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Glaciers:
A Water Resource

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A Water Resource

by Mark Meier and Austin Post

Most Americans have never seen a glacier, and most would say that glaciers are rare features found only in inaccessible, isolated wilderness mountains. Are they really so rare? Or are they really potentially important sources of water supply? Consider these facts:

- About three-fourths of all the fresh water in the world—equivalent to about 60 years of precipitation over the entire globe—is stored as glacial ice.

- In North America the volume of water stored as snow and ice in glaciers is many times greater than that stored in all the lakes, ponds, rivers, and reservoirs on the continent.

- In some States, such as Washington and Alaska, glaciers exert an influential—even a dominating—effect on the supply of dry-season water and regulate naturally the streamflow to balance the seasonal and year-to-year variations in precipitation.

What Is A Glacier?

Any large mass of snow and ice on the land that persists for many years may be called a glacier. Glaciers are formed where, over a number of years, more snow falls than melts. As this snow accumulates and becomes thicker, it is compressed and changed into dense, solid ice. Also, the mass of snow and ice tends to flow due to its own weight—downhill if it is on a slope or out in all directions from the center if it is on a flat area. The ice in a glacier flows from the area of surplus snow accumulation to the area where yearly melting exceeds accumulation. Where the rate of iceflow balances the rate of icemelt or the rate of calving into the sea, the glacier ends.

A strict definition of "glacier" is virtually impossible. Just as bodies of standing water range in size from huge lakes to small ponds, perennial ice masses range in size from the Antarctic ice sheet to tiny pockets of ice less than an acre in size. Few scientists would call these tiny ice patches "glaciers," yet they are hydrologically indistinguishable from glaciers in all characteristics but size and rate of flow.

Glaciers come in many forms. Some are found in protected amphitheaters carved out of mountainsides by ice erosion (cirque glaciers) or on exposed slopes (slope glaciers). Others are formed in the lee of ridges where snow is deposited by wind (drift glaciers). Large mountain glaciers may flow down valleys (valley glaciers). Relatively smooth land surfaces in high latitudes or on mountaintops may nourish radially flowing icedomes (icecaps). Extensive mountain glaciers (icefields) fill many adjoining valleys, so that only the highest peaks and ridges rise above the ice surface. Ice from glaciers in the mountains may spread out at the foot of a mountain range (piedmont glaciers). Vast land areas covered by ice (ice sheets) occur in Greenland and Antarctica; these are similar in many respects to the ice sheets that covered large parts of North America, Europe, and Asia during the ice ages.

Where Do Glaciers Occur?

In the conterminous (48) States, about 1,650 glaciers cover a total area of about 587 square kilometers (227 square miles) in parts of Washington, Wyoming, Montana, Oregon, California, Colorado, Idaho, and Nevada. Most of these are tiny cirque glaciers. The total summer streamflow derived from these glaciers in an average year is equivalent to about 1.4 billion cubic meters (360 million gallons or 1,107,000

Glacier Statistics by State

State	Approximate number of glaciers	Total glacier area in km² (mi²)		Estimated July-August streamflow from glaciers in millions of m³ (gal.)*	
Alaska **	?	74,700	(28,842)	187,000	(49,405,400)
Washington	950	420	(162)	1,070	(282,694)
California	290	50	(19)	80	(21,136)
Wyoming	100	50	(19)	100	(26,420)
Montana	200	42	(16)	80	(21,136)
Oregon	60	22	(8)	50	(13,210)
Colorado	25	1.5	(0.6)	2	(528.4)
Idaho	20	1.5	(0.6)	3	(792.6)
Nevada	5	0.3	(0.1)	0.5	(132.1)
Utah	1	0.1	(0.04)	0.1	(26.4)

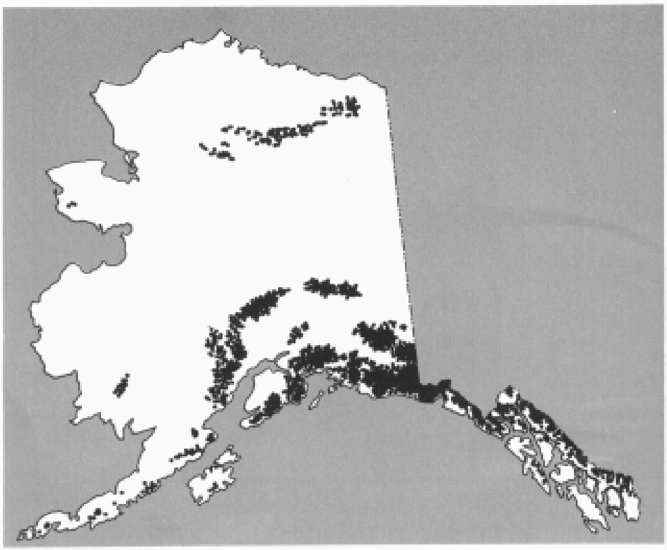
* One million cubic meters is 264 million gallons, and would cover 811,000 acres to a depth of 1 foot, or would fill 24,000 standard railway tank cars (making a train about 240 miles long).

** See chart pages 6 and 7 for breakdown of Alaskan glaciers.

Location of glaciers in the Western United States.

Yentna Glacier, Alaska, is a fine example of a large valley glacier having many tributaries. The even, undistorted medial moraines mark the juncture of ice streams from adjacent tributaries. In the background is Mount Foraker (5,300 m or 17,400 ft.).

acre-feet) of water for the 2 months. Washington State alone has about 950 glaciers covering 420 square kilometers (160 square miles) yielding a summer streamflow of about 1.1 billion cubic meters (280 million gallons or 870,000 acre-feet) of water.



Location of glaciers in Alaska.

About 3 percent of Alaska (about 74,700 square kilometers or 28,800 square miles) is covered by glaciers, which are mostly in mountains not far from major population centers. Most of the major rivers originate at these glaciers. The peculiar characteristics of glacial runoff—peak flows in midsummer, distinct day-to-night differences in runoff, large silt content of stream water, and occasional outburst floods—have a pronounced effect on the economy and pattern of life in Alaska.

Data on the number, location, and area of glaciers in the United States are approximate; many glaciers occur in relatively inaccessible and poorly mapped areas. Inventories of glacial ice have been made in the North Cascade Range of Washington (1971) and the Sierra Nevada of California (1975). All ice masses that are at least 0.1 square kilometer (about 0.04 square mile) in area were counted. The larger number of glaciers in the latest inventory reflects the counting of smaller ice masses not counted in previous inventories, rather than an increase in ice-covered areas.

Alaskan Glaciers

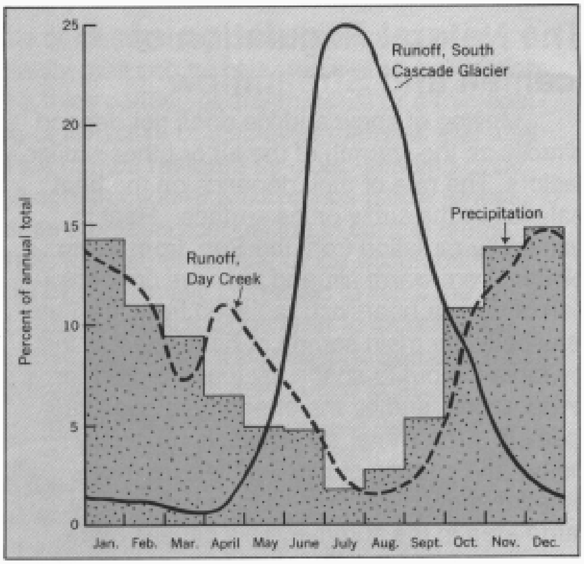
Approximate Area in km² (mi²)

NORTH	Brooks Range	723	(279)
WEST	Seward Peninsula	3?	(1.2)?
	Kilbuk-Wood River Mtns.	230?	(89)?
SOUTHWEST	Aleutian Islands	960	(371)
	Alaska Peninsula	1,250	(483)
INTERIOR	Alaska Range	13,900	(5,367)
	Talkeetna Mtns.	800	(309)
	Wrangell Mtns.	8,300	(3,205)
SOUTH-CENTRAL	Kenai Mtns.	4,600	(1,776)
	Chugach Mtns.	21,600	(8,340)
SOUTHEAST	St. Elias Mtns.	11,800	(4,556)
	Coast Mtns.	10,500	(4,055)
	APPROXIMATE TOTAL	74,700	(28,842)

Changes in Glacial Streamflow

The importance of glaciers as a source of water for use by people stems partly from the fact that the water is stored in winter when the need for irrigation and domestic water is least and becomes available during the heat of mid-summer when the need for it is greatest. This unusual pattern can be seen by comparing streamflows in two watersheds in the North Cascade Range. Day Creek, draining rugged terrain with no perennial snow or ice, has a seasonal distribution of streamflow that closely follows the seasonal precipitation pattern. The South Fork of the Cascade River, however, draining a high mountain basin about half covered with perennial snow and ice, has a streamflow pattern in which the peak is in midsummer when very little precipitation occurs.

Glacier-fed streamflow not only varies with the season but also changes markedly during a single summer day. Usually the flow reaches a peak in the late afternoon or early evening and a low in the early morning. Icemelt is usually greatest at midday; the delay in the runoff peak is due to the storage and movement of water in the glacier.

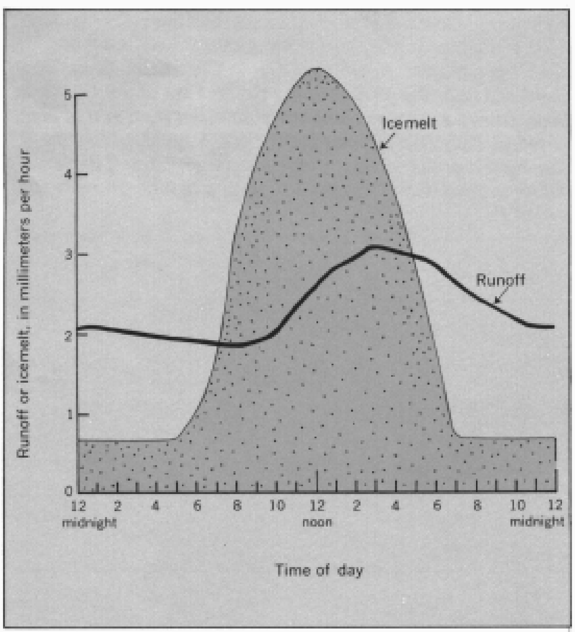


Runoff and precipitation for two small drainage basins in the North Cascade Range, Washington. The basin of Day Creek is in the foothills and contains no perennial snow or ice. Note that runoff from Day Creek follows precipitation closely except from January to March, when a small amount of the precipitation is stored as snow, and from April to June, when this water is released to the stream. On the other hand, the seasonal runoff from South Cascade Glacier, as measured near the glacier in the South Fork of the Cascade River, shows a pattern completely different from that of precipitation. Runoff is highest in July and August, which are also the 2 months of least precipitation, and runoff declines almost to zero during the winter months of high precipitation.

Blue Glacier, Olympic Mountains, Washington, shows crevasses near the margin.

The Natural Regulation of Icemelt and Streamflow

Melting of snow and ice does not depend directly on the warmth of the air or other similar factors. The rate of melt depends on the heat balance at the snow or ice surface. Heat is gained by radiation from the Sun, from warm clouds, from warm air, and from the condensation of dew or hoarfrost; radiation from the Sun is usually the main source of heat. Heat is lost by radiation out to space, by that required for evaporation, and by the energy that goes into icemelt. If the winter snowpack is unusually heavy, the coating of highly reflective (high-albedo) snow persists for a long time over a large area in the summer. This causes more solar radiation to be reflected (a heat loss) and less to be absorbed than during a normal year. Thus, the more snowfall, the less runoff. The converse is also true: the less precipitation, the more runoff. This is exactly opposite to the regime of a nonglacial stream.



Icemelt and runoff during the course of the day at South Cascade Glacier. These curves show average conditions for August 6-11 1961, which was a period of very clear weather. The icemelt is the average over the whole surface of the glacier and the runoff is the measured flow of water in the stream below the glacier.

Melting of snow and ice being dependent on heat balance rather than on the amount of snow or ice available produces a remarkable natural regulation of glacial runoff from year to year. The economic importance of this streamflow-stabilization effect is difficult to measure, but must be very large in such regions as the Pacific Northwest, where assured hydroelectric power and irrigation water are very important commodities.

Malaspina Glacier, St. Elias Mountains, Alaska, is a piedmont glacier.

The Artificial Regulation of Glacial Streamflow

Glacial melt is extremely sensitive to albedo—the percentage of incoming radiation that is reflected by a natural surface such as ice and snow. The albedo can be changed by artificial means, so it is possible to artificially regulate the melting rate of snow and ice. For example, if a clean snow surface is lightly dusted with a thin layer of dark material (such as coal dust), the albedo can be lowered significantly, and the rate of melting may be more than doubled. Glacial melt can be retarded by the application of a thick coating of any material or a thin coating of reflective or insulative material. The loss of ice can be restored by cloud-seeding or by the construction of wind baffles (snow fences) to cause increased deposition in certain areas. Thus, the rate of icemelt or ice accumulation might be artificially increased to raise the level of firm hydroelectric power or to increase ice reserves for future water supply. Some of these techniques are now being used in Asia.

Tampering with the natural regulation of glaciers may have important long-term effects on the hydrologic environment and may degrade wilderness values. In addition, glaciers are important elements of the scenery in many of the mountain areas of the United States. For instance, more than nine-tenths of the glacial area in the United States (not including Alaska) is in national parks, wilderness, or the National

Tikke Glacier in the Alsek Ranges of British Columbia.

Wilderness Preservation System. Artificial regulation of glaciers cannot be accomplished without some impact on those wilderness areas. At present, no artificial control of glacial melt is being considered for the United States.

Effect of Glacial Recession on Streamflow

Whenever water in the form of ice is added to storage, glaciers grow and advance, and the runoff is less than the precipitation. Whenever glaciers retreat, water is released from storage, and the runoff exceeds precipitation. The effect of this long-term storage and release of water

South Cascade Glacier, Washington, as it appeared after abnormal melting due to a long, clear summer (1963). Almost all the winter snow cover had been removed from the glacier surface, and other ice and snow was being melted. Considerable frozen water was taken out of storage and released to the stream.

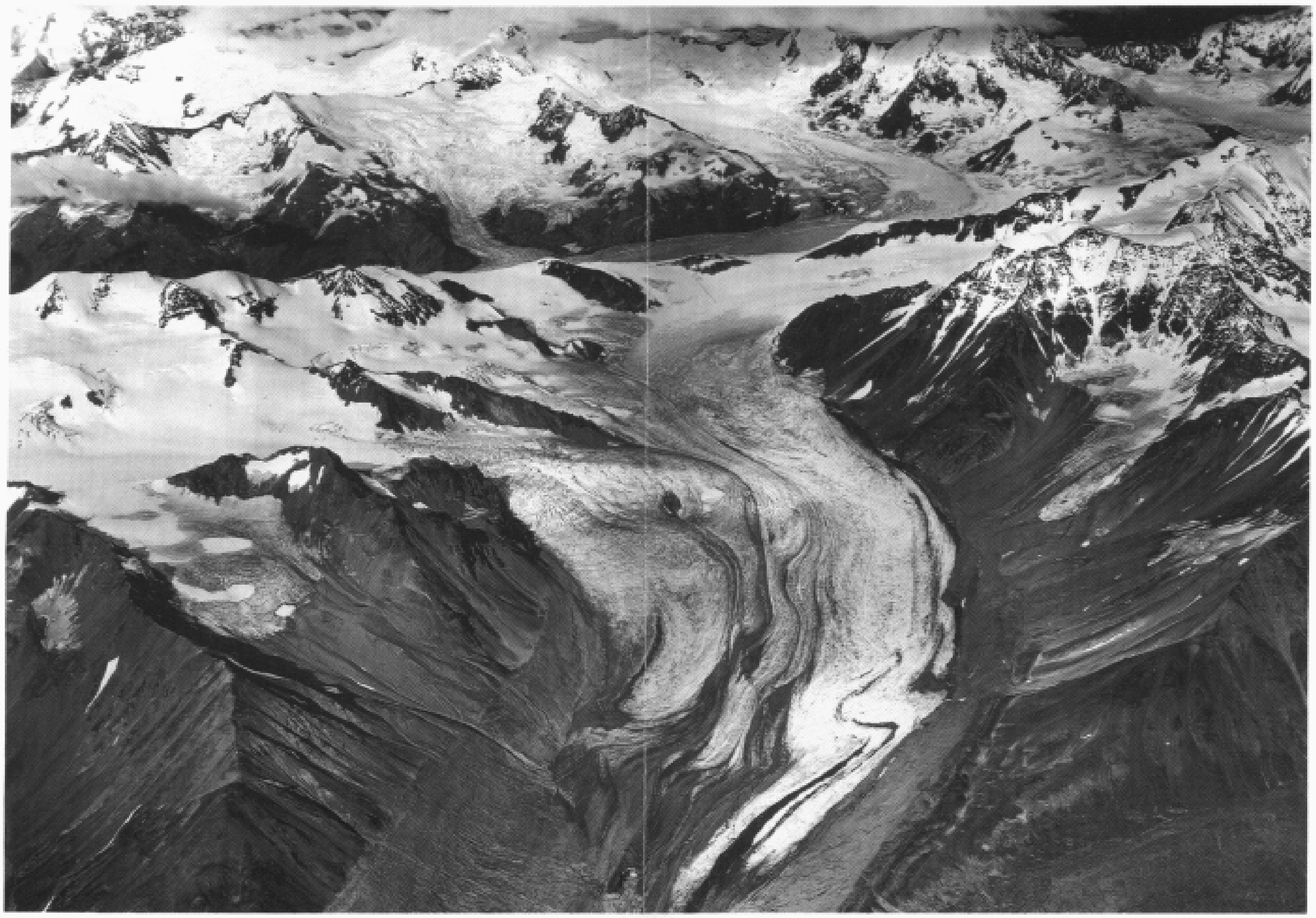
can be appreciable. South Cascade Glacier is now retreating very slowly, and the yearly runoff now averages slightly more than the precipitation. During the period 1900-1945 most glaciers in western North America were shrinking. As a consequence, the average flow of all glacial streams during this period was abnormally high, and runoff exceeded precipitation. This cannot long continue, however; either the glaciers will disappear, or the climate will change in such a way as to put water back in storage as ice.

The effect of glacial retreat or advance on streamflow has important consequences for long-range water-resources planning. This period of prevalent glacial recession happens to coincide with the "base" or "normal" period of

South Cascade Glacier as it appeared a year later, after the cool and cloudy summer of 1964. Note that the last winter's snow still lay over almost all of the glacier surface. This represents precipitation that was then going into ice storage and did not appear in the streamflow for that year. South Cascade Glacier is a principal research area for the U.S. Geological Survey's investigation in glacier hydrology.

record for many important hydrologic data. In some areas, this problem has been recognized. For example, the city of Tacoma, Wash., uses streamflow from the Nisqually Glacier for major hydroelectric power generation. A program of repeated mapping of Nisqually Glacier was started in 1930 to determine how much the long-term ice loss was contributing to the flow of streams used for this purpose. In many other areas, however, especially where many glaciers occur in relatively unknown terrain, planning for the future has gone on with little or no consideration of glacial variations. About 15 percent of the present summer flow of the Columbia River at the international border is derived from about 2,590 square kilometers (1,000 square miles) of glaciers in Canada, and perhaps a third of this flow during the period of record is from the gradual loss of ice from storage. About 5 percent of the present flow of the Tanana River in Alaska also is derived from ice loss.

Gulkana Glacier, Alaska Range, was studied intensively by the U.S. Geological Survey as part of the contribution to the International Hydrological Decade.

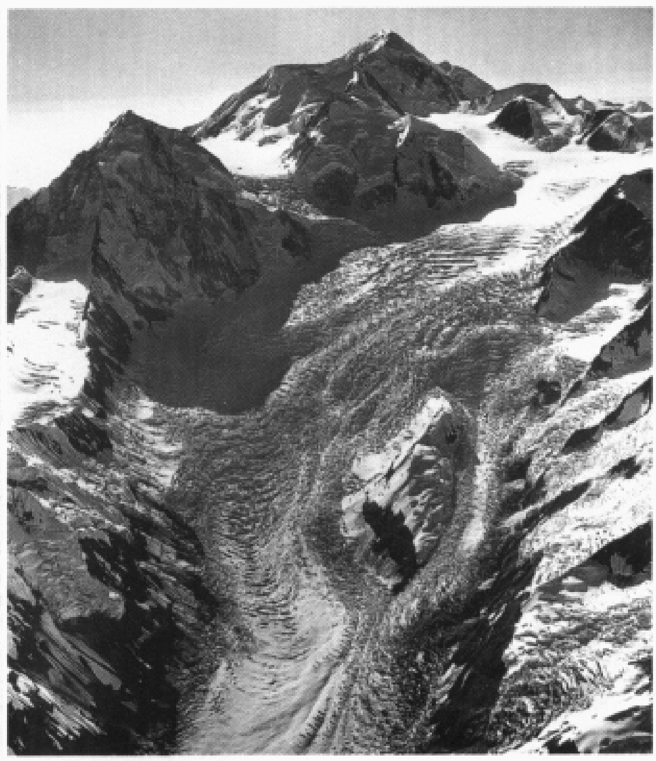


Glacial Outburst Floods

Occasionally, the internal "plumbing" (drainage channels within a glacier) becomes stopped up, apparently as a result of the movement of the ice, and water is stored in or adjacent to a glacier. Later, this water may be released as a sudden outburst flood, often described by the Icelandic term "jokulhlaup" (pronounced almost like yokel-layp). Outburst floods may become debris flows by incorporating large quantities of loose sediment from valley floors and walls. Between 1967 and 1992, at least 30 outburst floods and debris flows swept down valleys on the south and southwest slopes of Mount Rainier. Such floods can be quite large (up to 2,000 cubic meters per second or 70,000 cubic feet per second in the Nisqually River at Mount Rainier in 1955) or even catastrophic in some areas where large glaciers

Small glaciers in the North Cascades, Washington, are important sources of summer streamflow.

occur. The breakout of glacier-dammed waters from Lake George (Knik Glacier) near Anchorage, Alaska, is a well-known example. Outbursts from this lake occurred each year from 1918 to 1963, but only two outbursts have occurred since 1963. One of the largest floods on record is the 1922 jokulhlaup from Grimsvotn, Iceland, which discharged about 7 cubic kilometers (1.7 cubic miles) of water in a 4-day period, producing a flood that was estimated to reach almost 60,000 cubic meters (2 million cubic feet) per second of water at its peak. Few glacial outburst floods can be predicted with the present state of knowledge, but fortunately these floods are rare.



The vigorous Margerie Glacier in Glacier Bay National Monument, Alaska, is a good example of a steep, active valley glacier.

Where Can Glaciers Be Observed?

To really see glaciers in all their varied shapes, sizes, and beauties, one should travel to Alaska. Regular air traffic is routed over or very near some of the largest glaciers in North America. The visitor can approach glaciers closely by boat in Tracy Arm, Glacier Bay National Monument, Kenai Fiords, and Prince William Sound. The glaciers may also be reached overland at Mendenhall Glacier near Juneau, at Mount McKinley National Park, and at many points along the Seward-Anchorage, Glenn, and Richardson Highways.

The best places in the United States south of Alaska to see glaciers without engaging in arduous wilderness travel are in Mount Rainier National Park, Wash. Glaciers of appreciable size can also be approached closely by automobile or with short hikes at Mount Baker and Mount Shuksan in Washington and on the northeast side of Mount Hood in Oregon. Fairly large glaciers, approachable only by long trail journeys, occur in the Olympic and North Cascades National Parks and on the other high volcanoes of the Cascade Range from Glacier Peak in Washington to Mount Shasta in California. Tiny cirque glaciers occur in Glacier, Teton, Rocky Mountain, Yosemite, Kings Canyon, and Sequoia National Parks and in many of the high mountain national forest areas such as Bob Marshall, Mission Mountains, Beartooth, and Bridger-Glacier wilderness or primitive areas. Long trail journeys are necessary, however, to see these glaciers.

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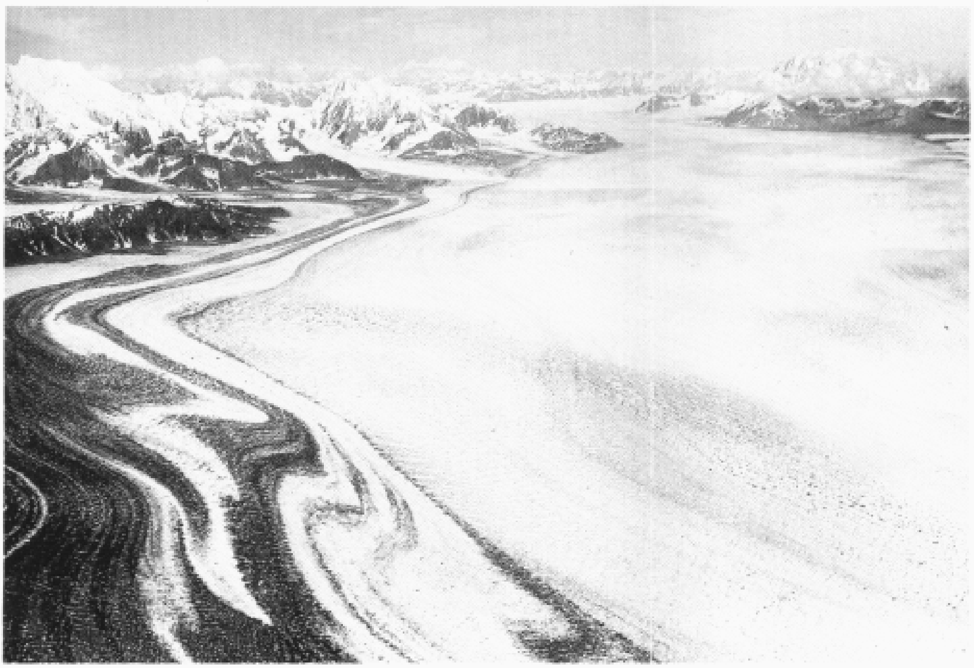

The largest glacier in the United States is the Bering Glacier, near Cordova, Alaska. With its associated icefield feeders it is 203 kilometers (126 miles) long and covers an area of more than 5,000 square kilometers (1,900 square miles). Only a fraction of the lower part of this immense glacier is shown in this view, looking northeast to where the glacier passes between Waxell Ridge (left) and Barkley Ridge (right).

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