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ARTICLE OF SPECIAL INTEREST



Driftwood log at height of about 15 m in forest of Sitka spruce at south end of Russell Fiord. Log was stranded by sudden outburst of Russell Lake, which is described in following article. Photographed June 8, 1987, by L.R. Mayo.

Advance of Hubbard Glacier and Closure of Russell Fiord, Alaska—Environmental Effects and Hazards in the Yakutat Area

By Lawrence R. Mayo

Introduction

Hubbard Glacier originates in the Icefield Ranges of Yukon Territory, Canada, and in the St. Elias Mountains of Canada and Alaska. It flows south and southeast for about 120 km through the St. Elias Mountains into Disenchantment Bay and Russell Fiord near Yakutat (fig. 1). Hubbard Glacier is the largest North American ice stream that presently calves into tidewater. It covers an area of about 3,400 km² and extends to sea level from an altitude of about 5,800 meters on the flank of Mount Logan, Canada's highest peak.

The terminus of Hubbard Glacier has fluctuated through a distance of more than 60 km within the past 1,000 years (fig. 1). Earlier advances that repeatedly dammed and released a very large lake in the Russell Fiord basin are recorded by ancient lake sediments that span the past 7,000 years (George Plafker, U.S. Geological Survey, written commun., 1987).

In a study of glacier-dammed lakes of Alaska, it was predicted that Hubbard Glacier would again block Russell Fiord by about 1991 (Post and Mayo, 1971). The temperature and salinity of Russell Fiord consequently were studied by Reeburgh and others (1976) to provide background data in anticipation of a future conversion of the fiord into a lake. They recognized that such a lake could potentially overflow at its south end, causing severe flooding near the town of Yakutat (fig. 1).

Historical records show that Hubbard Glacier has advanced 2 to 3 km during the past century (the actual distance varies along the terminus). In May 1986, this progressive advance carried it across the entrance of Russell Fiord, where it formed a massive ice dam. Rapid rise in the surface level of the newly created Russell Lake submerged forests to a height of 26 m and threatened to overflow into the Situk River, a highly productive and economically important salmon stream near Yakutat (fig. 1).

Many glaciers of southern Alaska are subject to major advances and retreats. These events have impacts on lakes, streams, and coastal morphology; on forests and wildlife; and on human ecology. Continuing studies of Hubbard Glacier by the U.S. Geological Survey and other State and Federal agencies are aimed at documenting the mechanism and impacts of the recent Hubbard Glacier advance and reconstructing the history of the glacier's earlier fluctuations. Knowledge obtained from these studies can be used to predict future changes and their environmental effects for Hubbard Glacier and other

tidewater glaciers. This paper summarizes the geologic history and recent advance of Hubbard Glacier, its effects, and the implications for assessments of glacier changes throughout southern Alaska.

Glacier history

Varved lake deposits dating $6,310 \pm 110$ and $4,890 \pm 100$ yr B.P. are interbedded with alluvium and glacial till in deltas near the south end of Russell Fiord (George Plafker, U.S. Geological Survey, and J.J. Clague, Geological Survey of Canada, written commun., 1987). These deposits indicate that major advances of Hubbard Glacier or possibly of neighboring glaciers blocked Russell Fiord during middle Holocene time, a period when glaciers throughout the world are generally believed to have been less extensive than at present.

Plafker and Miller (1958) have shown that Hubbard Glacier advanced to the mouth of Yakutat Bay about 1130 A.D. (± 160 years) and deposited the moraine upon which the present town of Yakutat is situated (fig. 1). A distributary ice stream of presumably the same age flowed southeast, filled Russell Fiord with ice, and deposited a terminal moraine at the south end of the fiord. The glacier subsequently retreated to an unknown position, then readvanced into the head of Yakutat Bay by about 1700 A.D. (Plafker and Miller, 1958) (fig. 1).

Hubbard Glacier retreated again after 1700 A.D. During that retreat, Alessandro Malaspina, an Italian explorer who worked for Spain, entered Yakutat Bay in 1791. Malaspina carried a map showing the possible western end of the elusive "Northwest Passage" at the head of the bay (Tarr and Butler, 1909). His observations within the bay indicate that the glacier had retreated at least 20 km since 1700 A.D., but beyond that point the bay was blocked by "perpetual frost." Malaspina named Disenchantment Bay for his frustrated hopes of finding a navigable passage. Tarr and Butler (1909) concluded that Malaspina's "perpetual frost" was probably only tightly packed floating icebergs rather than the terminus of Hubbard Glacier because the explorers did not report calving from the terminus of the glacier, which would have been an unforgettable hazard to their small boat.

In 1890, I.C. Russell, the first modern scientist to examine the Yakutat Bay region and the first member of the U.S. Geological Survey to study glaciers in Alaska, provided an accurate description of

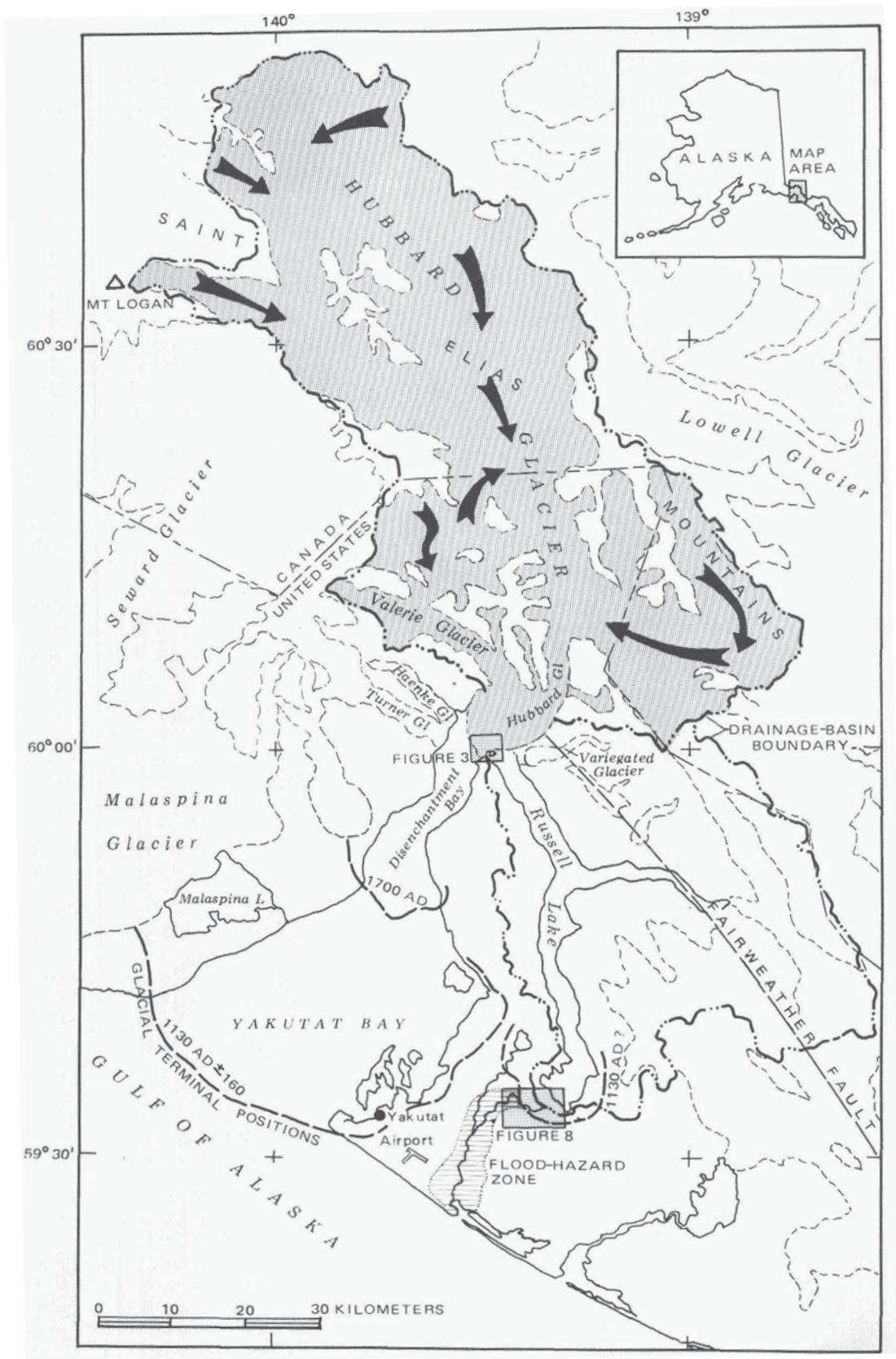


Figure 1. Hubbard Glacier system, showing flow directions (arrows), extent of advances about 1130 A.D. and 1700 A.D., and flood-hazard zone along Situk River. Dashed lines indicate glacier margins.

the position and features of Hubbard Glacier. His small-scale map and drawing of Hubbard Glacier (Russell, 1891) shows the glacier's terminus approximately 2 km from Osier Island, leaving open the mouth of a large fiord to the east. That position indicated approximately 28 km of retreat since the 1700 A.D. advance. Russell probably observed Hubbard Glacier near its maximum recessional position.

In 1891, Russell (1893) traveled into the fiord that later was named after him (Gannett, 1902) and recognized from the pioneer vegetation and fresh shoreline features along its walls that the fiord had been the site of a recent glacier-dammed lake.

An ethnographic description of this lake was given in 1952 to Frederica de Laguna (1972, p. 287) by Harry K. Bremner, a Tlingit Indian of Yakutat, whose father had witnessed the outburst of the lake as a child. Bremner stated: "About the middle of the last century ... people were near the lake picking strawberries... That was what my father was doing. Every time he came back to the boat, he found that it was going dry, so he would push it off into deeper water before going back for another load. When this happened a few times he realized that the water was really going down. Everybody ran and got into the canoes and started down the stream. Suddenly a big mass of salt water rushed downstream. Everybody got away safely. There was still enough water in the stream for the canoes. But after that, Situk River was just a little one."

Elders in Yakutat believe that this event occurred about 1860 (Elaine Abraham, oral commun., 1986). This is supported by annual rings of a spruce tree on the former lake bed, which indicate that the tree began growth in 1885.

During the 96 years since Russell's observations, Hubbard Glacier has readvanced about 2 km across the fiord entrance at the head of Disenchantment Bay (fig. 2).

Dynamics of Hubbard Glacier

From 1961 to 1986, Hubbard Glacier approached Gilbert Point near Osier Island (fig. 2), and the rate of glacier advance increased locally as it entered progressively shallower water at the entrance to Russell Fiord (fig. 3).

Most glaciers advance and retreat synchronously as a result of climatic variations which produce changes in the rate of snow accumulation or ice melting (Nye, 1960). Tidewater glaciers, however, are an exception. Glaciers that terminate in seawater can advance asynchronously and over long distances due to the forward movement of protective submarine terminal moraines (fig. 4A; Post, 1975). These glaciers can also retreat rapidly by calving into the ice-scoured and -deepened fiords behind the moraines if they recede only a short distance from the protective moraines against which they formerly were grounded (fig. 4B). The asynchronous behavior of tidewater glaciers is well illustrated by Columbia Glacier, which is now in rapid retreat (Meier and others, 1985) while Hubbard Glacier is advancing. Glaciers that end in deep lakes, such as Portage Glacier southeast of

Anchorage, behave in a similar way (Mayo and others, 1977).

Hubbard Glacier is in the early phase of a major new advance that began about 100 to 150 years ago. The glacier has a strong positive ice balance because its last recession resulted in the loss by rapid calving of most of its ablation zone. At present, 95 percent of Hubbard Glacier is above the local snowline or equilibrium line altitude (ELA) at 1,000 m altitude (fig. 4), and therefore is within the accumulation zone. A glacier that has fully advanced to an equilibrium position typically has about 60 to 70 percent of its total area within its accumulation zone (Meier and Post, 1962).

The current advance of Hubbard Glacier is controlled by the movement of a submarine moraine at the ice terminus, which was discovered by ice radar and fathometer surveys (Mayo, 1987). The glacier terminus is in shallow water that varies from 0 to 50 m deep at the crest of this moraine. The fiord is 205 m deep 2 km in front of the moraine crest, and the glacier bed is 320 m below sea level 2 km behind the moraine crest (fig. 5). The shallow water at the moraine limits the rate of ice calving (Brown and others, 1982). The process of displacement of the moraine into Disenchantment Bay by Hubbard Glacier is demonstrated by the fact that the glacier bed is now more than 300 m below sea level at the position where the glacier terminus had been mapped in 1895 by the International Boundary Commission (1952).

Recent glacier advance and lake formation

Photographs taken during repeated overflights of Hubbard Glacier in April and May 1986 by residents of Yakutat show that the glacier was advancing rapidly across the entrance of Russell Fiord at a rate of approximately 10 m per day and that submarine deposits were being raised above sea level by the plowing action of the glacier. Closure of the mouth of Russell Fiord was completed on May 29, 1986, and the newly-formed Russell Lake began filling (fig. 6). Although Hubbard Glacier advanced toward the terminus of Variegated Glacier to the east, the two glaciers remained separated by a stream flowing between them. Hubbard Glacier began to overrun Osier Island during the remainder of 1986, but stopped short of the summit of the island (figs. 2 and 3).

Scientists of the U.S. Geological Survey, the U.S. Forest Service, and the University of Alaska initiated research projects during the summer of 1986 in cooperation with the National Park Service, the City of Yakutat, and the National Geographic Society. Their studies included determination of the causes of Hubbard Glacier's behavior, measurements of the rate of filling of Russell Lake, precision remapping of the Yakutat Forelands, estimation of the flooding of the Situk River should Russell Lake overflow, and archeology in areas potentially subject to flooding.

The rapid ice advance in 1986 was caused by a weak and short-duration surge of Valerie Glacier, a tributary of Hubbard Glacier (fig. 1). The surge, which had a measured flow rate of 36 m/d in June 1986, produced unusual crevassing and marginal wrench faults in Valerie Glacier. The rapid advance of

Hubbard Glacier resulted in the plowing of shallow marine sediments between the glacier and the shore at the entrance to Russell Fiord. These sediments were pushed above sea level and calving losses at the terminus were eliminated, which then resulted in continuing advance. (Mayo, 1987). The surge ended in late June 1986, and no further rapid advance of Hubbard Glacier took place after that time.

At the same time that significant advance was occurring in shallow water near Gilbert Point (fig. 3), advance was negligible at locations along the terminus

of Hubbard Glacier where the water was more than 200 m deep in front of the moraine. This indicates that the rate of advance along the terminus of advancing tidewater glaciers is related inversely to the amount of subglacial sediment required to fill the fiord in front of the moraine. The location of the Hubbard Glacier ice dam in 1986 was controlled by the presence of shallow unconsolidated deposits on bedrock near the glacier terminus; but the timing of the closure in 1986 was controlled by the weak surge of the Valerie tributary of Hubbard Glacier. The bedrock core of

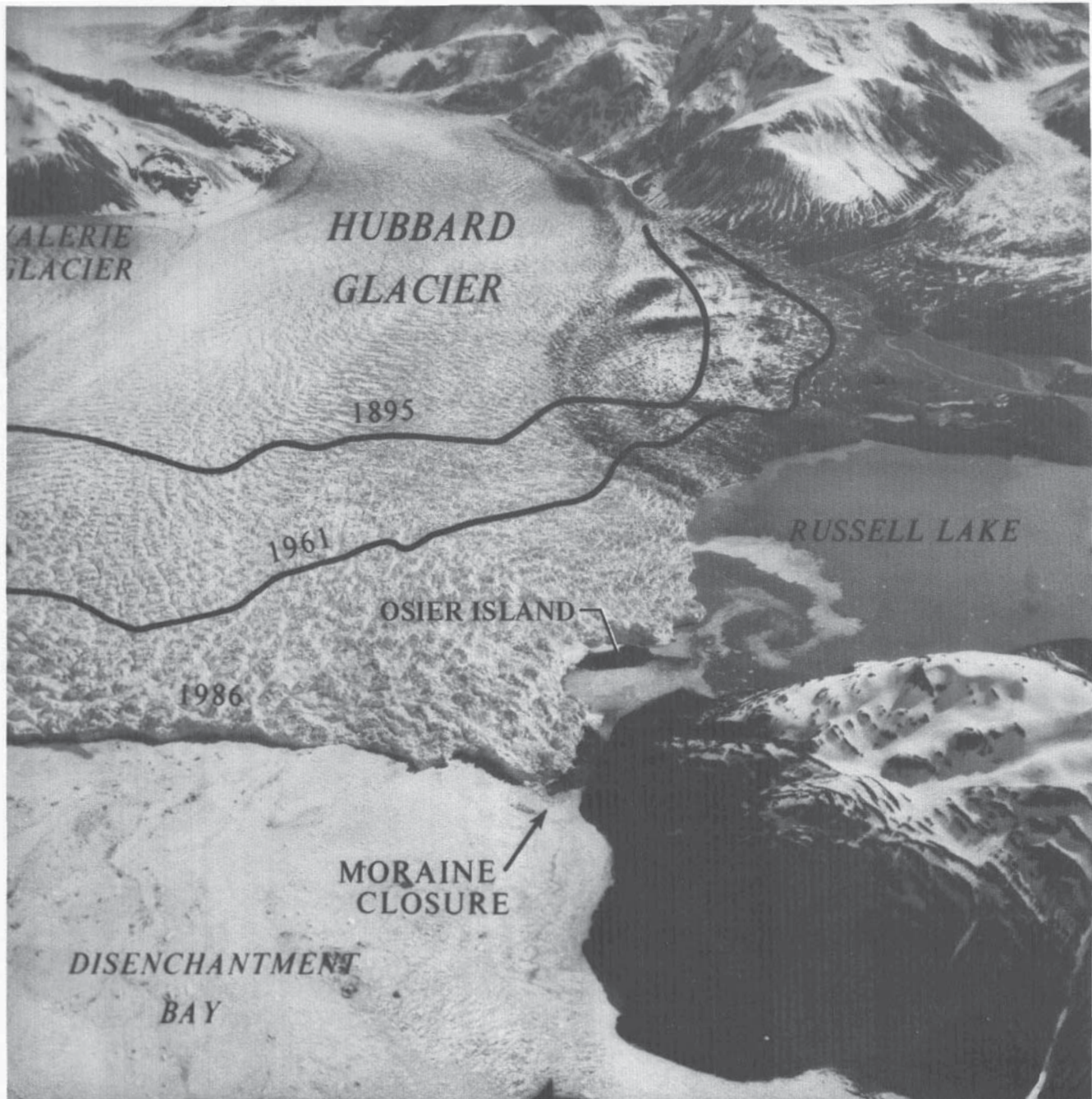


Figure 2. View east to terminus of Hubbard Glacier June 13, 1986. Glacier position in 1895 from International Boundary Commission (1952); position in 1961 from U.S. Geological Survey Mount St. Elias (A-4) and (A-5) 1:63,360 quadrangle maps. Gilbert Point is in the right foreground.

Osier Island served as a buttress against rapid ice flow and terminus advance in June 1986 (fig. 2).

During the summer of 1986, Russell Lake rose rapidly (fig. 6), inundating about 33 km² of forested land adjacent to the blocked fiord. Half of its drainage basin is occupied by glaciers, and ice melt and rainfall runoff from these glaciers produced about 80 percent of the runoff feeding the lake. The lake area, beginning at 195 km², was equal to about 10 percent of the basin area, so the measured lake rise during the summer of 1986 of 25.5 m (based on data of Seitz and others, 1986) was equivalent to an average about 2.5 m liquid runoff from the basin. Very high runoff rates, 3.8 m per year at Bering Glacier east of Hubbard Glacier, had been calculated from observed glacier equilibrium line altitudes (Mayo, 1986), but the simple volumetric measurement of runoff into Russell Fiord is the first direct data obtained for a large basin with glaciers in this part of Alaska.

As Russell Lake rose in the summer of 1986, several consequences were possible: (1) the lake could overflow and burst out through the new moraine formed from submarine sediments plowed against Gilbert Point by Hubbard Glacier at the north end of Russell Fiord, (2) the lake could overflow onto the Yakutat Foreland at the south end of Russell Fiord, or (3) the lake could burst out through the ice dam. Hubbard Glacier did not advance fully to the bedrock ridge at the entrance to Russell Fiord. The marine sediments plowed from the fiord in April and May 1986 were trapped between the glacier ice and the ridge, forming a moraine (fig. 2). As the glacier pushed forward, the moraine was squeezed and deformed

upward. The overflow point on the moraine rose at a rate that was faster than the filling rate of the lake (fig. 7), and overflow therefore did not occur.

Potential lake overflow sites also exist at the south end of Russell Fiord, 50 km beyond the terminus of Hubbard Glacier. The lowest site is situated 39 m above sea level in a recently reforested channel in the moraine at the head of Old Situk Creek (fig. 8). The overflow channel contains a lag deposit of boulders derived from the moraine, and is undoubtedly the channel used over a century ago by the Tlingit Indians to gain access by boat into Russell Lake. Remapping of the Yakutat Foreland (fig. 8) was undertaken as a joint project by the U.S. Forest Service and the U.S. Geological Survey in 1986 to obtain precise altitude data in areas possibly subject to flooding from the potential filling and overflow of Russell Fiord (fig. 1).

Before overflow could occur across the moraine at either end of the lake, the lake burst out through the 500-m-wide ice dam, which proved to be too narrow to contain Russell Lake. The calving rate from the Disenchantment Bay side of the ice dam exceeded the lateral deformation rate of the dam, causing it to become progressively narrower (eventually only 150 m wide; see fig. 9). Small ponds of meltwater trapped in crevasses at the edge of the ice dam indicated that water pressure in the dam was higher than at Russell Lake; this increased the calving rate into

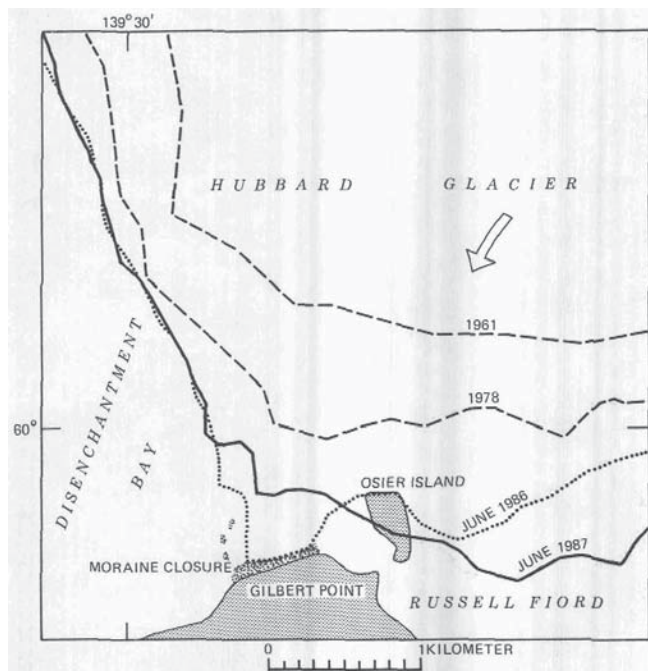


Figure 3. Terminal positions of Hubbard Glacier from 1961 to June 1987 at entrance of Russell Fiord. Glacier position in 1961 from maps cited in figure 2; position in 1978 from Krimmel and Sikonia (1986). Arrow indicates direction of flow. See figure 1 for location.

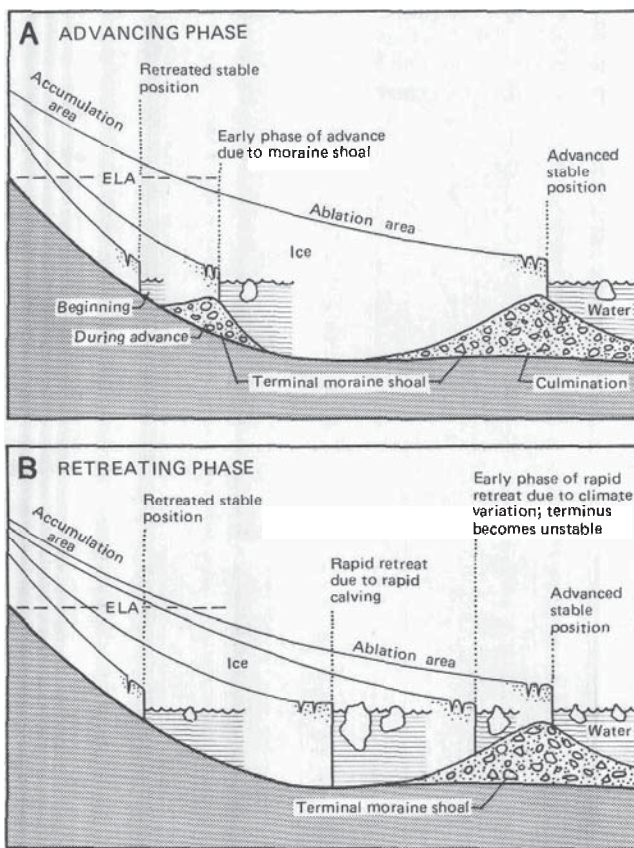


Figure 4. Cycle of advance and retreat of a tidewater glacier. ELA (equilibrium-line altitude) is position on glacier where annual snow accumulation equals annual snow melt.

Disenchantment Bay, resulting in a deep embayment in the ice dam during September and early October.

During the afternoon of October 7, 1986, lake water began flowing through the maze of crevasses in the ice dam, carrying with it small fragments of ice. In the late evening of the same day between 10:15 and 10:45 p.m. Standard Alaskan Time, when the lake height peaked at 25.5 m above sea level and with 5.3 km³ of water stored, the ice dam failed. Thunderous

calving every few seconds for several hours during the night indicated that failure occurred by progressive collapse of massive ice blocks into the outburst channel (fig. 10). At the same time, the channel widened by erosion of alluvial fan deposits and highly jointed bedrock on Gilbert Point.

Measurements of lake height were obtained during the outburst at a site located 8 km from the failing ice dam (Seitz and others, 1986). The maximum

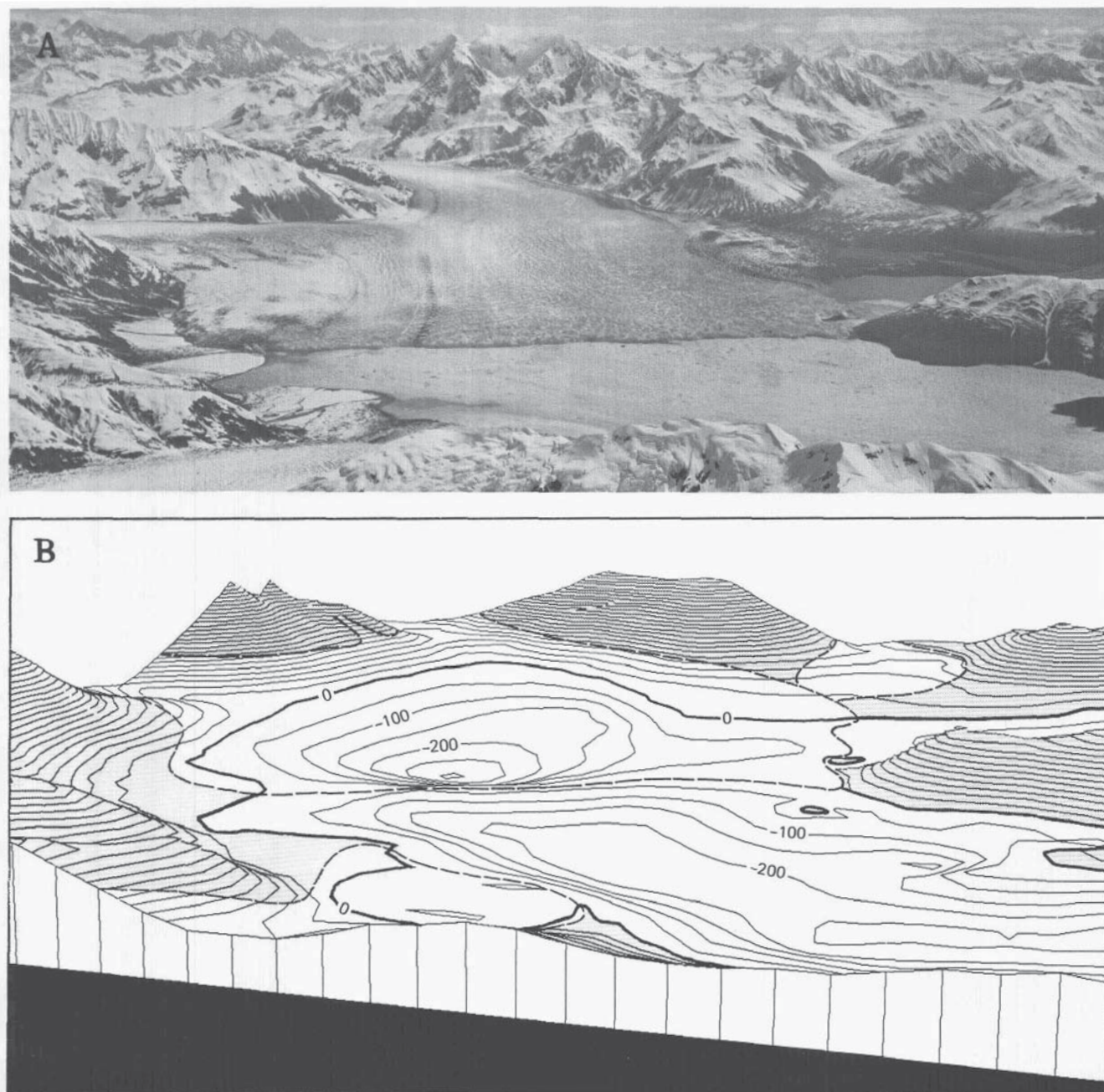


Figure 5. View northeast showing surface and bed of Hubbard Glacier. A, Photograph taken June 13, 1986. Turner Glacier in lower left corner; Gilbert Point and Russell Lake near right margin. B, Computer-drawn perspective contour map showing exposed land (shaded), glacier limits (dashed lines), bed of Hubbard Glacier (unshaded) and fiord bottom (unshaded). Contour interval 50 m; altitudes above and below mean sea level. Note submarine moraine at Hubbard Glacier terminus.

discharge rate took place between 1 and 2 a.m. on October 8, when the lake dropped 1.68 m. Assuming that the entire lake surface fell equally, the average discharge rate during the interval was 104,500 m³ per second, which greatly exceeded the highest measured rate of flow of the Yukon River, Alaska's largest river (29,000 m³/s, Jones, 1983). The lake area at that time was 224 km².

Russell Lake poured into Disenchantment Bay (fig. 11) with a velocity measured at 11 m/s at dawn, which was about 4 hours after the time of peak discharge. The momentum of the outburst flood carried the turbulent water 5 to 6 km across Disenchantment Bay to the west shore where it washed against the terminus of Turner Glacier.

The peak flow rate of the "Russell River" may be the greatest water discharge to occur in North America and the largest glacier outburst in the world measured during the past few centuries (table 1), but was much less than the estimated peak discharge of 15 to 17 million m³/s from late Pleistocene Glacial Lake Missoula when it burst out into the Columbia River between 16,000 and 12,000 years ago (O'Connor and Baker, 1987; Baker, 1973), creating the Channeled Scablands of eastern Washington. Prior to the 1986 outburst of Russell Lake, the greatest known historical outburst was from the June 5, 1976, failure of the Teton Dam, Idaho, which was 65,000 m³/s (Ray and Kjelstrom, 1978, Costa, 1985). The largest known historic glacier outbursts in Alaska have been from Chakachamna Lake, which is dammed by Barrier Glacier at Mount Spurr volcano, and from Berg Lake, which is dammed by Bering and Stellar Glaciers.

Russell Lake had not fully emptied by 9 p.m. on October 8 when observations stopped, but was still 2 to 3 m higher than the water surface in Disenchantment Bay. A normal tidal current was observed flowing from Russell Fiord on the morning of October 9, indicating that the outburst had ceased. The outburst of the lake probably had continued until about 3 a.m. on October 9, when the projected lake height recession was equal to the predicted tide level in Disenchantment Bay. The total outburst period therefore was approximately 28 to 30 hours.



Figure 6. View southeast across Russell Lake showing flooded forest, August 28, 1986. Lake height was 20 m above sea level at this time.

The outburst eroded the shore of Russell Fiord back by as much as 300 m in the vicinity of the failing ice dam. Most of the erosion was from an alluvial fan, most of which was swept into Disenchantment Bay, but as much as 50 m of the highly jointed bedrock also was eroded. Only a small remnant of the terminal moraine remained, and individual boulders of marble as large as 15 m in diameter had been carried away. Before the outburst, Osier Island had been mantled with glacial till and marine gravel, but these deposits and some bedrock were eroded and generally only small alder roots remained in bedrock fissures. Shrimp found near the top of Osier Island could have been derived only from the bed of Russell Fiord, where they were probably swept up by water turbulence in the lake during its outburst.

Vegetation that had been inundated by the lake was severely damaged. Mud and stones dropped from icebergs that had been floating in the lake had accumulated in tree branches as a form of "arboreal diamicton" (fig. 12), and icebergs that had been floating near the shore of Russell Lake remained grounded in alder forests well above sea level (fig. 13). A brown algal slime covered all vegetation to a height of about 15 m above sea level at the south end of the former lake, and some logs that had been floating were caught high in tree limbs (see photo on p. 3). By October 1987, one year after the lake had drained, all alder and devil's club vegetation that had been inundated was dead. Other vegetation, including spruce, hemlock, willows, and grasses, that had been flooded for less than a month had partially recovered, but was dead where inundated for longer periods. Several species of horsetails (*Equisetum*) were already recolonizing the floor of the dead forest in the summer of 1987.

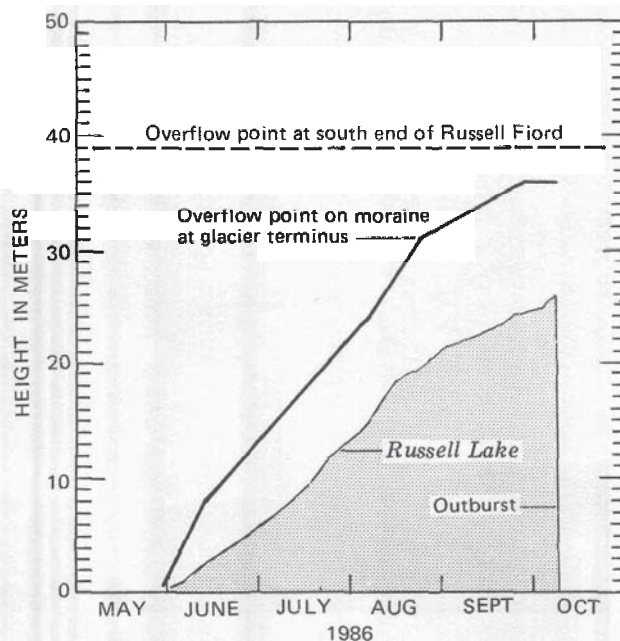


Figure 7. Height of potential overflow point on Hubbard Glacier moraine (measured by aneroid altimeter) and height of Russell Lake (data from Seitz and others, 1986), May to October 1986.

Table 1. Peak discharges of largest known historic glacial lake outbursts

[Sources: Russell and Berg Lakes, D.C. Trabant, and L.R. Mayo, U.S. Geological Survey, unpub. data; Lake George, U.S. Geological Survey, 1964, 1971, and unpub. data; other lakes, J.E. Costa, 1985, and J.E. Beget, 1986]

Location	Date	Peak discharge (m ³ /s)	Reference
1. Russell Lake, Alaska	1986	104,500	See text
2. Grimsvatn, Iceland	1934	50,000	Thorarinsson, 1957
3. Chong Kumdan, India	1929	22,650	Gunn, 1930
4. Berg Lake, Alaska	1983	17,000	Trabant and Mayo, unpub.
5. Chakachamna Lake, Alaska	1971	13,300	Lamke, 1972
6. Lake George, Alaska	1958	10,200	USGS, 1964
7. Lake George, Alaska	1961	10,100	USGS, 1971
8. Lake George, Alaska	1957	9,430	USGS, unpub.
9. Lake George, Alaska	1960	9,290	USGS, 1964
10. Lake George, Alaska	1949	8,100	USGS, unpub.
11. Gietro, Switzerland	1818	8,000	Haeberli, 1983
12. Lake George, Alaska	1953	7,700	USGS, unpub.
13. Lake George, Alaska	1954	7,450	USGS, unpub.
14. Lake George, Alaska	1955	7,300	USGS, unpub.
15. Lake George, Alaska	1956	7,100	USGS, unpub.
16. Lake George, Alaska	1965	6,680	USGS, 1971
17. Standline Lake, Alaska	1984	6,100	Sturm and Benson, 1986
18. Lake George, Alaska	1964	6,100	USGS, 1971

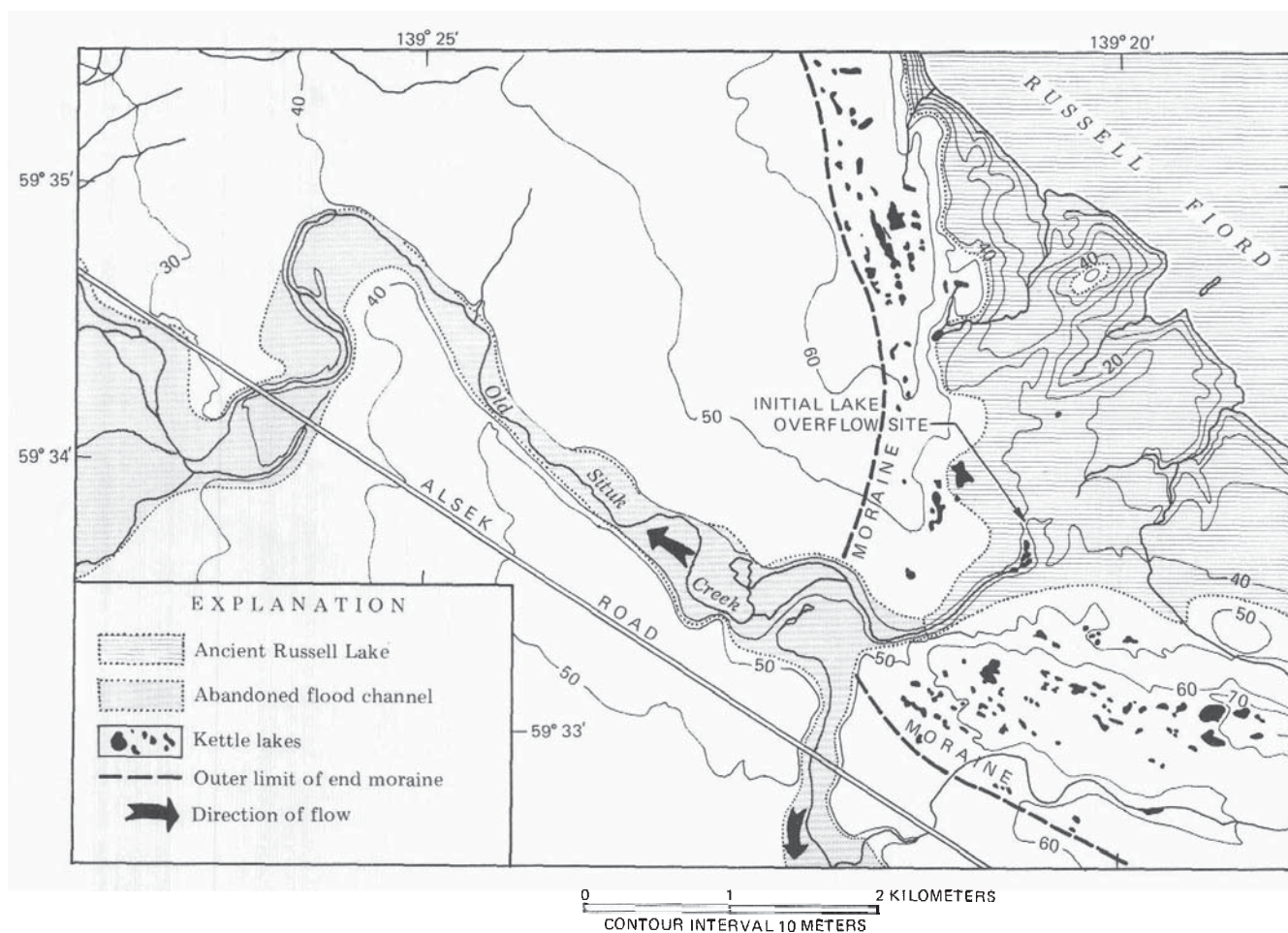


Figure 8. Situk River overflow site 22 km east of Yakutat at south end of Russell Fiord. Initial overflow point altitude is 39 m above sea level. Areas subject to flooding by Russell Lake extend to 45 m elevation. Abandoned flood channel is that of previous overflow of Russell Lake prior to about 1860. Abandoned shoreline and flood channel interpreted from map and aerial photographs.

The terminus of Hubbard Glacier readvanced during the winter of 1986-1987, overriding most of Osier Island during January. However, it retreated about the same amount during the following summer. At the present time, Hubbard Glacier shows no evidence of rapidly reclosing Russell Fiord. However, the steepened bedrock ridge at Gilbert Point exhibits incipient landslide scarps, which suggests that approximately 500,000 m³ of rock could slide into the narrow opening into Russell Fiord south of the glacier terminus (W.O. Powell, U.S. Forest Service, written commun., 1987). Although that amount of rock would probably not dam the entrance, it could reduce the calving rate of Hubbard Glacier and thereby might lead to rapid reclosure by the ice.

Haenke Glacier, which now enters Disenchantment Bay about 1 km from the terminus of Hubbard Glacier, surged during 1986-1987: it emerged from the mountains in February 1987 and advanced into Disenchantment Bay by June. Rock debris carried by the Haenke Glacier is entering Disenchantment Bay near the calving terminus of Hubbard Glacier. This additional sediment will decrease the water depth in the bay, which in turn could increase the advance rate of part of the terminus of Hubbard Glacier.

Glacial events and environmental effects: 1988 and beyond

Hubbard Glacier has advanced for the past 100 to 150 years by moving a submarine moraine into Disenchantment Bay. The glacier will continue to advance, reclosing Russell Fiord in a few years. Hubbard Glacier is capable of sustaining this strong advance because of its unusually large accumulation area compared with its ablation area. In addition,

landslides from Gilbert Point or debris deposited by the surging Haenke Glacier could rapidly decrease water depth and calving rate at the terminus of Hubbard Glacier, further increasing its rate of advance. Velocity of Hubbard Glacier is being monitored by satellite telemetry (Trabant, 1986) to provide data essential for assessing its future rate of advance.

The exact nature of future events at Hubbard Glacier is uncertain, but some elements are predictable. When the advancing glacier closes Russell Fiord again, the ice dam can be expected to be wider than it was in 1986 because the glacier currently is advancing along its entire terminus (fig. 3). In addition, the overriding of Osier Island in 1987 is evidence that the glacier is becoming thicker at that location. If the ice dam is wider and higher than it was in 1986, it may also be stronger; consequently Russell Lake may rise higher than it did in 1986.

The future Russell Lake could rise to the level of the channel at the south end of Russell Fiord and overflow through it into the Situk River, or it could burst out again by either of two processes. An outburst could occur between Osier Island and Gilbert Point, as it did in 1986, or it could take place through the main mass of Hubbard Glacier north of Osier Island if the rising lake floats the ice free from the fiord floor. In the latter case, a large amount of ice could be carried away by the outburst, leaving a truncated glacier terminus in deep water behind the protective moraine. The stability of the glacier then would be threatened because it could retreat catastrophically by rapid calving into deep water.

If Russell Lake were to overflow into the Situk River, which would occur about 12 to 18 months after the lake began to fill, the lake's surface would continue to rise several meters higher than the initial

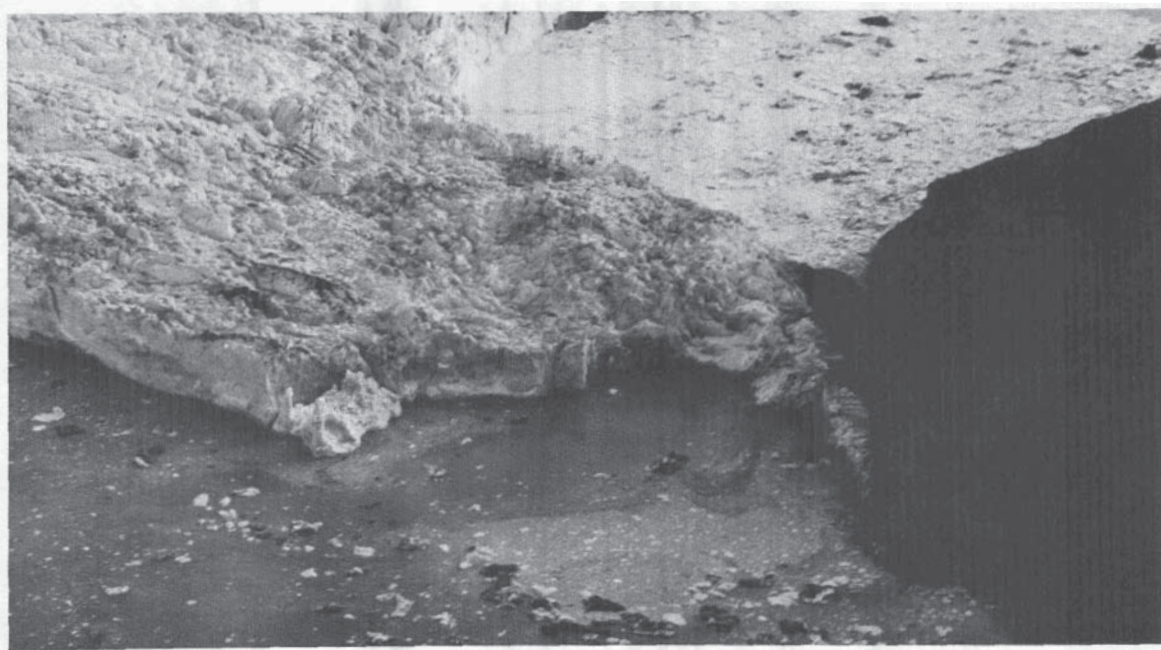


Figure 9. Hubbard Glacier ice dam on October 7, 1986, 10:47 a.m., about 12 hours before its failure. View looking east.

overflow point by an amount equal to the depth of water in the overflowing river. The lake basin would thus fill to a height of about 45 m above mean sea level. The extent of the zone of flooding along the river, interpreted from channel scars visible on aerial photographs, is shown in figure 8. The limits of the flood-hazard zone on the Yakutat Foreland closer to the Gulf of Alaska (fig. 1) also is evident on aerial photographs, but future flooding may not be restricted to the former flood channel. The land surface may have been differentially uplifted by tectonic activity, most notably the 1899 Yakutat earthquake, (Tarr and Martin, 1906), and the basin size and runoff rate may not be the same in the future as they were during the last overflow into the Situk River. Although the main channel extends west along Old Situk Creek, a smaller distributary channel extends south at the moraine front (fig. 8), and it also could carry water during times of high future flow.

The average discharge of water from the Russell Fiord basin can be estimated using a runoff model that is based on the observed equilibrium line

altitudes of glaciers (Mayo, 1986). The estimated average discharge would be about $220 \text{ m}^3/\text{s}$, and the peak flow each year could be about five times greater (a normal relationship for rivers in Alaska). Unusual flooding events could be even greater. In contrast, the flow of the Situk River during a rainy period in October 1987 was about $30 \text{ m}^3/\text{s}$, and the average discharge rate may be only 10 to $15 \text{ m}^3/\text{s}$. An order-of-magnitude increase in the flow of the river can be expected to destroy the forest in the revegetated channels, possibly creating sizable log jams that would further intensify the flooding. High flow probably would also cause erosion of soils and sediments, resulting in additional turbidity of the water. Because its basin is dominated by glacier runoff, Russell Lake would contain a significant concentration of suspended clay-size particles that would pass into the river. Changes in both flow and turbidity would affect the highly prized fish resources of the Situk River. Flooding would eradicate sections of the Alsek Road (fig. 8), inundate a small airfield, and affect subsistence fish camps, but at the same time would

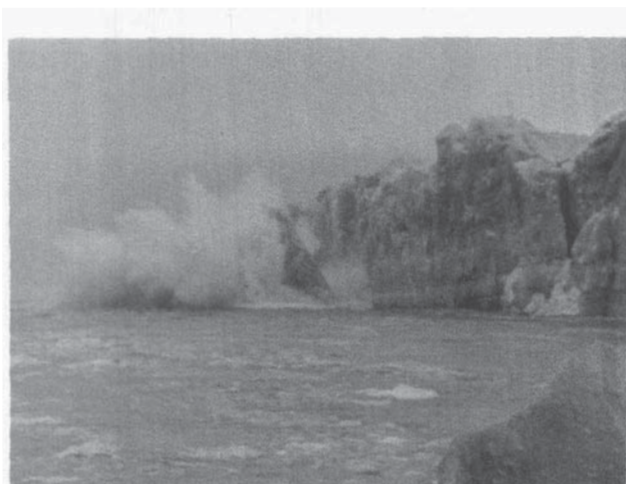


Figure 10. Hubbard Glacier ice dam disintegrating during outburst of Russell Lake; October 8, 1986, 1:56 p.m.



Figure 12. Rocks and mud deposited on alders from icebergs that had been floating in Russell Lake. Photograph taken October 9, 1986.



Figure 11. Outburst of Russell Lake and flow of "Russell River" into Disenchantment Bay; October 8, 1986, 9:01 a.m. Discharge rate at that time was approximately $77,000 \text{ m}^3/\text{s}$, and water speed in outburst channel was measured at 10.8 m/s soon after photograph was taken.

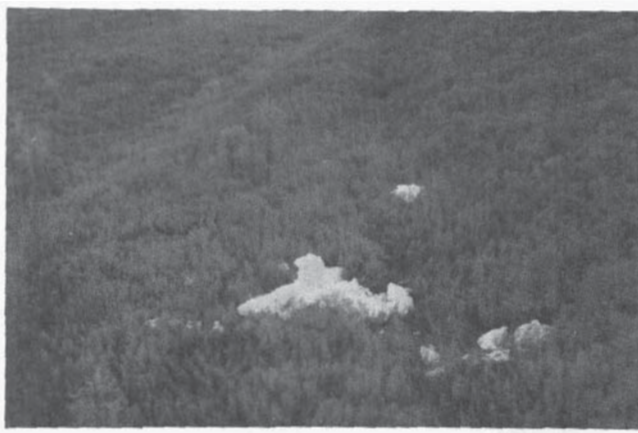


Figure 13. Icebergs stranded in mud-covered forest that had been flooded by Russell Lake. Photograph taken October 9, 1986.

create a new route by which both boats and fish could enter Russell Lake. During times of combined high tide and high river discharge, the Yakutat Airport, the primary point of access to the Yakutat area, might be subject to minor flooding.

Russell Fiord remains unfrozen at the present time owing to tidal inflow during the winter, but Russell Lake would probably develop winter ice with a cover of snow. The ice and snow cover would increase albedo locally as well as decrease the amount of heat provided by that body of water to the air during severe winter weather. These factors could cause the temperature of air blowing across Russell Fiord to be colder than at present during winter and spring.

After closure of Russell Fiord, tidal flux into Yakutat Bay would be reduced by the amount of water that presently cycles in and out of Russell Fiord. The resulting decrease in tidal currents in Yakutat Bay could cause a decrease in the rate of iceberg flushing from the bay. Migratory fish, which enter Russell Fiord from Yakutat Bay at present, would be blocked by Hubbard Glacier. However, a new path into Russell basin via the Situk River would become available after the lake filled.

The advance of Hubbard Glacier and creation of Russell Lake might also increase water pressure on the Fairweather fault (fig. 1), a plate boundary transform fault, where the fault crosses the Nunatak Arm of

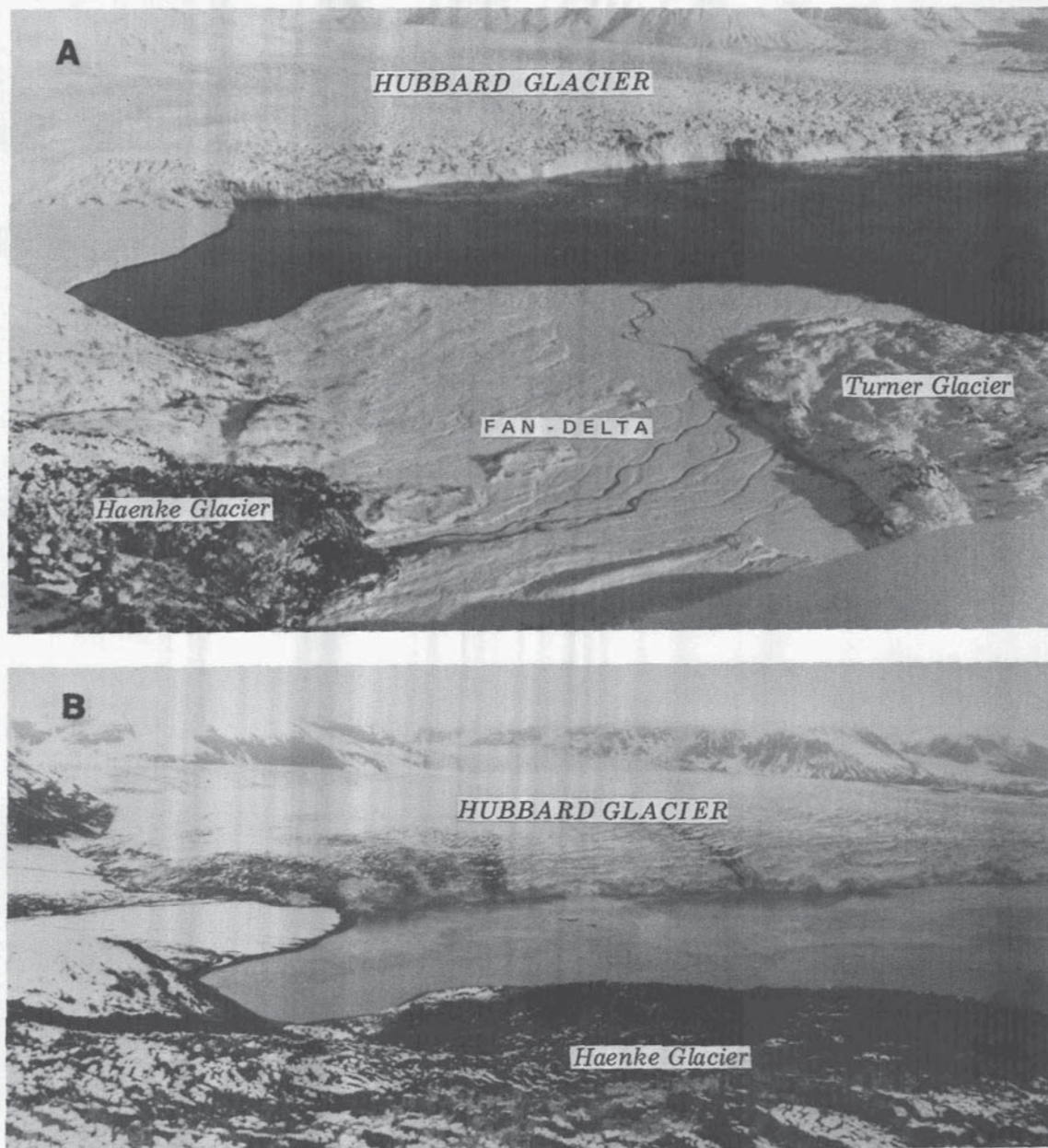


Figure 14. Terminus of surging Haenke Glacier: A, February 13, 1987; B, June 19, 1987. Haenke Glacier surged over fan-delta and terminus of Turner Glacier to become Alaska's newest tidewater glacier.

Russell Fiord (John Lahr, U.S. Geological Survey, oral commun., 1987). In addition the fiord would be converted into a lake with fresh water "floating" on residual, probably sulfate-rich and anoxic, seawater (Reeburgh and others, 1976). This would produce a drastic change in the ecosystem of the fiord.

Conclusions

The recent advance of Hubbard Glacier provides a large-scale example of the environmental and economic problems that can result from dynamic glacier fluctuations in Alaska. As glaciers advance and retreat, new glacier-dammed lakes can be formed, drainage basin boundaries can change substantially, the flow regime and quality of rivers can change, and fisheries and forests can be impacted. These changes can, in turn, alter transportation, economic, and recreational activities of people in the regions affected.

Detection of a submerged moraine beneath the terminus of the advancing Hubbard Glacier and the discovery of at least four major glacier advances and recessions during the past 7,000 years strengthens the hypothesis of Post (1975) regarding the behavior of tidewater glaciers. Ongoing studies at Hubbard Glacier suggest that the rate of advance of tidewater glaciers is controlled by the rate of sediment transport by the glacier to its calving terminus, by submarine mass wasting at the moraine front, and by the depth of water in front of the submarine moraine. Measurement of the rate of rise of Russell Lake in 1986 confirmed previously estimated very high runoff rates for the region that had been based on primarily observed equilibrium-line altitudes of glaciers.

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