Glaciers of North America–

GLACIERS OF THE CONTERMINOUS UNITED STATES

GLACIERS OF THE WESTERN UNITED STATES

By ROBERT M. KRIMMEL

With a section on GLACIER RETREAT IN GLACIER NATIONAL PARK, MONTANA

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SATELLITE IMAGE ATLAS OF GLACIERS OF THE WORLD

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Glaciers, having a total area of about 580 km², are found in nine western states of the United States: Washington, Oregon, California, Montana, Wyoming, Colorado, Idaho, Utah, and Nevada. Only the first five states have glaciers large enough to be discerned at the spatial resolution of Landsat MSS images. Since 1850, the area of glaciers in Glacier National Park has decreased by one-third

Glacier Retreat in Glacier National Park, Montana

By Carl H. Key,[6] Daniel B. Fagre[6], *and* Richard K. Menicke[7]

Glacier National Park encompasses a relatively large, mountainous region (4,080 km^2) of northwestern Montana that borders southern Alberta and British Columbia, Canada. It was established in 1910 because of its glaciers and unique, glacially carved topography located along the crest of the Rocky Mountains. In the 1990's, 37 named glaciers existed in Glacier National Park. All named glaciers within the park are mountain glaciers that have retreated dramatically since the middle 19th-century end of the Little Ice Age in the Western United States. All but one glacier are contained in the northern two-thirds of Glacier National Park between lat 48°30' and 49°00' N. and long 113°30' and 114°15' W. All head on the Continental Divide or near the divide on lateral connecting ridges. Mountain peaks in this glacierized region range from 2,560 m to 3,190 m in elevation at Mount Cleveland, the glacier-terminus elevations lying generally between 2,000 and 2,400 m.

Observations of the glaciers of Glacier National Park date from the second half of the 19th century. The earliest delineation of Glacier National Park glaciers is found on a map by Ayres (1898) that was made in conjunction with timber inventories of the former Flathead Forest Reserve. All of the present Glacier National Park was included in the map. The scale of Ayres' map is nominally 1:440,000, and some drainage features are incorrect, but it does provide clues to the areal extent of some of the first recognized glaciers in Glacier National Park. The first systematic mapping of the glaciers in the park is presented on the U.S. Geological Survey (USGS) 1:125,000-scale Chief Mountain and Kintla Lake quadrangle maps, published in 1904 and 1906, respectively. These maps resulted from planetable topographic surveys conducted between 1900 and 1904. It is important to note the number and relative sizes of named glaciers in these maps. Comparison with recent data shows that conspicuous changes have taken place during the 20th century. Unfortunately, the scale and horizontal control are such that quantitative measurements can only be crudely approximated to compare with contemporary map, photographic, and image sources.

In 1914, Alden published a description of Glacier National Park glaciers, which includes many oblique photographs of glaciers made from 1887 to 1913. Although not entirely complete, Alden's work remains the only monograph to describe characteristics of the park's glaciers at the start of the 20th century. In 1952, Dyson published an updated list of glaciers. However, it does not contain much descriptive material.

The most comprehensive and accurate depiction of Glacier National Park glaciers is obtained from USGS 1:24,000-scale quadrangle maps published in 1968 and compiled by the use of stereophotogrammetric techniques from aerial photographs made between 1963 and 1966. These maps provide an important benchmark for a parkwide assessment of glacier status. In addition, aerial photographs taken in 1950, 1960, 1968, and 1993 cover most of Glacier National Park's glaciers in late summer and provide additional data, both before and after the 1968 maps.

The USGS 1968 maps depict 83 ice-and-snow bodies having areas that exceed 0.1 km^2 within the boundary of Glacier National Park. Post and others (1971) use an area of 0.1 km^2 as a practical minimum size in order to indicate the presence of perennial ice-and-snow bodies in regional mapping and glacier-inventory surveys. Of these 83 ice-and-snow bodies, 34 are named glaciers. The three additional named glaciers within the park have areas less than 0.1 km^2 (table 3).

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TABLE 3.—*Named glaciers of Glacier National Park and vicinity, Montana*

[Glacier area at the end of the Little Ice Age is shown under “1850 area.” “Most recent area” refers to the primary body of a glacier in the year displayed below “Source year.” “Number of snow patches/glacierets” indicates the number of separate masses of perennial ice and snow in the cirque(s) associated with each glacier, based on 1:24,000-scale USGS quadrangle maps compiled from 1966 aerial photography. In most cases, the snow patches/glacierets are separate remnants of a glacier's former extent. Abbreviation: N., North. Leaders (–), not recorded; parentheses, estimated]

Number (fig. 23)	Named glacier	1850 area (square kilometers)	Most recent area (square kilometers)	Source year	Number of snow patches/ glacierets
3	Agassiz	4.06	1.02	1993	10
21	Ahern	–	.59	1966	10
4	Baby	–	.12	1966	1
33	Blackfoot	[1]7.59	1.74	1979	3
5	Boulder	–	.23	1966	1
14	Carter Glaciers	–	.47	1966	6
18	Chaney	–	.54	1966	10
13	Dixon	–	.29	1966	3
26	Gem	–	.02	1966	1
25	Grinnell	[2]2.33	.88	1993	6
1	Harris	–	.15	1966	1
31	Harrison	3.09	1.06	1993	18
10	Herbst	–	.14	1966	4
11	Hudson	–	.09	1966	4
19	Ipasha	–	.32	1966	8
32	Jackson	[1](3.44)	(1.02)	1979	23
2	Kintla	–	.66	1966	13
35	Logan	.92	[3].43	1993	1
37	Lupfer	–	.14	1966	1
15	Miche Wabun	–	.20	1966	3
22	N. Swiftcurrent	–	.07	1966	6
20	Old Sun	–	.42	1966	10
28	Piegan	–	.28	1966	1
34	Pumpelly	1.84	.72	1979	9
7	Rainbow	–	1.21	1966	6
36	Red Eagle	.49	[3].15	1993	2
29	Sexton	–	.40	1966	4
17	Shepard	–	.20	1966	5
27	Siyeh	–	.22	1966	3
30	Sperry	3.76	.87	1993	7
23	Swiftcurrent	.70	.14	1993	4
24	The Salamander	–	[2].23	1993	1
12	Thunderbird	–	.19	1966	6
8	Two Ocean	–	.43	1966	4
9	Vulture	.77	.21	1993	14
6	Weasel Collar	–	.56	1966	4
16	Whitecrow	–	.24	1966	10
39	[4]Gr ant	–	.34	1995	1
38	[4]Stanton	–	.37	1995	1
	Total	[5]25.55	[6]16.34		

[1] The area for Blackfoot Glacier encompasses Jackson Glacier. The area reported for Jackson Glacier is the estimated part of Blackfoot Glacier that yielded Jackson Glacier after the two became separate glaciers.

[2] The area for Grinnell Glacier encompasses what would later be called The Salamander, an ice apron.

[3] Considered to be stagnant or no longer active in 1979 by Carrara and McGimsey.

[4] Grant and Stanton Glaciers are located outside Glacier National Park.

[5] Total area includes 11 of 37 named glaciers in Glacier National Park.

[6] Total area from 1966, 1979, and 1993. Source material includes 37 named glaciers in Glacier National Park and 2 outside the park.

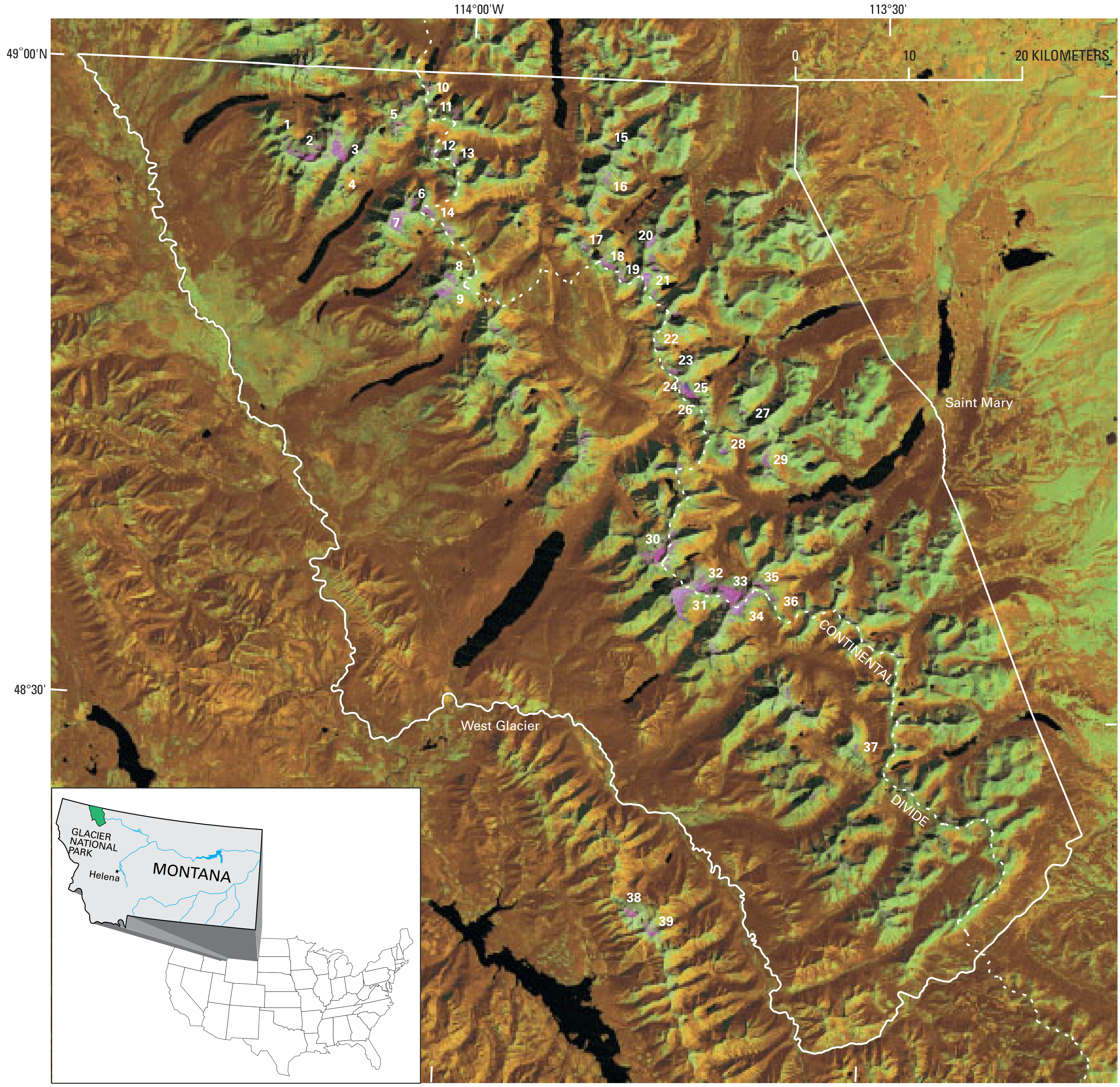


Figure 23.—*Computer-generated, unsupervised spectral classification of a Landsat TM scene (LT50410260095244, bands 3, 4, 5, Path 41, Row 26) of Glacier National Park and vicinity, Montana, collected on 1 September 1995. The image, which shows the boundary of Glacier National Park, has been rectified geometrically to (UTM) zone 12. Sixty multispectral clusters are represented in false color in order to approximate mean cluster reflectance in bands 4, 5, and 3 for red, green, and blue (RGB), respectively. Dark red to brown represents coniferous forest; light to dark orange includes herbaceous and shrub habitats; and yellow green to gray indicates dormant grass, rock, and nonvegetated terrain types. Areas of perennial ice and snow stand out in bright pink to dark purple and cover about 36 km^2 within Glacier National Park, including amounts estimated within dark shadow zones. The TM pixel resolution at 28.5 m (1 hectare=12.31 pixels) is about 6.6 times greater than that of Landsat multispectral scanner (MSS) data (1 hectare=1.86 pixels). Therefore, the TM pixel resolution is sufficient to resolve many of the smaller ice- and-snow patches that were present in 1995 from those that were mapped on USGS 1:24,000-scale quadrangle maps in 1968. Perennial ice and snow constitute a relatively small part of the entire region, and glaciers occupy even less area. Numbers 1–37 identify named glaciers (see table 3), some of which are now stagnant: 1, Harris; 2, Kintla; 3, Agassiz; 4, Baby; 5, Boulder; 6, Weasel Collar; 7, Rainbow; 8, Two Ocean; 9, Vulture; 10, Herbst; 11, Hudson; 12, Thunderbird; 13, Dixon; 14, Carter; 15, Miche Wabun; 16, Whitecrow; 17, Shepard; 18, Chaney; 19, Ipasha; 20, Old Sun; 21, Ahern; 22, North Swiftcurrent; 23, Swiftcurrent; 24, The Salamander; 25, Grinnell; 26, Gem; 27, Siyeh; 28, Piegan; 29, Sexton; 30, Sperry; 31, Harrison; 32, Jackson; 33, Blackfoot; 34, Pumpelly; 35, Logan; 36, Red Eagle; 37, Lupfer. Numbers 38 (Stanton Glacier) and 39 (Grant Glacier) are located outside Glacier National Park.*

A number of individual glaciers have been studied since the early 1930's. The most important work, which also provides reviews of previous investigations, includes that by Johnson (1980), Carrara and McGimsey (1981), and Carrara (1989).

An assessment by the authors of all available data shows that the area of existing ice-and- snow bodies in Glacier National Park totals approximately 36 km^2. Although the part that is glacier ice is difficult to determine, it is estimated to be less than 17 km^2 (table 3). This estimated cumulative area is based on a comparison of the size of the ice-and-snow bodies having areas greater than 0.1 km^2, as delineated in the 1968 quadrangle maps, with actual 1979–93 field measurements of 12 of these glaciers.

Analysis of a September 1995 Landsat thematic mapper (TM) image (fig. 23) indicates that almost all the discernible ice and snow is located in the northwestern (including Kintla, Agassiz, and Rainbow Glaciers) and south-central (including Sperry, Jackson, Blackfoot, Harrison, and Pumpelly Glaciers) regions of Glacier National Park. Current estimates of glacier size reveal that individual glaciers continue to shrink. Only five glaciers (Blackfoot, Jackson, Harrison, Agassiz, and Rainbow Glaciers) have areas larger than 1.0 km^2. Sperry and Grinnell Glaciers have areas of about 0.9 km^2. Five glaciers (Kintla, Weasel Collar, Chaney, Ahern, and Pumpelly Glaciers) have areas between 0.5 and 0.8 km^2.

On a regional scale, if one looks beyond Glacier National Park, perennial ice-and-snow accumulations of any size are scarce. In the 100 km examined north of Glacier National Park into Canada, only seven small ice-and-snow accumulations were noted. None approaches the 0.1 km^2 minimum glacier size. In the mountain ranges within 160 km of Glacier National Park to the south and west, Dyson (1952) identified only nine glaciers. Three are in the Cabinet Range, three in the Mission Range, two in the Flathead Range, and one in the Swan Range. Stanton and Grant Glaciers in the Flathead Range are nearest Glacier National Park and are the largest of the nine. In the 1995 Landsat image, Stanton Glacier has an area of approximately 0.37 km^2, whereas Grant Glacier has an area of 0.34 km^2 (fig. 23).

Today, the glaciers within Glacier National Park are an isolated group, the greatest accumulation of alpine glaciers within Montana. Where compared with their historical areal extent, they are an excellent example of the glacier retreat that is taking place throughout the Rocky Mountains. A variety of dynamics contribute to the health of the park's glaciers, including conditions that favor shelter from solar radiation, elevational temperature lapse rates, and catchment of winter precipitation. Glacier persistence in some cases may be due more to their orientation to storm tracks and wind-assisted depositional patterns (for example, drifting of snow across the Divide) than to thermal buffering. However, all these factors are integrated, and the topographic orientation and physiographic setting distinctly modify the primary drivers of climate.

Most Glacier National Park glaciers, especially the larger ones, are cirque glaciers having aspects that vary from northwest, through north and east, to southeast. The cirque morphologies range from deeply concave floors and high, nearly vertical headwalls to shallow, concave, nearly straight or undulating floors pitched on relatively steep slopes that have minimal headwalls. In addition, glaciers are found in niches in sloping gullies (Lupfer Glacier), near ridge-top saddles (Boulder Glacier), or in slight depressions (Gem Glacier, a dome-shaped mass near the apex of the Continental Divide). Other small glaciers (glacierets) and snow patches are situated in similar situations. After about 150 years of retreat, many glaciers have been reduced to ice aprons or stagnant ice masses plastered along steep slopes. The Salamander and parts of Kintla, Agassiz, and Harrison Glaciers have been separated from shrinking primary glacier-ice masses in recent decades.

Major cirque glaciers typically are hanging, are perched above cliffs, and in some cases, constitute a cascading series of glaciers or a "glacier staircase," like the former North Swiftcurrent Glaciers (fig. 24). Little Ice Age cirque glaciers that advanced over cliff margins pushed morainal material and ice off steep rock faces. This probably produced unconsolidated, reconstituted ice-and-sediment masses at the base of these slopes. Consequently, terminal moraines are absent below many cirques. This complicates the accurate mapping of the extent of many middle 19th-century glacier termini. Generally, well-defined lateral moraines do exist, and in the absence of additional evidence, the limit of Little Ice Age glaciers can be sufficiently well delineated, at least out to the cliff margins.

At several glaciers, terminal moraines exist where cliffs are absent or are sufficiently distant that they were not reached during Little Ice Age glacier expansion. Good examples exist at the Sperry and Red Eagle Glaciers, as well as in the deglacierized valleys below Heavens Peak and Mt. Clements (Demorest, 1938). In addition, at least two glaciers, Agassiz and Jackson Glaciers, extended far enough below bedrock slopes so that they created forest trimlines (krummholz), which provide explicit boundaries for the maximum extent of middle 19th- century advances.

Johnson (1980) describes the long series of observations on Grinnell and Sperry Glaciers, and he exhibits topographic maps that were compiled at a scale of 1:6,000 from 1960 aerial photographs. He also delineates profiles and terminus positions from 1887 through 1969. These maps complement another set of USGS topographic maps compiled at a scale of 1:4,800 from aerial photographs taken in 1950 for Sperry and Grinnell Glaciers. Carrara and McGimsey (1981) discuss the recession of Agassiz and Jackson Glaciers through 1979, the period of greatest retreat, and establish the age of most of the recent moraines as contemporary with the Little Ice Age that ended in the middle 1800's. This age (middle 1800's) had been hypothesized as early as 1939 (Matthes, 1939, 1940), similar to the age of moraines elsewhere in North America, Iceland, and Europe, but was not definitively dated in Glacier National Park until the work of Carrara and McGimsey in the late 1970's.

The moraines in Glacier National Park are significant because of their relatively young age and large size. They represent a long-standing glacial

Figure 24.*—Oblique photograph (taken about 1912) showing hanging cirque glaciers and the "glacier staircase" of North Swiftcurrent Glaciers (Alden, 1914). No terminal moraine exists on the upper part of the cliff, whereas a recognizable moraine is associated with the lower glacier.*

maximum (indeterminate age, but perhaps 40 to 150 years ago?) that overrode previous advances, which may have taken place during the preceding 9,000–10,000 years (Carrara, 1989). Because of the apparently long and relatively stable climatic interval preceding the Little Ice Age, it is believed that most of the glacier ice remaining in Glacier National Park was formed during the Little Ice Age and is not a relic from the Pleistocene Epoch (Matthes, 1939, 1940). In addition to his work on the moraines, Carrara (1989) presents details on the record of glacier fluctuations since the end of the Wisconsinan glacial stage. In 1988, Carrara and McGimsey published a map detailing neoglacial recession through 1979 in the Mount Jackson area, which includes Sperry, Jackson, Blackfoot, Harrison, Pumpelly, Logan, and Red Eagle Glaciers.

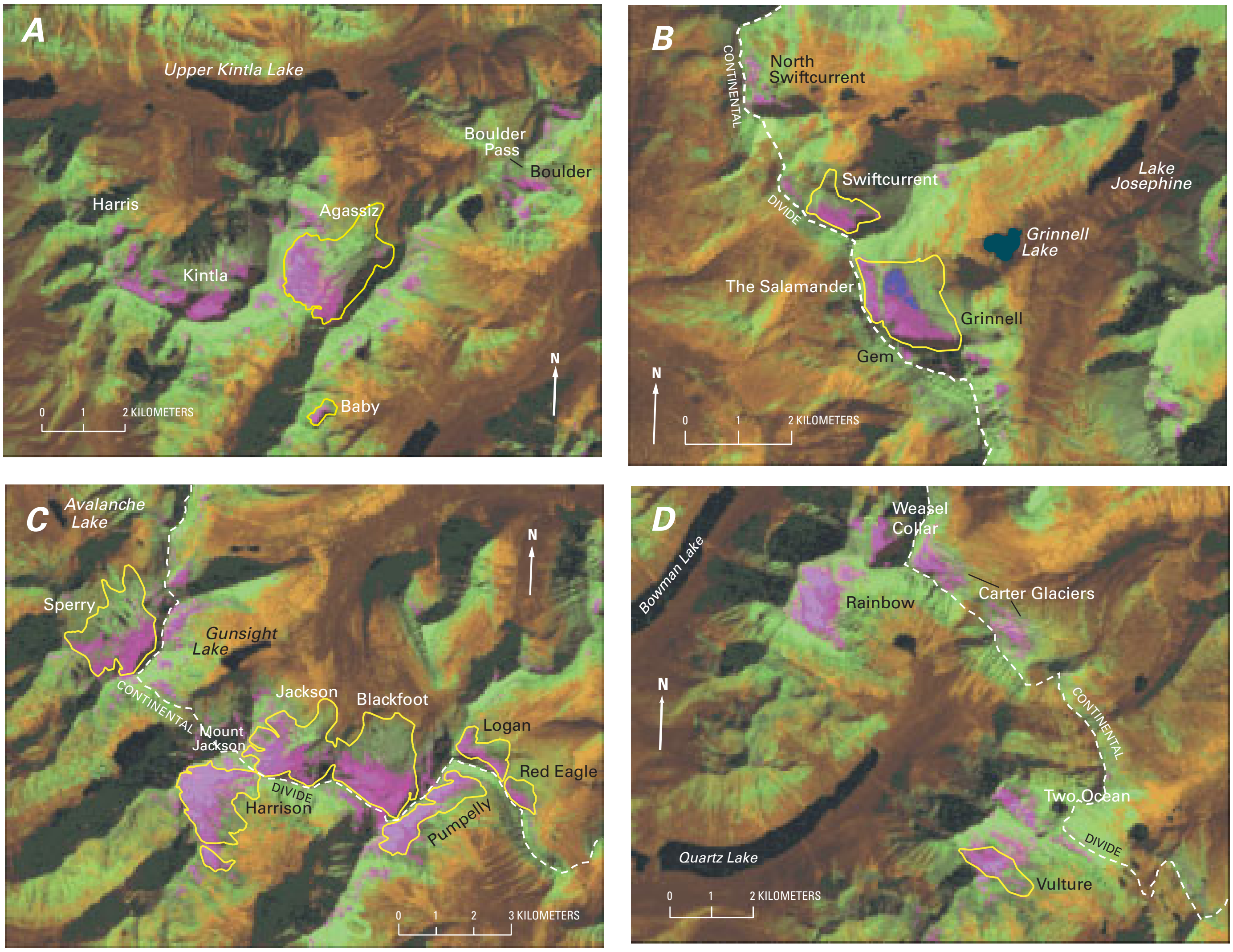
The Little Ice Age comprised a several-hundred-year-long cool period (about 1400 to about 1850 in North America), during which Glacier National Park glaciers formed and expanded. This continued until a warming climate initiated glacier retreat after the middle 1800's. Figure 25 illustrates the magnitude of that recession as of 1995 for the 11 glaciers where Little Ice Age moraines have been mapped. Because figure 25 displays both perennial ice and snow, the actual area covered by these glaciers in 1995 is only a subset of that shown. Glacier area would not include, for example, the small, separate snow patches nor the irregular, thin projections of ice along glacier margins. The overall reduction in area since the middle 19th century ranges between 77 percent and 46 percent on the six glaciers mapped from 1993 aerial photographs. At least two glaciers, Logan and Red Eagle Glaciers, have become stagnant ice masses. Parkwide, it is not known precisely how many named glaciers are now stagnant. The number probably includes many that had areas of less than 0.7 km^2 at the end of the Little Ice Age. Perennial ice-and (or)-snow patches likely remain at many of these locations.

Since the end of the Little Ice Age, small glaciers that were insulated or protected by the surrounding topography tended to lose proportionately less area to recession. Commonly, they changed rapidly to a stagnant condition. The larger glaciers generally experienced proportionately greater and more rapid reduction in area than the smaller glaciers, but they still continue to be active (fig. 25*A*). During the last 150 years, the larger glaciers, which had descended below cirque margins into subalpine terrain, would have had the greatest exposure to solar radiation and warmer temperatures for longer periods of time. As these large glaciers retreated and shrank in area, they regularly separated into discrete ice masses.

Earlier in the 20th century, Grinnell Glacier split into two ice masses (fig. 25*B*). The upper one, now called The Salamander, exists as an ice apron and has changed little since it separated sometime prior to 1929 (Dyson, 1941). In 1911, Blackfoot Glacier (fig. 25*C*) encompassed the current Jackson Glacier (Alden, 1914) but was distinctly separate from it by 1939 (Dyson, 1941). Sperry, Pumpelly, and Agassiz Glaciers each separated into smaller parts located in depressions within their cirques, so that each consisted of one primary mass and several smaller ice masses no longer connected to the main body of the glacier. The individual ice masses, like nearby remnant glaciers, generally became increasingly shielded by their surroundings and did not change much over time, so that they persisted as perennial ice-and- snow patches. These favored locations were protected from solar radiation and likely accumulated considerable wind-blown snow over a greater proportion of their surface area. These patterns are typical of most Glacier National Park glaciers and probably represent the condition of other nearby cirque glaciers undergoing prolonged recession throughout the Rocky Mountains of the U.S.

The glacial recession, though pervasive and continuous since the middle 1800's, progressed at variable rates over time and to varying degrees on different glaciers. Through the first decade of the 20th century, early

Figure 25.*—(opposite page) Four enlargements of figure 23 (labeled* A, B, C, *and* D*) provide a comparison of the area covered by glacier ice in 1995 with that of the middle 19th century. Perennial ice and snow remaining on 1 September 1995 are shown in pink to purple colors. Yellow lines represent glacier-maximum margins during the Little Ice Age, as mapped from distinctive lateral and terminal moraines on 1993 aerial photographs and adapted from the work of Carrara and McGimsey (1988) and Johnson (1980).* **A**, *Glaciers in the vicinity of Agassiz Glacier. The unmapped Harris Glacier has essentially vanished and is today represented by just one glacieret. Only two separated parts of the unmapped Kintla Glacier remain active and have discernible crevasses; the eastern part (largest) is the primary fragment. During the middle 19th century, Boulder Glacier extended across Boulder Pass, where a prominent terminal moraine is visible. The small Baby Glacier, bounded by a conspicuous moraine, has lost proportionately less than has Agassiz Glacier.* **B**, *Grinnell and Swiftcurrent Glaciers. The bluish patch abutting Grinnell Glacier to the north is Upper Grinnell Lake, a proglacial lake that has formed since the 1930's.* **C**, *The complex of glaciers in the Mt. Jackson area.* **D**, *Vulture Glacier and environs. Rainbow Glacier is one of Glacier National Park's largest glaciers but has been little studied and has not yet been mapped. Weasel Collar remains active, as evidenced by crevassing, and sits in a dramatic, deep, fan-shaped cirque that narrows to the north over an extreme precipice. Today, Carter Glaciers are reduced to a series of stagnant ice aprons and patches. Vulture Glacier is one of Glacier National Park's highest and has an east-to-southeast aspect and a present terminus at about 2,440 m.*



photographs and descriptions indicate that glaciers thinned but retreated little from the end moraines of the Little Ice Age (fig. 26) and that termini were still at -or- very near the inner margins of lateral and terminal moraines (Alden, 1914; Sperry, 1938; Dyson, 1941). In all cases, it must be noted that, although initially the distance of retreat was small, substantial thinning—and therefore appreciable volume loss—likely took place. This preceded the eventual retreat of termini. From 1910 onward, recession rates increased (Dyson, 1948; Johnson, 1980). This corresponded to a period of increased scientific interest in Glacier National Park glaciers, and many of the early investigators bore witness to dramatic instances of glacier recession. Following the middle 1940's, recession rates decreased, and glaciers became increasingly confined within cirque margins.

On Agassiz and Jackson Glaciers, retreat from 1850's trimlines below 1,800 m averaged less than 7 m a^{-1} until about 1911 (Carrara and McGimsey, 1981). Retreat rates increased steadily to 14–42 m a^{-1} by 1926 and to 112–117 m a^{-1} by 1932. At both glaciers, retreat exposed convex bedrock slopes. These slopes likely supported thinner ice and contributed to the rapid retreat during that interval.

By 1939, Jackson Glacier had separated from Blackfoot Glacier (fig. 25*C*) and rested within the confines of its present-day cirque. Its average rate of retreat decreased between 1932 and 1944 to about 10 m a^{-1}. Agassiz Glacier (fig. 25*A*), on the other hand, continued retreating up its valley slope at a rate of 90 m a^{-1} until 1942. From the middle 1940's until 1979, both

glaciers continued to retreat but at very low rates, less than 3 m a^{-1}. By 1979, Agassiz and Jackson Glaciers had been reduced to about 30 percent of their middle 19th- century area.

Sperry Glacier's retreat (fig. 25*C*) has a history similar to that of Agassiz and Jackson Glaciers, although variations in recession are not as dramatic. Figure 27 shows the changes in its size from 1850 to 1993. Until 1913, it retreated from its Little Ice Age moraine at a rate that varied between 1 and 5 m a^{-1}. From 1913 through 1945, retreat increased substantially to between 15 and 22 m a^{-1}. During this period, Sperry Glacier lost about 68 percent of its area. Since 1945, the rate of retreat has slowed to an average of 11 m a^{-1} between 1945 and 1950 and to about 5 m a^{-1} between 1950 and 1979. At that time, Sperry Glacier occupied only about 26 percent of its maximum area in the middle 19th century.

Grinnell Glacier (fig. 25*B*) displayed less overall variation and greater constancy in retreat than the glaciers already discussed. However, between the 1920's and middle 1940's, it experienced the largest amount of retreat of any Glacier National Park glacier (fig. 28). Through 1887, Grinnell receded an average of 2 m a^{-1}. Recession averaged 11 m a^{-1} from 1887 to 1911 but decreased to 5 m a^{-1} by 1920. During the period 1850 to 1920, the average recession was about 6 m a^{-1}. The rate of recession of Grinnell Glacier increased after 1920, averaging 15 m a^{-1}, for a total loss of 51 percent in glacier area by 1946. Between 1946 and 1979, recession averaged about 4 m a^{-1} and further reduced the glacier to 41 percent of its former area.

Figure 29 depicts the changes of Grinnell Glacier during the 43-year period from 1938 to 1981. Substantial changes are evident not only in the margin but also in the thickness of the glacier. Compared to the size and thickness of the glacier 50 years earlier (about 1887), when Grinnell Glacier included The Salamander ice apron, the magnitude of change is most noteworthy. Recession of Grinnell Glacier has been influenced by its deeply concave cirque, as well as by the formation of Upper Grinnell Lake in the early 1930's from meltwater that ponded in a concave basin exposed by the retreating glacier (fig. 29).

Between 1966 and 1979, small advances of parts of the glacier margins were noted at several glaciers, including Grinnell, Jackson, Blackfoot, and Harrison Glaciers (Carrara, 1989). Other parts of these glaciers did not advance, and overall sizes either remained essentially the same or receded slightly during the period.

Figure 26.*—Overlooking Blackfoot Glacier to the west in August 1914 by E.C. Stebinger, USGS. Mount Jackson is the highest peak in the center, and Reynolds Mountain is to the far right. Glacier ice remains on, or very near, the prominent lateral moraine, paralleling the glacier across the central-right part of the photograph. Rates of recession were comparatively slow from the end of the Little Ice Age through the early 20th century, in contrast to rapid recession in subsequent decades of the 1920's to 1940's. Early visitors had an opportunity to see Glacier National Park glaciers at or near their 19th century maximum extents. Today, most of the glacier ice visible in the right one-half of the photograph has melted away and exposed bedrock. From the same viewpoint, the current terminus would lie almost in a direct line with Mount Jackson (see fig. 25*C*).*

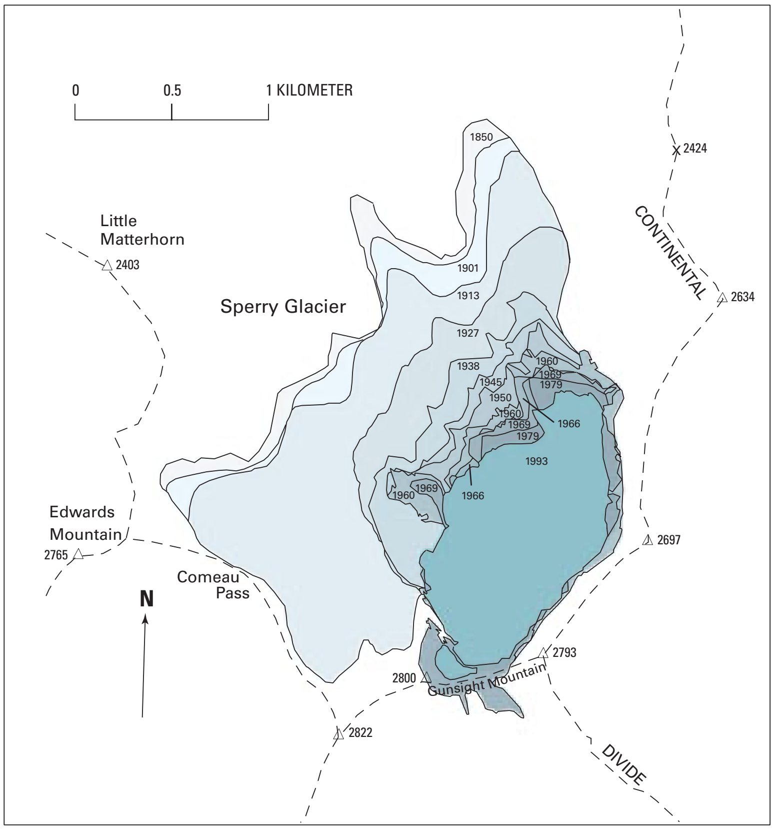


Figure 27.—*Neoglacial recession chronology of Sperry Glacier showing the series of termini mapped since the middle 19th century. This model was developed within a geographic information system (GIS) by incorporating data from previous glacier maps (Johnson, 1980; Carrara and McGimsey, 1988; P.E. Carrara, unpub. data), USGS 1:24,000-scale quadrangle maps (1968) (compiled from USGS 1966 1:40,000-scale aerial photographs), and aerial photographs [1945, 1950, 1960, 1968 (U.S. National Park Service 1:15,840-scale), and 1993]. Two challenges of using such models are, first, establishing a common geographic datum to rectify the various data sets spatially and, second, resolving discrepancies between sources. The latter often causes problems of scale and precision due to historical information's being generated from different, and sometimes rudimentary, types of technology available at the time of measurement.*

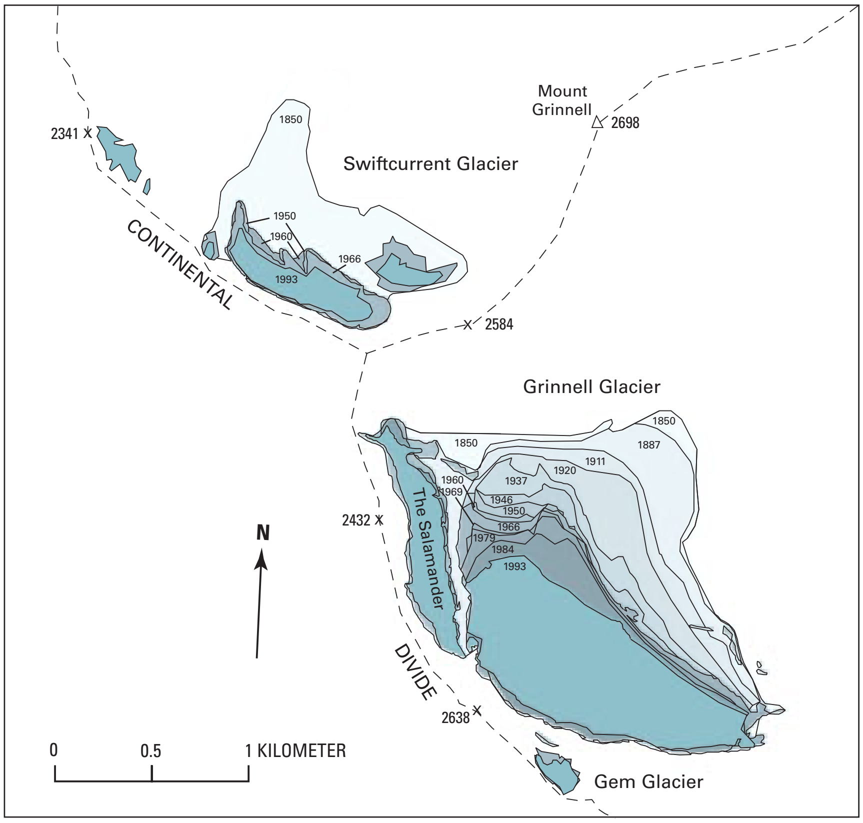


Figure 28.—*Neoglacial recession chronology of Grinnell and Swiftcurrent Glaciers showing the series of termini mapped since the middle 19th century. Grinnell Glacier, along with Sperry Glacier (fig. 27), is relatively accessible and has been frequently observed, so it has yielded a fairly complete record of recession. The first field measurement of the terminus position on Grinnell Glacier was recorded in 1931 (Johnson, 1958). By contrast, Swiftcurrent Glacier, with the exception of the moraine-defined 1850 perimeter, lacks positional delineations prior to 1950, the year of Glacier National Park's first aerial photographic survey. The value of an archived series of aerial photographs and satellite images is highlighted by the fact that mapping of the 1950 margin was not undertaken until 1993.*

Other Glacier National Park glaciers, because of their unique characteristics, have responded somewhat independently to changes in climate and show variations in recession. The magnitude of shrinkage in Grinnell Glacier (fig. 29) is most representative of the larger glaciers in the park. The smaller glaciers here, while experiencing increased rates of retreat from the 1920's through 1940's, did not recede nearly as far nor did they thin as much in magnitude, though most either disappeared completely or reached a steady state during that period. Collectively parkwide, such significant changes translate into dramatic losses of stored water, which result in concurrent variations in stream hydrology and sedimentation.

By the end of the 1970's, Glacier National Park glaciers had been confined mostly to high cirque basins for more than three decades. It is clear that retreat rates decreased in the three decades leading up to that time, but it is also evident that, even as glaciers became increasingly buffered at higher elevations, broad-scale recession continued as proportionately more surface area became sheltered by cirque walls. Between 1979 and 1993, Sperry Glacier retreated from 45 to 75 m (an average rate of 3 to 5 m a^{-1}) and lost about 11 percent of its surface area (fig. 27). During the same period, Grinnell Glacier retreated 117 to 130 m (an average rate of 8 to 9 m a^{-1}), receding about 26 percent (fig. 28). However, a significant amount of this retreat is due to icebergs' calving.

Between 1979 and 1993, Agassiz, Jackson, and Blackfoot Glaciers receded only about 50 m, but all exhibited signs of continued thinning, including newly exposed bedrock or increased bedrock outcrops within the perimeter of the glaciers. Harrison Glacier, which had lost 61 percent of its area by 1979, continued to retreat through 1993, when it had lost 12 percent of its 1979 area. Overall, it decreased to 35 percent of its

Figure 29.—*Paired 1938 (left) and 1981 (right) photographs of Grinnell Glacier and The Salamander. In the 1981 photograph, significant retreat and thinning are clearly evident on the lower level Grinnell Glacier; note comparative glacier-ice thickness indicated along the cliff below The Salamander. Formation of Upper Grinnell Lake, which began in the early 1930's, has resulted in icebergs' calving along the terminus of much of the Grinnell Glacier. This has significantly increased the rate of recession. Snow-and-firn lines on the glacier surface are relatively similar in the two photographs. Only a minor change is noted in the area of The Salamander, as compared to the large amount of area lost by Grinnell Glacier. In comparison, krummholz (dark treed patches of stunted conifers on slopes in the background showing the approximate location of the tree line) have been relatively stable over the same period. The 1938 photograph was taken by T.J. Hileman, probably in late summer; the 1981 photograph by C.H. Key in late summer.*

maximum area during the Little Ice Age (fig. 25*C*). Vulture Glacier, having a 1993 area of only 0.21 km^2, had receded about 18 percent since 1966. In 1993, it occupied only about 28 percent of its 1850 area (fig. 25*D*). Swiftcurrent Glacier, another small glacier (1993 area of 0.14 km^2), appears to be fairly stable. It had receded nearly to its 1993 size by 1966, and it has a relatively high terminus elevation of 2,200 m in a well-shaded, northeast-facing cirque (fig. 28).

The retreat of the glaciers observed in Glacier National Park in recent years is consistent with a trend observed in temperate glaciers in other regions during the last 150 years. Evidently, climate (temperature and precipitation) is the primary controlling factor. Two reasonable hypotheses warrant consideration. In the first, the temperature warmed quickly during the middle 1800's and then remained relatively stable, so that today's glaciers are still responding to that one change. In the second, the temperature has continued to warm since the Little Ice Age, although it has included some brief periods of cooling. In neither hypothesis has precipitation increased. Sigurðsson and Williams (1998) agreed with the second hypothesis with respect to Iceland's glaciers.

The hypothesis that temperature has continued to warm since the Little Ice Age implies that fluctuations of glacier termini are more closely coupled to temperature change and react within shorter time frames than would be implied by the hypothesis that temperature warmed quickly during the middle 1800's and then remained relatively stable. To address these issues specifically, the authors recommend the following be instituted: (1) intervals and magnitudes of climate variation be correlated more explicitly to the recession rates of glaciers in the park, (2) new long-term mass-balance measurements be carried out, and (3) complete thermodynamic budgets be determined that account, individually and over time, for glacier-bed morphology, elevation, and exposure to solar radiation. In any case, it is significant that, in spite of favorable topographic settings, Glacier National Park's larger glaciers are shrinking and have not reached an equilibrium with today's climate.