GLACIER BALANCE DATA FOR 1972

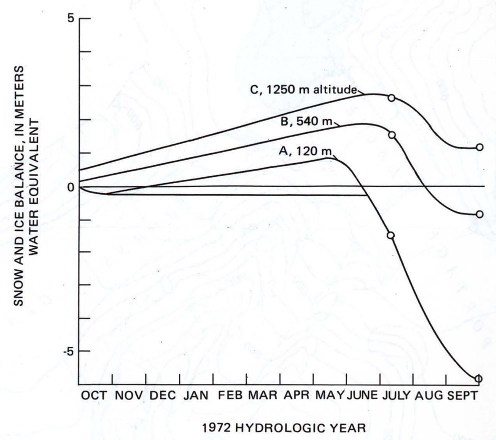
Snow- and ice-balance measurements were made at three points on Portage Glacier during 1972: at point A low in the ablation zone, at point B near the normal equilibrium altitude, and at point C in the largest area of the accumulation zone (see graph and map below). The glacier mass balance terminology of Mayo, Meier, and Tangborn (1972) is used in this discussion.

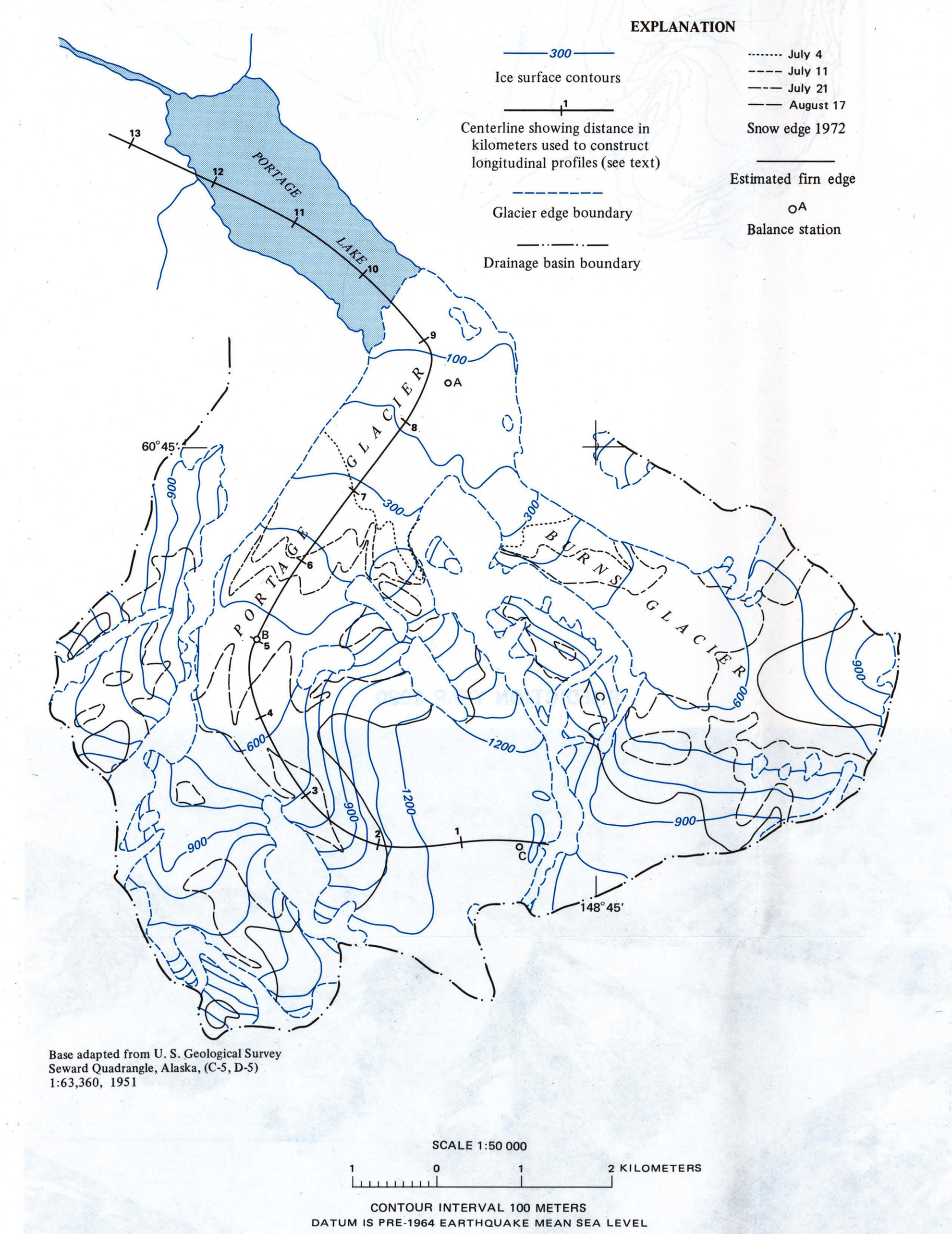
At point A, an estimated 1.5 m water equivalent of ice melted from October 1, 1971, to July 11, 1972. A balance stake was installed in July 1972. A total of 5.8 m water equivalent of ice ablated during the 1972 hydrologic year (October 1, 1971, to September 30, 1972).

Balance point B is at 540 m altitude, immediately above the old firn edge and in the accumulation area during a normal year. The equilibrium altitude, the altitude on the glacier where annual accumulation is equal to ablation, can be seen on aerial photographs as the lower limit of firn (previous year's snow) and subjacent ice. The present equilibrium altitude at Portage Glacier is approximately 500 m. On July 11, 1972, the snow at point B was 2.9 m deep and had a water equivalent of 1.6 m. The density was 0.55 Mg/m^3 (megagrams per cubic meter) which is approximately the same as the snow density measured each July since 1967 at Wolverine Glacier, 36 km to the south. Point B became snow-free on August 12, 1972, and an additional 0.8 m water equivalent of old firn melted by the end of the hydrologic year. This measurement indicates that the 1972 annual firn and ice balance was more than 0.8 m negative compared to the average balance over the past few years.

Snow- and firn-balance measurements were made in the upper firn basin at point C. The snowpack on July 11, 1972, was presumably close to the maximum for the year. The snow depth was 5.4 m and had a water equivalent of 2.7 m. On October 1, 1972, 1.1 m water equivalent of new firn remained at point C. The October measurement was made in a new crevasse wall and is the least accurate of the balance measurements.

The three balance-measurement site locations are shown on the map below. This map also shows four transient snowline positions and the September 1972 firn edge which were mapped from aerial photographs. This snow- and firn-edge information delineates the area of old firn and ice which was progressively exposed by ablation of snow and aids the extrapolation of the three balance measurements over the entire glacier surface.

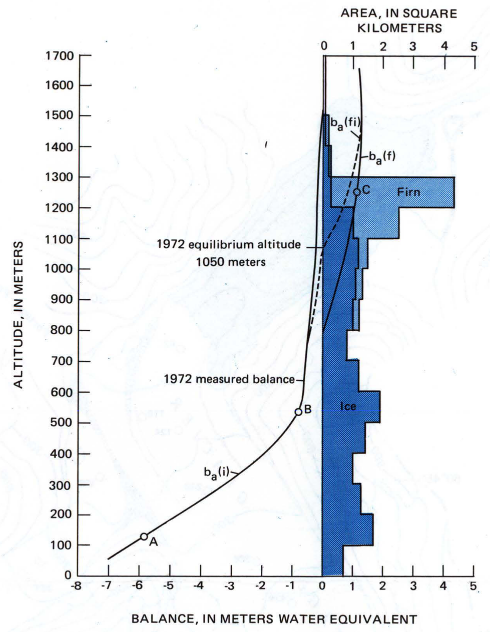




BALANCE CALCULATIONS FOR 1972

The 1972 area/altitude distribution, transient snowline positions, and balance measurements can be combined to calculate the average water balance over the entire glacier. The estimated accuracy of these computed balances is ±20 percent. Therefore, the balance calculations are used to indicate positive and negative situations and the magnitude of snow and ice exchanged by the glacier each year. Burns Glacier was omitted from computations of the Portage Glacier balance in 1972 because Burns contributed a negligible amount of ice to Portage.

The 1972 area of Portage Glacier was 21.5 km^2, with a new firn accumulation area of 6.6 km^2. Thus, the accumulation-area ratio (accumulation area/total area) was 0.31 which indicates a strongly negative balance year. An accumulation-area ratio of about 0.60 is generally required for equilibrium conditions (Meier and Post, 1962). The balance gradient for old firn and ice, $b_a(i)$, new firn, $b_a(f)$, and the altitude distribution of glacier areas (see graph below) can be integrated to calculate the annual changes of Portage Glacier. The 0.3 m of firn accumulation and 1.3 m of old firn and ice melt resulted in an annual firn and ice balance, $\bar{b}_a(fi)$, of -1.0 m. This value multiplied by the glacier area (21.5 km^2) gives a volume of $-22x10^6 m^3$ water equivalent.



The additional ice loss by calving from the terminus into Portage Lake was calculated using measurements of the underwater ice cross section near the terminus, the height of ice above water from the 1972 topographic map, and the ice velocity at the terminus. The average glacier thickness at the terminus is 125 m and the width is 1,150 m. Ogive positions (see photographs, sheet 1) for 3 consecutive years indicate that the annual velocity is about 10 percent greater than the ogive spacing. The 1972 centerline velocity was approximately 220 m/yr. Nye (1965, p. 677) predicted that the average velocity of a glacier in a parabolic channel with the dimensions of Portage Glacier's channel will be 0.63 times the centerline velocity, assuming no basal slip. With basal slip, which presumably occurs at Portage, the average velocity is greater and a factor of 0.75 has been used for Portage Glacier. The centerline flow rate, 220 m/yr, times 0.75 is 165 m/yr, the average ice flow rate.

Although the ice is moving forward at an average rate of 165 m/yr, the terminus is presently retreating at a rate of about 30 m/yr. As a result, the glacier now calves from the terminus approximately 195 m each year, which is a volume of $28x10^6 m^3$ of ice. Thus the 1972 firn and ice balance, including calving, was calculated to be -2.3 m water equivalent averaged over the entire glacier area. The 1972 balance of Portage Glacier was unusually negative as indicated by the numerous exposed old firn edges.

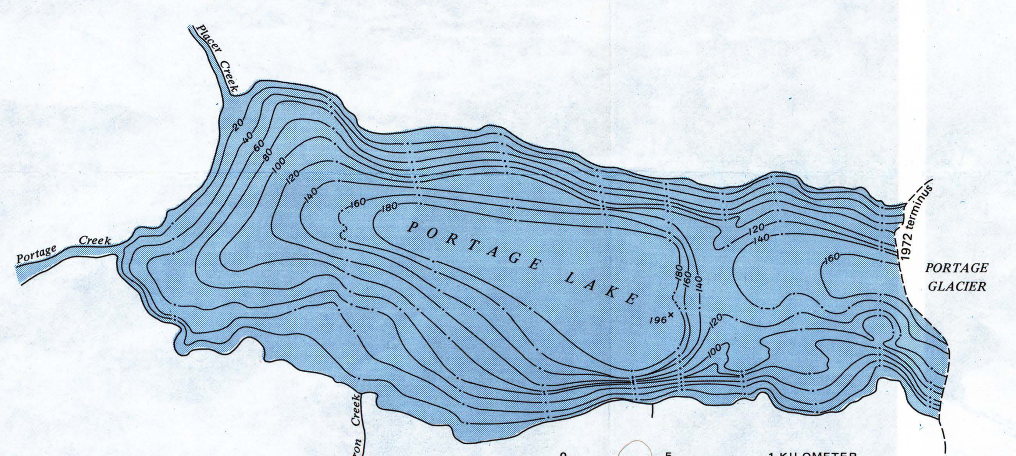
BATHYMETRY OF PORTAGE LAKE

Portage Lake was first sounded in 1939 by Barnes (1943, p. 232). The maximum water depth near the 1939 terminus position was 120 m. The 1960 soundings by Schmidt (1962, p. D202) at the same estimated location indicated only 80 m water depth and thus a rapid sedimentation rate for the lake. Soundings in 1964 by Arthur Kennedy and R. A. M. Schmidt (written commun., 1967) showed the maximum depth at the 1964 terminus to be 140 m.

Sounding profiles along one longitudinal and eight transverse crossings of Portage Lake were made in July 1972 using a recording fathometer (see map below). No corrections were made for instrument calibration or the steep side slopes of the lake. The 1972 data agree with the 1939 and 1964 soundings. The sedimentation rate of 50 m in 21 years as determined by the 1960 data is not verified by the 1972 data.

Portage Lake has steep (more than 30°) bedrock surfaces along most of the lake wall and more gentle (less than 30°) slopes of alluvium at the northwestern end near the present U.S. Forest Service observatory. Two depressions in the lake floor are separated by a rounded ridge that has no counterpart above lake level. These depressions have flat central areas which probably contain ponded diamicton (a slurry of watery clay, sand, gravel, and boulders) which are derived from icebergs and from material suspended in the melt-water runoff from Portage Glacier. The ridge on the lake floor is interpreted to be a moraine because of its bowl-shaped back (east) side, steep forward side, and arcuate shape of its crest. It was deposited by an advance of Portage Glacier and rounded when overridden by a subsequent advance. A landslide from the northeast shore of the lake has occurred in the last two decades, but is too small to account for the mass of material in the ridge and is not alined with the rounded ridge on the lake bottom.

The northwest depression has a fathometer-indicated maximum depth of 196 m. The depression in which the glacier now terminates has a maximum indicated depth of 160-170 m. The deep water of Portage Lake is the primary cause of the present rapid glacial recession. This is discussed further elsewhere on this sheet.



CAUSE OF FLUCTUATIONS GLACIER BALANCE FROM 18th CENTURY TO PRESENT

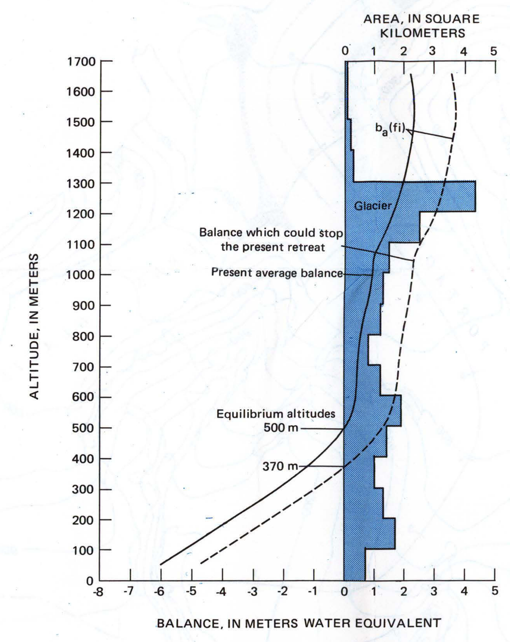
The 1972 balance information can be used to interpret the causes of the fluctuations of Portage Glacier. However, an understanding of the present instability of the glacier is required before the causes of past variations can be discussed.

Meier and Tangborn (1965, fig. 5, p. 557) reported the balance gradient on South Cascade Glacier, Washington, for 7 years and found that the balances changed from year to year by approximately constant values over the entire glacier surface. This conclusion is supported by unpublished U.S. Geological Survey data from Wolverine and Gulkana Glaciers in Alaska. Therefore, the 1972 Portage Glacier balance gradient was used to approximate other balance situations by shifting the annual balance-gradient curve along the balance axis.

The 1972 balance represents conditions for only 1 year, which, from other longer term Alaskan glacier studies, is known to be a nonrepresentative year. The recent average equilibrium altitude, 500 m, is known, however, so the measured balance gradient can be shifted +1.0 m along the balance axis to approximate present average balance conditions.

Integration of the 500-m equilibrium-altitude balance gradient with the 1972 area distribution of Portage Glacier indicates that surface melting is approximately equal to firn accumulation. Therefore, under the present climatic regime, Portage Glacier cannot support the calving into Portage Lake except by terminus retreat and glacier thinning.

The glacier balance and equilibrium altitude required to sustain calving at this time with no terminus retreat can be derived similarly. The 1972 balance gradient must be shifted +2.3 m (see graph below) to simulate glacier balance conditions that would maintain the terminus at the present position. The equilibrium altitude for a steady state would be 370 m. No local evidence, such as new perennial snowfields forming below 500 m altitude, recent advances of low altitude glaciers, or accumulation of firn on medial moraines, has been found that would indicate that such a low equilibrium altitude has occurred in the recent past. Thus, a relatively large change in climate in the near future would be required to halt the present retreat of Portage Glacier. Although such a change might be possible in response to the present worldwide climatic cooling trend, its likelihood cannot be predicted and therefore is not discussed herein.



The state of health of Portage Glacier in the past can be analyzed in the same way as the present balance was analyzed. The advance which culminated in 1880-1900 probably took place over several hundred years. Two causes of that advance are possible. Possibly the climate was very different from today, so that Portage Glacier accumulated snow more rapidly than melting and calving into the deep lake removed ice. Alternatively, the climate could have been very much like it is today, but the amount of calving was significantly reduced by a shallower area at the terminus. Post (1975), in his study of Columbia Glacier, which terminates in Columbia Bay of Prince William Sound, has determined that water depth at the terminus of calving glaciers is a "critical factor in determining the stability of these glaciers." The authors have concluded that Portage Glacier advanced prior to 1880-1900 from a combination of a slightly lower equilibrium altitude than that of today (since nearby glaciers also advanced slightly) and protection of the terminus by a subaqueous moraine shoal.

In 1880-1900 Portage Glacier (51 km^2 area) terminated on land, filling the present Portage Lake basin with glacial ice. The extent of the glacier at that time (see map, sheet 1) is well marked by trimlines in mature vegetation and by lateral moraines on the valley walls. A 3.9-km^2 lake in Bear Valley was dammed by Portage Glacier. Numerous strandlines throughout the former lake's depth range indicate that this ice-dammed lake periodically filled and released, probably causing severe flooding along Portage Creek. The highly pitted outwash in Bear Valley indicates that numerous icebergs from Portage Glacier calved into this lake.

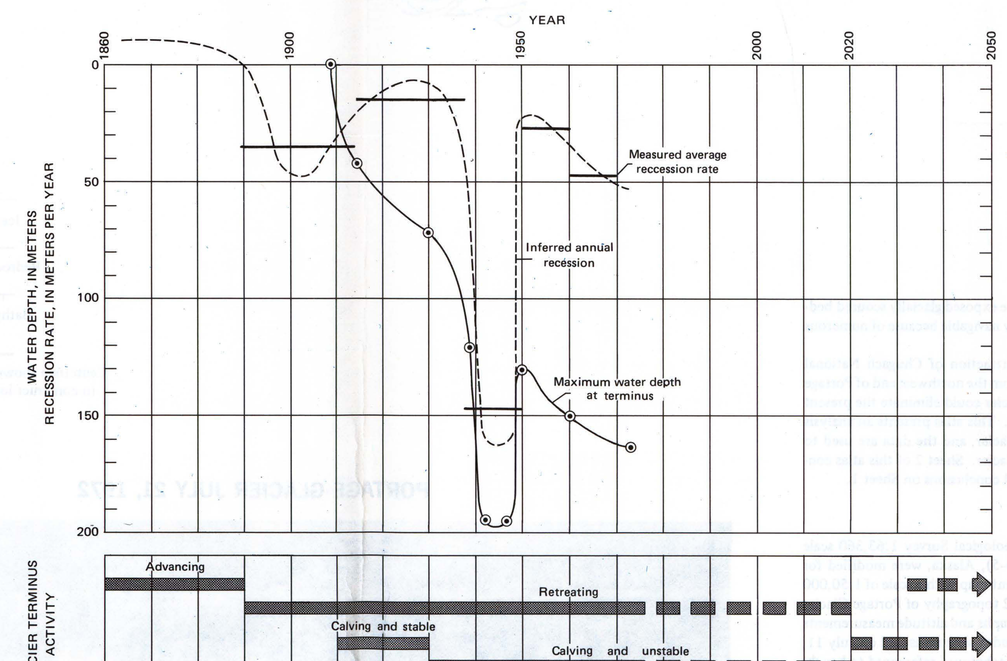
Integration of the 1880-1900 area/altitude distribution and the present balance gradient with an equilibrium altitude of 500 m results in an annual firn and ice balance of 0.0 m water equivalent. Thus, the glacier in 1890 would have been stable under the present climatic regime.

The initial recession from about 1890 to 1914, at an average rate of 33 m/yr, was probably due primarily to climatic factors because the glacier terminated on land, unless the 1890 advance had been the result of a glacier surge. However, ice structures of Portage Glacier indicate that Portage is not a surging glacier. A climatic change is also suggested by the facts that no other surging glaciers are known in the area today (Post, 1969) and that adjacent glaciers, such as Spencer, are also known to have started receding at about 1890 (Viereck, 1967).

The recession of Portage Glacier continued from 1914 to 1939 at a relatively slow rate, averaging 16 m/yr. During the same time, Portage Lake was becoming larger and deeper and calving was increasing. From 1890 to 1972, Portage Glacier lost $3.6x10^9 m^3$ of ice at an average rate of $44x10^6 m^3/yr$. Therefore. climatic changes and calving have combined to cause a rapid retreat of the glacier.

The instability of calving glaciers (Post, 1975) applies to Portage Glacier. By about 1930 Portage Lake was at least 70 m deep at the terminus and the regime of Portage Glacier gradually became unstable. As the glacier receded, the water depth increased, which in turn caused calving to increase markedly. This rapid retreat is in process today and will continue as long as the water at the terminus is relatively deep.

From 1900 to 1930 (see graph below) the rate of retreat did not correspond directly to the depth of lake water at the terminus, which indicates that the effects of the lake on the glacier were minor. Since 1930, the rate of recession has corresponded directly to the water depth at the terminus. Thus, water depth greater than 70 m at the terminus of Portage Glacier is the primary factor controlling the recession rate. The most rapid recession, 140-160 m/yr, occurred from 1939 to 1949 when the terminus was exposed to water 200 m deep. From 1950 to 1955 the glacier rested on the 130-m-deep ridge across the lake floor, and the recession rate decreased to 20 m/yr. The recession rate has now increased because the water depth has again increased.



PREDICTION FOR YEAR 2020

Portage Glacier has steadily thinned and retreated since 1930. The glacier terminus will probably continue to retreat to a location where the maximum depth of Portage Lake at the glacier terminus is approximately 70 m. That point is estimated to be 1.5 km behind the 1972 glacier terminus position, or possibly even farther. At an average rate of retreat of 30 m/yr, then, the terminus position could stabilize approximately 1.5 km behind the 1972 terminus position by year 2020. If the bedrock (lake bottom) at that point is deeper than estimated (see longitudinal profiles on the right), the glacier will continue to recede.

Will Portage Glacier then calve from a stable terminus position in shallow water (maximum 70 m), or will it continue to retreat onto land with all calving eliminated?

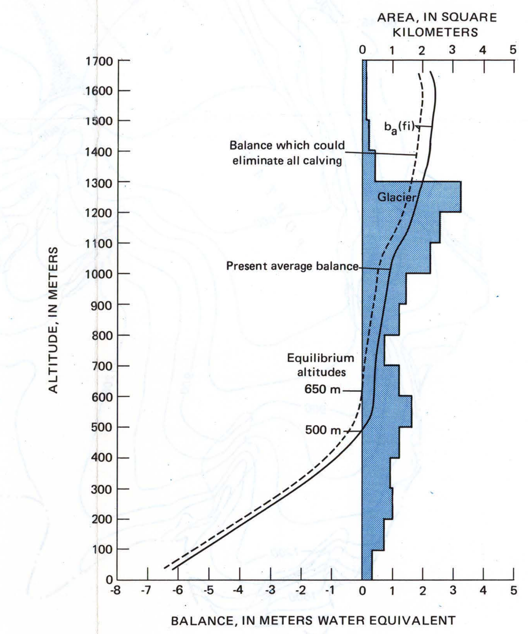
The area/altitude distribution inferred for year 2020 (see map, sheet 1) can be integrated with the balance gradient in two positions to project the activity of the glacier at that time (see graph below).

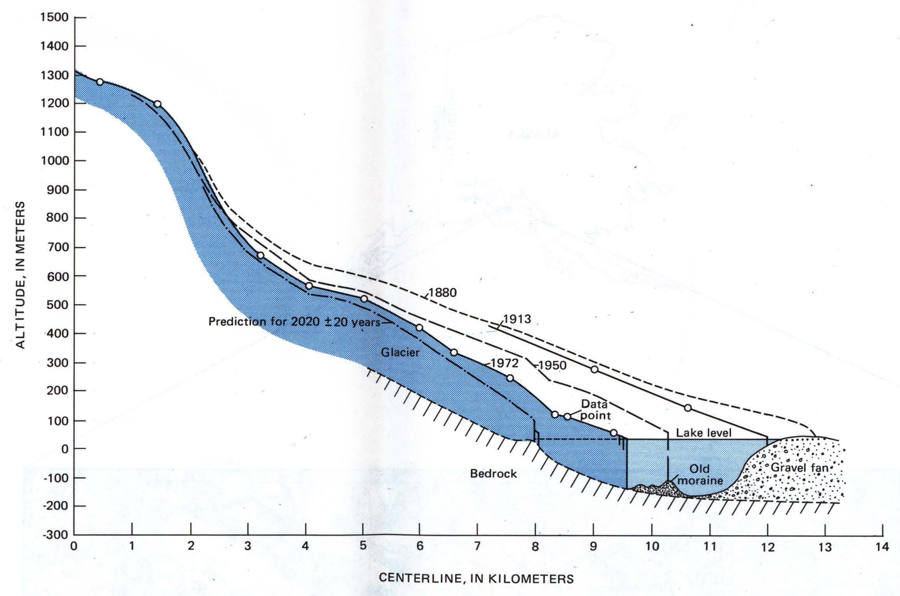
The first test is to assume that the equilibrium altitude will remain at about 500 m, as it is under the present climatic regime. The accumulation area ratio would be 0.78 which would indicate a positive balance. Integration of the 500-m equilibrium-altitude balance gradient and the year 2020 area distribution indicates a positive balance of 0.4 m/yr averaged over a glacier area of 18 km^2, or that $7x10^6 m^3$ of ice per year would be available for calving. This would be 30 percent of the present calving rate.

A second test might be to assume a climatic change that would eliminate calving. Because the computed year 2020 balance under present climatic conditions is +0.4 m, a balance curve shift of -0.4 m could eliminate the calving. This shift would be the result of an equilibrium altitude of 650 m (see graph below), which, in turn, would require a mean annual precipitation decrease of about 0.5 m, a mean temperature increase of about 1.0°C, or some combination of both. In short, complete elimination of calving would require a significant shift from the present climate.

Still another possibility exists, but is considered to be less likely than any of the above. A crevasse zone at the 1972, 100-m contour of Portage Glacier, not far from the present terminus, indicates a bedrock step or valley constriction. Iceberg discharge may be sufficiently inhibited at this point to allow the glacier to reach equilibrium without further retreat.

After having retreated, Portage Glacier probably will remain near the southeast shore of Portage Lake for a long time, until moraine debris accumulates at the terminus in sufficient amounts to shield the glacier from the lake water. Under these conditions the glacier could begin advancing into Portage Lake once again.





NATURAL HAZARDS AT PORTAGE GLACIER

Even though an appraisal of natural hazards is not the primary purpose of this atlas, our investigations have revealed hazards.

Avalanches of glacial ice may occur on the numerous steep slopes. An ice avalanche in 1972 followed the slippage of a small glacierette north of Burns Glacier. The 100-m-long glacierette slipped approximately 100 m downslope and released about 30 percent of its mass as a muddy ice avalanche which flowed onto the surface of Burns Glacier.

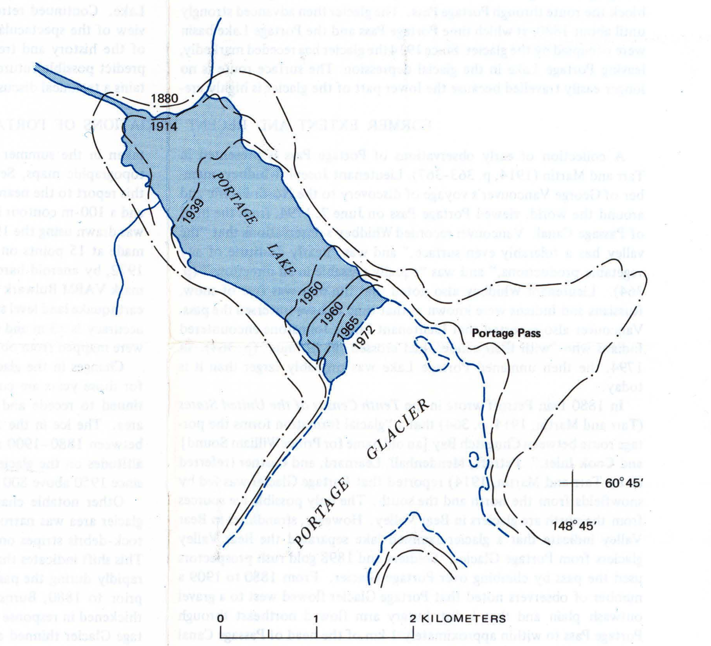
Ice caverns along the north flank of Portage Glacier are the result of small outburst floods from glacier-dammed lakes. These ice caverns collapse within a year or two of their formation.

Recently deglaciated valleys throughout the world have been the sites of large landslides. In Alaska, the giant Lituya Bay wave (Miller, 1960) and a devastating wave at Grewingk Glacier near Homer in 1967 are recent examples of waves caused by landsliding in such valleys. Portage Lake may be subject to large waves caused by similar landslides, and the waves could damage areas along the lakeshore. The northeast shore of Portage Lake is potentially unstable because the rock wall is not now supported by glacier ice. A small landslide occurred during the past few decades along that shore near the 1960 terminus position, but no damaging wave resulted.

SUMMARY

The recorded history, present status, and future of Portage Glacier can be summarized by comparing the longitudinal profiles of the glacier, lake, and ground as measured along the glacier centerline (see profiles above). Judging from botanical data, travelers' reports of the ice height, and moraines, Portage Glacier in 1880-1900 attained a maximum ice thickness of 400 m in the basin now occupied by Portage Lake. From 1900 to 1972 the glacier terminus retreated 3.4 km, and the ice stream thinned 200 m over the entire area of the glacier that is visible from Portage Lake. The map (below left) summarizes the observed terminus positions from 1880 to 1972. The projection of the bedrock profile (above) was made by extending the lake bottom profile and by interpreting the crevasse patterns of the glacier.

The present terminus of Portage Glacier is unstable and the rapid recession is caused by calving of icebergs into the 170-m-deep water of Portage Lake. The calving rate is equal in magnitude to the annual ablation by surface melting and cannot be sustained by the present rate of snow accumulation. Thus, the glacier will continue to recede until the terminus becomes stable in shallower water. About 1.5 km of continued recession probably will occur by approximately the year 2020. The glacier may then terminate with an imposing, stable or slowly advancing ice front which would continue to calve at a reduced rate if the lake is 70 m or less in depth at the ice face. Burns Glacier presently lacks sufficient activity to alter this projection. In the year 2020 Portage Glacier probably will not be visible from the present visitor facility, but it could be seen to advantage from a point at 300 m altitude on the ridge west of Portage Pass.



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RECONNAISSANCE HYDROLOGY OF PORTAGE GLACIER BASIN, ALASKA

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1977