STATE OF ALASKA

DEPARTMENT OF NATURAL RESOURCES

DIVISION OF GEOLOGICAL AND GEOPHYSICAL SURVEYS

Steve Cowper, *Governor*

Lennie Gorsuch, *Commissioner*

Robert B. Forbes, *Director and State Geologist*

June 1989

Report of Investigations 88-10

JOKULHLAUPS FROM STRANDLINE LAKE, ALASKA, WITH SPECIAL ATTENTION TO THE 1982 EVENT

By
Matthew Sturm and Carl S. Benson

STATE OF ALASKA
Department of Natural Resources
DIVISION OF GEOLOGICAL & GEOPHYSICAL SURVEYS

The Division of Geological and Geophysical Surveys was established under Alaska Statute 41.08 to 'conduct geological and geophysical surveys to determine the potential of Alaskan land for production of metals, minerals, fuels, and geothermal resources; the locations and supplies of groundwater and construction materials; the potential geologic hazards to buildings, roads, bridges and other installations and structures; and shall conduct such other surveys and investigations as will advance knowledge of the geology of Alaska. . . .

'In addition, the division of geological and geophysical surveys shall: (1) collect, record, evaluate, and distribute data on the quantity, quality, and location of underground, surface, and coastal water of the state; (2) publish or have published data on the water of the state; (3) require the filing with it of the results and findings of surveys of water quality, quantity, and location; (4) require of water well contractors, the filing with it of basic water and aquifer data normally obtained, including but not limited to well location, estimated elevation, well-driller's logs, pumping tests and flow measurements, and water-quality determinations; (5) accept and spend funds for the purposes of this section, AS 41.08.017 and 41.08.035, and enter into agreements with individuals, public or private agencies, communities, private industry, state agencies and agencies of the federal government; (6) collect, evaluate, and distribute geologic data on seismic events and engineering geology of the state; (7) identify potential seismic hazards that might affect development in the state; and (8) inform public officials and industry about potential seismic hazards that might affect development in the state.'

Activities of the Division are administered by the Director and State Geologist. Division offices are located at:

Director and State Geologist
3700 Airport Way
Fairbanks, Alaska 99709
(907)451-2760

400 Willoughby Center
(3rd floor)
Juneau, Alaska 99801
(907)465-2533

794 University Ave.
(2nd floor)
Fairbanks, Alaska 99709
(907) 474-7147

18225 Fish Hatchery Road
P.O. Box 772116
Eagle River, Alaska 99577
(907)696-0070

This report is for sale by DGGS for $4. DGGS publications may be inspected at the following locations. Address mail orders to Fairbanks office.

3700 Airport Way
Fairbanks, Alaska 99709

400 Willoughby Center
Juneau, Alaska 99801

U.S. Geological Survey
Public Information Office
701 C Street
Anchorage, Alaska 99513

Information Specialist
U.S. Geological Survey
4230 University Drive, Room 101
Anchorage, Alaska 99508

CONTENTS

FIGURES

TABLE

JÖKULHLAUPS FROM STRANDLINE LAKE, ALASKA, WITH SPECIAL ATTENTION TO THE 1982 EVENT

by
Matthew Sturm[1] and Carl S. Benson[2]

ABSTRACT

Jökulhlaups, or outburst floods, have occurred every 1 to 5 yr from Strandline Lake, one of the largest glacier-dammed lakes in North America. They flood the Beluga River, which was once in an undeveloped region but now is spanned by bridges and powerlines leading to Alaska's largest urban area. In 1982, we initiated a study of the mechanisms that produce these jökulhlaups to improve our ability to predict them and thereby to mitigate their damages. Reliable precursors appear to be development of a distinct calving embayment in the lobe of the Triumvirate Glacier, which dams Strandline Lake, and formation of a number of supraglacier pools. Contour maps made from photos taken immediately before and after the jökulhlaup of September 17, 1982 indicate that over 95 percent of the lake drained, releasing about 7×10^8 m^3 of water. The lake is dammed by a glacier lobe that fractures and subsides during a jökulhlaup, which indicates that the release mechanism is hydrostatic lifting of ice off a subglacial spillway; the exposed areas surrounding the glacier margins suggest that the spillway may be controlled by bedrock. Large variations occur in the refilling period of Strandline Lake. Modifications of subglacial drainage into Strandline Lake as a result of jökulhlaups, combined with complex sub- and marginal drainage patterns, appear to exert controls which are not understood but which contribute to the variable filling rates.

---

[1]U.S. Army Cold Regions Research and Engineering Laboratory, Ft. Wainwright, Alaska 99703-7860.
[2]Geophysical Institute, University of Alaska, Fairbanks, Alaska 99775.

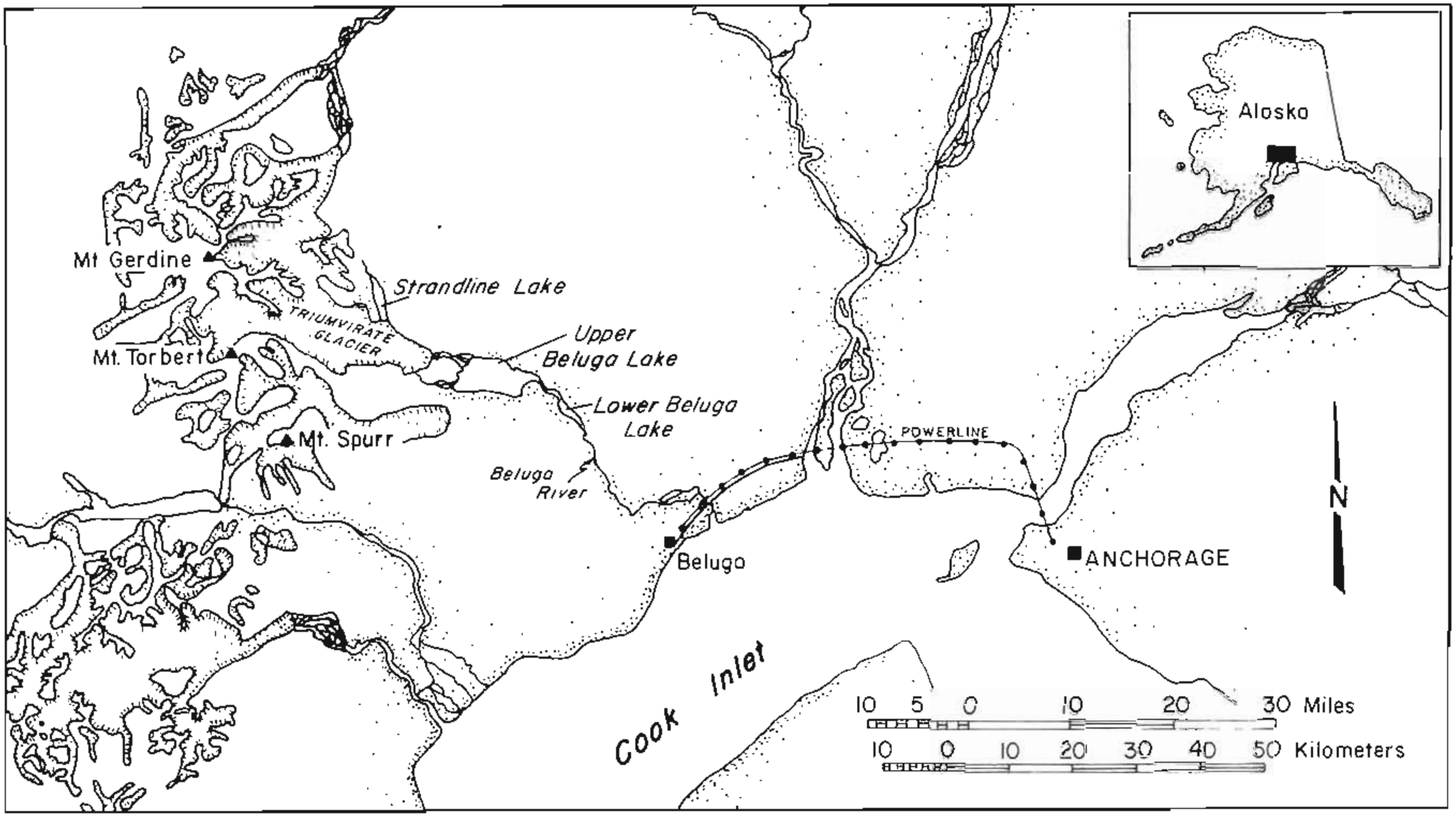

Figure 1. Location map of study area. Note powerline from Beluga natural gas field to Anchorage which crosses the Beluga River near its mouth.

INTRODUCTION

The Icelandic term 'jökulhlaup' refers to a flash flood produced when water trapped within or behind a glacier is suddenly released. Jökulhlaups may be caused either by the breakout of a glacier-dammed lake or the release of a water reservoir produced by geothermal heat beneath a glacier. Most jökulhlaups in Alaska occur from glacier-dammed lakes. Jökulhlaups are characterized by rapid, extremely high discharges. Discharges increase exponentially with time, because drainage tunnels in the ice increase in diameter as their walls melt from dissipation of potential energy created by the flowing water (Matthews, 1973; Björnsson, 1974; Nye, 1976).

This paper discusses jökulhlaups from glacier-dammed Strandline Lake; it is based on a detailed analysis of topographic maps made by photogrammetry from vertical aerial photographs taken immediately before and after the jökulhlaup of September 17, 1982, together with field observations and historical records, including eyewitness accounts of jökulhlaups since 1940. Strandline Lake, one of the largest active glacier-dammed lakes in North America (Post and Mayo, 1971; Matthews, personal commun., 1982), has tunneled under its ice dam and flooded the Beluga River every 1 to 5 yr for at least the past 25 yr. Once a remote wilderness river, the Beluga River is now spanned by bridges and powerlines leading to Anchorage, Alaska's largest city. The destructive consequences of jökulhlaups from Strandline Lake have greatly increased.

Strandline Lake appears to drain after reaching a critical level where the ice dam lifts enough to break the seal on a subglacial spillway and triggers a jökulhlaup. Long-range prediction of jökulhlaups could be based on the filling rate of the lake basin, since the critical high-water level is known, but the filling rate is so variable that monitoring would have to be more closely controlled than is feasible for a lake this remote. We have therefore attempted to identify some precursors of jökulhlaups that may be observed from aircraft or satellite. These include rapid calving from the glacier front that dams the lake and the filling of a number of small, marginal supraglacier pools (Sturm and Benson, 1982; 1985).

FLOOD HISTORY

A partial history of jökulhlaups from Strandline Lake is given in table 1. No information is available for floods before 1940. Until development of gas and oil properties along the Beluga River in the 1960s, effects of jökulhlaups on the Beluga River attracted little notice. When a bridge was built across the Beluga River the situation changed, and more complete accounts are now available for the floods of 1974, 1979, 1980, and 1982. Our history includes personal communications with F. Shomper (events of 1974, 1979, and 1980), E. Whittemore (events of 1974, 1979, and 1980), and D. Witte (event of 1979). Landsat imagery and aerial photography have been used to supplement this history.

In 1984, Strandline Lake dumped again, and we were able to observe the jökulhlaup in greater detail than before. These observations will be discussed in another report.

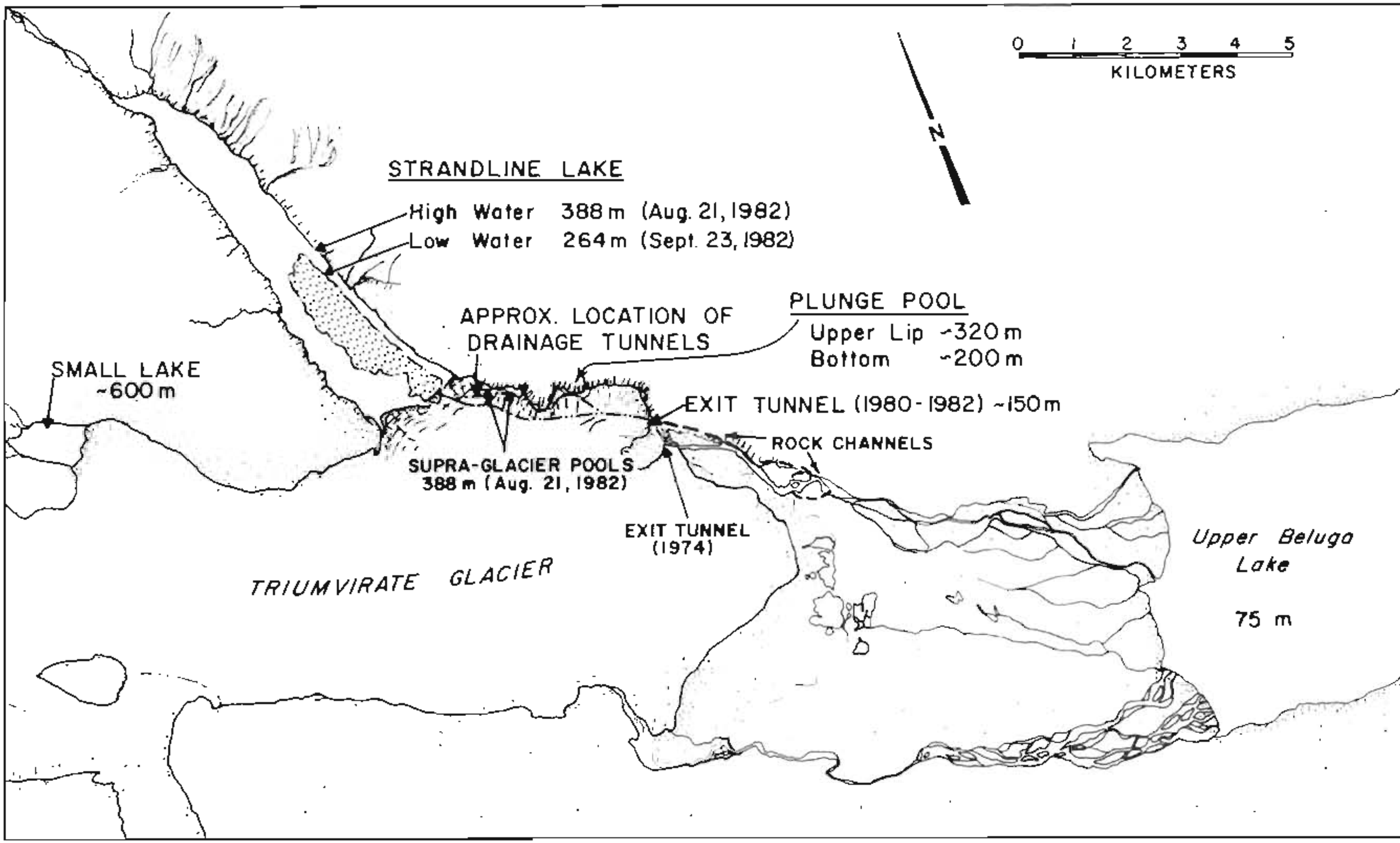

Figure 2. Features along flood course of 1982 Strandline Lake jökulhlaup and locations of jökulhlaup exit tunnels in prior years. Heavy dashed lines indicate abandoned channels cut in bedrock. Dot-dash lines indicate approximate location of existing drainage tunnels.

THE STRANDLINE LAKE JÖKULHLAUP SYSTEM

Strandline Lake occupies a steep-walled valley near the terminus of Triumvirate Glacier in the Tordrillo Mountains, 120 km west of Anchorage (fig. 1). Triumvirate Glacier descends from Mt. Torbert and Mt. Gerdine just north of Mt. Spurr (which last erupted in 1953); near the glacier terminus, a small lobe--the 'ice dam'--flows northward about 0.4 km into a side valley and dams Strandline Lake (figs. 2 and 3). A large calving embayment in this ice dam is one of the precursors of a jökulhlaup (fig. 4).

Multiple channels in bedrock have been exposed, as the terminus of the Triumvirate Glacier recedes (fig. 2). In at least two places, V-shaped channels have been cut more than 20 m into bedrock adjacent to, but higher in elevation than, the rock channel travelled by the 1982 jökulhlaup. The upstream ends of these abandoned channels are truncated by the more recent channels. When the Triumvirate Glacier was thicker and extended farther, these now-abandoned channels would have been subglacial, and they may have been formed by jökulhlaups. Other complex bedrock topography near the ice dam probably influences drainage paths. For example, the large supraglacier pool shown in figures 2 and 5 forms immediately upstream from a major rock bastion (near C_3 of fig. 5), and a ridge of bedrock and morainal material is exposed at low water in front of the ice dam (figs. 3, 5, and 7).

Jökulhlaups from Strandline Lake follow complex channels. During the early stages of a jökulhlaup, water flows along the margin of the glacier in a channel which begins where water is forced up along the rock bastion upstream of the first supraglacier pools (figs. 2 and 5). The water follows the rock-ice margin until it drops into a rock-cut plunge pool 120 m deep, from which it flows under the ice again (fig. 2). When the lake drained in 1979, 1980, and 1982, the supraglacier pools also drained, and ice below them collapsed along fractures (figs. 5 and 6). The drainage path from the supraglacier pools to the plunge pool had to have been replaced by subglacial lake drainage, because the upper lip of the plunge pool (320 m) is 60 m higher than the level to which the lake drained (fig. 2). During the final stages of a jökulhlaup, therefore, all flow occurs beneath the glacier along a path such as C_1 to C_4 in figure 5. Waters emerge from a tunnel in the terminus and flow through a narrow, 2-km-long rock canyon before spreading over outwash plains at the head of Beluga Lake. Drainage tunnel configurations can change rapidly; for example, the position of the exit tunnel at the terminus of the Triumvirate Glacier moved 350 m between 1974 and 1982.

Jökulhlaups flow into Upper and Lower Beluga lakes, which act as a natural flood-control system and mitigate downstream flood destruction at roadways, bridges, powerlines, and gas and oil installations near the river. During the jökulhlaup of July 1979, the Beluga Lakes rose about 10 m in 40 hr (Douglas Witte, personal commun., 1982). The combined surface area of the lakes is 4.9×10^7 m^2; this indicates that about 5×10^8 m^3 of flood water was temporarily stored in the lakes. Simultaneously, however, the water level in Strandline Lake dropped more than 128 m, a displacement of 7×10^8 m^3. Therefore, about two-thirds of the total 1979 jökulhlaup water was temporarily ponded in the Beluga Lakes and then discharged more slowly through the Beluga River; a flood crest of only 4.5 m was observed at the bridge 20 km downstream from the Beluga Lakes.

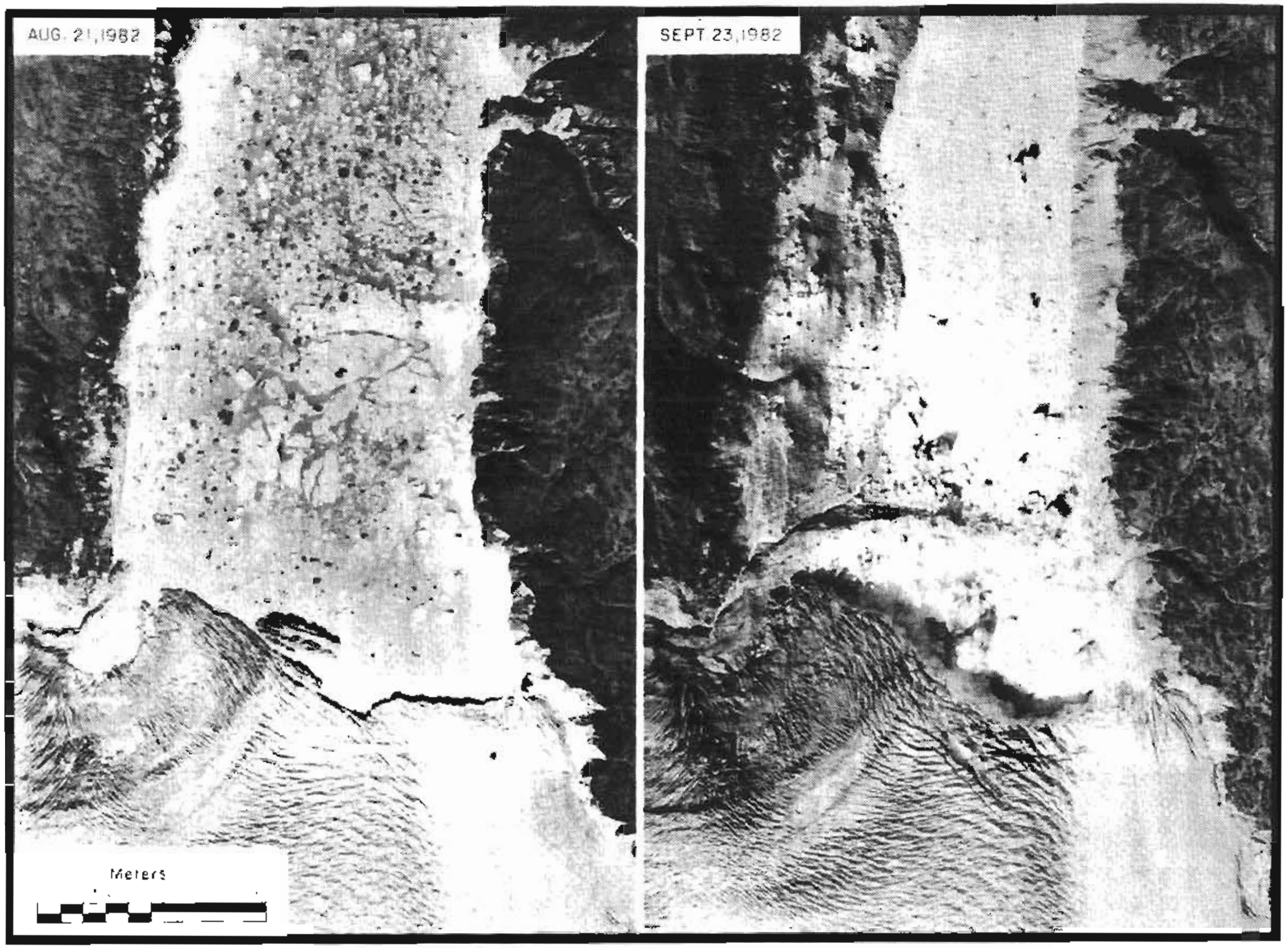

Figure 3. Vertical aerial photographs of Triumvirate Glacier taken before and after the September 17, 1982 jökulhlaup. Largest stranded bergs observed from September 23 photograph were over 120 m high, consistent with calculated glacier thickness.

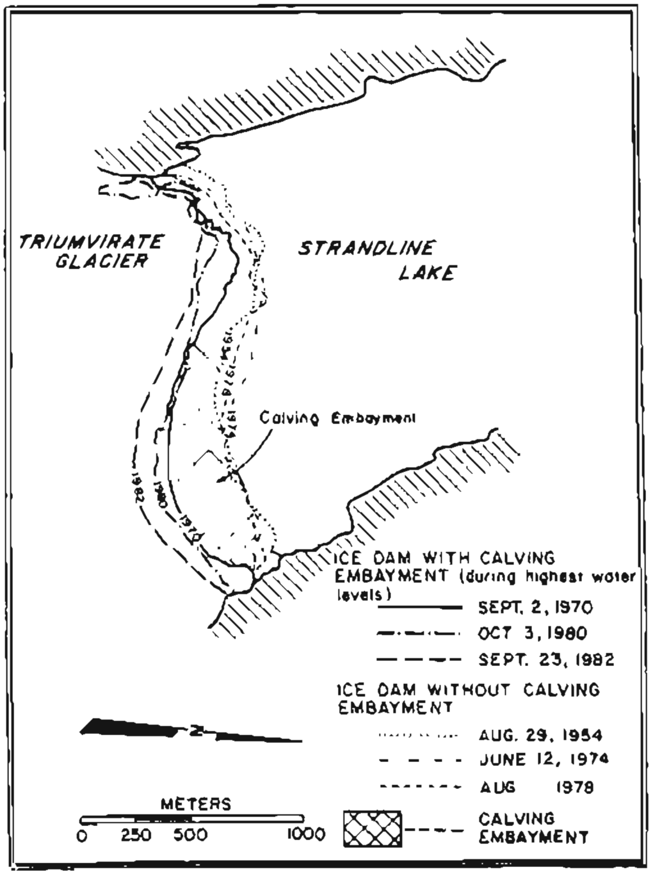

Figure 4. Various positions of the Triumvirate Glacier 'ice dam' and calving embayments that form prior to the jökulhlaups.

FLOOD PRECURSORS

Strandline Lake derives its name from the prominent strandlines that mark former lake levels. These strandlines indicate that the lake's high-water stage has varied over 50 m in elevation, but, from 1979 to 1982, the high-water stage appears to have been about 388 ± 10 m. If the present glacier thickness remains the same, this water level would be an excellent indicator of imminent flooding, but because the lake is so remote it is not easy to determine the water level.

The supraglacier pools of water located immediately downglacier from the ice dam (fig. 2) were observed to fill before the jökulhlaups of 1974, 1979, 1980, and 1982 (Whittemore, personal commun., 1982); we also observed them to fill before the 1984 jökulhlaup. A month before the 1982 jökulhlaup the water level in the pools was the same as the lake. Because of the ice topography, the pools could not have filled by lakewater running over the surface of the ice. Thus, a subglacial hydraulic connection must have existed between the lake and the pools. Most likely, the water is forced to the surface along the rock bastion near C_3 in figure 5 (see also fig. 2), because the first and largest supraglacier pool forms immediately upstream of the bastion at the origin of the marginal stream. This mechanism of forming supraglacier pools appears to function only when the lake level is high; the filled pools are therefore visible precursors to a jökulhlaup.

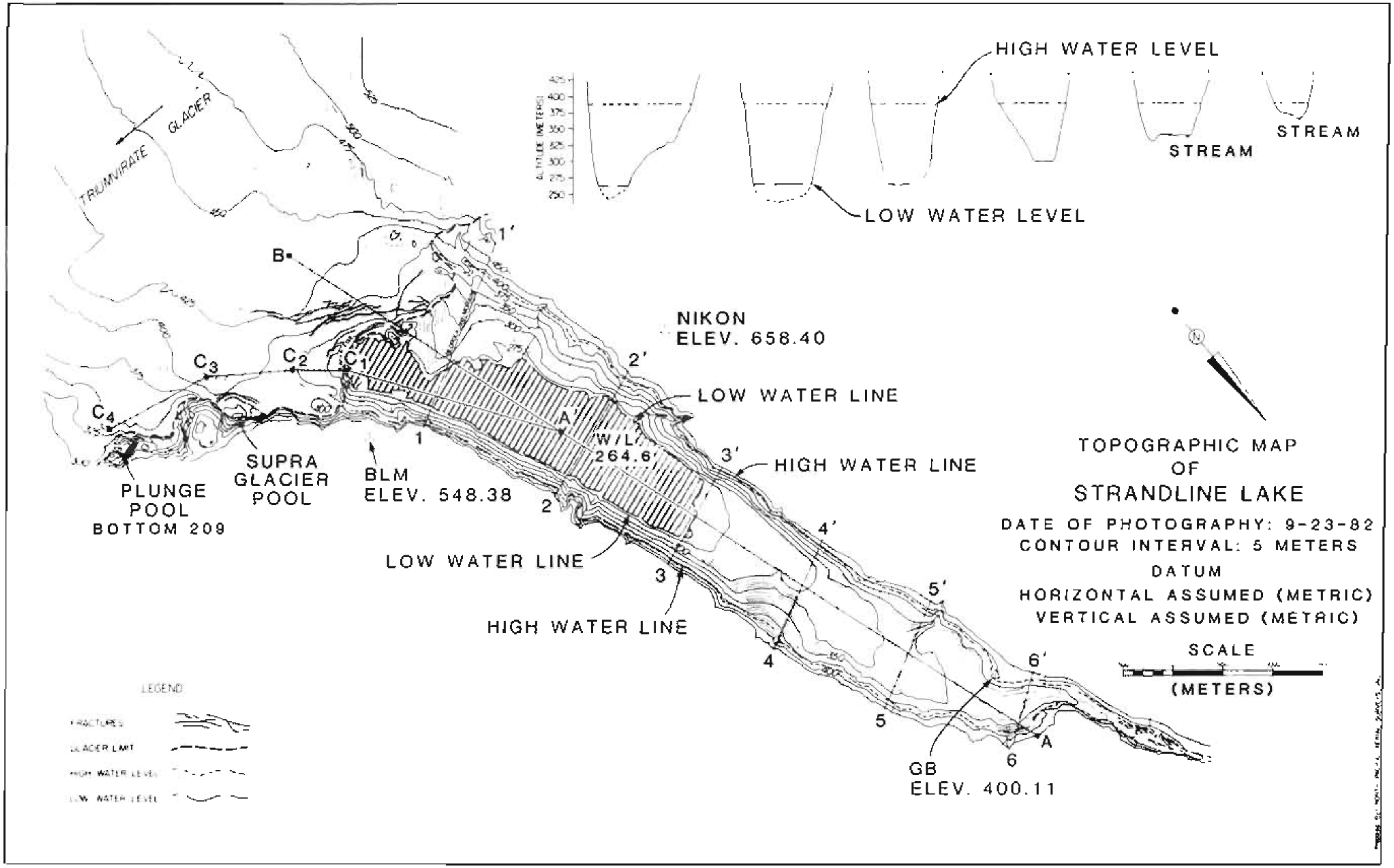

Figure 5. Plunge pool, supraglacier pools, and subglacial drainage path of Triumvirate Glacier at Strandline Lake. High water (Aug 21) and low water (Sep 23) levels at Strandline Lake before and after event of September 17, 1982 indicated on map and in cross sections (above right). Cross sections 1-1' through 6-6' show lake bottom and stream bed contours (estimated where covered by water). Hachures indicate area where ice calved away or collapsed during lake drainage. See figure 7 for longitudinal cross sections A-A'-B and A-A'-C.

The development of a calving embayment in the lobe of the Triumvirate Glacier that dams Strandline Lake is the most useful precursor, because it can be observed by aircraft and satellite (Miller, 1982). The lobe advances and retreats in a cycle apparently controlled by the lake level. When the lake drains, the lobe has a positive mass balance, and its terminus advances as much as 0.5 km into the lake basin. When the lake fills to a critical level, the lobe begins to float, and calving increases. This leads to a negative mass balance and retreat of the lobe's terminus from the newly created calving embayment. Extensive calving chokes Strandline Lake with icebergs just before a jökulhlaup. This cycle has been pieced together from examination of over 56 Landsat images (12 of them enlarged to 1:125,000), aerial photographs, and reports from long-term observers of the lake. Figure 4 tracks the movement between 1970 and 1982 of the lobe of Triumvirate Glacier which forms the ice dam.

Although precursors are reliable short-term predictors of jökulhlaups, long-range predictors must take into account the filling mechanisms of Strandline Lake. The lake fills from three sources: (1) surface runoff from the glacier; (2) the Strandline Lake watershed; and (3) flow beneath the glacier. Discharge from these sources is difficult to measure.

JÖKULHLAUP OF 1982

In August 1982 we were asked by Chugach Electric Company, whose main power transmission line crosses the Beluga River, for advice about potential flooding from Strandline Lake. Air and ground reconnaissance showed the lake was filled to a high level and choked with ice. Flowering plants were found covered by water as deep as 2 m. A large calving embayment extended 0.3 km into the ice dam, and supraglacier pools were full. On the basis of these observations and the history of previous jökulhlaups, we predicted that a jökulhlaup would occur soon (Sturm and Benson, 1982). It occurred on 17 September 1982.

Methods

With a jökulhlaup clearly imminent, we contracted to have a set of vertical aerial photographs of Strandline Lake and the Triumvirate Glacier taken on August 21, 1982, and a second set taken on September 23, 1982, 6 days after the event (fig. 3). From the vertical aerial photos, photogrammetric topographic maps of the lake and ice dam--both before and after the lake drained--were constructed at a scale of 1:10,000, with contour intervals of 5 m (figs. 5 and 6). The lake water surface of August 21 was used as datum for photogrammetry, with an assumed altitude of 388 m, which is approximately equivalent to its true altitude above sea level; the vertical control on each map is considered accurate to ± 2.5 m. These maps have enabled us to measure the volume of the lake basin, to determine the volume of water that drained, and to make cross sections of the glacier and lake before and after the jökulhlaup (figs. 5, 6, and 7). The cross sections show post-jökulhlaup subsidence of the ice dam and allow estimation of ice thickness. Other glacier-dammed lakes have been investigated by examining oblique aerial photographs (Post and Mayo, 1971) and by photogrammetry with vertical aerial photos (Collins and Clarke, 1977). However, the detailed photogrammetric analysis herein, of vertical photographs taken immediately before and after a jökulhlaup, is the first known to have been done.

Volume of Lake

During the 1982 jökulhlaup, the lake water level dropped from 388 to 264 m. The volume of water that drained was calculated by measuring the area of the lake basin at the higher and lower water levels (388 m and 264 m) and at intermediate contours of 375 m, 350 m, 325 m, 300 m, and 275 m. The volumes of the 'slabs' of water between these levels were summed and gave a total of 7.1×10^8 m^3. After drainage, a residual volume of heavily ice-choked water remained in the lake basin. From a cross section of the lake basin (fig. 7), we estimated the volume of residual water to be 0.2×10^8 m^3, together with 0.4×10^8 m^3 of icebergs left stranded on the lake floor, or less than 4 percent of total lake volume. Thus, about 95 percent of Strandline Lake drained during the jökulhlaup of 1982. In 1984, we observed the lake on the day after it drained and could see that its level was lower than when observed in 1982, 6 days after drainage. Most likely, the 1982 observation occurred after the lake had begun to fill again.

Changes in the Triumvirate Glacier Ice Dam

The jökulhlaup of 1982 produced dramatic changes in the Triumvirate Glacier which, indirectly, have been helpful in constructing the configuration of the subglacial drainage system. A troughlike depression greater than 0.5 km wide formed between extensive fractures during the 1982 jökulhlaup. The extent of this depression has been mapped by comparing topographic maps of the ice surface before and after the jökulhlaup (fig. 6). The zero-subsidence contour roughly coincides with fracture zones. The fractures, which in some cases cut across existing crevasses, exceeded 10 m in width, with vertical displacements (normal faulting) of > 20 m. Large fracture-bounded sections of the glacier were slumped and rotated; these fractures probably penetrated the glacier completely to allow such displacement. In many cases, the fractures were filled with water immediately before the lake drained, which suggests that they were connected with the lake drainage system; they probably delineated the floating part of the glacier, which took the form of a deep reentrant with a calving bay at its outer edge. The reentrant was aligned with the axis of the Strandline Lake valley and extended more than 1 km downglacier; it included the area where supraglacier pools formed.

The volume displaced by subsidence was calculated by measuring the areas enclosed by subsidence contours (fig. 6). The volume displaced in the main troughlike depression was at least 30×10^6 m^3. (This does not include 5.3×10^6 m^3 of ice lost by calving or the 0.6×10^6 m^3 of subsidence at the largest supraglacier pool.) About 5 m of subsidence occurred farther downglacier (in an area not shown on fig. 6) but was difficult to measure because the region is far from photogrammetric control. The displaced volume in this region is estimated to be 5×10^6 m^3 but is not included in our total estimate. These additional estimates support our conclusion that the 30×10^6 m^3 of subsidence volume displacement shown in figure 6 is a minimum value.

The volume displaced by subsidence most likely represents lake water under the glacier before the jökulhlaup. It is about equal to our estimate of the volume of stranded icebergs in the drained lake, so that the volume of lake water that drained is 7×10^8 m^3. One could argue that the displaced

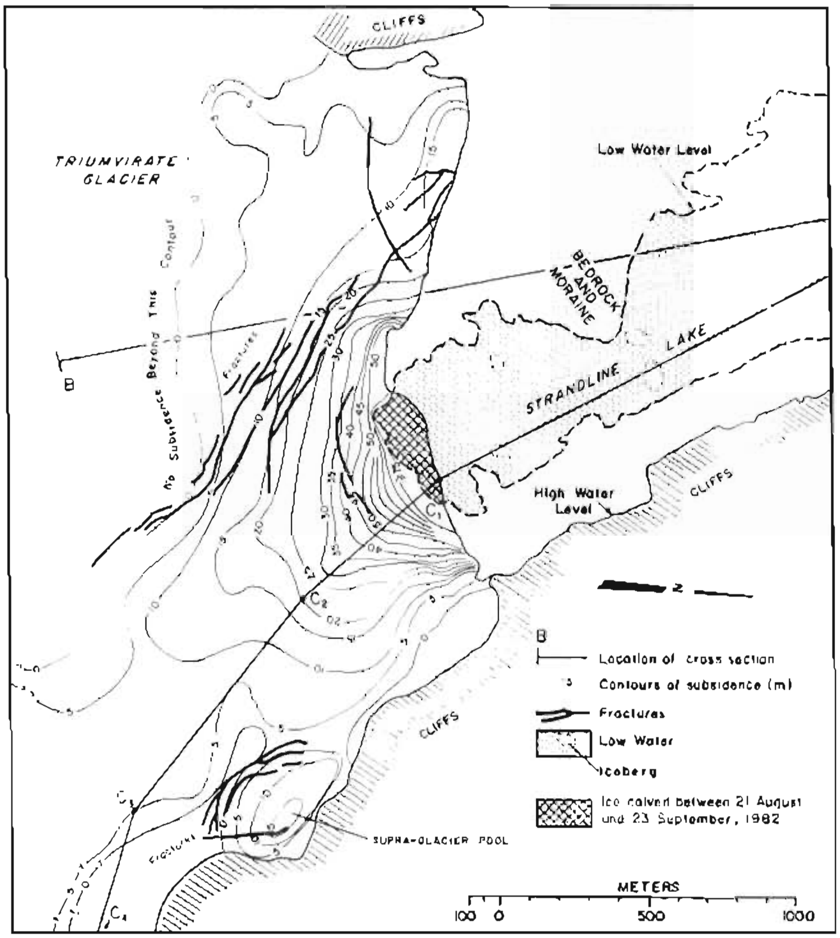

Figure 6. Contour map showing extent of subsidence and the location of fractures in ice dam after drainage of Strandline Lake in September 1982. No contours shown for subsidence greater than 75 m.

volume was melted from the bottom of the glacier as potential energy of the lake water was converted to heat during the drainage. However, potential energy released by the lake water as it drained out through the subglacial exit, 150 m above sea level, was not adequate to melt a volume of ice equal to the volume of subsidence. This can be shown by considering the available energy.

Energy

Energy dissipated within the glacier system during the 1982 jökulhlaup was calculated by using the measurements from lake volume calculations above. The potential energy released as the water drained through the tunnel exit was 13.1×10^{14} joules. According to Matthews (1973), the portion of this potential energy that is transformed into kinetic energy represents only about 1 percent of the total. We have a report of a 'roostertail' 10 m high as water exited the tunnel during the peak of the 1979 jökulhlaup. This suggests an exit velocity of 14 m sec^{-1} from the confined tunnel during peak discharge. If the peak discharge, $Q = 6 \times 10^3$ m^3 sec^{-1}, is divided by the cross-sectional area of the exit tunnel, $A = 315$ m^2, the maximum exit velocity of the water at peak discharge would be 19 m sec^{-1}, which is in reasonable agreement with the estimate based on the 'roostertail.' If we assume that half the total water mass achieved this velocity, we obtain a kinetic energy value of 0.3×10^{14}J, which is consistent with Matthews's (1973) estimate. Subtracting this portion from the total potential energy leaves 12.8×10^{14}J to be released within the glacier. This energy dissipation could melt an ice volume of 4×10^6 m^3, which is one order of magnitude less than the volume of subsidence.

If all potential energy released within the glacier were expended in melting the ice, it could melt a 4-km-long tunnel with a radius of 18 m from the lake ice margin to the exit. Because the tunnel geometry is complex, and because several paths were followed--some of which were abandoned before the final drainage, it is reasonable to expect a smaller radius in the primary drainage tunnel. After the 1984 jökulhlaup, an exit tunnel with a 10-m radius was observed, which is in reasonable agreement with our estimate based on the previous calculations.

Discharge

No hydrographs of jökulhlaups from Strandline Lake are available, so discharge must be estimated. Witte estimated that the jökulhlaup of 1979 lasted for 2 days (personal commun., 1982). However, it is likely that the initial stages of the event went unnoticed and that Witte's observation applies only to its catastrophic stage. The same estimates were made for the 1982 jökulhlaup. During 1984 we were able to observe another jökulhlaup from Strandline Lake and found that more than 20 days elapsed between the initial leakage of water and completion of the jökulhlaup. If we assume that the events of 1979, 1982, and 1984 each spanned 20 days, their mean discharge would have been about 4×10^2 m^3 sec^{-1}. But jökulhlaup discharges vary widely and produce short-duration peak values much greater than mean values. Clague and Matthews (1973) empirically related the peak discharge, Q_{max}, of 11 jökulhlaups to the maximum lake volume, V_{max}, as follows:

$$Q_{max} = 75 \ (V_{max} \times 10^6)^{0.67}$$

Applying their formula to Strandline Lake, we obtained a peak discharge value of 6.1×10^3 m^3 sec^{-1}. In comparison, the Mississippi River at Vicksburg has a mean discharge of 15.5×10^3 m^3 sec^{-1}, and the Missouri River near St. Louis has a mean discharge of 2.0×10^3 m^3 sec^{-1}.

Ice Thickness

Although no independent measurements of glacier ice thickness are available from ice radar or seismic methods, ice thickness and configuration of the ice dam can be estimated from aerial photogrammetry. The two longitudinal cross sections in figure 7 show water and ice conditions before and after the lake drained. Cross section A'- B runs through a large, free-floating iceberg, newly separated from the glacier front. The berg is still upright and must be free-floating to have moved away from the calving face. The average freeboard of the berg, Δh_b, is 13 m. For hydrostatic equilibrium:

$$\rho_i g h_b = \rho_w g (h_b - \Delta h_b),$$

where

ρ_i = density of ice = 0.9 t m^{-3},

ρ_w = density of water = 1.0 t m^{-3},

h_b = total iceberg thickness (m),

and

g = acceleration of gravity = 9.8 m s^{-2}.

From this we calculate the berg thickness, h_b, to be 130 m. As shown in figure 7, the berg, at this thickness, would just barely ground on the bedrock moraine ridge, which would explain why it remained near the glacier face.

The glacier freeboard, Δh_g, is equal to the iceberg freeboard, Δh_b, along cross section A'-B, figure 7. We assume that the glacier was afloat, and that after the lake drained it rested directly on the bottom. This permits us to draw in the lake bottom along the cross section. At the immediate ice face, slumping and fracturing altered the glacier surface profile (dashed lines, fig. 7). Close to the area represented by cross section A'-B, the lake drained to expose the bottom, and ice thickness, measured where the entire ice cliff was exposed, was consistent with the flotation model.

We assume that the part of the glacier shown in cross section A'-C_4 was also afloat before the lake drained; here, the glacier freeboard, Δh_g, is 14.5 m (fig. 7). As would be expected, the ice is thicker here than at the edges. We suspect the subglacial spillway lies along the area represented by cross section A'-C_4, as it is the deepest part of the valley. The spillway should occur at the point where floating glacier ice is grounded, and this coincides with the point of zero subsidence, approximately 1 km downglacier.

Transverse profiles of the glacier face before and after the lake drained (fig. 8) were drawn to support the above arguments. Because considerable slumping and fracturing took place at the immediate ice face, the profile was located 150 m back from the face. Using the freeboard value of the glacier to calculate ice thickness, we have drawn in the bottom of the floating ice. Using the volume of ice subsidence, we have drawn in the lake bottom profile. The lake bottom profile, including its asymmetry, derived from the ice-subsidence values is consistent with observed lake bottom profiles (fig. 5).

DISCUSSION

The overall mechanism that releases floods from Strandline Lake appears to be hydrostatic lifting of the ice dam when the lake fills to a critical level. The subsidence and fracturing of the ice dam when the lake drains is consistent with this hydrostatic mechanism. With the buoyant support of the water removed, the floating ice subsides.

The critical seal between the rock and overlying ice is expected to lie along a zone of minimum (before drainage) altitude of ice surface and maximum

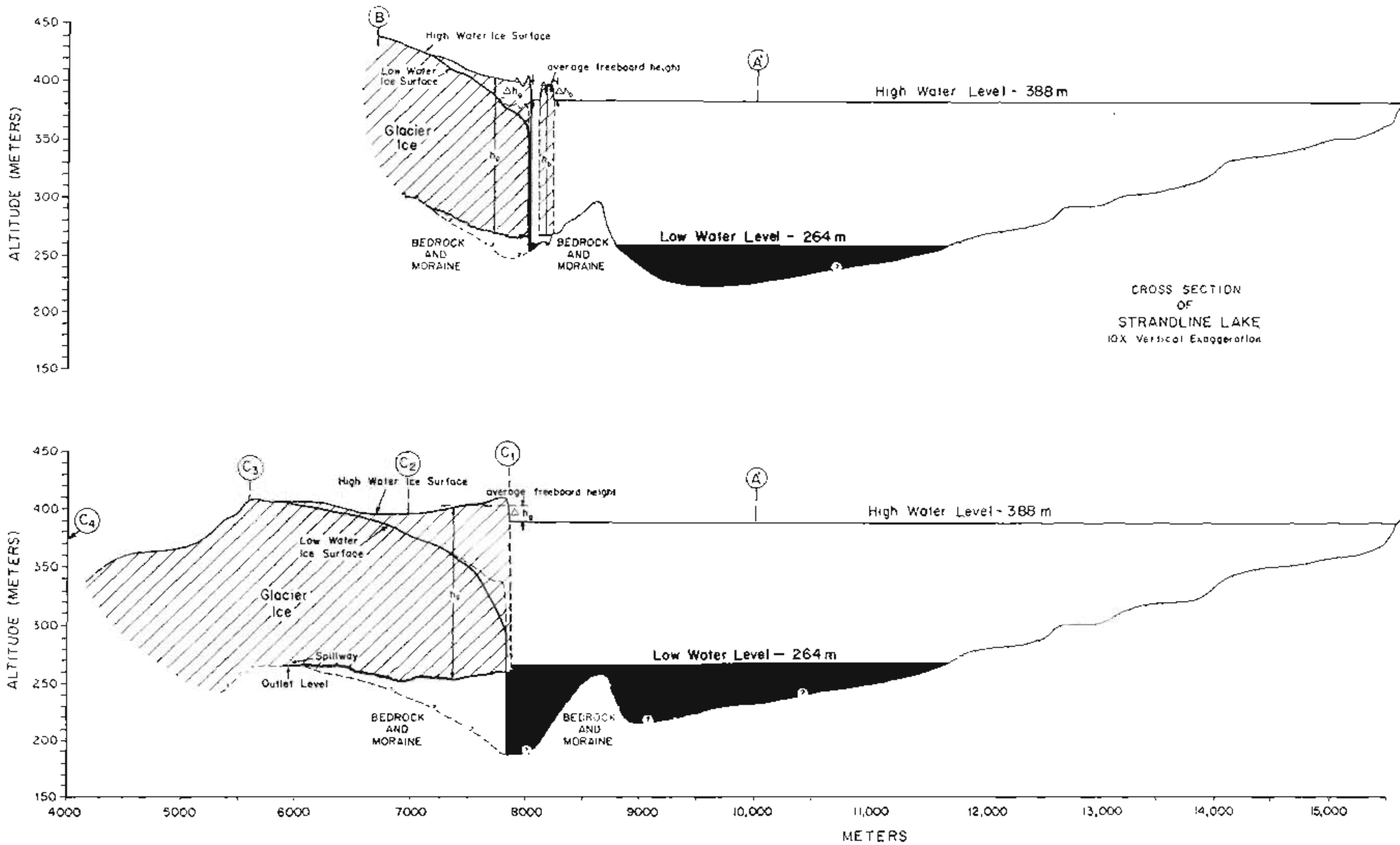

Figure 7. Longitudinal cross sections through Strandline Lake at high water (Aug 21) and low water (Sep 23) levels before and after the event of September 17, 1982. Location of cross sections shown in figs. 5 and 6. Lakebed and glacier bottom contours drawn using calculated ice thickness of 130 m and assuming ice subsided until it rested on the bottom.

(after drainage) subsidence (line A'-C_4 in fig. 7). The grounding line of the ice before drainage can be located by the fractures and zero-subsidence contour (fig. 6). The downglacier point of zero subsidence is difficult to locate, but we assume it to lie near the area represented by point C_3 on figures 5 and 7.

The seal lies at an altitude no higher than 264 m (1984 observations indicate it may be 20 m lower), where maximum ice pressure is 12.9 bars; hydrostatic water pressure here would be 12.2 bars when the water level reaches 388 m. This close agreement suggests that the release mechanism which triggers a jökulhlaup involves lifting of the ice off a critical seal. This, in turn, allows the flowing water to carve exit tunnels in the base of the glacier.

The postdrainage ice surface most likely reflects the shape of the glacier bed. If so, a shoal may exist near the grounding line, as Post (1975) and Powell (1981) observed in tidewater glaciers. In a setting similar to Strandline Lake, Booth (1986) described valley-constricting embankments at mouths of alpine valleys dammed by the Puget lobe of the Cordilleran ice sheet. Recently deglaciated bedrock terrain along the Triumvirate Glacier margin and terminus is deeply cut by stream channels, and much of the glacier bed probably consists of similarly complex terrain. Apparently, the controlling seal occurs at a shoal of bedrock and moraine at an altitude no greater than 264 m; downglacier from the seal, stream channels are incised in the glacier bed.

Before the subglacial drainage system is fully developed, complex flow patterns along the glacier margin emerge (figs. 5 and 6). The supraglacier pools fill through subglacial hydraulic connections with the lake; one of the main channels appears to force water up along the rock bastion which lies just downglacier from the first supraglacier pool (near C_3 on fig. 5).

In the latter stages of a jökulhlaup, the supraglacier pools, along with the marginal drainage, collapse as the main drainage goes beneath the glacier along the path indicated by C_1 to C_4 in figure 5. The plunge pool (figs. 2 and 5) is connected to the drainage system along the glacier margin in the initial stages of the jökulhlaup, but when the lake level falls below 320 m (the upper lip of the plunge pool), this drainage system ceases to carry flood waters. All of these features along the glacier margin are auxiliary to the main drainage which tunnels under the glacier.

The release mechanism for jökulhlaups from Strandline Lake appears to be hydrostatic lifting, but the recharge mechanism of the lake is more complex. As table 1 indicates, Strandline Lake has filled and discharged in as little as 1 yr or as long as 5 yr (1974-79). Variations in the amount of annual precipitation and drainage from surface streams are not sufficient to account for these variations in filling rate. It seems likely that subglacial drainage may be altered after a jökulhlaup has occurred. In some cases, subglacial drainage into Strandline Lake may be augmented, leading to rapid filling rates. In other cases, subglacial drainage that formerly fed the lake is diverted to other channels, such as those observed near the terminus on the south side of the Triumvirate Glacier (fig. 2). Slow filling because of subglacial leakage from the lake (due to incomplete sealing under the ice dam)

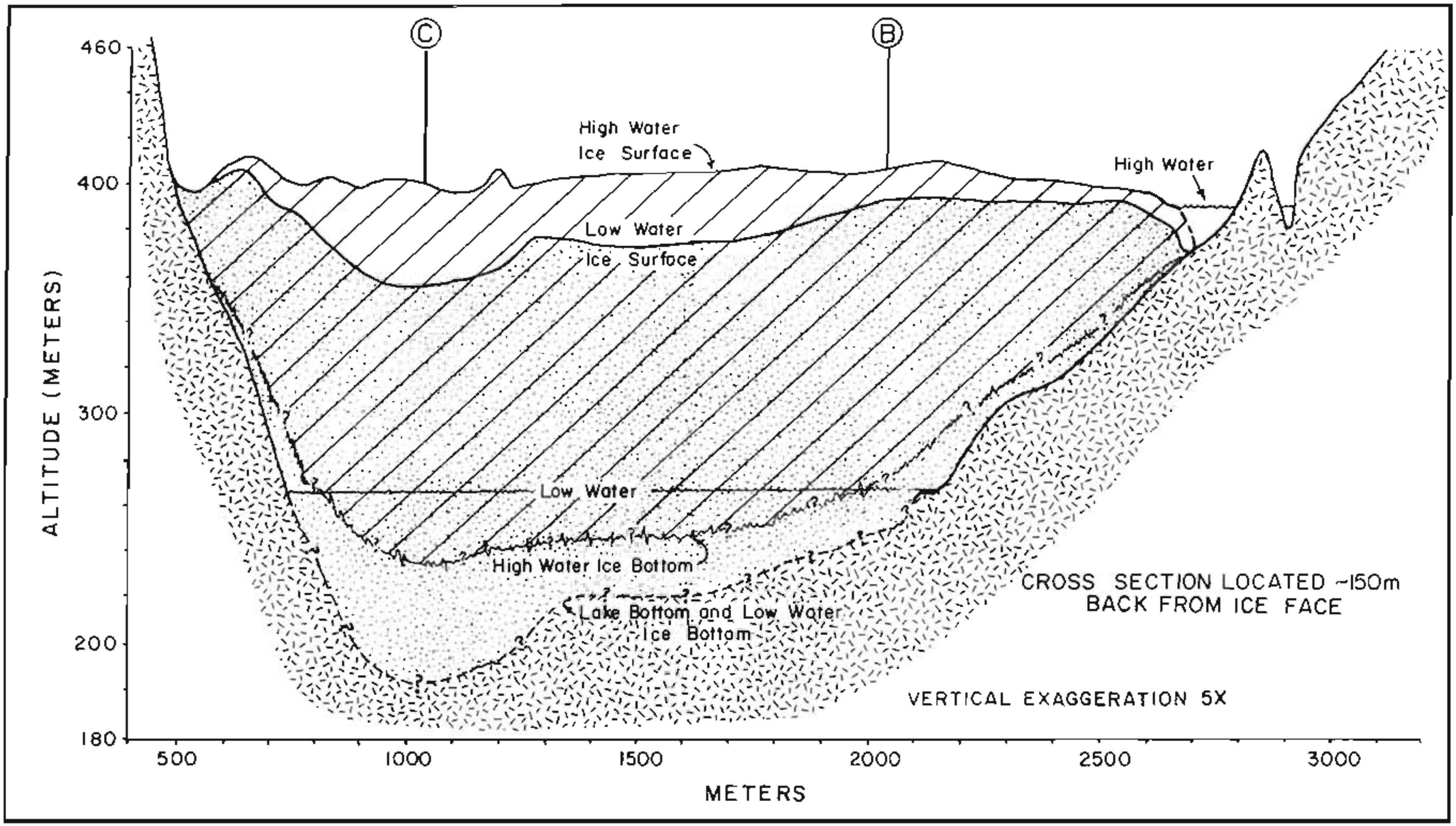

Figure 8. Transverse cross section of floating ice shelf before and after Strandline Lake drained. High water ice bottom based on calculated ice thickness of 130 m. Lake bottom (low water ice bottom) profile is estimated where not exposed and based on an ice subsidence roughly equivalent to water depth beneath the floating ice. This profile is consistent with transverse cross sections in figure 5.

is not as likely, because the Triumvirate Glacier is thick enough to reseal this drainage tunnel once it ceases to carry its catastrophic flow.

The subglacial drainage which feeds the supraglacier pools and marginal drainage may become active early enough to prevent the lake from filling to the level required to lift the ice dam from its seal. Modifications of the subglacial drainage into the lake, combined with complex sub- and marginal drainage patterns, appear to control variations in the filling rates and need to be understood before we can predict jökulhlaups from this system.

The complex system of channels being revealed as the Triumvirate Glacier retreats is only one piece of evidence from the past history of this glacier-dammed lake system. The presence of strandlines 50 m above the 1982 high-water level indicates that past jökulhlaups were larger than the one in 1982. The volume of the lake corresponding to the highest strandline is approximately 12×10^8 m^3, or 65 percent more than the 1982 volume. This suggests that some extremely large jökulhlaups have come from Strandline Lake.

Our understanding of jökulhlaups from Strandline Lake has improved as a result of this study. However, variations in filling rate and the mechanisms that cause marked variability in discharge still pose important questions (Sturm and others, 1987) which must be addressed in order to predict jökulhlaups from Strandline Lake.

ACKNOWLEDGMENTS

This work was supported by the Alaska Department of Natural Resources Division of Geological and Geophysical Surveys with field support from Chugach Electric Company of Anchorage, Alaska. Special thanks are extended to E.P. Whittemore, Douglas Witte, and Francis Shomper for their descriptive accounts of jökulhlaups from Strandline Lake, and to Helgi Björnsson and Bill Long for helpful comments on the manuscript. Field assistance was provided by M. Arline, C.F. Benson, T.S. Clarke, G.E. Liston, C.S. Moore, G. Nibler, D. Smith, E.A. Sturm, and V. Watson.

REFERENCES

Björnsson, Helgi, 1974, Explanation of jökulhlaups from Grimsvötn, Vatnajökull, Iceland: Jökull, 24 AR, 1974, p. 1-26.

______, 1976, Marginal and supraglacial lakes in Iceland: Jökull, 26 AR, p. 40-50.

Booth, D.B., 1986, The formation of ice-marginal embankments into ice-dammed lakes in the Eastern Puget Lowland, Washington, U.S.A., during the Late Pleistocene: Boreas, v. 15, no. 3, p. 209-264.

Clague, J.J., and Matthews, W.H., 1973, The magnitude of jökulhlaups: Journal of Glaciology, v. 12, no. 66, p. 501-504.

Collins, S.G., and Clarke, G.K.C., 1977, History and bathymetry of a surge-dammed lake: Arctic, v. 30, no. 77, p. 217-224.

Matthews, W.H., 1973, Record of two jökulhlaups, Symposium on the hydrology of glaciers: Union Geodesique et Geophysique Internationale, Association Internationale D'Hydrologie Scientifique, Commission De Neiges et Glaces, Cambridge, September 7-13, 1969, Publication 95, p. 99-110.

Miller, J.M., 1982, Community Science Forum: Fairbanks Daily News-Miner, July 24, 1982, p. B-2.

Nye, J.F., 1976, Water flow in glaciers: Jökulhlaups, tunnels and veins: Journal of Glaciology, v. 17, no. 76, p. 181-208.

Post, Austin, 1975, Preliminary hydrography and historic terminal changes of the Columbia Glacier, Alaska: U.S. Geological Survey Hydrologic Investigations Atlas HA-559, 3 pl. (scale 1:10,000).

Post, Austin, and Mayo, L.R., 1971, Glacier dammed lakes and outburst floods in Alaska: U.S. Geological Survey Hydrologic Investigations Atlas HA-455, 3 pl. (scale 1:1,000,000).

Powell, R.D., 1981, A model for sedimentation by tidewater glaciers: Annals of Glaciology, v. 2, p. 129-134.

Sturm, Matthew, Beget, J.E., and Benson, C.S., 1987, Observations of jökulhlaups from ice-dammed Strandline Lake, Alaska: Implications for paleohydrology, in Mayer, L, and Nash, D., eds., Catastrophic Flooding: Winchester, Mass., Allen and Unwin, p. 79-94.

Sturm, Matthew, and Benson, C.S., 1982, Report on Strandline Lake flooding hazard: Unpublished report submitted to Chugach Electric Company, Anchorage, Alaska, by Geophysical Institute, University of Alaska, Fairbanks.

______, 1985, A history of jökulhlaups from Strandline Lake, Alaska: Journal of Glaciology, v. 31, no. 109, p. 272-280.

Table 1. Summary of Strandline Lake flood history.

Year	Event	No. yrs since last flood	Flood stage, Beluga River bridge	Precursor events	Source
1940	flood	?	?	?	'Beluga' Joe Sneller, recorded by E.P. Whittemore, 1978.
1954 (29 Aug)	lake full			Calving bay, moderately heavy iceberg concentration in lake	USGS photos 23 vv 1370 PMC M.
1958	flood	?	?	?	Walter Shultz, Anchorage Times, 15 Jul 79.
1960	lake low				Aerial photos (oblique), Austin Post, USGS.
1970 (2 Sep)	lake full			Calving bay with heavy iceberg concentrations in lake	Aerial photos (vertical), Austin Post, USGS.
1970-?	flood?	?	?	Calving bay with heavy iceberg concentrations in lake	Flood possible in 1970 based on appearance at 2 Sep 70. No observations of the lake recorded between 2 Sep 70 and 12 Jun 74.
1974 (12 Jun)	lake about 3/4 full			?	Aerial photos (vertical) obtained from North Pacific Aerial Survey, Inc. (NPAS).
1974 (mid-Sep)	flood	?	1 m below old bridge	Increased calving; ice dam had calved back from its June position	Oblique photos, E.P. Whittemore.
1979 (11 Jul)*	flood	4.8	Destroyed old bridge	Heavy calving from calving embayment and had calved back from previous position	Oblique photos, E.P. Whittemore.
1980 (3 Dec)*	flood	1.4	Rose 4.3 m at new bridge	Heavy calving, large calving embayment; marginal lakes full	Oblique photos, E.P. Whittemore.
1982 (17 Sep)*	flood	1.8	?	Heavy calving and deep embayment; all marginal lakes full	Aerial photogrammetry and field observations by authors.
1984** (31 Aug-16 Sep)	flood	2.0	?	Heavy calving and moderate embayment; all marginal lakes full	Aerial photogrammetry and field observations by authors.

* Dates indicate catastrophic stage of a longer event.
** Note added in proof.
? Indicates uncertainty.