it seemed likely that this procedure could be automated and made more precise by the use of photogrammetric plotting instruments.

This possibility was discussed with Randle Olsen and others of the Geological Survey's Topographic Division in Menlo Park; they were eager to participate in such a trial project. We supplied a grid of locations where we wished data points, together with diapositives of the photography and control data. They located recognizable features near each data point, transferred these feature identifications from one stereo pair of images for one date to another stereo pair of images for another date, drilled tiny holes to mark these locations, and then measured their xyz coordinates according to a local stereo model controlled by known survey stations. The plotter used for these measurements is tied in to a computer system which then calculates the coordinates of the points on the glacier surface in a standard UTM coordinate system and supplies the results in the form of a deck of cards. In addition to measuring the surface coordinates, the photogrammetrist also measured a series of points along the terminus of the glacier in order to map the terminus position, and measured a number of points to determine elevations of the surface of Terentiev Lake.

In using aerial photography taken at 5500 m altitude, the accuracy of determination of coordinate locations is thought to be about 2 m in both horizontal and vertical directions; displacements are thus determined with an accuracy of about $2\sqrt{2}$m, ~3 m. As the glacier flows 2 to 6 m d^{1} near the terminus, it is obvious that this accuracy is sufficient for measurements of velocity over a period of a few weeks. The vertical changes which are measured are influenced by ablation and are not the true vertical velocities of the ice. However, this method does permit the measurement of changes of the surface altitude of the ice which are significant over periods of several months. Upglacier from the terminus, a slightly higher flight altitude is required and the crevassing is neither as distinctive nor as pervasive, and therefore the accuracy is slightly decreased. One problem which was encountered relates to the large amount of strain as the glacier extends over the moraine shoal. In many cases crevasse-related features visible in one photograph could not be identified in the next due to the enormous strains and ablation occurring in the month or so between two sets of aerial photography.

The data-collection plan was designed to obtain data about every 6 weeks during the whole period of the experiment for the lowest 4 km of Columbia Glacier (table 7). As the lowest kilometer was most difficult, this was measured only once in 1977, and it will be measured once more in 1978. The purpose of analyzing repetitively the lowest part of the glacier is to measure the change in velocity with time, data which are critical for studies of the changing stability of the glacier terminus. In addition to these studies, the lowest 14 km of the glacier (from 53-67 km) will be analyzed several times during the year to determine seasonal changes in motion. Experiments will be conducted to try to measure the velocity over the reach from 35 to 53 km and at selected locations further upglacier; however, it is likely that the velocity will not be sufficiently high nor the persistence of features sufficiently long to obtain good data in these upglacier regions.

Table 7. Number of points measured for determination of velocity by aerial photography

		REACH (km)			
DATE	STATUS*	66-67	62-66	53-62	35-53
7/24/76					
	c	14	118		
10/1/76					
	c	16	52		
11/17/76					
	c	16	48		
1/19/77					
	c	15	48		
3/7/77					
	c	19	41		
4/23/77					
	c	77	80		
6/2/77					
	p	75	75	180	
7/7/77					
	p	15	60	180	
8/30/77					
	p	15	60	180	
11/8/77					
	f	15	60	180	
1/15/78					
	f	15	60	180	
4/15/78					
	f	15	60	180	150
7/7/78					
	f	75	60		
8/30/78					

* c=completed
p=planned, photography obtained
f=planned for future photography

A typical example of the results from this velocity study using aerial photography is shown in figure 10. This plot shows the direction and magnitude of the surface velocity in the horizontal plane. Figure 11 shows the variation with time of velocity in the center of the glacier, and figure 12 shows the change in ice surface altitude from 1974 to 1976. In addition it is possible to display many other interesting features of the flow from the Columbia Glacier by using computer plotting programs. For example, contour plots can be made of speed or longitudinal velocity components or strain rates; the directions and magnitude of principle strain rate components can also be plotted. The data can then be used as boundary conditions or as verification for models which attempt to predict the future behavior of Columbia Glacier.

Radio-Echo Sounding

by R. D. Watts

A portable radio-echo sounder for use on a temperate glacier was developed for Columbia Glacier work in 1974 (table 8a, 8b) (Watts and others, 1975; Watts and England, 1976). This sounder required that transmitting and receiving antenna wires be stretched out on the ice surface. Due to the extensive crevassing such a system, or any other ground-based system, can not be used over most of the lower part of the Columbia Glacier to obtain the data necessary for the predictive modeling of the dynamics of the glacier. Thus development was begun on an airborne system.

All major electronic elements in the system have been received. The navigation system has been successfully tested in its basic range-range configuration aboard the Porter airplane. The navigation data processor is being tested and will soon be installed and tested in the airplane.

The critical elements at this point are the following hardware items: antenna, transmitter, transmit/receive switch, and variable-gain amplifiers. We have discussed the technical problems involved in design of these elements with experts in the field, and are considering contracts for the design of the system elements. At this point, this plan seems to be the most expeditious way to have a system built and flying before the 1978 field season.

The echo-sounding system has been designed so that we will be able to obtain polaroid pictures in the field which look like glacier cross-sections.The profiles will be recorded and can be played back at various horizontal and vertical scales for field examination and profile planning. The primary data will be recorded on magnetic tape for later computer processing, including deconvolution and plotting.

MODELING

Estimation of Flow Variables

by M. F. Meier and E. A. Senear

Values of ice thickness, discharge, velocity, width, and surface slope were estimated for two reasons. First, sensitivity analyses must be made in order to determine the accuracy of field measurements needed to satisfy modeling requirements. Second, numerical models need approximate values for "tuning up" and evaluation in order to

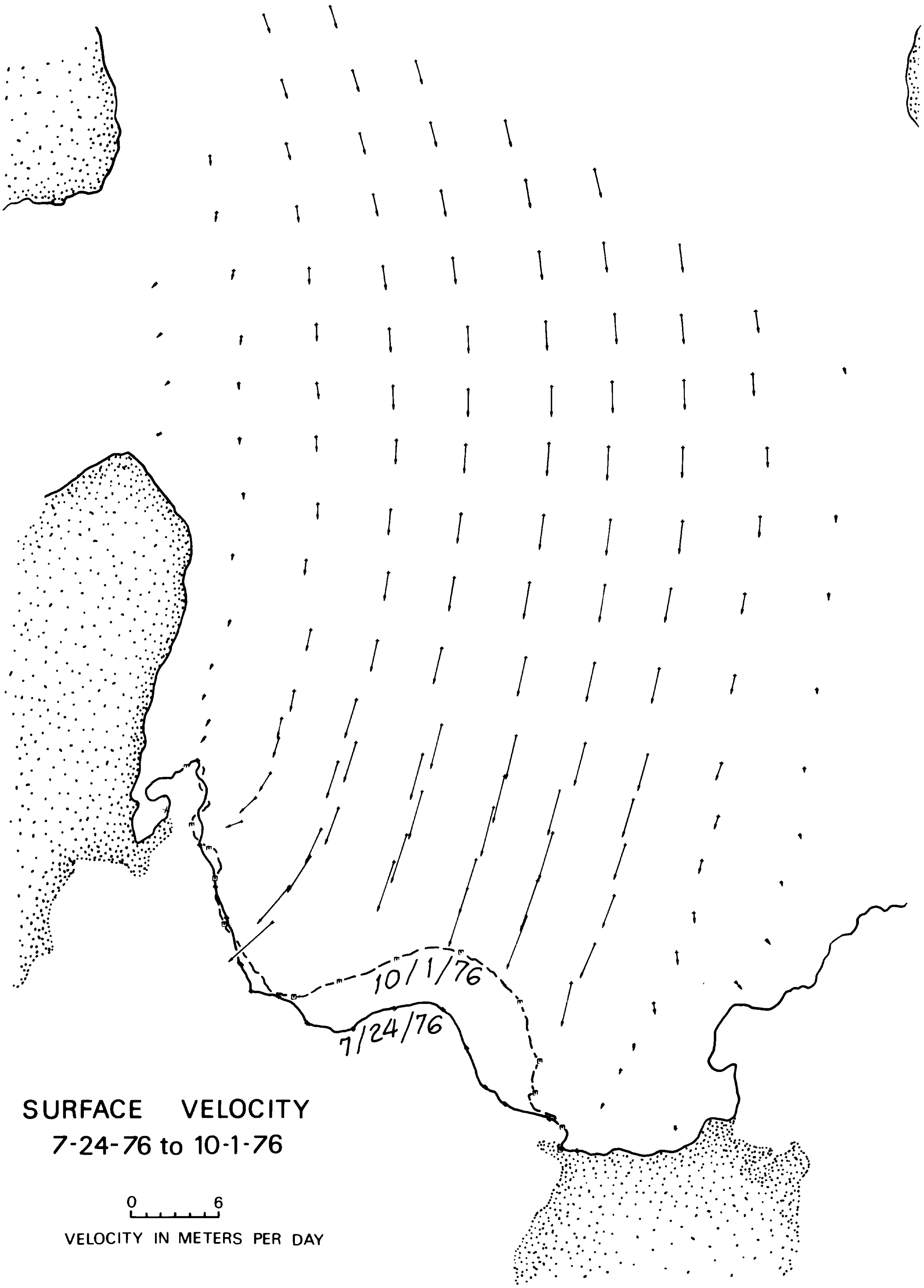


Figure 10. Velocity vectors by aerial photographs 07/24/76 to 10/01/76. Measurement error is about 0.04 md^{-1}.

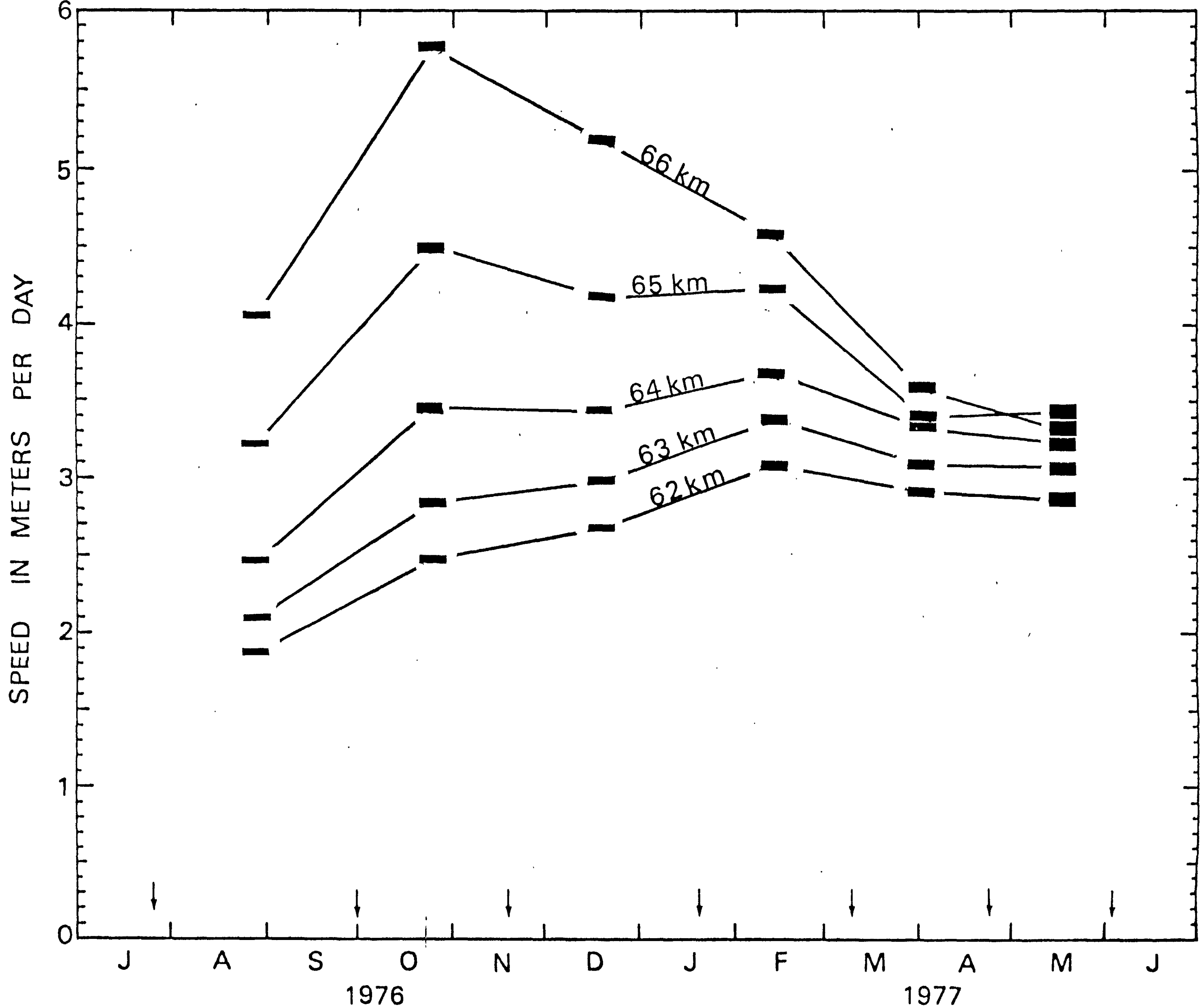


Figure 11. Speed of ice flow along the centerline as a function of time. Distances (in km) are from head of glacier; terminus is between 66 and 67 km depending on date. Arrows indicate times of air photography used in measuring speed. Small rectangles represent average speed between times of photography, lines serve only to connect these rectangles. Measurement error is given by height of rectangle.

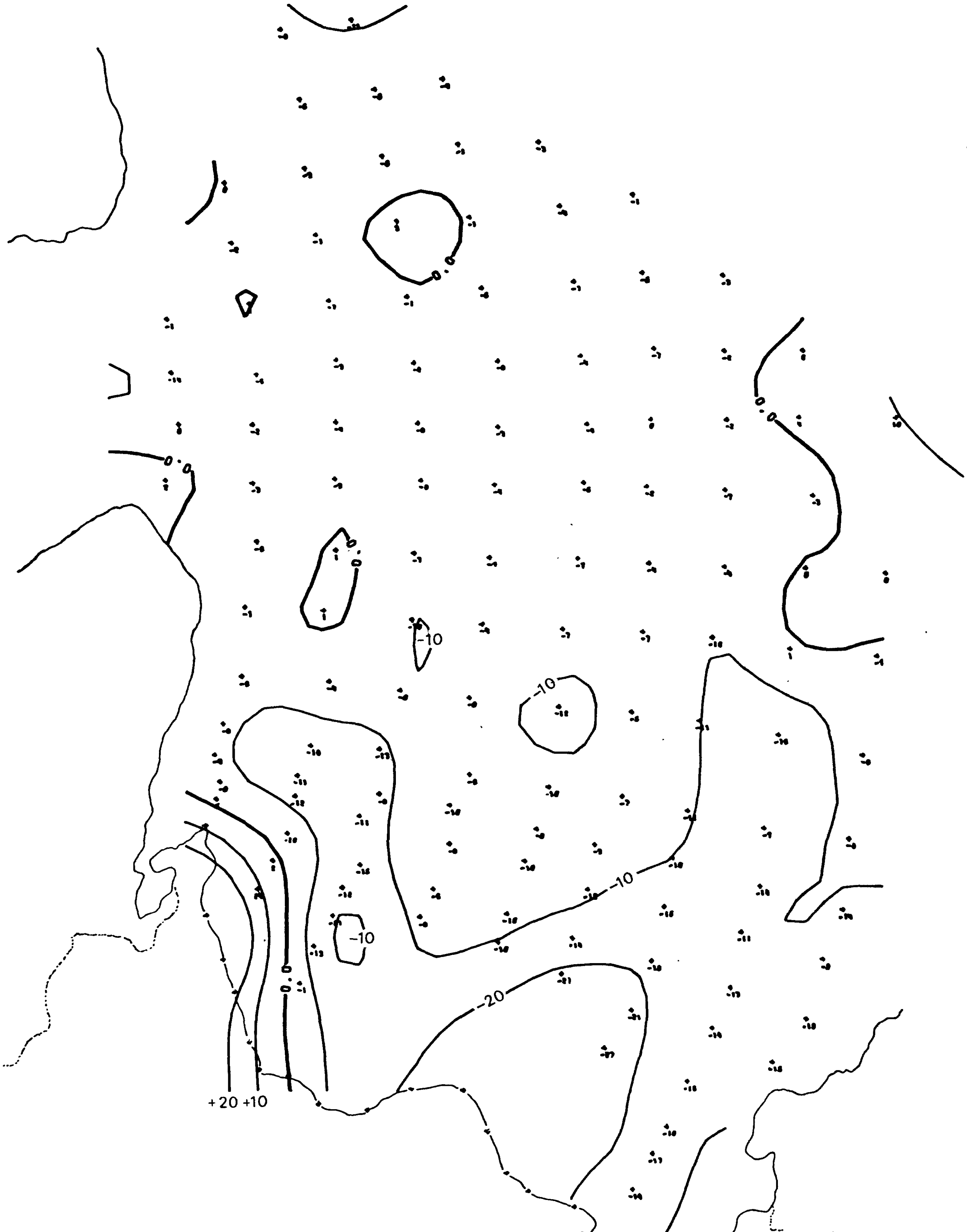


Figure 12. Surface height change in meters, 1974 to 07/24/76. Measurement error is about 5.8 m, largely due to error in 1974 mapping.

Table 8a. Coordinate locations of 1974 ice thickness measurement stations

[Surveys based on 1977 control surveys. All values in meters]

	UTM zone 6		Local sea level		Surface
Station	Easting	Northing	X	Y	altitude
G1	496365.7	6764675.6	16372.2	10679.9	189.5
G2	496631.8	6765499.5	16638.5	11504.1	192.3
G3	496692.1	6766444.4	16698.8	12449.4	199.0
G4	496595.8	6767458.0	16602.4	13463.4	232.9
G5	496857.9	6768467.1	16864.7	14472.9	257.2
G6	496954.2	6769387.9	16961.0	15394.1	266.3
G7	496929.9	6770344.3	16936.7	16350.8	273.5
G8	496698.9	6771256.5	16705.5	17263.4	302.4
G25	497600.3	6779318.8	17607.3	25328.9	560.7
G26	497534.7	6779610.5	17541.7	25620.8	568.9
G27	497407.2	6779864.7	17414.2	25875.1	574.2
G28	497210.0	6780217.3	17216.9	26227.8	575.1
G29	497043.4	6780560.9	17050.2	26571.5	574.3
G30	496888.2	6780924.7	16894.9	26935.4	571.6
G31	496710.4	6781296.8	16717.1	27307.7	569.2
G32	496485.2	6781784.0	16491.8	27795.1	559.1
G33	496312.6	6782086.1	16319.1	28097.3	561.5
G34	496184.8	6782227.5	16191.3	28238.8	553.4
G35	495975.8	6782192.5	15982.2	28203.8	556.8
G36	496228.5	6782175.0	16235.0	28186.3	553.0
G37	497820.1	6777967.5	17827.3	23977.1	525.6
G38	497492.4	6778517.0	17499.4	24526.8	527.2
G39	497312.1	6778341.8	17319.1	24351.5	523.5
G40	497066.3	6778109.8	17073.2	24119.5	516.5
G41	496740.9	6777789.5	16747.6	23799.0	505.4
G42	496502.9	6777497.8	16509.5	23507.2	496.8
G43	496271.3	6777161.8	16277.8	23170.6	487.5
G43.5	496186.1	6776999.0	16192.6	23008.2	485.2
G44	496063.5	6776762.0	16070.0	22771.1	483.9
G45	495993.8	6776637.5	16000.2	22646.6	483.0
G46	496844.5	6764769.0	16851.3	10773.3	191.2
G47	496922.7	6765161.8	16929.5	11166.3	193.4
G48	496929.9	6765434.1	16936.7	11438.7	195.4
G50	497062.7	6765963.7	17069.6	11968.5	201.2
G51	497065.6	6766279.2	17072.3	12284.1	205.3
G52	497096.3	6766834.9	17103.2	12840.1	210.5
G53	497346.8	6767425.2	17353.8	13430.5	227.8
G54	497260.2	6767894.5	17267.1	13900.1	238.1
G55	497162.9	6768488.0	17169.8	14493.8	253.5
G56	497247.0	6769073.9	17253.9	15080.0	271.6
G57	497240.1	6769511.3	17247.0	15517.5	274.6
G58	497220.4	6770036.7	17227.3	16043.1	269.7
G59	497234.2	6769872.8	17241.1	15879.1	271.1
G60	497248.0	6768792.7	17254.9	14798.6	264.9
G61	497288.8	6768403.6	17295.7	14409.4	251.7

Table 8a. Coordinate locations of 1974 ice thickness measurement stations--Continued

[Surveys based on 1977 control surveys. All values in meters]

Station	UTM zone 6 Easting	UTM zone 6 Northing	Local sea level X	Local sea level Y	Surface altitude
G62	497281.0	6770413.9	17287.9	16420.4	278.5
G63	497351.1	6771023.9	17358.1	17030.7	292.3
G64	497395.9	6771478.7	17402.9	17485.7	302.8
G65	501626.6	6778528.1	21635.2	24537.9	567.7
G66	497984.1	6779353.0	17991.3	25363.2	550.5
G67	499437.6	6780322.3	19445.4	26332.9	592.4
G69	502188.3	6783277.9	22197.1	29289.6	645.3
G70	503842.0	6782632.7	23851.5	28644.1	640.0
G72	502331.3	6785895.0	22340.3	31907.7	680.5
R1	498654.6	6776024.4	18662.1	22033.2	530.6
R2	498674.0	6776125.1	18681.5	22134.0	535.9
R3	498691.7	6776223.4	18699.2	22232.3	538.4
R5	498663.0	6776392.5	18670.5	22401.4	538.9
R6	498649.8	6776474.1	18657.2	22483.1	538.6
R7	498618.8	6776556.7	18626.3	22565.7	539.5
R8	498596.2	6776626.9	18603.6	22636.0	539.3
R9	498584.4	6776707.8	18591.8	22716.9	538.5
R10	498590.2	6776793.5	18597.6	22802.7	537.5
R12	498591.5	6776962.2	18598.9	22971.3	535.2
R13	498570.5	6776046.1	18577.9	23055.3	534.3
R14	498496.0	6777168.1	18503.4	23177.4	531.5
R15	498439.1	6777318.7	18446.5	23328.0	528.8
R16	498306.4	6777615.1	18313.7	23624.5	526.8
R17	498244.9	6777759.8	18252.2	23769.3	527.5
R18	498117.4	6778018.5	18124.8	24028.2	527.4
R19	498069.5	6778135.6	18076.7	24145.3	526.8
R20	498006.3	6778283.8	18013.5	24293.4	528.3
R21	497972.4	6778376.1	17979.6	24385.9	528.0
R22	497928.5	6778498.1	17935.6	24507.9	5.7.6
R23	497771.4	6778772.9	17778.5	24782.8	530.3
R24	497629.2	6779093.9	17636.3	24103.9	551.1
R102	501749.1	6782642.8	21757.8	28654.2	634.2
R103	501335.2	6782281.8	21343.7	28293.1	625.2
R104	500929.7	6782020.1	20938.1	28031.4	614.2
R109A	506822.4	6785704.5	26833.2	31717.2	689.7
R109B	507008.1	6785640.9	27019.0	31653.5	691.9
R110	506486.5	6785848.3	26479.1	31861.0	691.4
R111	506212.8	6785977.5	26223.3	31990.3	702.9
R112	505904.3	6786105.9	25914.7	32118.7	702.4
R113	505552.3	6786250.1	25562.4	32263.0	707.6

Table 8b. 1974 radar ice thickness measurements

[Ice thickness usually applies to a point between two measurement stations. Coordinates of measurement stations are given in table 8a. Thickness data were not obtained at all measurement stations and some thickness measurements were made from unsurveyed stations.]

Stations	Thickness (m)	Stations	Thickness (m)
G 1 - 2	219	G 46 - 47	600
G 2 - 3	269	G 47 - 48	567
G 3 - 4	318	G 48 - 49	642
G 25 - 26	749	G 49 - 50	613
G 26 - 27	765	G 50 - 51	706
G 27 - 28	708	G 51 - 52	765
G 28 - 29	820	G 52 - 53	711
G 29 - 30	807	G 53 - 54	687
G 30 - 31	810	G 54 - 55	714
G 31 - 32	602	G 55 - 56	767
G 32 - 33	305	G 56 - 57	713
G 33 - 34	450	G 57 - 58	722
G 38 - 39	855	G 58 - 59	700
G 39 - 40	793	G 60 - 61	725
G 40 - 41	805	G 62 - 63	788
G 41 - 42	735	G 63 - 64	775
G 42 - 43	861	R 4 - 5	351
G 43 - 44	1117	R 5 - 6	407
G 44 - 45	1062	R 6 - 7	454

Table 8b. 1974 radar ice thickness measurements--Continued

Stations	Thickness (m)	Stations	Thickness (m)
R 7 - 8	560	R 100 - 101	883
R 8 - 9	567	R 101 - 102	960
R 9 - 10	585	R 102 - 103	873
R 10 - 11	657	R 103 - 104	806
R 11 - 12	688	R 104 - 105	808
R 12 - 13	607	R 105 - 106	808
R 13 - 14	639	R 107 - 108	825
R 14 - 15	631	R 108 - 109	959
R 15 - 16	855	R 117 - 110	892
R 16 - 17	798	R 114 - 115	859
R 17 - 18	999	R 114 - 116	926
R 18 - 19	992		
R 22 - 23	972		
R 23 - 24	851		

produce results as soon as possible after the completion of the field measurement program.

A sensitivity analysis for determining field data collection accuracies had to be made before any numeric modeling was performed. Modeling requirements were estimated by assuming that discharge was the basic flow quantity, and that four flow parameters were required (two associated with the Glen flow-law for internal ice deformation, two associated with basal sliding or ice to rock coupling). Data accuracy requirements were studied by noting the effects of differing data accuracies when used in four discharge equations to determine the flow parameters. The four equations are:

$$(1)\quad Q(35) + Q(E35) + \Delta Q(35\text{-}41) = Q(41)$$

$$(2)\quad Q(41) + \Delta Q(41\text{-}50) = Q(50)$$

$$(3)\quad Q(50) + Q(W50) + \Delta Q(50\text{-}54) = Q(54)$$

$$(4)\quad Q(54) + \Delta Q(54\text{-}60) = Q(60)$$

where Q is discharge through a cross-section at the longitudinal coordinate indicated by numbers in parentheses (E is East Branch and W is West Branch), and ΔQ is the change in discharge (due to thickness change and annual mass balance) between two cross sections.

Calculation of Q requires data on thickness and surface velocity (in addition to width and slope, which can be read off maps with high accuracy); ΔQ requires data on rate of change of thickness and annual balance, in addition to width. A thickness of 30 m was assumed; this cannot be reduced appreciably due to radio-echo sounder limitations. Combinations of errors in other measurements were applied in order to minimize error in discharge at the four cross-sections without causing unworkable restrictions on the field program. The following errors were found to be tolerable for calculating flow parameters and were used in the design of the field program: thickness 30 m, surface velocity $3my^{-1}$, balance $0.2my^{-1}$ (ice equivalent), thickness change $0.2my^{-1}$. Combining all these errors affects the discharges at 4 cross-sections as shown in table 9. Thus, the existing program should allow measurement of discharge to within about 4 to 6 percent, assuming sufficient data density.

Table 9. Effects of measurement error on discharge at four cross-sections

Cross section (km)	Estimated discharge ($x10^3m^3y^{-1}$)	Discharge error ($x10^3m^3y^{-1}$)	Discharge error Percent
41	1240	49	4.0
50	966	56	5.8
54	1288	54	4.2
60	1123	49	4.3

The modeling programs will attempt to fit velocity, thickness, or discharge most closely in the lower reaches of the glacier, so that the specified errors will be slightly relaxed in the upper reaches and tightened in the lower reaches.

For the purpose of evaluating different models, values of centerline thickness and velocity were estimated for those parts of the glacier where no radio-echo sounding data exist. Thickness, h, was calculated from

$$h = \frac{\tau}{f \rho g \sin \alpha}$$

where τ is the basal shear stress, f a cross-section shape factor, ρ ice density, g gravitational acceleration, and α surface slope. An average value for τ of 1.1 bars was used for computing thicknesses in unmeasured areas. This value was calculated for the lower glacier where ice thicknesses are known. Surface slope was smoothed over 10 km. Velocity u was calculated from

$$\frac{u}{h} = \frac{n+1}{n+2} 0.11 \tau^n$$

with $\tau = 1.1$ and $n = 2.5$ (Budd and Jenssen, 1971). A map of the bedrock topography (contour interval 100 m) was drawn on the basis of radio-echo sounding data (table 8b) and these thicknesses, controlled by the assumption of a parabolic cross section.

In order to facilitate experiments with different glacier flow models, an idealized one-dimensional unbranched equivalent to Columbia Glacier was constructed. This construct was limited to the main and middle west branches of Columbia Glacier, excluding the east and west branches and all small tributaries to the main branch. A table of mean thickness $\bar{h}$, width, and balance for each kilometer of the main branch was compiled. The previously calculated h was used to determine $\bar{h}$ ($\bar{h} = 2/3h$), the width was measured from a map and balance was taken from an estimated Columbia Glacier balance curve produced by L. R. Mayo. The discharge from 0 to 62 km was calculated, and then scaled to agree with a discharge based on known thickness and surface velocity at 62 km ($1.1 \times 10^6 m^3 y^{-1}$).

Finite Element Modeling

by W. G. Sikonia

An investigation of glacier stability in the lower reaches of Columbia Glacier has been initiated, but this is an area of abrupt changes in ice thickness. Available finite-difference models of ice flow probably will not work in this local area. Two existing finite element computer programs have been acquired: one from William F. Schmidt of the University of Maine, and one from Charles F. Raymond of the University of Washington. Both programs are two space-dimensional glacier-flow models for a given instant. The Schmidt model was written for an IBM 370 computer, and has been loaded into a Geological Survey IBM 370 in Reston; the Raymond model is on the CDC 6400 at the University of Washington. To date we have made trial runs with the Schmidt model for both vertical and horizontal two-dimensional glacier sections. In particular, a comparison of a computed surface flow pattern with that observed by photogrammetric means near the terminus has produced favorable results. The program allows boundary conditions of velocity or force at nodes, as well as the specification of element body and surface stresses. Interior nodes are determined automatically from boundary nodes by a grid-generation program, and a variety of plots depicting results can be made, including plots of velocity vectors, stresses, and strain rates. Raymond has also run his model successfully for a vertical section of Columbia Glacier.

The goal of this research is to investigate the stability of the glacier i. e., to try to determine (1) why Columbia Glacier has been able to maintain its present position for so long, (2) what conditions would be sufficient to cause a catastrophic retreat, and (3) whether such conditions will occur within the next ten years.

Regarding future work, it will probably be necessary to add time to the model as an independent variable.Appropriate representations of sliding and calving must be specified. It may prove feasible to investigate a three-space dimensional model.

A Simple Model of Instability of a Calving Glacier Terminus

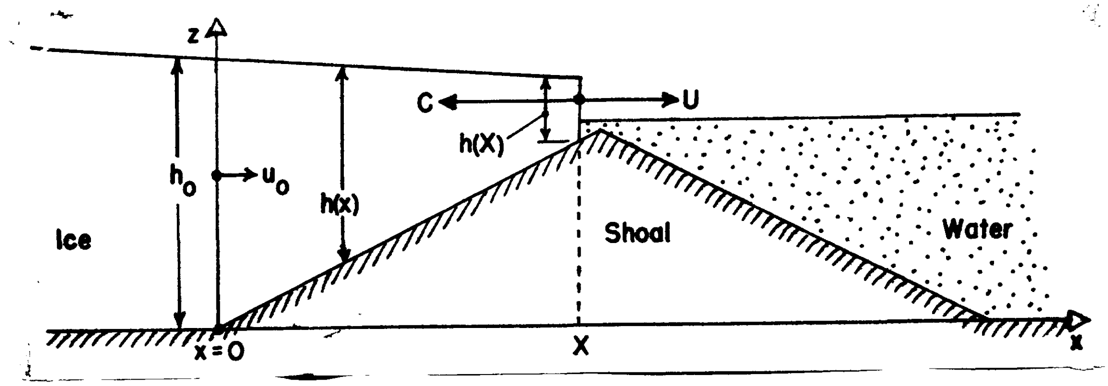
by S. M. Hodge

Calving glaciers that are stationary, are retreating slowly, or are advancing terminate on a shoal, whereas those that are retreating rapidly terminate in deep water. Termination on a shoal may lead to an instability; should the terminus start to retreat from the shoal it continues to do so at an ever-increasing rate. It is commonly thought that such instability is caused by a calving rate which increases with increasing water depth or increasing total height of the ice front. Such a hypothesis is not necessary however. Instability can be modeled by considering only the effect of the equation of continuity and the unique situation of *extending* flow which occurs at the terminus of such a glacier.

As the ice moves up the shoal, the ice thickness decreases. The change is more rapid than can be compensated for by surface ablation, and as a result the ice velocity increases as the terminus is approached. Because the rate of change of the terminus position, $\dot{X}$, must equal the difference between the calving rate, C, and the ice velocity, U, at the terminus:

$$\dot{X} = U - C,$$

any value of U less than C will cause the front to recede into a region of even smaller ice velocity. This in turn causes an increase in the rate of recession and instability results.



A simple numerical model is deveoped by assuming an infinitely wide glacier, whose thickness does not change with time, and in which all the ice motion over the shoal is due to sliding. Using continuity to calculate U, we transform this equation into

$$\dot{X} = \frac{u_o(t)\, h_o + b(t)\, X}{h(X)} - C(t)$$

where u_o and h_o are the ice velocity and thickness, respectively, at x=0. The mass balance of the surface, b, is assumed to be independent of x; this is a reasonable assumption near the terminus. The ice thickness h(x) is calculated from specified surface and bed profiles. The ice velocity u_o, the balance b, and the calving rate C are assumed to vary seasonally.

Solutions X(t) are calculated for different shoal profiles and different mean values, amplitudes, and phases of the funtions $u_o(t)$, b(t), and C(t). Initially the front is assumed to be at the peak of the shoal. As time progresses, $\dot{X}$ can, in general, be positive or negative depending on the relative values of u_o, b, and C. If X is positive, the terminus advances; if negative, it retreats. If the terminus were to advance over the crest of the moraine, the intense fracturing which would occur there probably would cause disruption of the glacier. The solution has not been allowed to move the terminus beyond the crest.

Three response modes are found: stable, permanently unstable, and temporarily unstable. In the stable mode the terminus never recedes from the top of the shoal. In the permanently unstable mode the terminus recedes so far initially that it never regains the top of the shoal one year after recession started; during the first few years it may oscillate between recession and partial readvance, but eventually it goes into continuous and catastrophic retreat. In the temporarily unstable mode the terminus recedes slightly during part of the year but regains the top of the shoal within a year; on a long-term basis the glacier is thus stable.

The solutions demonstrate that the transition from temporarily to permanently unstable is extremely sensitive to numerical values of the parameters. The presence of seasonal embayments at a calving glacier terminus, which may be related to seasonal changes in ice velocity and calving rate, should therefore be taken as a "danger signal"; only a very slight change in one of the parameters may well be sufficient to initiate a catastrophic retreat. It must be emphasized, however, that this simple model does not yet explain the complex three-dimensional geometry of embayment formation.

One-Dimensional Columbia Glacier Calculations

by L. A. Rasmussen

Using estimated bed topography and surface mass balance, and measured surface topography, the glacier-flow model described in Rasmussen and Campbell (1973) was applied to the centerline of an idealized one-branch glacier that is, as nearly as possible, equivalent to the Columbia Glacier. The model contains four flow parameters: a parameter indicating the selection of several recently proposed laws of glacier flow, the power-law exponent included in these laws, a bed-friction coefficient, and an ice-to-ice shear-viscosity coefficient. The measured discharge at 62 km was used as a downstream boundary condition, and this one-dimensional version of the model was run until steady-state equilibrium was reached.

Only the four flow parameters were adjusted (not the topography, balance, or the discharge at 62 km) until a steady-state thickness profile was produced that agreed with the actual centerline thickness profile, especially in the 40- to 62-km section where the Columbia Glacier is itself a one-branch glacier. The model results thus obtained still exhibit a substantial and systematic difference from the actual profile (fig. 13). The gradient of the difference from 40 km (+100 m) to 62 km (-100) is 200 m in 20 km, or about one half of one degree. The possible causes of the difference include:

-the model is inherently incorrect; for example, it does not include sliding at the bed.

-the reduction of the calculation to one dimension is not valid; the full (two-dimensional) model does not combine tributaries linearly, which is how the "equivalent" one-branch glacier was formed.

-the adjustment of the four flow parameters was not optimum; however, studying the variation of each parameter over the reasonable range of its values does suggest that the optimum adjustment, within these reasonable ranges, would not differ significantly from the best fit obtained. See, for instance, figure 14.

-the error in the computer results is large; rigorous hand checking suggests the absence of analysis or programming errors, in a steady-state solution the rounding error is always exceedingly small, and an examination of the truncation error showed it also to be small.

-the glacier is not in steady-state equilibrium with the assumed balance data.

-the glacier is not in steady-state equilibrium with any balance; the recently observed dh/dt is negative in the 50- to 62-km section.

-the assumed bed topography is incorrect.

-the discharge at 62 km is incorrect.

-the difference represents an actual physical phenomenon; that is, the glacier is divesting itself of a large quantity of mass.

STATUS: PROGRESS AND PROBLEMS

by M. F. Meier

This program was designed to produce quantitative, predictive statements about future iceberg production as soon as possible. In almost all respects the first summer's field work went very well. Some data-gathering sub-projects, such as the hydrographic sounding at Columbia Glacier, are now virtually complete. Some sub-projects, such as the measurement of ice flow and balance, are on schedule but require observations in 1978 for completion. Some other sub-projects, such as ice-thickness measurements, are not scheduled until 1978. No major delays or difficulties in data acquisition have appeared. Progress in the modeling of ice-flow dynamics has proceeded well. Development of an airborne radio-echo sounder progressed much as expected, although the first attempts to produce a transmit-receive switch were not successful.

One major problem in understanding exists: the mechanics (and thus the predictability) of calving, which may lead to the formation of embayments.

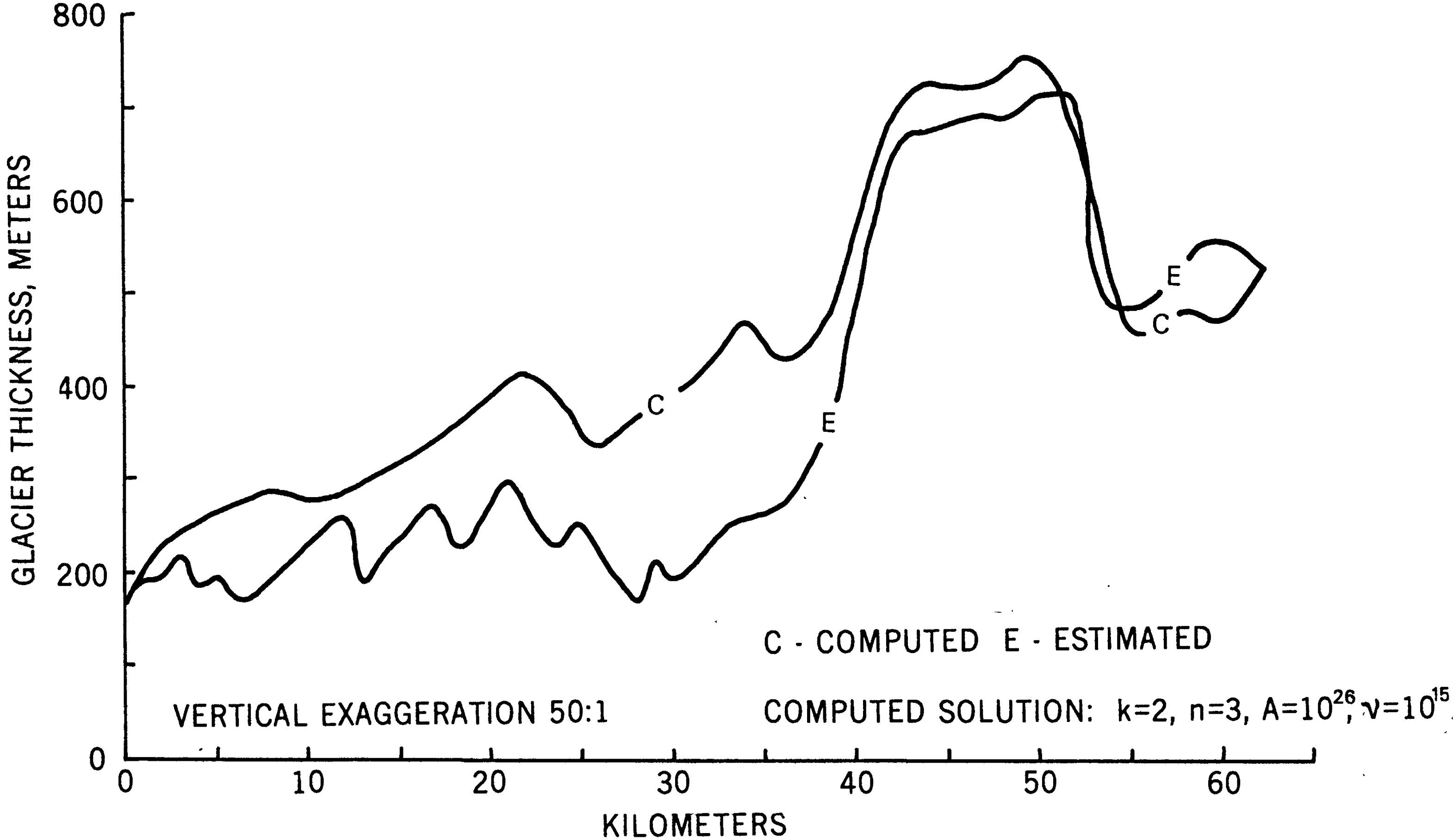


Figure 13. One-dimensional model results; computed thickness is compared with estimated or known thickness. The degree of fit from 40 to 62 km is a valid test of the model, the fit from 0 to 40 km is less important because no actual data on glacier thickness are available in this reach.

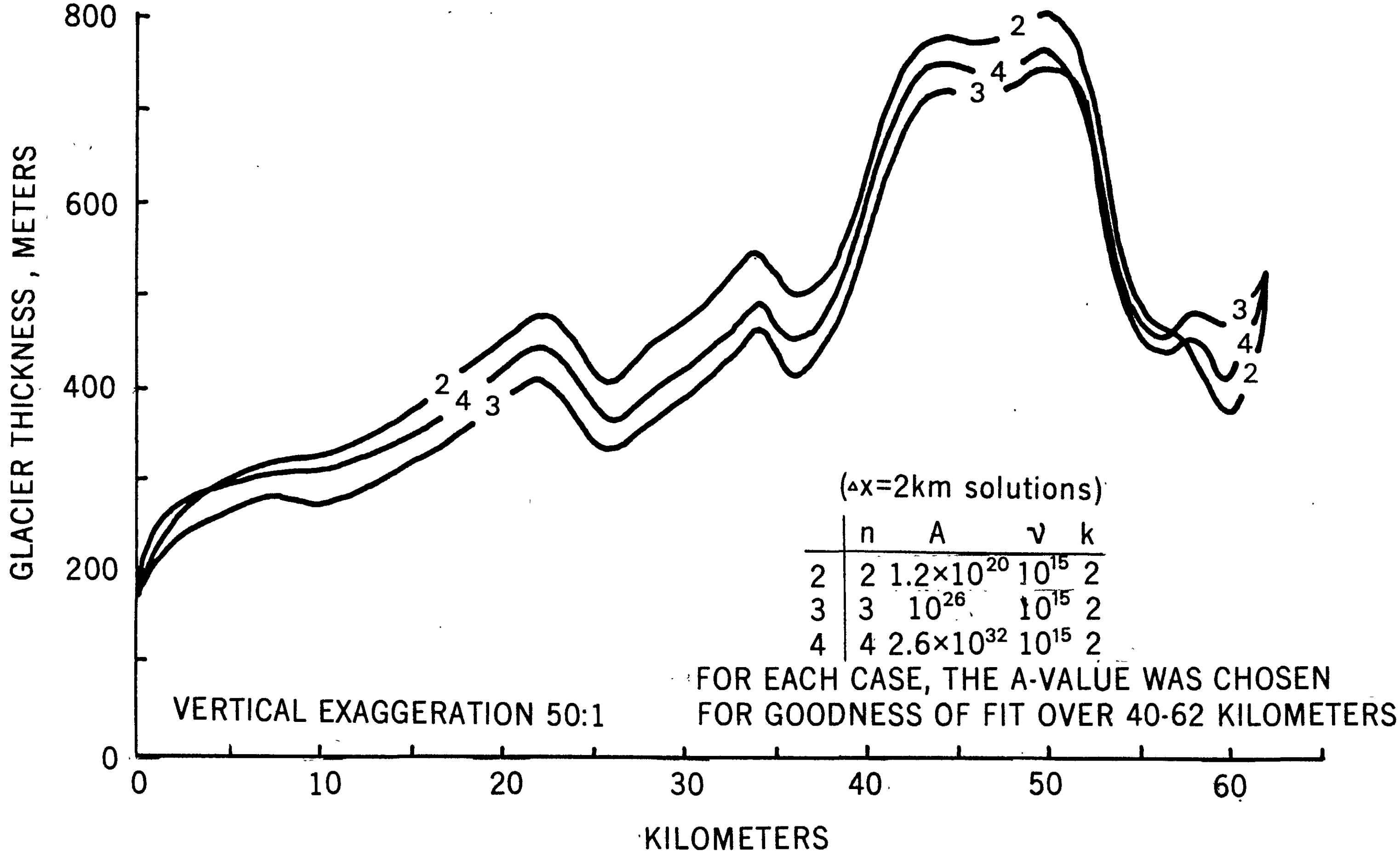


Figure 14. Dependence of the computed ice thickness on the value of exponent η in the ice flow law. The value 3 is a best fit with estimated thickness (fig. 13).

Observations in 1977 showed that individual calving events--especially the few very large ones--could not be predicted and did not appear to be related in time to any obvious combinations of tide, ice-cliff configuration, etc. It is likely that sudden release of large glacier-dammed lakes causes unusual calving episodes, but coincidence in time between the two phenomena has not yet been established. It is possible that the average calving rate over a year's time may relate to specific and measurable variables. But calving is a very episodic process, and it is difficult to generalize at this stage.

Seasonal embayment formation and closure are now characteristic of the Columbia Glacier terminus, but cannot yet be explained. Until they are, simple theories of calving-glacier instability do not provide a complete understanding. Unfortunately, a three-dimensional dynamic model may be required, and it is not yet certain whether this can be constructed by stacking or slicing two-dimensional flow models, especially with our present inability to write a "calving law". Apparently embayment formation is triggered by abnormal calving (perhaps caused by unusual water discharge) somewhere along a terminus cliff which is on the verge of instability. Local retreat of the terminus then accelerates due to the instability. The problems at this time are to determine the effect of fluctuation in subglacial water, and to explain why embayment formation ceases.

Most evidence points toward the conclusion that Columbia Glacier will not remain much longer as such a large and impressive feature of the landscape. The ice is thinning rapidly near the terminus (figs. 9 and 12), huge embayments form (fig. 5), and preliminary dynamic modeling suggests that the glacier is out of equilibrium (fig. 13) for the present climate. This is the last of the Neoglacially-extended calving glaciers in Alaska: when and how fast will it go? This question remains to be answered.

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