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

By CARL H. KEY, DANIEL B. FAGRE, *and* RICHARD K. MENICKE

SATELLITE IMAGE ATLAS OF GLACIERS OF THE WORLD

Edited by RICHARD S. WILLIAMS, Jr., *and* JANE G. FERRIGNO

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Glaciers, having a total area of about 580 km^2, 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

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Abstract

Glaciers are found in the following States of the Western United States: Washington, Oregon, California, Montana, Wyoming, Colorado, Idaho, Utah, and Nevada. According to the most recent sources, these glaciers have a total area of about 580 km^2. The earliest recorded glacier observations were made in 1857, and all the major glacier areas were known by the early part of the 20th century. Glacier inventories have been completed or are in progress for several major glacierized areas. The major source materials for modern glacier inventories of the Western United States are the various U.S. Geological Survey topographic map series at scales of 1:24,000, 1:62,500, 1:100,000, and 1:125,000 and the vertical aerial photographs used to compile these maps. Where these sources are not available, oblique aerial photographs have been used to delineate the extent of glaciers and to update glacier margins where significant change has taken place. Landsat images and digital data have been used in glacier studies in the conterminous United States. However, the spatial resolution of Landsat is such that only glaciers in the States of Washington, Oregon, California, Montana, and Wyoming can be effectively observed from Landsat 1, 2, and 3 data. In the remaining States, the Landsat data can often offer regional views of moraines from past glaciation and can also be useful in the study of glacial geology and the variations in seasonal snow cover.

Introduction

Glaciers are found in the following States of the Western United States: Washington, Oregon, California, Montana, Wyoming, Colorado, Idaho, Utah, and Nevada. The single most comprehensive work on the glaciers in these States is volume 1 of "Mountain Glaciers of the Northern Hemisphere," edited by William O. Field (Field, 1975), and he relied on the expertise of numerous people as coauthors. The work attempted to list all glaciological literature and other reference material (including maps, aerial photographs, and terrestrial photographs available for each area), in addition to creating a comprehensive glacier inventory. Numerous references are cited

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at the end of each chapter. Perhaps the single most referenced source on the distribution of glaciers in the conterminous United States is a paper by Meier (1961a), who reported on a survey of United States glaciers carried out from 1957 to 1959. Brown (1989) summarized the status of work on compiling a glacier inventory of the United States. Snyder (1996) compiled a bibliography of glacier studies by the U.S. Geological Survey (USGS) that includes numerous citations to studies of glaciers in the Western United States. This section in "Satellite Image Atlas of Glaciers of the World" must, by the nature of the subject, parallel the work of Meier (1961a) and Field (1975), but it will also stress those data available from the Landsat 1, 2, and 3 series of satellites.

The distribution of glaciers in the Western United States can be most logically categorized by using the physiographic provinces that encompass various mountain ranges. These mountain ranges can be divided arbitrarily by States, which are used as the primary geographic categorization in this section for glaciers in the Western United States.

Historical Observations

All of the major glacier areas in the Western United States were known by the early 20th century. The earliest recorded glacier observations were made by Kautz in 1857 (Kautz, 1875). Other pre-1900 glacier observations include those of Clarence King (1871), John Muir (1894), and I.C. Russell, who published two comprehensive works: "Existing Glaciers of the United States" (Russell, 1885) and "Glaciers of Mount Rainier" (Russell, 1898). These reports contained maps of glacier cover for a small area of the Sierra Nevada (fig. 1), Mount Shasta, the Lyell Glacier[4] (Yosemite National Park), and Mount Rainier (fig. 2), as well as numerous sketches of glaciers. A series of reports by F.E. Matthes from 1931 to 1945, published in the Transactions of the American Geophysical Union (Matthes, 1931, 1932, 1933, 1934, 1935, 1936, 1937, 1938, 1939, 1940, 1941, 1942, 1944, and 1945), attempted to summarize contemporary glacier research for that period. With the advent of regionally comprehensive vertical aerial photographs and topographic maps compiled from these photographs, some detailed glacier inventories have subsequently been compiled (Post and others, 1971; Graf, 1977; Raub and others, 1980; and Spicer, 1986). Another comprehensive source of glacier data that includes information on United States glaciers is the Permanent Service on the Fluctuations of Glaciers (now part of the World Glacier Monitoring Service), which has published seven volumes since 1967 summarizing glacier changes during seven successive 5–year periods (Kasser, 1967 and 1973; Müller, 1977; Haeberli, 1985; Haeberli and Müller, 1988; Haeberli and Hoelzle, 1993; Haeberli and others, 1998).

The long-term measurement of changes in termini position and mass balance of glaciers (Fountain and others, 1991; Østrem and Brugman, 1991) is important to understanding both the relationship of glacier fluctuation to climate change and to the contribution of glacier meltwater to the total annual discharge of a hydrologic basin (Fountain and Tangborn, 1985a,b). The latter application is especially important where the drainage basin is used for irrigation or for the generation of hydroelectric power.

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[4] The geographic place-names given in the text have been approved for each State by the U.S. Board on Geographic Names. Unapproved names for glaciers are shown in italics.

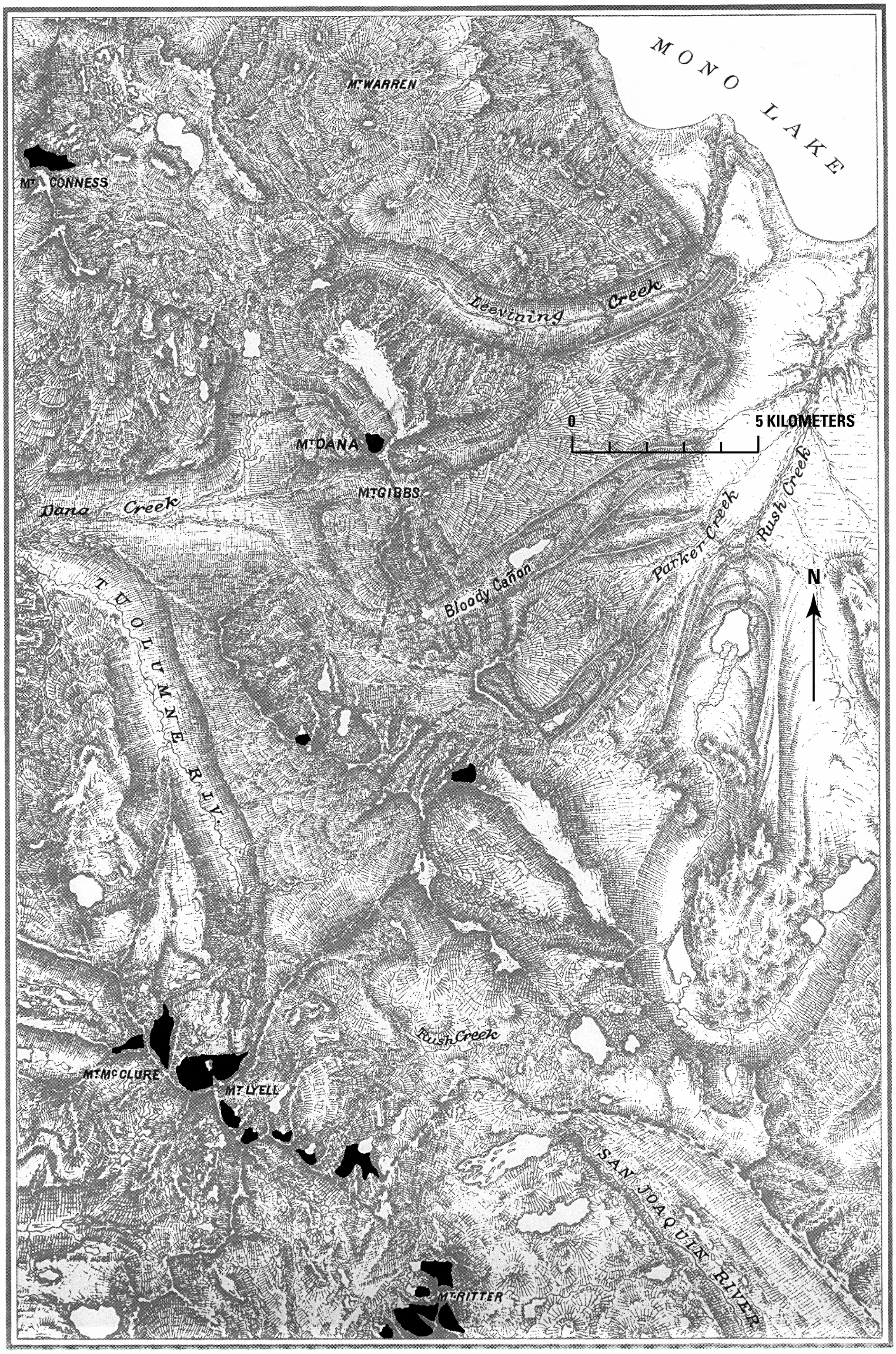
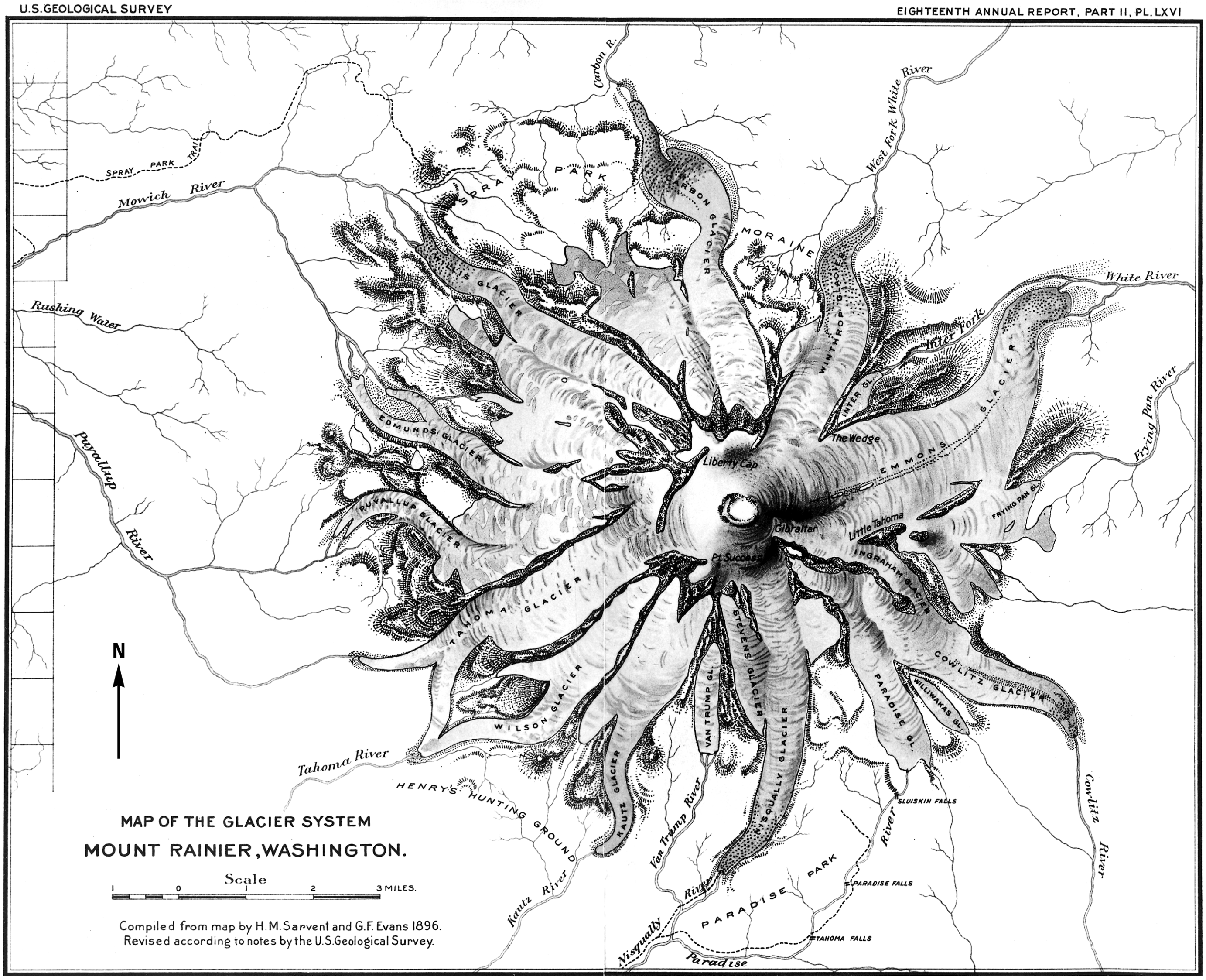


Figure 1.—*Historical map of a part of the Sierra Nevada, Calif., taken from "Existing Glaciers of the United States" (Russell, 1885). The coverage of this early map is shown in figure 14. Glaciers are indicated by solid black.*



Glacier Inventories

Figure 2.*—Early map of the glaciers of Mount Rainier, Wash., taken from Russell (1898). Compare with figure 10, a Landsat 3 return beam vidicon (RBV) image of Mount Rainier. All the glaciers retreated between 1900 and 1980; retreat was minor at the Carbon Glacier but was greater than 1 km at the Cowlitz Glacier.*

Any work that attempts to list pertinent glaciological data on all the glaciers in a given area can be considered to be a glacier inventory, and international guidelines are available for the preparation of glacier inventories (UNESCO, 1970; Müller and others, 1977). Glacier inventories have been completed or are in progress for several major glacierized areas in the Western United States and Alaska (Brown, 1989), and these will be discussed as appropriate under each area. The definition of the term glacier is critical to any glacier inventory, as well as to an evaluation of the utility of Landsat images for the observation of glaciers. Broad definitions of glacier normally require that the snow or ice is perennial and that the mass moves under its own weight (UNESCO, 1970). Qualifications of this definition must be made for specific purposes. For example, the hydrologist may be interested in all perennial snow or ice, but the person who studies glacier mass transport is interested only in ice movement.

For glacier inventories, the most important factor is that the snow and ice be perennial. Discrepancies in measurements of area may result when a relatively wet winter is followed by a cool summer. Under these circumstances, many snow patches that could be called glaciers may remain at the end of the ablation season. The end result would be widely fluctuating glacierized areas in short time periods, which is generally unacceptable for inventory work. Therefore, most inventories are made during a year, or multiple years, of abnormally light winter snow and (or) a hot, dry summer, which reduce snow-patch areas to a minimum.

Another practical problem in most glacier inventories is that it is normally impossible to record every small mass of snow and ice that might fit the glacier definition. For this reason, a minimum size limit, in addition to the more common definition of glacier, is often stipulated in glacier inventories. The minimum size is determined by the quality of data, the hydrologic importance of the snow and ice, and the interest spurred by tourists and recreationalists. For an inventory in the north Cascades (northern Cascade Range) of Washington State, a minimum area of 0.1 km^2 was used (Post and others, 1971). For an inventory in the Sierra Nevada of California, a minimum area of 0.01 km^2 was used (Raub and others, 1980; unpub. data). It is not the intent of this Landsat image atlas to inventory glaciers, and no arbitrary minimum size for glaciers has been assigned; however, the effective spatial resolution of Landsat's sensors imposes a minimum on the order of 1 km^2 where used for glaciological studies.[5] However, 1 km^2 as the minimum glacier size would be absurd in California because only one glacier, Palisade Glacier, is more than 1 km^2 in area (Raub and others, 1980; unpub. data).

Mapping of Glaciers

In the Western States, numerous small glaciers exist over a very large area. Glacier distribution and area are listed in table 1. Because of the scattered distribution, no comprehensive study of glacier extent was done previous to the compilation of modern topographic maps. A few studies were made of isolated areas before 1960, however. Most of these consisted of general observations and, in some cases, photographic records; they are, for the most part, referenced in Field (1975). In some areas, a few outstanding photographs of glaciers, taken primarily for artistic purposes or the promotion of tourism, exist from as early as 1900. Some of these have found their way into modern reports and are used to compare glaciers qualitatively.

The major source materials for modern glacier inventories are the various USGS topographic map series at scales of 1:24,000, 1:62,500, 1:100,000, and 1:125,000 and the vertical aerial photographs that were used to compile these maps. In some instances, modern maps are not available for important glacierized areas, in which case modern oblique aerial photographs have been used to delineate the extent of each glacier. This oblique aerial photography also has been used to update glacier margins in areas where significant change has taken place.

The tool most useful in describing the geometry of a glacier is a topographic map. Commonly, the USGS topographic map series do not show sufficient detail to satisfy a specific glaciological need, and a special map must be produced for a specific glacier. Such special maps, mostly unpublished, have been made for the South Cascade, Nisqually, and Klawatti Glaciers (Meier, 1966), Blue Glacier (Tangborn and others, 1990), and Shoestring Glacier in Washington; the Eliot and Collier Glaciers in Oregon; the McClure and Palisade Glaciers in California; the Grinnell and Sperry Glaciers in Montana; the Dinwoody Glacier in Wyoming; and several glaciers in Colorado. Normally the vertical aerial photographic surveys used for these maps were done in the early fall, a time particularly advantageous to the mapping of

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[5] Theoretically, for the 79-m pixel size of the Landsat multispectral scanner image, a glacier 0.2 km^2 in area could be resolved (approximately 2.8 times the pixel size). From a practical standpoint, however, a glacier 1 km^2 in area (1 mm^2 on a 1:1,000,000-scale Landsat multispectral scanner image) is about the smallest that can be unambiguously delineated under optimum contrast conditions.

TABLE 1.—*Areas of glaciers in the western conterminous United States*

[Glacier areas in the first column are taken from Meier (1961a); dashes mean not determined by Meier. Glacier areas in the second column are from Meier (1961a) where a more recent source is not available. The change in area between 1961 and the more recent source is normally due to a more complete data set rather than a true change. An asterisk indicates that the value is estimated. Glacier numbers correspond with those in figure 5]

Location	Area (square kilometers)	
	Meier (1961a)	More recent source, where available
Washington		
1. North Cascades[1] (northern Cascade Range)	251.7	[2]267.0
2. Olympic Mountains	33.0	[3]45.9
3. Mount Rainier	87.8	[4]92.1
4. Goat Rocks area	1.5	1.5
5. Mount Adams	*16.1	*16.1
6. Mount St. Helens	7.3	[5]5.92/2.16
Total	397.4	428.5/424.8
Oregon		
7. Mount Hood	9.9	[4]13.5
8. Mount Jefferson	3.2	3.2
9. Three Sisters area	7.6	[4]8.3
10. Wallowa Mountains	—	*.1
Total	20.7	25.1
California		
11. Mount Shasta	5.5	[4]6.9
12. Salmon-Trinity Mountains	.3	.3
13. Sierra Nevada	13.1	[6]50.0/63.0
Total	18.9	57.2/70.2
Montana		
14. Glacier National Park	13.8	[7]28.4
15. Cabinet Range	.5	[7].5
16. Flathead-Mission-Swan Ranges	*1.2	[7]*2.3
17. Crazy Mountains	*.5	[7]*.4
18. Beartooth Mountains	10.8	[7]10.9
Total	26.8	42.5
Wyoming		
19. Big Horn Mountains	.3	[7]1.0
20. Absaroka Range	*.7	[7]*.7
21. Teton Range	2.0	[7]1.7
22. Wind River Range	44.5	[7]31.6
Total	47.5	37.5
Colorado		
23. Rocky Mountain Park-Front Range, others	1.7	[7]1.5
Idaho		
24. Sawtooth Mountains	—	[8]*1.0
Utah		
25. Wasatch Mountains	—	[9].2
Nevada		
26. Wheeler Peak	.2	.2

[1] The region bounded by the Canadian border on the north, Snoqualmie Pass on the south, the Puget Lowlands on the west, and the Columbia and Okanogan Rivers on the east.

[2] Post and others, 1971.

[3] Spicer, 1986.

[4] Driedger and Kennard, 1986.

[5] Brugman and Meier, 1981. Before/after eruption of 18 May 1980.

[6] Raub and others, 1980; unpub. data. The 50-km^2 area includes glaciers plus moraine-covered ice; the 63-km^2 area includes glaciers, moraine-covered ice, and small ice bodies not large enough to be considered glaciers.

[7] Graf, 1977.

[8] Estimated; various observers have reported numerous small glaciers.

[9] Timpanogos Cave, Utah, USGS 1:24,000-scale topographic map.

glaciers because the residual snow cover is at a minimum and new snow has not started accumulating. The maps not only provide an accurate position of the glacier terminus but, even more important, give reliable ice elevations throughout the entire area. This third geometric dimension is especially valuable because, through the compilation of later maps from new vertical aerial photographic or ground surveys, volumetric change can be determined over a given time. Ice gain or loss is hydrologically important, and the distribution of the gain or loss over the glacier is vital to understanding the glacier's state of health and its relationship to climate.

In this chapter, no attempt is made to use Landsat multispectral scanner (MSS) or Landsat 3 return beam vidicon (RBV) images to define the shape or size of a glacier. In almost all cases, vertical aerial photographs are available that have spatial resolutions of one or two orders of magnitude better than the Landsat MSS images. With the exception of a few isolated cases, even the 1:125,000-scale topographic maps depict the glaciers more precisely than does Landsat. Occasionally though, misinterpretation of photographic data has resulted in map errors. Although numerous glaciers have undergone changes in terminus position of 100 m or more since the map compilations, no routine attempt has been made to correct the maps by using Landsat image data.

Landsat Images of the Glaciers of the Western United States

The spatial resolving power of the MSS of the Landsat 1, 2, and 3 systems is such that only glaciers in the States of Washington, Oregon, California, Montana, and Wyoming can be observed effectively. In the remaining States, the Landsat images commonly offer striking views of moraines from past glaciation and can also be useful in the study of glacial geology and variations in seasonal snowpack.

The effective spatial resolution of the Landsat MSS sensors is generally considered to be about 200 m under normal conditions of contrast. Under optimum conditions (high contrast) during the satellite pass and with careful image and photographic processing, MSS images can give glaciological information approaching 100 m in spatial resolution (Krimmel and Meier, 1975). The best possible analysis of Landsat imagery is achieved by using digital data rather than photographic prints. The Landsat MSS digital unit is a pixel, and each pixel has a reflectance (gray-scale) value, given as a digital number (DN), ranging from 1 to 127 (MSS bands 4–6) or 1 to 63 (MSS band 7) (1 is dark and 127 or 63 is bright). Manipulation of digital data not only allows simple analysis of single MSS bands but also permits the use of analytical techniques, such as band-to-band ratioing and date-to-date (temporal) comparisons of sequential images.

A very simple way to determine snow cover is by radiance threshold. A radiance value is picked above which it is assumed that all material is snow. A summation of these pixels with radiance values higher than the arbitrary value then represents the snow-covered area. However, in mountainous areas, some snow is always in shadow, which results in a reduced radiance. Also, most of the edge of the snow cover is irregular, and along that boundary, many pixels are only partially snow covered (mixed pixels) and normally may have reduced brightness. The radiance of any given pixel is an integration of the brightness values of all material within that pixel. Some subjectivity always exists in picking the radiance level for a given percent of snow cover, and the resulting regional snow-cover determination is a result of the selected radiance. Of course, other features in the image can also result in high radiance values, notably clouds.

The identification of ice is commonly more difficult than that of snow. Simple radiance thresholds do not identify ice because much of it is less bright than the surrounding rock, glacial outwash, or vegetation. Digital band-to-band ratios have been successfully used to identify both ice and snow under shadow conditions (Meier and Evans, 1975). On a regional scale, however, instead of digital data, it has proven to be more cost-effective to use analog photographic film combined with the subjective input of brightness variations in order to gain a knowledge of morainal landforms and trimlines.

Some digital-image processing has been used for selected glaciers. South Cascade Glacier in the State of Washington is about 3 km long and has an area of 2.5 km^2. It has been the site of remote sensing experiments since the 1960's (Meier and others, 1966). An exceptional Landsat image is required to obtain information about a glacier this small (Krimmel and Meier, 1975). Two cloud-free scenes, one from 11 August 1973 and one from 16 September 1973, were used to determine the change in snow-cover area. Figure 3 shows the August digital image compared to the September digital image, the pixels that are snow (DN>100 on MSS bands) in August, but not in September, being shown as heavy solid circles. Although such techniques may be useful in analyzing special cases in small areas, it has proven to be impractical for large areas

Figure 4.*—(opposite page) Temporal color composite Landsat image (1420–18303, band 5; 16 September 1973; Path 50, Row 26; and 1258–18322, bands 5, 6, and 7; 7 April 1973; Path 50, Row 26) of two north Cascades (northern Cascade Range) images in Washington State and British Columbia, Canada. This image shows areas that were snow covered on 16 September 1973 as a brilliant red, areas that were snow covered on 7 April 1973 as a white, and healthy vegetation as a tan color (Deutsch, 1983, fig. 31–72, p. 1735) The southeast quadrant of the image includes most of the glaciers of the north Cascades. Relief in the north Cascades is extreme, the valley to summit difference being as high as 2,000 m. Mount Baker (image center), at 3,285 m, is the highest peak; many other peaks approach 2,500 m. Annual precipitation in the north Cascades increases rapidly from about 1 m in the Puget Lowlands to as high as 4.5 m at the crest of the Cascade Range. Precipitation diminishes rapidly east of the crest to less than 0.5 m (Phillips and Donaldson, 1972). The major glacier concentrations are on Mount Baker and on high peaks near the crest of the north Cascades.*

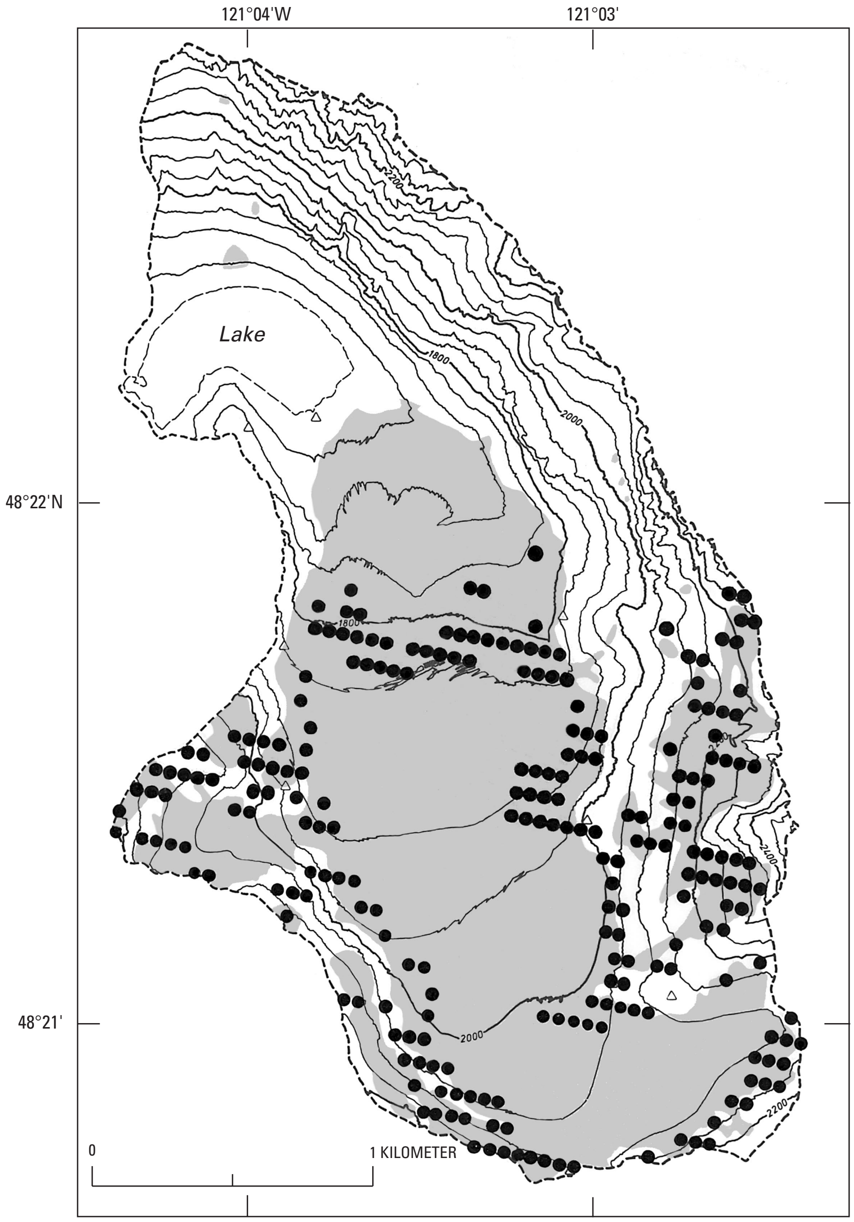
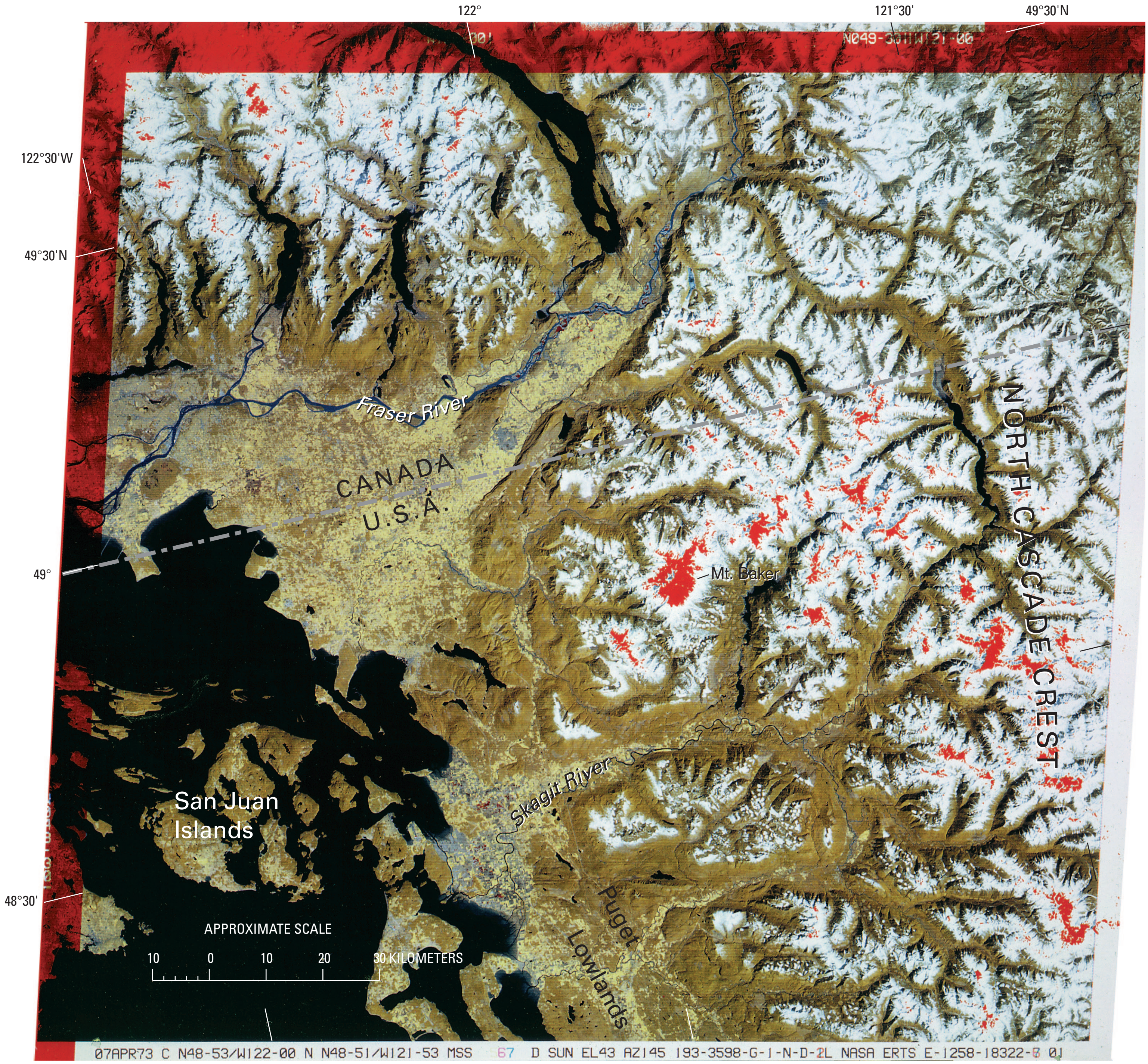


Figure 3.*—Pixel-by-pixel temporal composite of two Landsat images of the South Cascade Glacier basin, Washington. All pixels having a radiance of 100 in MSS band 5 on images from 11 August 1973 (1384–18311) and 16 September 1973 (1420–18303) were considered to be snow. The heavy solid circles within the basin area show pixels that were snow on 11 August but not snow on 16 September. The shaded area within the basin represents areas of snow, firn, or ice cover at the end of the melt season in 1973, as determined from field observations. Most of the snow-cover loss between 11 August and 16 September was near the glacier edge, at high elevation, or on the lower glacier just below the equilibrium line (about 1,850 m). The small triangles indicate the positions of benchmarks.*

because of the high cost of digital data, and in addition, critical data needed from the end of the melt season commonly cannot be obtained because of cloud cover.

A similar date-to-date comparison of images can also be made optically. In figure 4, all the material having greater than a certain brightness level (assumed to be snow) is shown for a fall image (16 September 1973). This is then registered to a spring image (7 April 1973), which thereby produces a bitemporal color-composite image showing the location of perennial snow.

The RBV sensors carried on Landsats 1 and 2 offered no advantage over the MSS sensors for glacier observation. However, on Landsat 3, the RBV was modified to produce a panchromatic image having a pixel resolution of about 30 m (2.6 times better than the MSS image). Commonly the exposure of the photographic product was such that only some of the image was



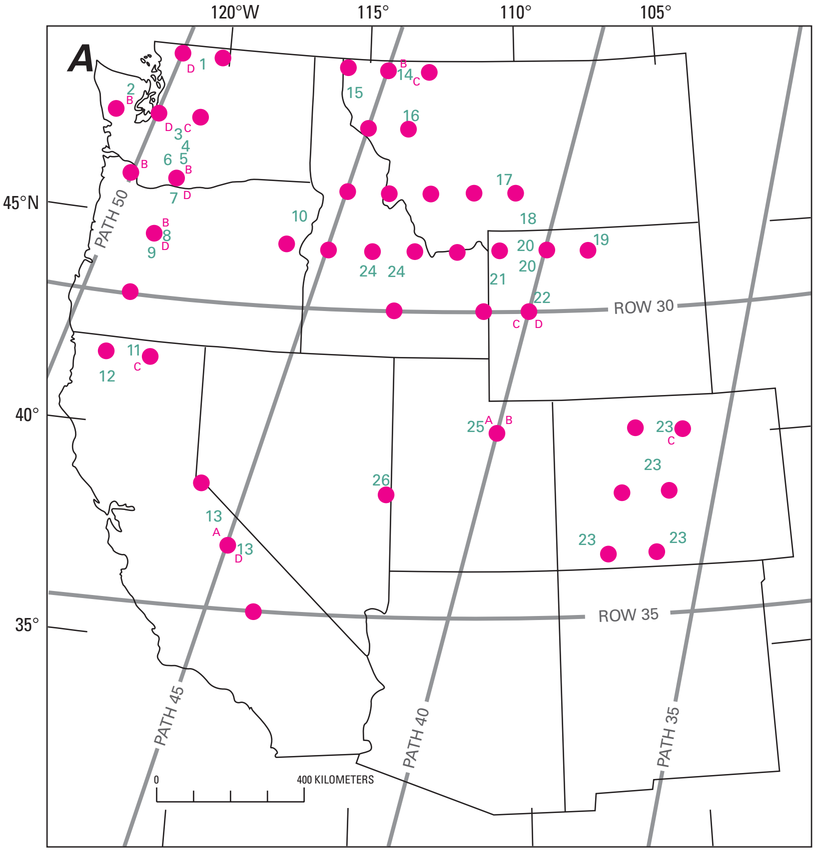


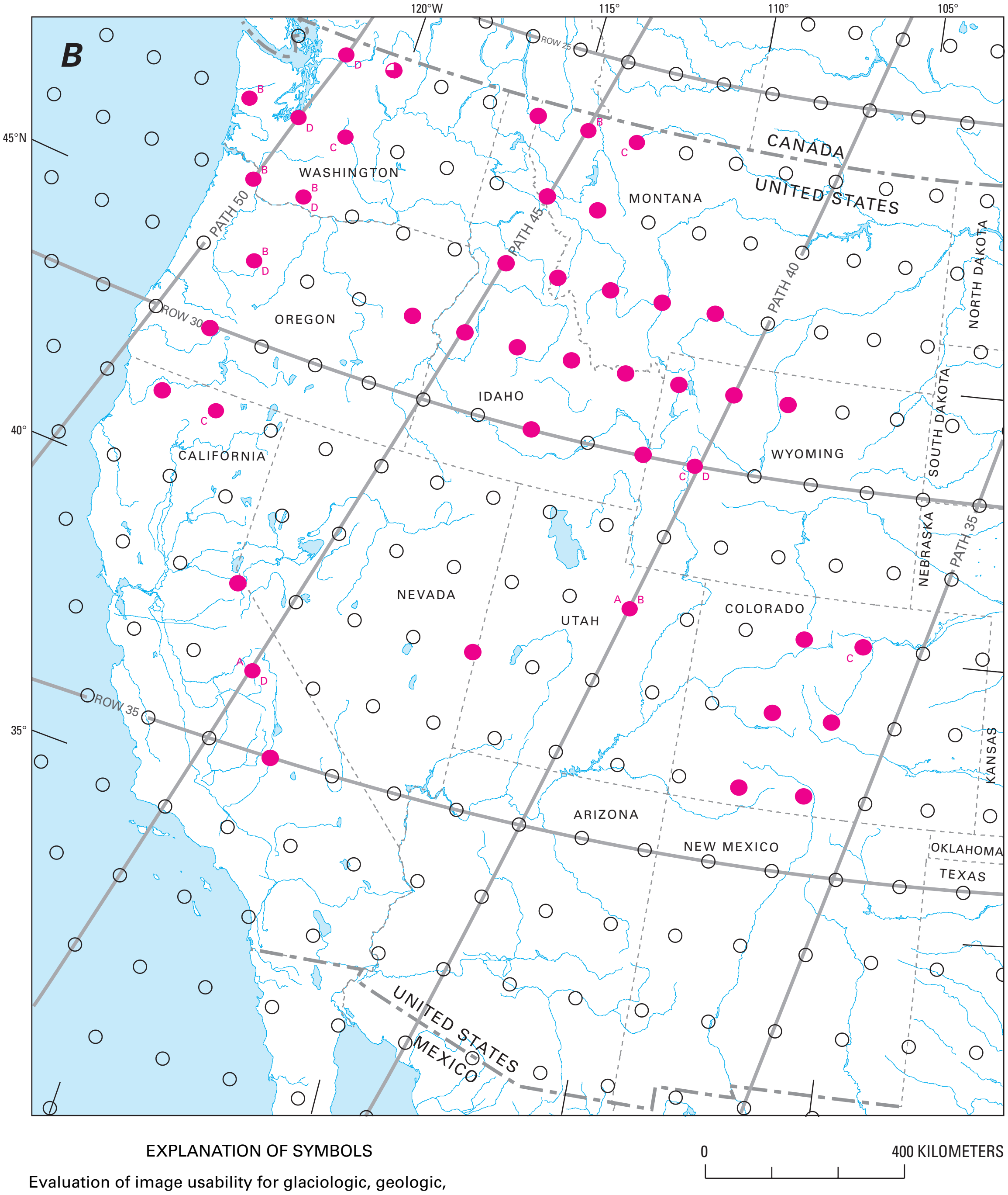
Figure 5.—Western conterminous United States showing Landsat nominal scene centers and optimum Landsat images of the glaciers. **A**, *Landsat nominal scene centers, indicated by solid circles, are shown only for areas where glaciers exist. All except one of these nominal scene centers has an excellent image available. Red letters in the four quadrants around a scene center show that a usable Landsat 3 RBV subscene also exists. Scattered numerals indicate important glacier areas and are keyed to table 1.* **B**, *(opposite page) optimum Landsat 1, 2, and 3 MSS and Landsat 3 RBV images of the glaciers of the Western United States. See table 2 for detailed information.*

usable. Unfortunately, the data from this sensor are not now generally available. A few exceptional scenes of glacierized areas are in individual collections, but the available and usable Landsat 3 RBV images do not cover a sufficient area to allow glacier delineation over large regions.

Selection of Landsat Images

The optimum satellite image for the analysis of glacier cover would have no clouds, would have a high solar-elevation angle so that deep north-, northwest-, and west-facing valleys are not in shadow, and would have only perennial snow. Clouds commonly obscure the mountains where glaciers exist, although enough images have been processed of the United States so that cloudless scenes can normally be found. The high solar-elevation angle and minimum snow-cover factors are contradictory. The optimum Sun angle is in late spring and early summer, but the snowpack at this time of year is still heavy in the mountains. Because minimum snowpack is more important, the Sun-angle factor is rarely considered. In addition, the date of minimum snow cover changes from year to year. Optimum conditions, therefore, commonly are present on clear days in the fall before new snow falls.

In the western conterminous States, optimum conditions for satellite images typically fall between mid-September and mid-October. In addition to selecting imagery from the best time of year, it is also important to select a year that did not have an abnormally heavy snowpack or an uncommonly cool summer. Either of these conditions would leave excess snow in the fall and give an impression of greater snow (interpreted as glacier) coverage. With these factors in mind, the optimum images for all the glacierized areas in the western conterminous United States were selected and are listed in table 2. The locations of important glacierized areas are shown in figure 5, which keys these areas to table 1.



EXPLANATION OF SYMBOLS

Evaluation of image usability for glaciologic, geologic, and cartographic applications. Symbols defined as follows:

- Excellent image (0 to ≤5 percent cloud cover)
- Good image (>5 to ≤10 percent cloud cover)
- Nominal scene center for a Landsat image outside the area of glaciers
- A B C D Usable Landsat 3 return beam vidicon (RBV) scenes. A, B, C, and D refer to usable RBV subscenes

TABLE 2.—*Optimum Landsat 1, 2, and 3 MSS and RBV images of glaciers of the western conterminous United States*

[See fig. 5 for explanation of symbols used in "code" column]

Path-Row	Nominal scene center (lat-long)	Landsat identification number	Date	Solar elevation angle (degrees)	Code	Cloud cover (percent)	Remarks
36–32	105°02'W. 040°14'N.	2618–16525	01 Oct 76	38	●	0	Colorado Front Range. Some snow in the highlands
36–32	105°02'W. 040°14'N.	2222–17011	01 Sep 75	48	●	0	Entire Colorado Front Range
36–32	105°02'W. 040°14'N.	30929–16504– C	19 Sep 80	42	●	5	Superb Landsat 3 RBV of glaciers of Colorado Front Range (fig. 22). Archived by USGS–SGP[1]
36–33	105°31'W. 038°49'N.	21338–16451	21 Sep 78	41	●	0	Central Colorado. Considerable new snow in the highlands. No significant glaciers in the region
36–33	105°31'W. 038°49'N.	5843–15511	08 Sep 77	41	◐	30	Central Colorado. No significant glaciers in the region
36–34	105°59'W. 037°24'N.	30209–17041	30 Sep 78	42	●	0	South-central Colorado. No significant glaciers in the region
37–32	106°28'W. 040°14'N.	30516–17073	03 Aug 79	54	●	5	North-central Colorado. No significant glaciers in the region. Some previous winter snow in the highlands
37–32	106°28'W. 040°14'N.	21699–17025	17 Sep 79	43	●	0	Excellent image of north-central Colorado. No significant glaciers in the region
37–33	106°57'W. 038°49'N.	21699–17032	17 Sep 79	44	●	0	Excellent image of central Colorado Rocky Mountains. No significant glaciers in the region
37–33	106°57'W. 038°49'N.	21303–16491	17 Aug 78	49	●	0	Excellent image of central Colorado Rocky Mountains. No significant glaciers in the region
37–34	107°25'W. 037°24'N.	1425–17190	21 Sep 73	46	●	0	Southwestern Colorado. No significant glaciers in the region
37–34	107°25'W. 037°24'N.	30210–17095	01 Oct 78	42	●	0	Excellent image of southwestern Colorado. No significant glaciers in the region
39–29	107°46'W. 044°30'N.	1409–17285	05 Sep 73	46	●	0	Small glaciers in the Bighorn Mountains, Wyo. Snow in the highlands
39–29	107°46'W. 044°30'N.	5147–17022	13 Sep 75	40	●	0	Excellent image of Bighorn Mountains, Wyo.
40–29	109°12'W. 044°30'N.	5490–16444	21 Aug 76	43	●	0	Some snow in the highlands. Glaciers and moraines in the Beartooth Mountains, Absaroka Range, Wyo.
40–29	109°12'W. 044°30'N.	2244–17224	23 Sep 75	39	●	0	Small glaciers in the Beartooth Mountains, Wyo.
40–30	109°44'W. 043°05'N.	21720–17195	08 Oct 79	35	●	5	Excellent MSS image. Glaciers and moraines of the Wind River Range (fig. 18), Wyo.
40–30	109°44'W. 043°05'N.	30573–17231– C	29 Sep79	38	●	0	Good Landsat 3 RBV image of Wind River Range moraines, Wyo. Archived by USGS–SGP
40–30	109°44'W. 043°05'N.	30915–17131– D	05 Sep 80	44	●	0	Superb Landsat 3 RBV image of moraines and glaciers of the Wind River Range, Wyo. Archived by USGS–SGP
40–32	110°46'W. 040°14'N.	6000–16574	18 Oct 77	31	●	0	No significant glaciers in the region. Good image of moraines of Uinta Mountains, Utah (fig. 21)
40–32	110°46'W. 040°14'N.	30933–17133– A	23 Sep 80	40	●	0	Moraines and cirques in the western Uinta Mountains, Utah. Archived by USGS–SGP
40–32	110°46W. 040°14'N.	30933–17133– B	23 Sep 80	40	●	5	Moraines and cirques in the eastern Uinta Mountains, Utah. Archived by USGS–SGP
41–28	110°04'W. 045°55'N.	2965–17034	13 Sep 77	38	●	0	Crazy Mountains, Mont. No significant glaciers in the region
41–29	110°38'W. 044°30'N.	21685–17241	03 Sep 79	45	●	0	Northern part of Teton Range, Wyo. No significant glaciers in the region

TABLE 2.—*Optimum Landsat 1, 2, and 3 MSS and RBV images of glaciers of the western conterminous United States* —Continued

[See fig. 5 for explanation of symbols used in "code" column]

Path-Row	Nominal scene center (lat-long)	Landsat identification number	Date	Solar elevation angle (degrees)	Code	Cloud cover (percent)	Remarks
41–30	111°10'W. 043°05'N.	5509–16492	09 Sep 76	39	●	0	Central western Wyoming and eastern Idaho. No significant glaciers in the region
42–28	111°30'W. 045°55'N.	1790–17354	21 Sep 74	39	●	0	Southwestern Montana. No significant glaciers in the region
42–29	112°04'W. 044°30'N.	1790–17361	21 Sep 74	40	●	0	Southwestern Montana and northeastern Idaho. No significant glaciers in the region
42–33	114°08'W. 038°49'N.	22064–17363	16 Sep 80	45	●	0	Wheeler Peak, Nev. No significant glaciers in the region
43–28	112°56'W. 045°55'N.	30558–17395	14 Sep 79	41	●	0	Western Montana. Good image of moraines. No significant glaciers in the region
43–29	113°30'W. 044°30'N.	1791–17415	22 Sep 74	40	●	0	Eastern Sawtooth Range, Idaho. No significant glaciers in the region
43–30	114°02'W. 043°05'N.	22029–17405	12 Aug 80	51	●	0	Southern Sawtooth Range, Idaho. No significant glaciers in the region
44–26	113°09'W. 048°44'N.	30523–17452	10 Aug 79	49	●	5	Glacier National Park and Lewis Range, Mont. Some previous winter snow in the highlands (fig. 17)
44–26	113°09'W. 048°44'N.	30559–17445	15 Sep 79	39	●	0	Glacier National Park and Lewis Range, Mont.
44–26	113°09'W. 048°44'N.	30919–17342– C	09 Sep 80	39	●	0	Glacier National Park and Lewis Range, Mont. Archived by USGS–SGP
44–27	113°47'W. 047°20'N.	30523–17454	10 Aug 79	50	●	0	Flathead, Mission, and Swan Ranges, Mont. No significant glaciers in the region
44–28	114°22'W. 045°55'N.	2230–17452	09 Sep 75	43	●	0	Bitterroot Range, Idaho- Mont. No significant glaciers in the region
44–28	114°22'W. 045°55'N.	30559–17454	15 Sep 79	41	●	0	Bitterroot Range, Idaho- Mont. No significant glaciers in the region
44–29	114°56'W. 044°30'N.	2626–17371	09 Oct 76	33	●	0	Sawtooth Range, Idaho. Some snow in the highlands. No significant glaciers in the region (fig. 20)
44–29	114°56'W. 044°30'N.	30559–17460	15 Sep 79	42	●	0	Sawtooth Range, Idaho. No significant glaciers in the region
44–35	117°56'W. 035°58'N.	1396–18001	23 Aug 73	54	●	0	Southern Sierra Nevada, Calif. No significant glaciers in the region
45–26	114°36'W. 048°44'N.	22085–17505	07 Oct 80	31	●	0	Glacier National Park and Lewis Range. Cabinet Mountains, Mont.
45–26	114°36'W. 048°44'N.	30542–17505– B	29 Aug 79	44	●	5	Glacier National Park and Lewis Range, Mont.
45–27	115°13'W. 047°20'N.	21653–17452	02 Aug 79	51	●	5	Western Montana. No significant glaciers in the region
45–28	115°48'W. 045°55'N.	21293–17323	07 Aug 78	49	●	0	Western Sawtooth Range, Idaho. No significant glaciers in the region
45–29	116°22'W. 044°30'N.	21293–17325	07 Aug 78	49	●	0	Southwestern Sawtooth Range, Idaho. No significant glaciers in the region
45–34	118°54'W. 037°24'N.	30578–17532	04 Oct 79	40	●	0	Sierra Nevada, Calif. No significant glaciers in the region (fig. 13)
45–34	118°54'W. 037°24'N.	30578–17532– A	04 Oct 79	40	●	0	Northern Sierra Nevada, Calif. (fig. 14). Archived by USGS–SGP
45–34	118°54'W. 037°24'N.	30578–17532– D	04 Oct 79	40	●	0	Southern Sierra Nevada, Calif. (fig. 15). Archived by USGS–SGP
46–26	116°02'W. 048°44'N.	30561–17561	17 Sep 79	38	●	0	Cabinet Mountains, Idaho-Mont. No significant glaciers in the region

TABLE 2.—*Optimum Landsat 1, 2, and 3 MSS and RBV images of glaciers of the western conterminous United States* —Continued

[See fig. 5 for explanation of symbols used in "code" column]

Path-Row	Nominal scene center (lat-long)	Landsat identification number	Date	Solar elevation angle (degrees)	Code	Cloud cover (percent)	Remarks
46–29	116°39'W. 047°20'N.	1380–18093	07 Aug 73	53	●	0	Wallowa Mountains, Oreg. No significant glaciers in the region
46–33	119°52'W. 038°49'N.	30561–17591	17 Sep 79	45	●	0	Northern Sierra Nevada, Calif. No significant glaciers in the region
48–31	121°45'W. 041°40'N.	21710–18055	28 Sep 79	39	●	0	Mount Shasta, Calif.
48–31	121°45'W. 041°40'N.	30905–17595– C	26 Aug 80	47	◑	15	Mount Shasta, Calif. Archived by USGS–SGP
49–26	120°20'W. 048°44'N.	21657–18080	6 Aug 79	49	◕	10	Northern Cascade Range, Wash.
49–27	120°57'W. 047°20'N.	1419–18251	15 Sep 73	41	●	0	Northern Cascade Range, Mount Rainier, Wash.
49–27	120°57'W. 047°20'N.	30888–18043– C	09 Aug 80	49	●	0	Mount Rainier, Wash. (fig. 10). Archived by USGS–SGP
49–28	121°32'W. 045°55'N.	22053–18143	05 Sep 80	43	●	0	Mount St. Helens, Goat Rocks, Mount Adams, Mount Hood, Wash. (fig. 12)
49–28	121°32'W. 045°55'N.	30888–18050– B	09 Aug 80	49	●	0	Mount Adams, Wash. Archived by USGS–SGP
49–28	121°32'W. 045°55'N.	30942–18031– D	02 Oct 80	34	●	0	Mount Hood, Wash. Archived by USGS–SGP
49–29	122°06'W. 044°30'N.	21657–18091	06 Aug 79	51	●	0	Mount Jefferson, Three Sisters Range, Oreg. Some previous winter snow in the highlands.
49–29	122°06'W. 044°30'N.	30150–18160– B	02 Aug 78	53	●	0	Mount Jefferson, Oreg. Some previous winter snow in the highlands. Archived by USGS–SGP
49–29	122°06'W. 044°30'N.	30150–18160– D	02 Aug 78	53	●	0	Three Sisters Range, Oreg. Some previous winter snow in the highlands. Archived by USGS–SGP
49–30	122°39'W. 043°05'N.	1041–18271	02 Sep 72	48	●	0	Southern Oregon. No significant glaciers in the region. Some snow in the highlands
49–31	123°11'W. 041°40'N.	21693–18111	11 Sep 79	44	●	0	Salmon and Trinity Mountains, Mount Shasta, Calif.
50–26	121°46'W. 048°44'N.	1420–18303	16 Sep 73	39	●	0	Northern Cascade Range, Wash.
50–26	121°46'W. 048°44'N.	30223–18211– D	14 Oct 78	29	●	0	Northern Cascade Range, Wash. Archived by USGS–SGP
50–27	122°23'W. 047°20'N.	30583–18190	09 Oct 79	32	●	0	Northern Cascade Range, Olympic Mountains, Mount Rainier, Wash.
50–27	122°23'W. 047°20'N.	30889–18102– D	10 Aug 80	48	●	0	Mount Rainier, Wash. Archived by USGS–SGP
50–28	122°58'W. 045°55'N.	30889–18104– B	10 Aug 80	48	●	0	Mount St. Helens, Wash. (fig. 12C) Archived by USGS–SGP
51–27	123°50'W. 047°20'N.	2993–17590	11 Oct 77	28	●	0	Olympic Mountains, Wash. (fig. 9)
51–27	123°50'W. 047°20'N.	30926–18144– B	16 Sep 80	38	●	0	Olympic Mountains, Wash. Archived by USGS-SGP

[1] USGS-SGP is the U.S. Geological Survey-Satellite Glaciology Project (renamed the Glacier Studies Project).

Glaciers of the State of Washington

It has been estimated that 75 percent of the glaciers in the United States exclusive of Alaska are in the State of Washington (Meier, 1961a). The glaciers of Washington are conveniently grouped into six geographic divisions: (1) the north Cascades (northern Cascade Range), including the area from the Canadian border south to Snoqualmie Pass and from the Twin Sister Mountain area (about 15 km southwest of Mount Baker) in the west to long 120° W. in the east; (2) the Olympic Peninsula; (3) Mount Rainier; (4) the Goat Rocks area (about 50 km southeast of Mount Rainier); (5) Mount Adams; and (6) Mount St. Helens. Landsat images and other illustrations for each of the geographic divisions accompany the following discussions of each region.

Glaciers of the North Cascade Range

The most recent and comprehensive glacier inventory of the north Cascades, made in late 1969 by the USGS, shows that about one-half of the glaciers in Washington are in this region (Post and others, 1971). The source material for this inventory consisted of USGS large-scale (7.5-minute quadrangles, 1:24,000-scale) topographic map sheets and USGS oblique aerial photographs. The oblique aerial photography was used where maps were not available and also where the termini positions needed to be updated to the inventory date of 1970. This inventory counted 756 glaciers that had a total area of 267 km^2. Since that time, several additional small glaciers have been “discovered”; however, these small glaciers do not increase the total area significantly. The major concentrations of glaciers in the north Cascades are on Mount Baker, at the head of the Thunder Creek drainage, and on Glacier Peak. The largest glacier in this area is the Boston Glacier (lat 48°45' N., long 121°01' W.), which has an area of 7.0 km^2. The longest glacier, the Deming Glacier (lat 48°45' N., long 121°51' W.) on Mount Baker, is 4.8 km in length.

The north Cascades region is characterized by high relief; many of the valley floors are less than 500 m in elevation, whereas the nearby summits are in excess of 2,500 m. Precipitation is heavy; annual precipitation is commonly more than 4 m near the west side of the crest of the Cascade Range. On the east side of the crest, precipitation is considerably less.

The South Cascade Glacier is located within the north Cascades region at lat 48°22' N., long 121°03' W. Not necessarily representative of the glaciers of the north Cascades, it is a relatively flat glacier and has no major ice falls. However, it would be difficult to pick any one glacier that is typical of the north Cascades. This glacier has been studied in detail since 1957 (Meier and Tangborn, 1965; Meier and others, 1971; Fountain and Fulk, 1984). It is about 3 km long and 2.5 km^2 in area and has an equilibrium line altitude (ELA) of 1,860 m. Studies in the South Cascade Glacier basin have been directed toward glacier mass balance (Meier, 1961b; Meier and Post, 1962; Tangborn, 1965, 1968; Tangborn and others, 1975, 1977; Krimmel, 1989, 1993, 1994; Meier and others, 1980; Mayo, 1984; Walters and Meier, 1989), basin water balance (Tangborn, 1963; Krimmel and others, 1978; Sullivan, 1994; Krimmel, 1995, 1996, 1997, 1998, 1999, 2000, 2001) ice dynamics and subglacier and englacier water flow (Fountain, 1989, 1992a, b, 1993, 1994), and many other related topics (Meier, 1958, 1967; Tangborn, 1962).

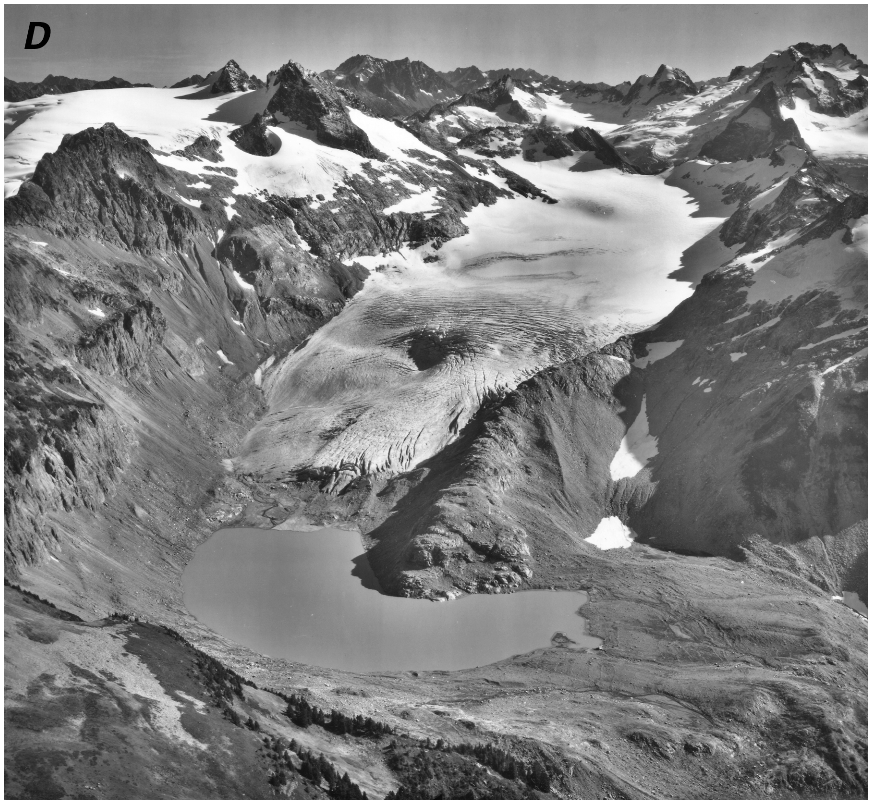
The history of the South Cascade Glacier shows advances at about 3000 B.C. and during the 16th and 19th centuries. A sheared-off tree stump some 100 m above the 1970 ice level was dated by the radiocarbon method at about 5,000 years B.P. (before present). This suggests that the glacier had been at its present size or smaller for some centuries prior to 3000 B.C.

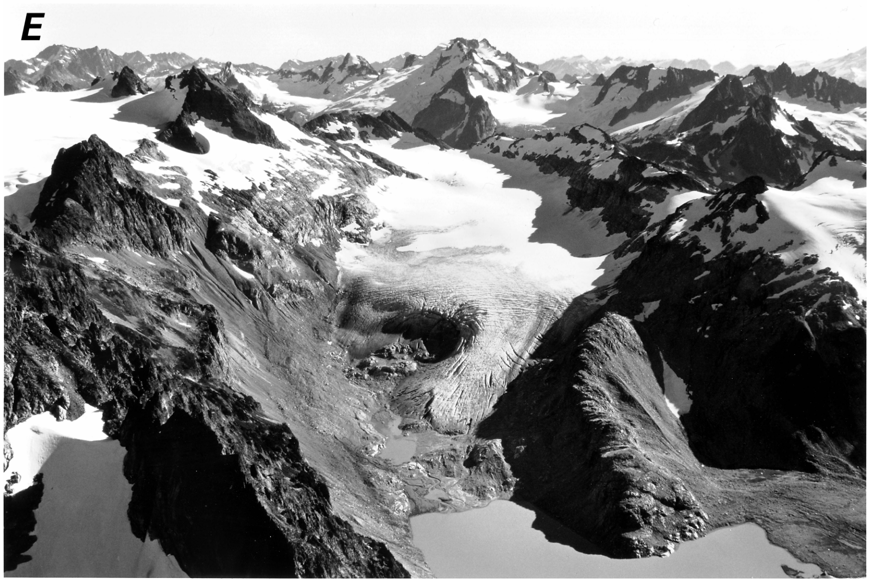
Figure 6.—*Photographic record of South Cascade Glacier, Wash., from 1928 to 1996.* **A**, *In 1928, the glacier had been retreating since the neoglaciation maximum length in the late 19th century. The average retreat rate from 1928 to 1980 was about 18 m a^{-1}; the maximum retreat rate took place from about 1950 to 1960 as the glacier retreated across the lake. The retreat rate during the 1970's was about 12 m a^{-1}. All the glaciers of the north Cascades experienced an overall retreat during the 20th century. Oblique aerial photograph by Wernstadt, U.S. Forest Service.* **B**, *South Cascade Glacier in 1939. Photograph taken by Watson.* **C**, *South Cascade Glacier in 1955. Photograph taken by Richard Hubley, University of Washington.* **D**, **E**, *see opposite page*

Sometime after 3000 B.C., the glacier made an advance that ended in the 16th century about 1.5 km downvalley from the 1970 position. The glacier retreated an unknown distance from the 16th century position and then readvanced to nearly the 16th century position near the end of the 19th century (Miller, 1969).

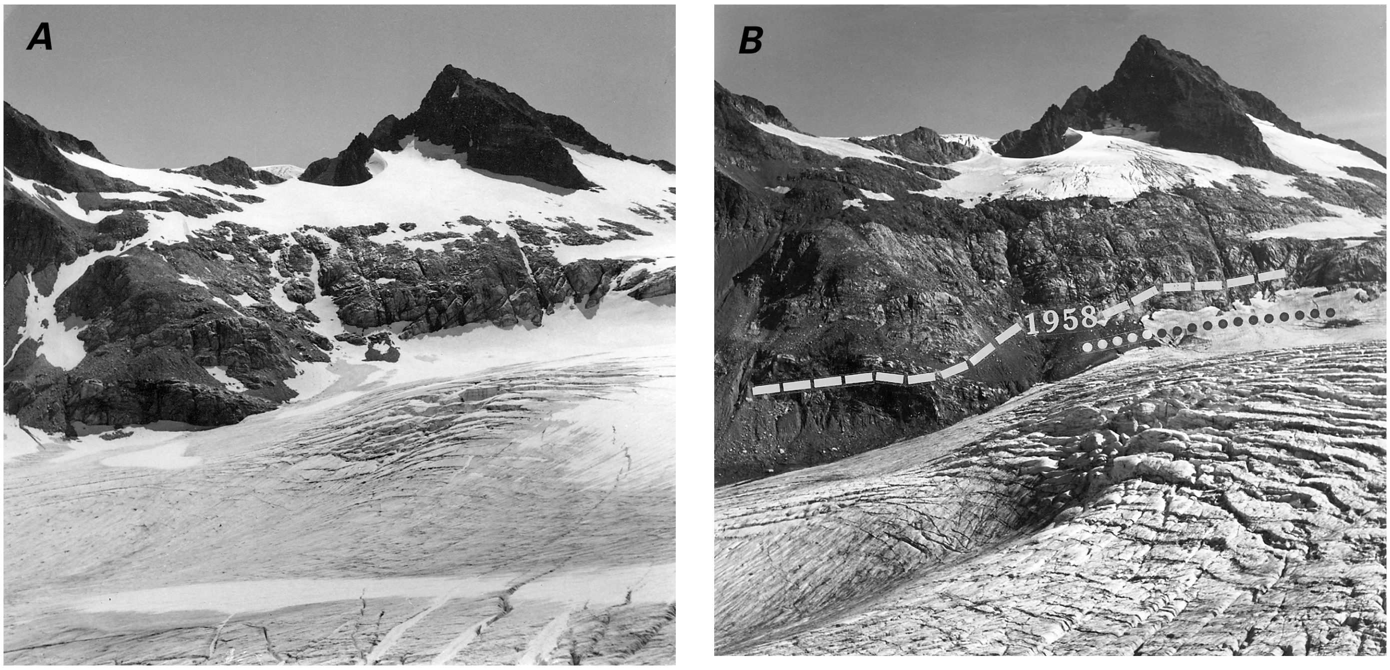
Since the late 19th century advance of the South Cascade Glacier, its terminus has been continuously receding. A 1928 oblique aerial photograph

Figure 6.—**D***, South Cascade Glacier on 10 October 1983. Photograph number 83RI–188 taken by R.M. Krimmel, USGS.* **E***, South Cascade Glacier on 9 October 1996. Black-and-white oblique aerial photograph from original 35-mm color slide taken by R.M. Krimmel, USGS.*





(fig. 6*A*) shows the terminus at today's west shore of South Cascade Lake. A photograph from 1939 (fig. 6*B*) shows about 100 m of lake opened, and the first vertical aerial photograph, from 1953, shows about one-half of the lake opened. By 1955, more of the lake was free of glacier ice (fig. 6*C*), and by 1968, the entire lake was clear of glacier ice. Since 1968, recession has continued, averaging about 12 m a^{-1}, although very minor advances have been recorded during this period. During the winter, ice motion continues but is not offset by ice ablation, and a seasonal advance takes place. In 1972, extremely heavy winter snowpack covered the terminus well into late summer. Because the snow protected the terminus from melting, it advanced a few meters. Figure 6*D*, showing the glacier in 1983, is an example from the collection of recent large-format oblique and vertical aerial photographs archived by the University of Alaska's Geophysical Institute in



Fairbanks, Alaska. The University of Alaska archive includes most of the major glaciers in the United States. Figure 6*E* shows the position of the glacier terminus in 1996.

Figure 6 illustrates the exceptional photographic record for South Cascade Glacier. Figure 7 illustrates a time sequence of terrestrial photographs used for qualitative analysis of ice-level changes.

The annual mass balance of South Cascade Glacier has ranged from –2.6 m to +1.4 m and has had an average of –0.7 m from 1966 to 1995. Figure 8 shows the cumulative mass balance from 1884 to 1995. Annual runoff from the entire area of the basin (fig. 3) is normally about 4 m. Precipitation accounts for 93 percent of this total; the remainder is derived from loss of ice mass.

South Cascade Glacier has an average thickness of 100 m and a maximum thickness of 220 m (Krimmel, 1970). Its average velocity is about 10 m a^{-1}. The maximum velocity, about 30 m a^{-1}, is found near the center of the lower glacier. Maximum seasonal velocity takes place in the early summer and is 140 percent of the annual velocity; minimum velocity takes place during the fall and winter.

South Cascade Glacier is one of only a few glaciers worldwide that have been analyzed with regard to their dynamic response to change in climate. A hypothetical 1-m addition to the glacier surface for only 1 year would produce a thickening of the terminus that would amount to 5 m after 23 years. This would be followed by a slow return to normal, but it would have an excess of 0.6 m persisting at the terminus 100 years later. The actual glacier response is a combination of responses to weather events for each year of the last century or more, and thus it is complex and has a long “memory” (Nye, 1965).

Balance measurements have been made at numerous other north Cascades glaciers, and for the most part, these show trends similar to those at South Cascade Glacier. *Vesper Glacier* was measured during balance years 1974–75 (Dethier and Frederick, 1981); Pelto made measurements on Columbia, *Daniels*, *Foss*, *Ice Worm*, Lower Curtis, Yawing, Rainbow, *Spider*, and Lynch Glaciers from 1984 to 1994 (Pelto, 1996); and North Cascades National Park personnel measured North Klawatti, Silver, *Noisy*, and Sandelee Glaciers during 1992–96.

Figure 7.*—Ice-level changes of South Cascade Glacier, Wash.* **A***, South Cascade Glacier in July 1958. Photograph taken by Austin Post, USGS.* **B***, South Cascade Glacier in August 1979. Photograph shows a loss of about 30 m near the equilibrium line since 1958. The dashed line is the 1958 position of the ice edge. The dotted line indicates the level of the active glacier ice. Photograph taken by R.M. Krimmel, USGS.* **C***,* **D***,* **E***, see opposite page.*

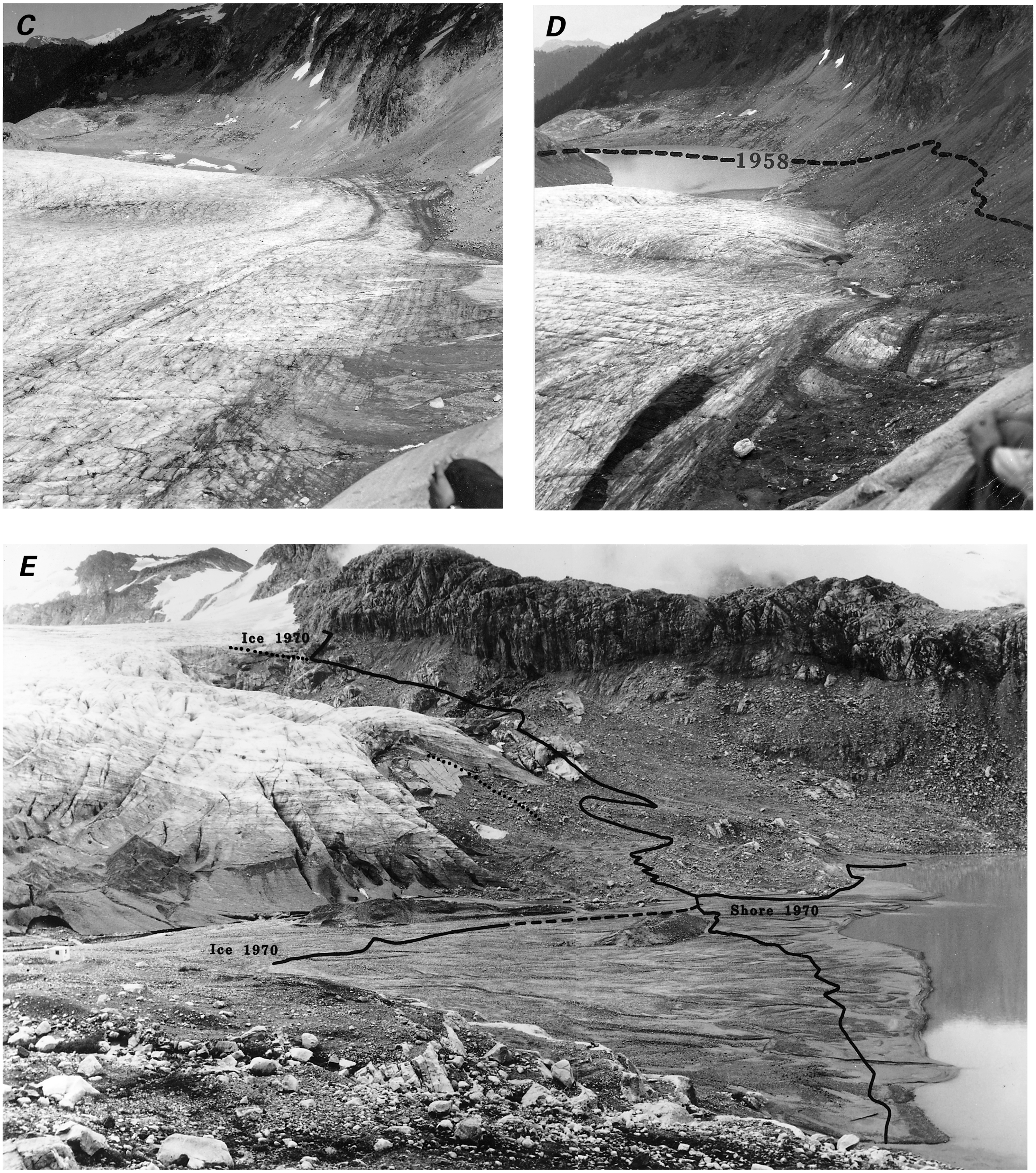


Figure 7.—**C**, *Lower South Cascade Glacier in July 1958. Photograph taken by Austin Post, USGS.* **D**, *Lower South Cascade Glacier in August 1979. Photograph shows a loss of about 60 m since 1958. The dashed line is the 1958 position of the ice edge. Photograph taken by R.M. Krimmel, USGS.* **E**, *Lower South Cascade Glacier in August 1978. Ice loss on lower Cascade Glacier at the terminus from 1970 to 1978 was about 30 m, and recession during that period was about 90 m. The dashed line is the 1970 terminus position inferred from, but not visible in, a 1970 photograph. Dotted lines show 1970 levels of ice in areas between the photograph point and the far edge of the glacier. The inconspicuous building on the extreme left is 2 m high. Photograph taken by R.M. Krimmel, USGS.*

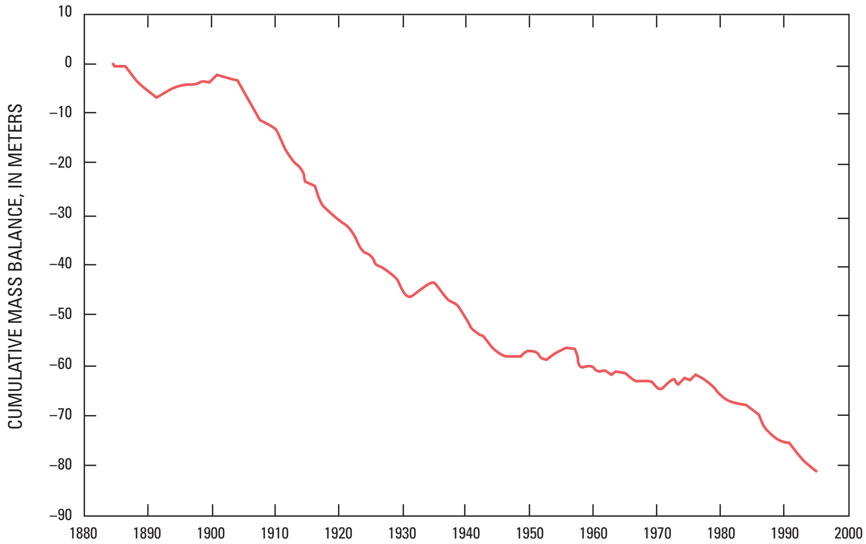


Figure 8.*—Cumulative mass balance for South Cascade Glacier, Wash., for the years 1884–1995 (adapted from Tangborn, 1980). For the years 1884 to 1957, balance was calculated by a precipitation-temperature model; the balance was directly measured for the years 1958–95.*

Glaciers of the Olympic Peninsula

Storm systems affecting the Olympic Peninsula tend to approach from the west and southwest. Because the Olympic Peninsula (fig. 9) forms a barrier to the moist clouds from the Pacific Ocean, strong precipitation gradients are found from the west to the east. Although most coastal stations receive 2 m of precipitation, about 3 m of precipitation is received 15 km inland, and at the crest of the Olympic Mountains 60 km inland, the annual precipitation is 6 m. Farther inland, to the northeast of the summits, the precipitation drops off rapidly to as low as 0.4 m. Because the freezing level during winter is often below 1,000 m, snow is heavy in the mountains, and glaciers exist on many of the higher peaks (Phillips and Donaldson, 1972).

The major glacier concentration is on the Mount Olympus massif, where three major glaciers, the Blue, Hoh, and White Glaciers, and numerous other smaller glaciers account for about 80 percent of the area of perennial snow and ice in the Olympic Mountains. Small glaciers are found on Mount Anderson at 2,233 m and on Mount Carrie at 2,133 m; numerous small glaciers or ice patches exist above 2,000 m in shaded areas on these and other peaks. The total area of perennial snow and ice on the Olympic Mountains is about 45.9 km^2 (Spicer, 1986).

The Blue Glacier is one of the most extensively studied glaciers in the United States. The variations of the Blue Glacier during recent centuries (Heusser, 1957) and its mass balance (LaChapelle, 1965), structure (Allen and others, 1960), internal deformation (Shreve and Sharp, 1970), and flow (Meier and others, 1974) have been the subjects of major research efforts.

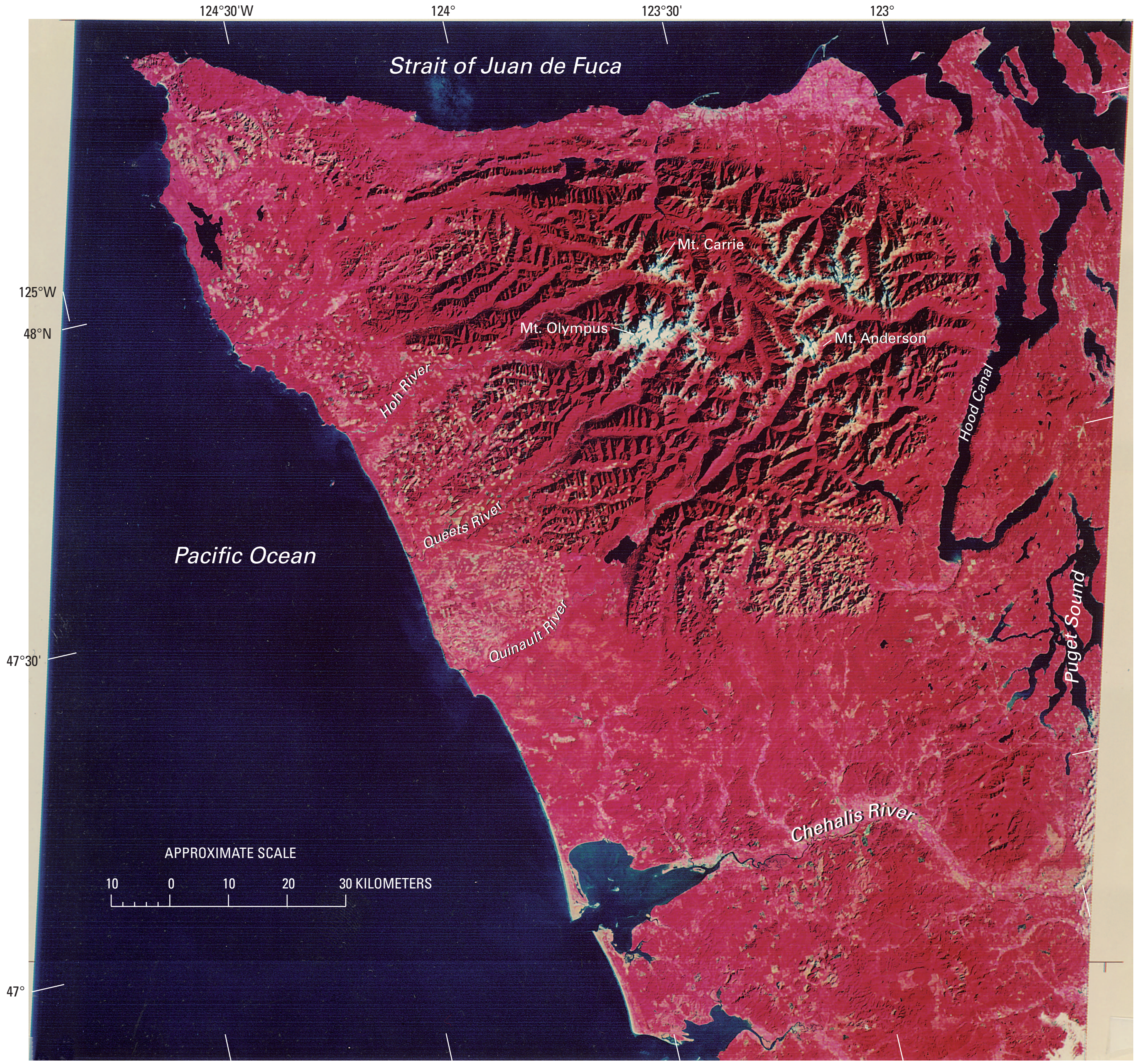


Figure 9.—*Landsat 2 MSS false-color composite image (2993–17590, bands 4, 5, and 7; 11 October 1977; Path 51, Row 27) of the Olympic Peninsula, Puget Sound, and vicinity, Wash. The Olympic Peninsula is a very distinct physiographic unit. To the west is the Pacific Ocean, to the north is the Strait of Juan de Fuca, to the east is the Hood Canal and Puget Sound, and to the south is the valley of the Chehalis River. Relief in the Olympic Mountains is extreme. Relatively low valleys extend into the interior, and the 300-m contour is within 8 km of the 2,429-m high Mount Olympus (north of image center). Other peaks greater than 2,000 m in elevation are numerous; all are east of the Mount Olympus massif. Evidence of the much greater extent of past glaciation is easily seen. The valleys of the Hoh, Queets, and Quinault Rivers, all draining to the west, have the classic broad, relatively straight shape that indicates erosional modification by glaciers. Glaciers from these valleys ended in piedmont lobes. Much smaller glaciers existed from the range toward the east because a precipitation pattern similar to the present probably existed during past glacials. Evidence of past glacier cover in Puget Sound is indicated by the small lakes and fjords.*

Glaciers of Mount Rainier

Mount Rainier, a large stratovolcano, is 4,395 m high (fig. 10) and supports the largest concentration of glaciers in the United States, outside of Alaska (Dreidger, 1986, 1993). The largest glacier in the Western United States, the Emmons (11.2 km^2 in area), the longest glacier, the Carbon (8.2 km long), and the lowest glacier terminus, the Carbon (1,070 m), are all on Mount Rainier. The combined area of the 25 named and 50 or so unnamed glaciers on Mount Rainier and its satellite peaks is 92.1 km^2. The total volume of ice on Mount Rainier is 4.4 km^3 (Driedger

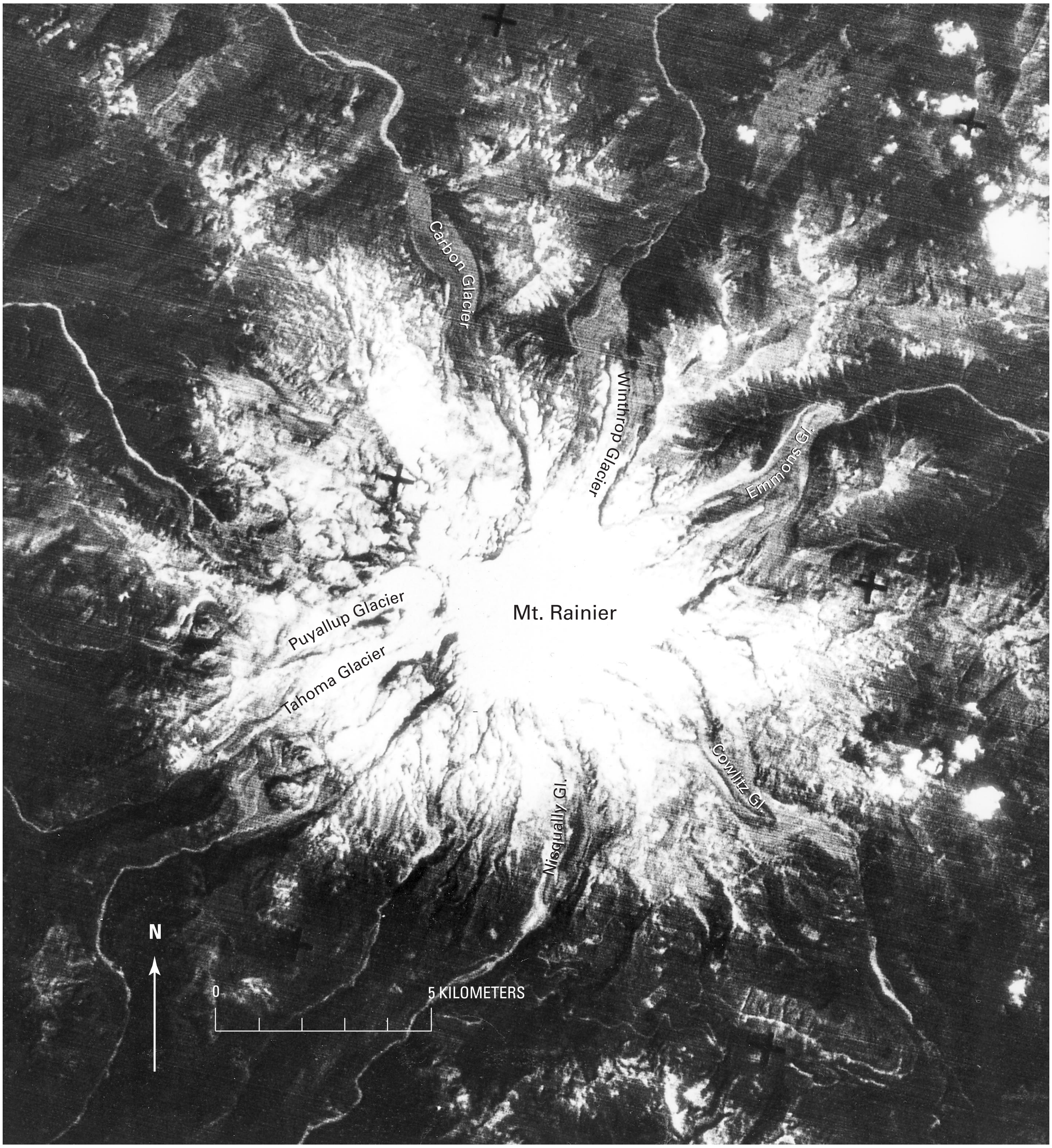


Figure 11.—Nisqually Glacier from the old Nisqually River bridge, Mount Rainier, Wash. The exact date and photographer of this photograph are unknown, but the date is approximately 1900. This is an example of a photograph that was presumably taken for nonscientific reasons but now provides valuable information on the position of the glacier terminus.

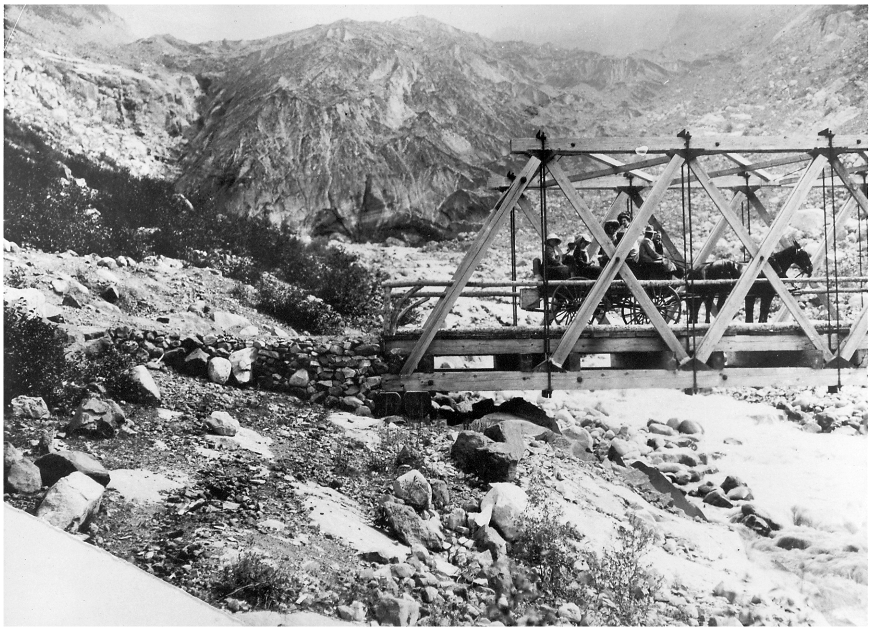


Figure 10.—(opposite page) Mount Rainier, Wash., from a part of Landsat 3 RBV image 30888–18043–C on 9 August 1980 (Path 49, Row 27). The glacier termini are seen extending well beyond the snow-covered higher elevations in this Landsat image. Most of the glaciers terminate well above the vegetation trimlines, and the actual termini are in places identifiable by a darker perimeter where the steep glacier edge forms a shadow. Landsat 3 RBV images allow terminus fluctuations as small as 30 m to be observed under optimum conditions. Abbreviation: Gl., Glacier.

and Kennard, 1984, 1986). The potential for the interaction of volcanic activity and the glacier-ice cover makes Mount Rainier a very dangerous volcano that could produce, as it has in the geologic past, jökulhlaups (Driedger, 1988; Driedger and Fountain, 1989; Walder and Driedger, 1995) and lahars (Walder and Driedger, 1993). Richardson (1968) discussed jökulhlaups in the Pacific Northwest region.

Nisqually Glacier is the most accessible major glacier in the conterminous United States and offers numerous tourists their first closeup look at a glacier. This glacier also has the longest record of annual observations of the position of its terminus—since 1918—of any glacier in the Western Hemisphere. The history of the Nisqually Glacier is documented as well by numerous early photographs (Veatch, 1969). Figure 11 is an example of an early photograph of the glacier. The Nisqually Glacier has been the subject of several glaciological research projects (Hodge, 1972, 1976, 1979). Since 1931, annual measurements have been made of the change in thickness, and detailed topographic maps of the Nisqually Glacier were made by the USGS from vertical aerial photography at scales of 1:10,000 (see Heliker and others, 1984; U.S. Geological Survey, 1978) and 1:12,000 dated 16 August 1951, 4 September 1956, 19 August 1961, 25 August 1971, and 31 August 1976. The Nisqually Glacier 1976 map sheet (1:10,000 scale) (U.S. Geological Survey, 1978) was preceded by four earlier map sheets: Nisqually Glacier 1931, 1936, 1941, and 1946, published in 1960; Nisqually Glacier 1951, 1956, and 1961, published in 1963; Nisqually Glacier 1966, published in 1968; and Nisqually Glacier 1971, published in 1973. The terminus receded almost continuously from the first observation in 1857 through 1963 (Kautz, 1875; Heliker and others, 1984). In 1964, active ice advanced, and this advance continued to 1969 (Sigafoos and Hendricks, 1972). Advance began again in 1976 and was continued into 1982. Between 1983 and 1986, little change was noted in the terminus of Nisqually Glacier. From 1986 to 1990, a pronounced recession occurred, accompanied by thinning, and retreat was continuing in 2001 (Carolyn L. Driedger, oral commun., 2001). Since 1857, the total recession has been 1,945 m, and the total advance, 294 m (Heliker and others, 1984). An intensive study during the late 1960's and early 1970's showed speeds that varied from 60 to 160 mm d^{-1} near the terminus and from 200 to 700 mm d^{-1} near the equilibrium line. The speed was seasonably dependent, the early summer speed being generally about two times the late fall speed (Hodge, 1974).

Glaciers of Southern Washington

Glaciers of southern Washington exist only in the Goat Rocks area, on Mount Adams, and on Mount St. Helens (fig. 12*A*). In the Goat Rocks area, numerous small glaciers (each less than 1 km^2 in area) are present on the north or west sides of the crest of the Cascade Range near Gilbert Peak (2,496 m). These glaciers form on slopes lee to the prevailing southwesterly storm winds.

Mount Adams (3,744 m) is the second highest summit in the State of Washington. The mountain has 10 major named glaciers, the largest of which is the Adams Glacier. Because most of the termini of Mount Adams' glaciers are completely covered with rock debris, it is difficult to define the precise glacier limits.

Most of the glaciers on the flanks of Mount St. Helens were either reduced in size or eliminated during the catastrophic explosive volcanic eruption of 18 May 1980 (fig. 12*B*) (Brugman and Post, 1981). The preeruption glacier area was approximately 5 km^2 and had a volume of 0.18 km^3. Seventy percent of this ice was removed on 18 May 1980, including all or virtually all of the Wishbone, Loowit, Leschi, and Forsyth Glaciers. The ice was removed either by the paroxysmal blast, which caused the displacement of

Figure 12.—*Glaciers of southern Washington.* **A**, *Landsat 2 MSS false-color composite image (22053–18143, bands 4, 5, and 7; 5 September 1980; Path 49, Row 28) showing part of southwestern Washington and northwestern Oregon. The ice remaining on Mount St. Helens (northwest part of image) 4 months after the 1980 eruptions, on Mount Adams (north-central part of image), and in the Goat Rocks area (extreme north-central part of image) is covered by tephra deposits and is not visible in this image. The ice in these three areas accounts for all the ice in Washington State south of Mount Rainier. Ice cover on Mount St. Helens previous to 18 May 1980 was 5.02 km^2, but it was only 2.16 km^2 after that date (Brugman and Meier, 1981). Ice cover on Mount Adams is about 16 km^2; in this image, summer snow is visible at higher elevations. Ice cover in the Goat Rocks area is 1.5 km^2 (Meier, 1961). Mount Hood, Oreg., (south-central part of image) has 13.5 km^2 of ice, the largest area of ice in that state.* **B**, **C**, *see opposite*

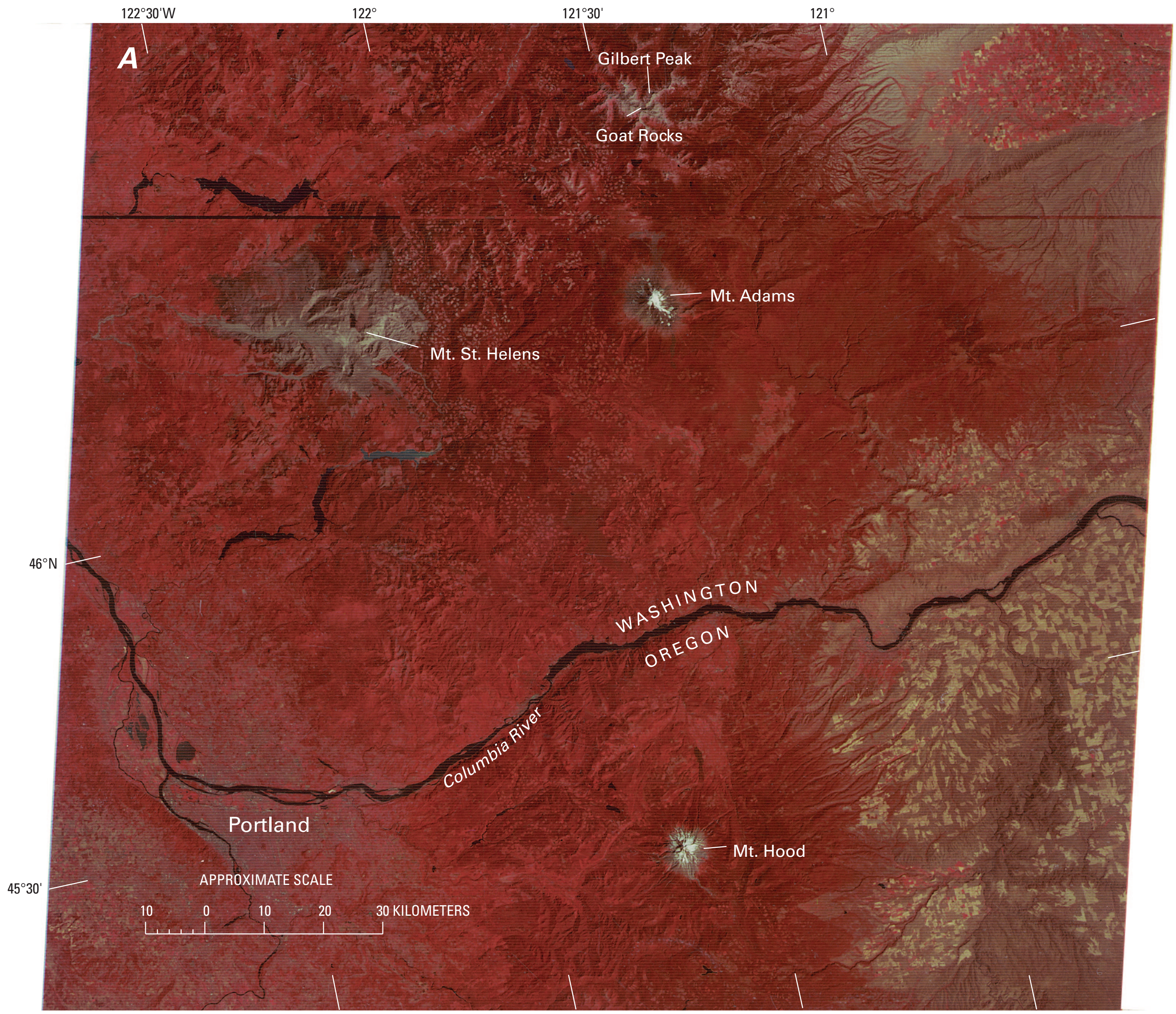
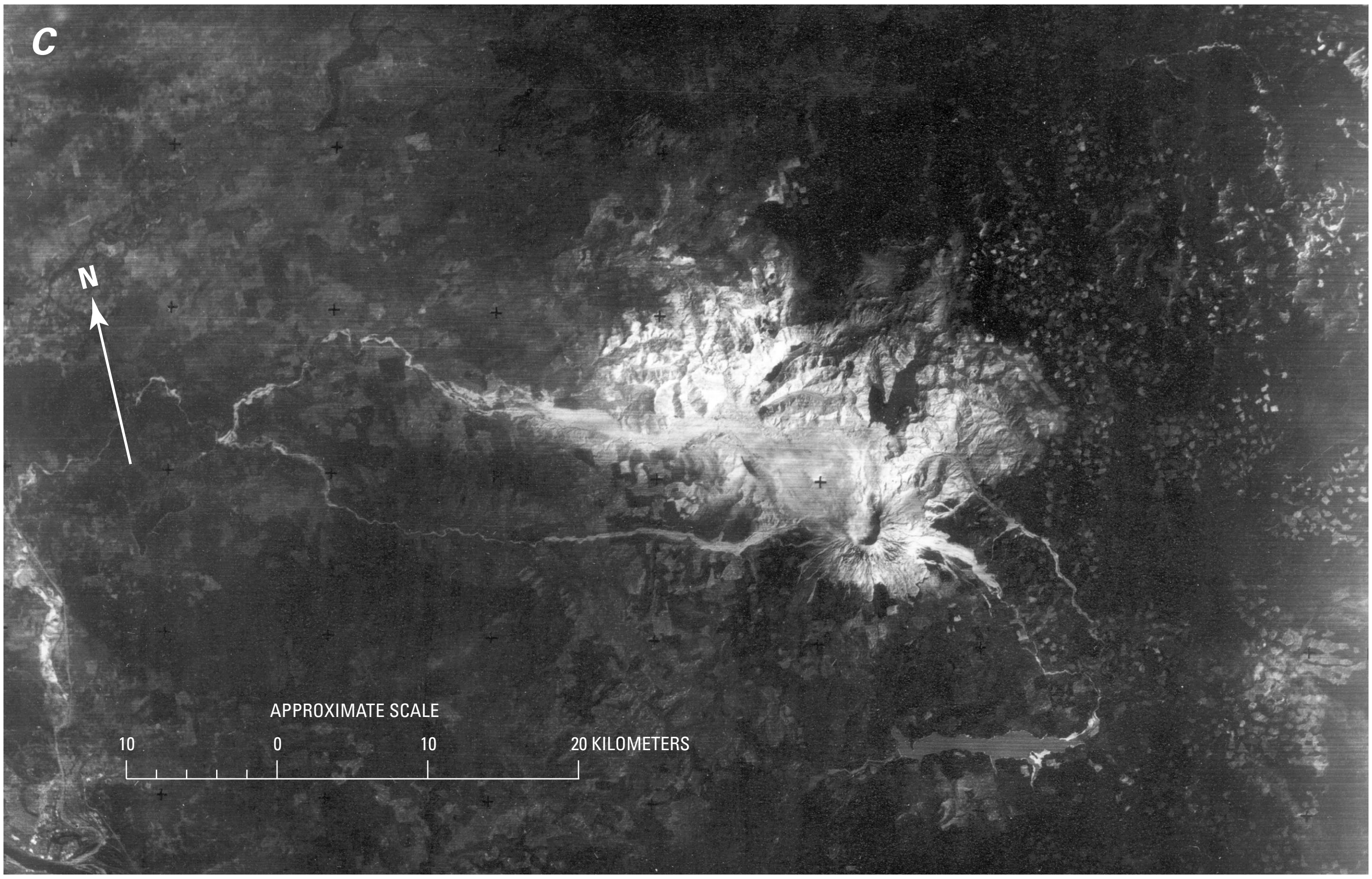


Figure 12.—B, *Oblique aerial photograph of Mount St. Helens, Wash., looking toward the northeast at about noon on 18 May 1980, approximately 3.5 hours after the beginning of the explosive eruption. Virtually all the glaciers were beheaded or destroyed by the collapse of the north slope of the volcano and the subsequent blast that removed approximately 2.6 km^3 of volcanic material from the summit and northern part of the mountain (Foxworthy and Hill, 1982). Tephra blankets the remaining parts of the glaciers radiating from the now-missing summit region. The vertical, billowing eruption plume of tephra and other volatiles emanates from the 1.5-km-wide horseshoe-shaped crater (fig. 12*C*) and extends well into the stratosphere. A small base surge is also visible on the southeast edge of the crater. USGS photograph number 80–S3–137 by R.M. Krimmel, USGS.* C, *Landsat 3 RBV image 30889–18104–B taken of Mount St. Helens on 10 August 1980 (Path 50, Row 28), 3 months after the catastrophic explosive eruption (fig. 12*B*). The horseshoe-shaped crater is visible at the apex of a large fan-shaped area to the north, the region most devastated by the lateral "blast" (Tilling, [1984]). Light-colored tephra deposits blanket the slopes of the volcano, including the remnants of the surviving glaciers.*



the underlying bedrock and the landslide process, or by melting from pyroclastic flows. The remaining snow and ice were covered with an average 1 m of tephra, which acted as in insulator against summer ablation (Driedger, 1981). The Shoestring Glacier was the site of an ongoing ice-dynamics study previous to the eruptions of 1980. During the 18 May 1980 eruption, however, 68 percent of this glacier, including the entire accumulation zone, was removed. Preeruption velocity was 20 to 50 cm d^{-1}; posteruption velocity was 10 to 20 cm d^{-1} (Brugman and Meier, 1981). The posteruption geometry of Mount St. Helens is such that a new glacier could form in the crater area (Jordan and Kieffer, 1982) (fig. 12*C*). The floor of the north-facing horseshoe-shaped crater is at 1,880 m in elevation, has steep-sided walls that enhance avalanche accumulation, is on the lee side of a steep ridge, so accumulation will be further enhanced, and has a northern exposure. In fact, snow from the previous winter was observed under rockfall debris in the crater in the late summer of 1983 (R.J. Janda, oral commun.). It is unlikely that a significant glacier will form in the crater, however, as long as the active lava-dome-building phase of Mount St. Helens continues.

Glaciers of the State of Oregon

Glaciers are found in Oregon on the Cascade Range volcanoes of Mount Hood (fig. 12*A*), Mount Jefferson, and Three Sisters Range, and in the Wallowa Mountains in eastern Oregon. Studies have been made to determine the ice volume on Mount Hood and the Three Sisters Range in response to requirements for a volcanic-hazards assessment. The total ice area on Mount Hood is 13.5 km^2; the total volume is 0.16 km^3 (Driedger and Kennard, 1986). The glaciers in the Wallowa Mountains may be locally significant, but they are less than 0.1 km^2 and are insignificant at the 79-m pixel resolution of Landsat MSS images.

A photographic study of the Collier Glacier on the North Sister Peak during the period 1934–60 showed general recession (Hopson, 1960). A topographic map of the Collier Glacier was compiled from aerial photographs acquired on 8 September 1958, on 8 September 1968, and on 29 September 1979. A longitudinal elevation profile from this map shows that no major change in the thickness of the glacier took place between 1959 and 1979. The extreme upper part of the glacier was about 16 m thicker in 1979 than in 1959; however, changes in the rest of the glacier were less than 5 m.

Glaciers of the State of California

Glaciers are present in California on Mount Shasta (4,319 m), in the Trinity Alps (approximately lat 41° N., long 123° W.), and in the high Sierra Nevada. The glaciers on Mount Shasta have a total area of 6.9 km^2 (Driedger and Kennard, 1984). The glaciers in the Trinity Alps are insignificant at the spatial resolution of the Landsat image.

A comprehensive glacier inventory of the Sierra Nevada has been completed (Raub and others, 1980; unpub. data). A major part of the area included in the Sierra Nevada glacier inventory is included in a single Landsat image (fig. 13), and part of the region is seen in more detail in Landsat 3 RBV images (figs. 14 and 15). In this inventory, glaciers and ice patches as small as 0.01 km^2 are counted. The total inventory counted 497 glaciers and 788 ice patches for a total area of 63 km^2. The largest glacier in the Sierra Nevada is the Palisade Glacier, which has an area of 1.6 km^2.

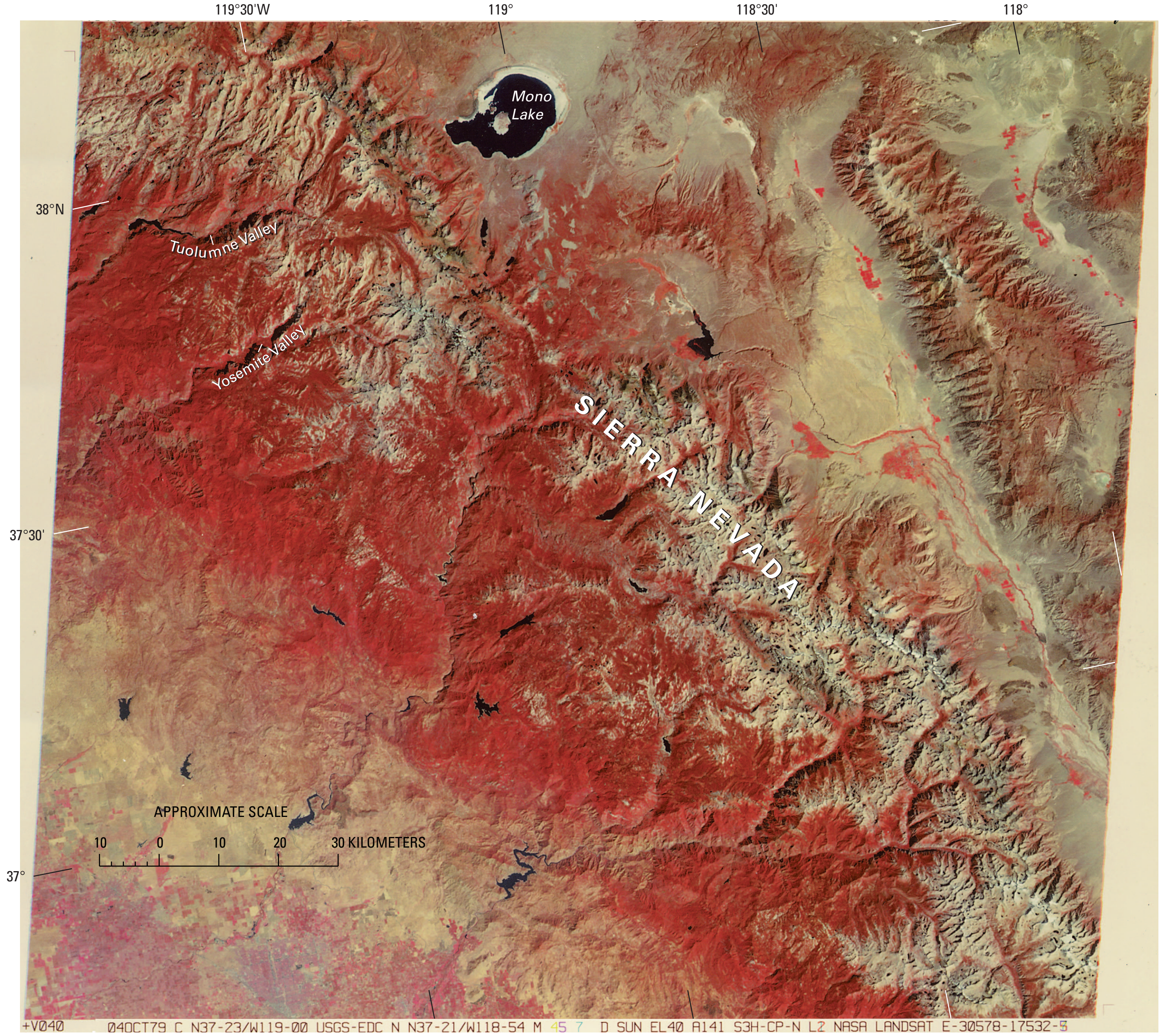
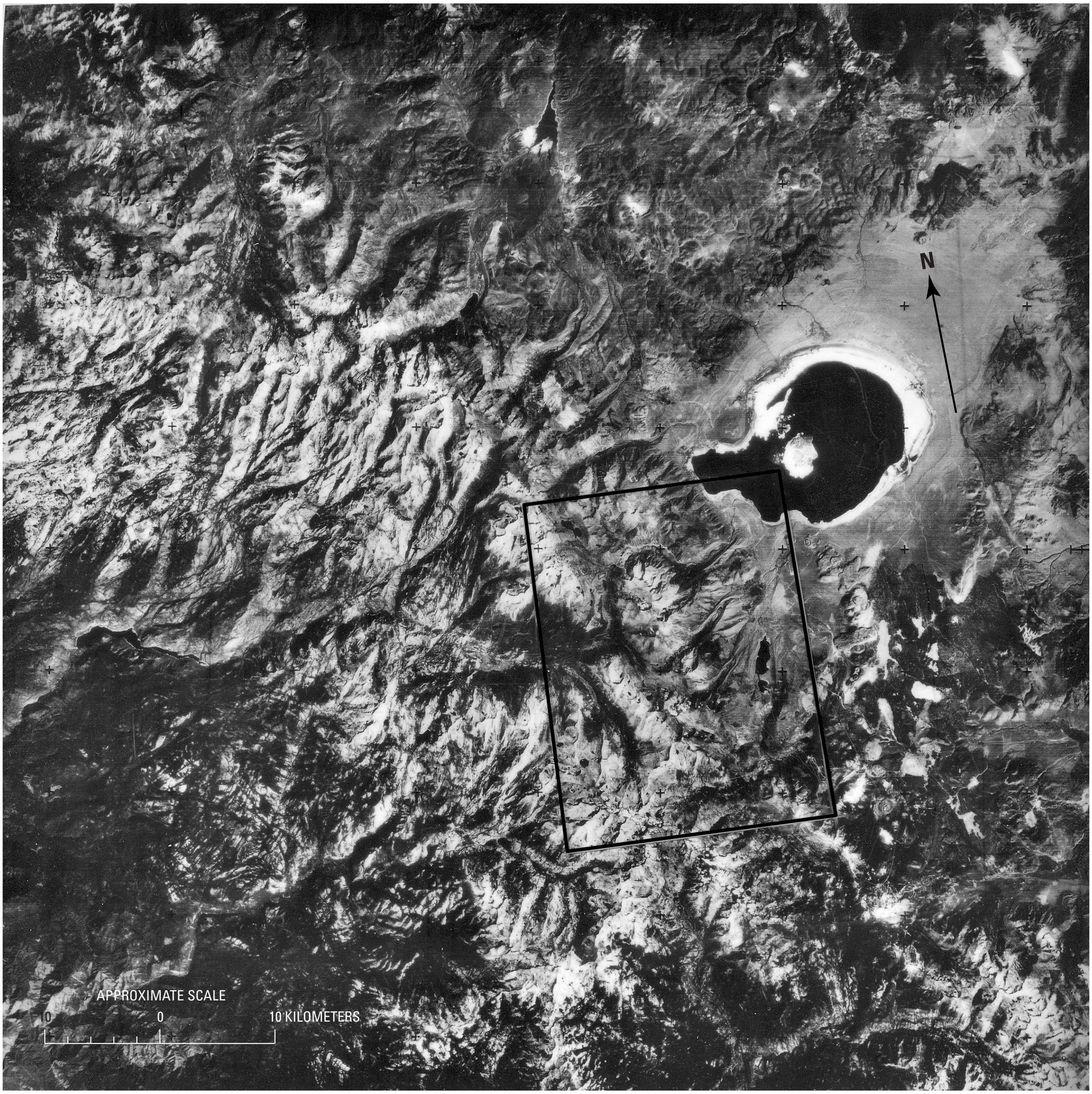


Figure 13.—*Landsat 3 MSS false-color composite image (30578–17532, bands 4, 5, and 7; 4 October 1979; Path 45, Row 34) of the Sierra Nevada of California. These mountains, extending from the northwest corner to the southeast corner of this image, have a total ice area of 63 km^2, as determined by a glacier inventory (Raub and others, 1980). This includes 497 glaciers and 788 ice patches too small to be counted as glaciers. None of these 1,285 ice bodies, the largest of which is Palisade Glacier (1.6 km^2), is significant at Landsat MSS resolution. The only significant glaciers in California not seen in this image cover 6.9 km^2 on Mount Shasta (Driedger and Kennard, 1986). Well-defined moraines extend eastward toward Mono Lake (north-central part of image) and westward in the glacier-carved Tuolumne and Yosemite Valleys (northwest corner of the image).*



The glacier inventory and the high-quality Landsat MSS and Landsat 3 RBV images available for the Sierra Nevada provide the material needed for a direct comparison between an inventory that has been meticulously compiled from maps, conventional vertical and oblique aerial photographs, and direct observation and the synoptic view of glaciers offered by Landsat. Figure 16, an excerpt from a map in the Raub inventory (Raub and others, 1980; written commun.), correctly delineates each glacier. The Landsat 3 RBV image (fig. 15), having a 30-m pixel resolution, allows some glacier delineation, but areas in shade and areas of ice and moraine-covered ice are difficult to delineate. Landsat offers an excellent overall picture but must be supplemented with knowledge obtained by more conventional methods.

Figure 14.*—Landsat 3 RBV image (30578–17532–A; 4 October 1979; Path 45, Row 34) of the high central Sierra Nevada, centered at lat 37°57' N. and long 119°18' W., including Mono Lake (east-central part of image) and most of Yosemite National Park. The glaciers in this image are too small for any quantitative measurements. However, the extent of past glaciation can easily be mapped. The black rectangle, including the southwest part of Mono Lake, indicates the map area shown in figure 1.*

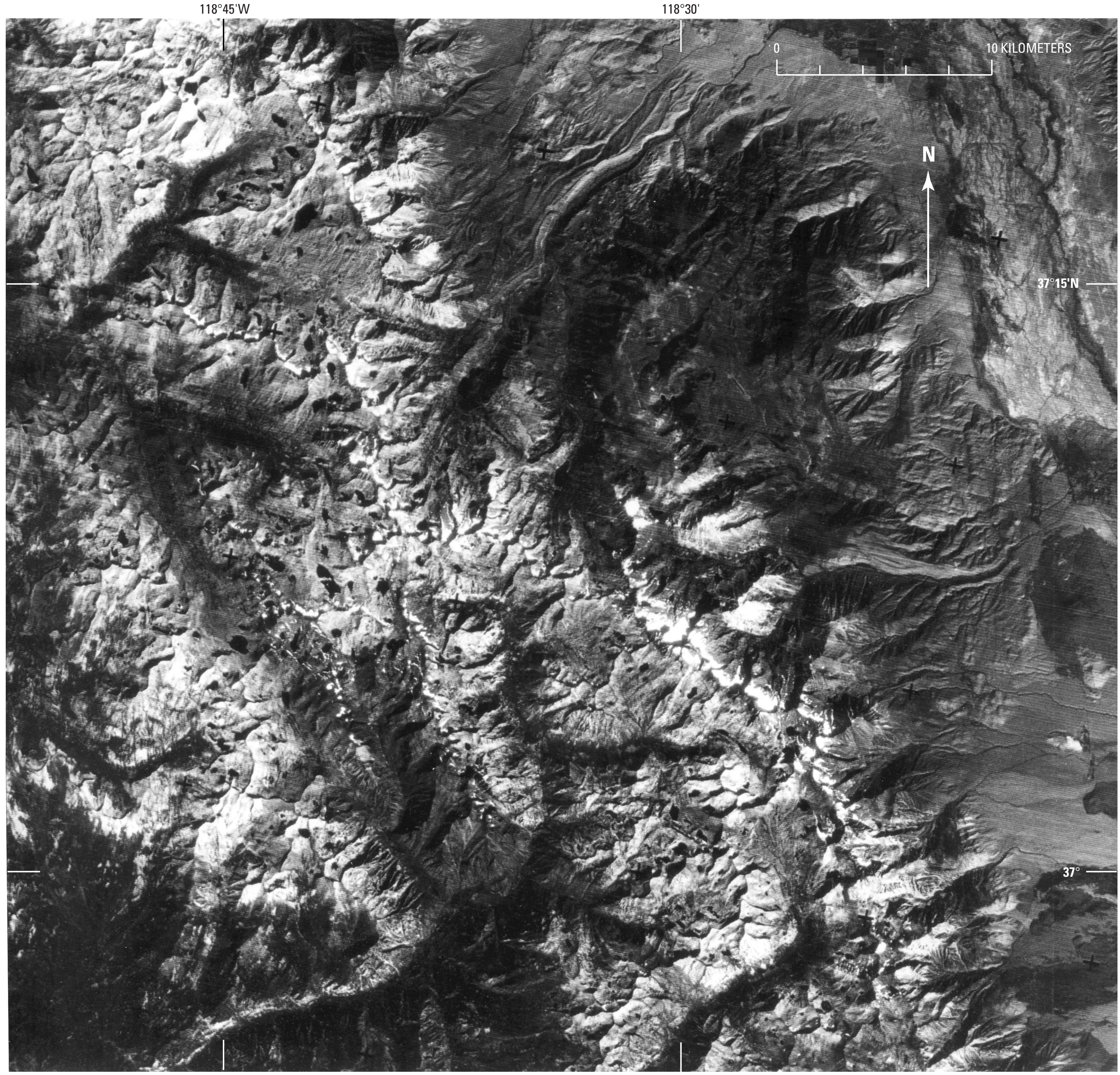


Figure 15.—*Enlargement of part of Landsat 3 RBV image 30578–17532–D taken on 4 October 1979 (Path 45, Row 34) of the high central Sierra Nevada. This Landsat image is identical in location to figure 16 and demonstrates the difficulties of compiling a detailed glacier inventory from Landsat images. Whereas snow is easily seen on this panchromatic image, it is difficult to distinguish from light-colored rock. Where glacier ice is covered with debris, it is virtually impossible to distinguish. Areas in shade are also hard to delineate. On the other hand, the overall view offered by Landsat gives a good indication of the extent of present and past glaciation in a region.*

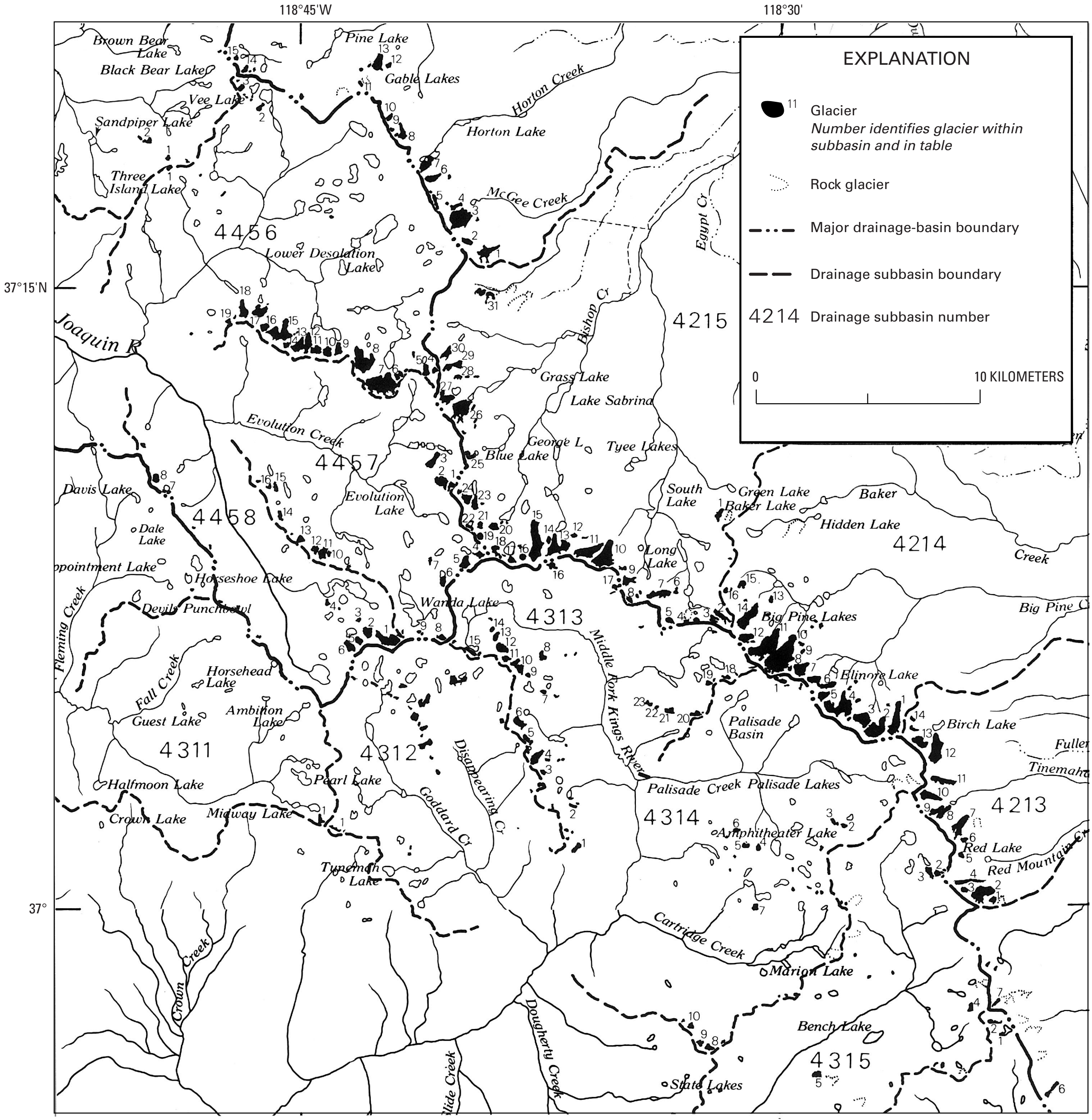


Figure 16.—Glaciers of the central Sierra Nevada west of Bishop, Calif., delineated from vertical and oblique aerial photographs and direct field observation. This map excerpt is from the Sierra Nevada glacier inventory (Raub and others, 1980). Glaciers much too small to be identified on a Landsat image are shown. Compare this figure to figure 15, a Landsat 3 RBV image of the same area.

Glaciers of the States of Montana, Wyoming, Colorado, Idaho, Utah, and Nevada

Glaciers in the inland states of the Western United States are significant at the resolution of the Landsat image only in Glacier National Park (fig. 17) and the Beartooth Mountains, Mont., and in the Wind River Range, Wyo. (figs. 18 and 19). Small glaciers, generally less than 1 km^2, are scattered throughout many of the high mountains of the Western States. These glaciers are discussed by Meier (1961a) and Field (1975) and are best identified on USGS topographic maps and (or) aerial photographs. Figures 20, 21, and 22 are selected images from these other mountain areas and show the geomorphic evidence of major past glaciation.

A long history of research is documented on glaciers in Glacier National Park, Mont. (Johnson, 1980), in the Wind River Range, Wyo. (Wentworth and Delo, 1931), and in Colorado (Waldrop, 1964). Glacier-ice cores from

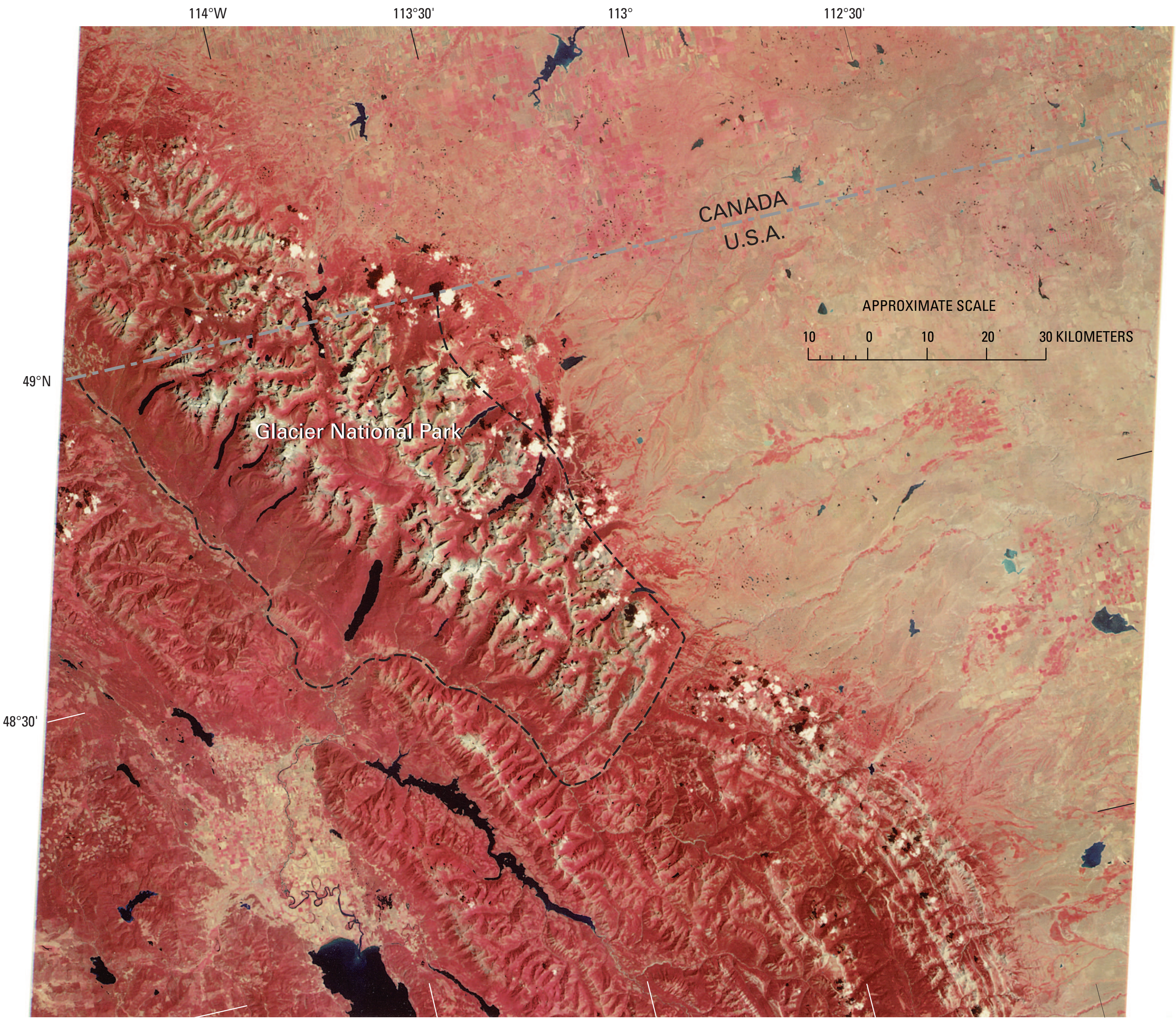
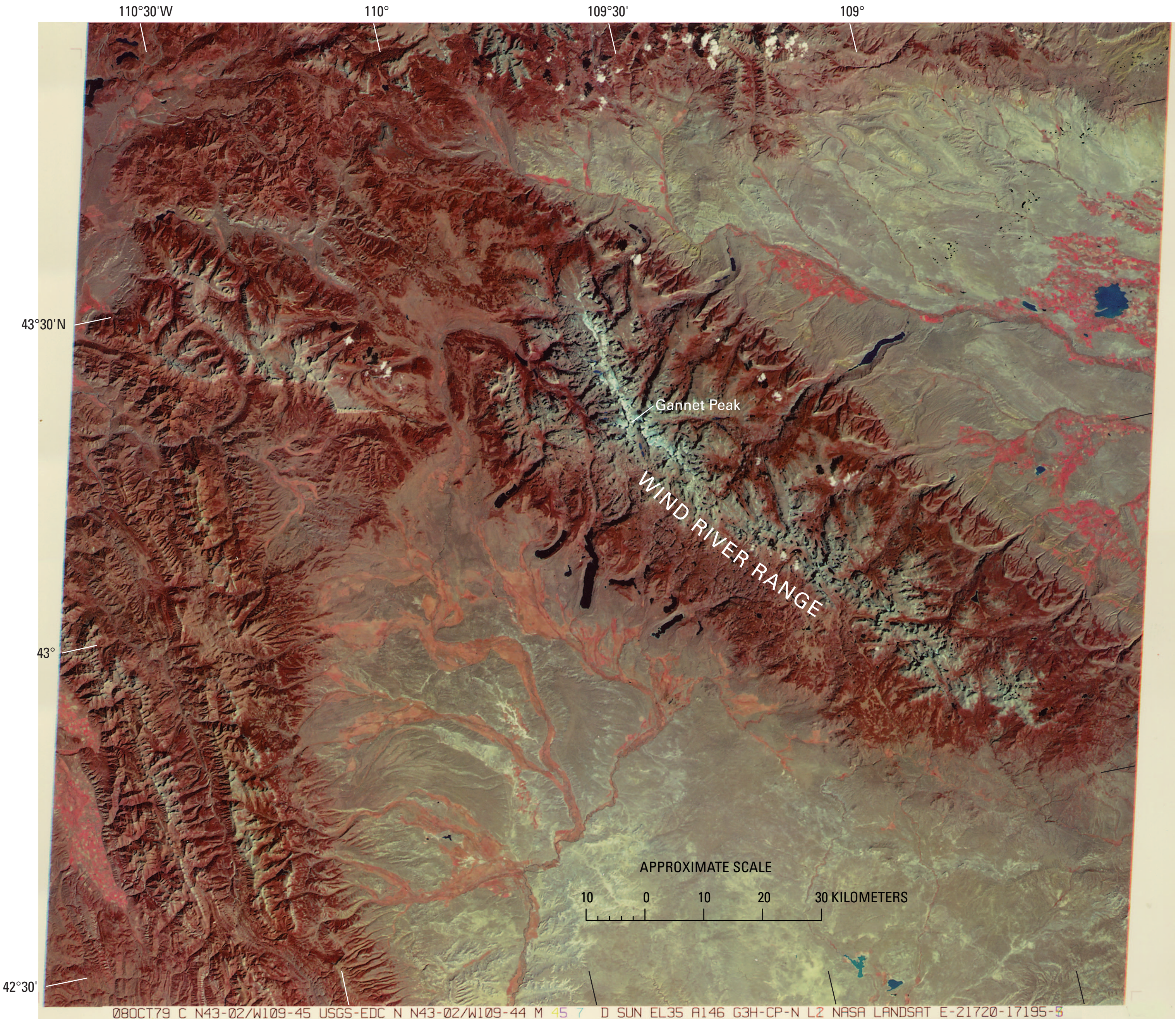


***Figure 17.**—Landsat 3 MSS false-color composite image (30523–17452, bands 4, 5, and 7; 10 August 1979; Path 44, Row 26) of Glacier National Park, Mont. According to Graf (1977), the park contains 28.4 km^2 of glacier ice, about two-thirds of Montana's glacier cover. Moraines extend beyond lake-filled valleys into the plains to the east and into forested valleys to the west.*



the Wind River Range have been used to study changes in atmospheric quality and climate (Naftz, Miller, and See, 1991; Naftz, Rice, and Ranville, 1991; Naftz, 1993). Glaciological studies have also been carried out on the Upper Fremont Glacier, Wyo. (Naftz and Smith, 1993). Reed (1964, 1965, 1967) carried out glaciological studies on Teton Glacier, Grand Teton National Park, Wyo.

***Figure 18.**—Landsat 2 MSS false-color composite image (21720–17195, bands 4, 5, and 7; 8 October 1979; Path 40, Row 30) of the glaciers of the Wind River Range in west-central Wyoming. This range supports the largest concentration of glaciers in the Rocky Mountains of the United States. Graf (1977) reported a total of 31.6 km^2 of ice in this range and a total for Wyoming glacier cover of 35 km^2. High peaks (up to 4,210 m) show negligible new snow. Moraines extend 50 km toward the northeast and 35 km toward the southwest from the crest of the range. Overdeepened valleys are now occupied by lakes.*

Figure 19.—*Oblique aerial photograph taken on 6 August 1979 from above the Continental Divide in the Wind River Range, Wyo.; the view is toward the southeast. The Minor and Mammoth Glaciers are in the foreground. The glaciers flowing away from the viewer on the east side of the divide are, from left to right, Gannett, Dinwoody, Helen, and Fremont Glaciers.*

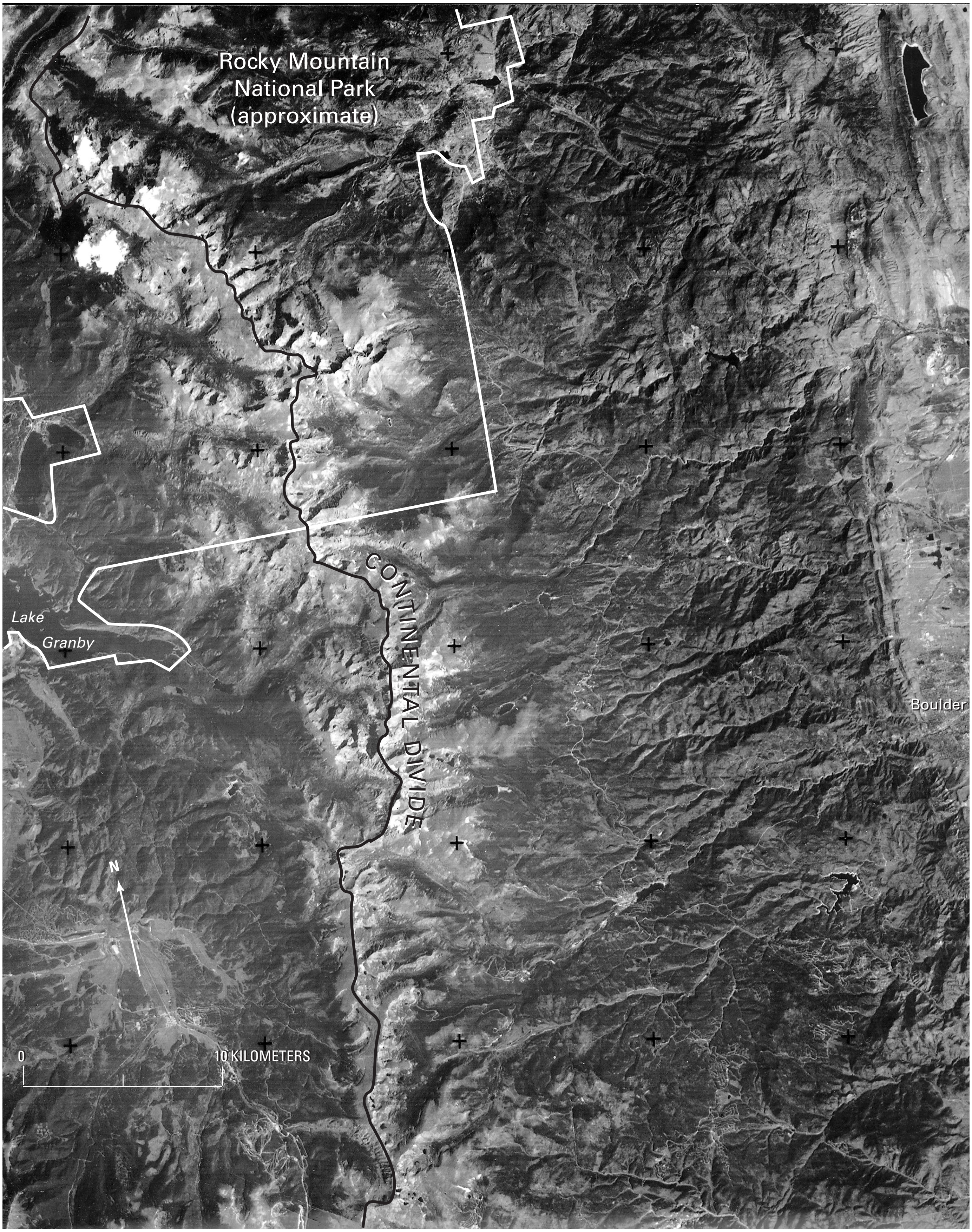


Figure 20.*—Enlargement of part of a Landsat 3 RBV image (30929–16504–C; Path 36, Row 32) that includes most of the glaciers in the State of Colorado. It was taken on 19 September 1980 and is centered at about lat 40°12' N. and 105°30' W. The area shown extends from the city of Boulder on the east to Lake Granby on the west, to Rocky Mountain National Park on the north, and to near Berthod Pass on the south. The glaciers are only discernible as small snow patches in cirques in the Rocky Mountains along the east side of the Continental Divide. Moraines extend both east and west from the divide.*

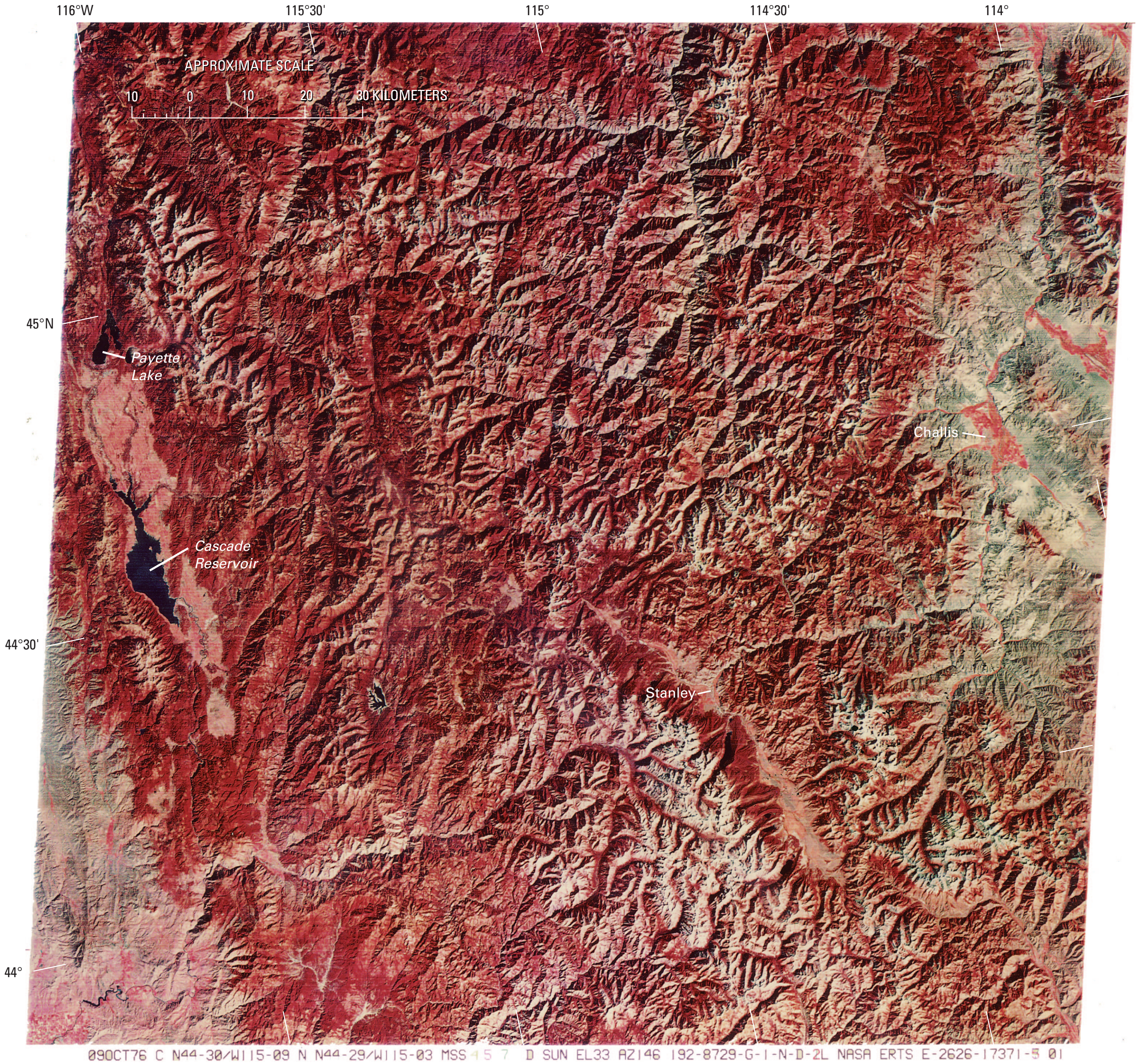


Figure 21.—*The Sawtooth Range of south-central Idaho covers an extensive area and has numerous peaks 3,500–3,800 m in elevation. Glacier cover in Idaho, all of it in the Sawtooth Range, is estimated to be 1 km^2, but it only exists as small ice patches in protected areas where the snowpack is locally increased by wind redeposition. This Landsat 2 MSS false-color composite image (2626–17371, bands 4, 5, and 7; 9 October 1976; Path 44, Row 29), its center about 140 km northeast of Boise, Idaho, shows new snow at higher elevations. Extensive moraines are seen in valleys in the southeast quadrant of the image.*

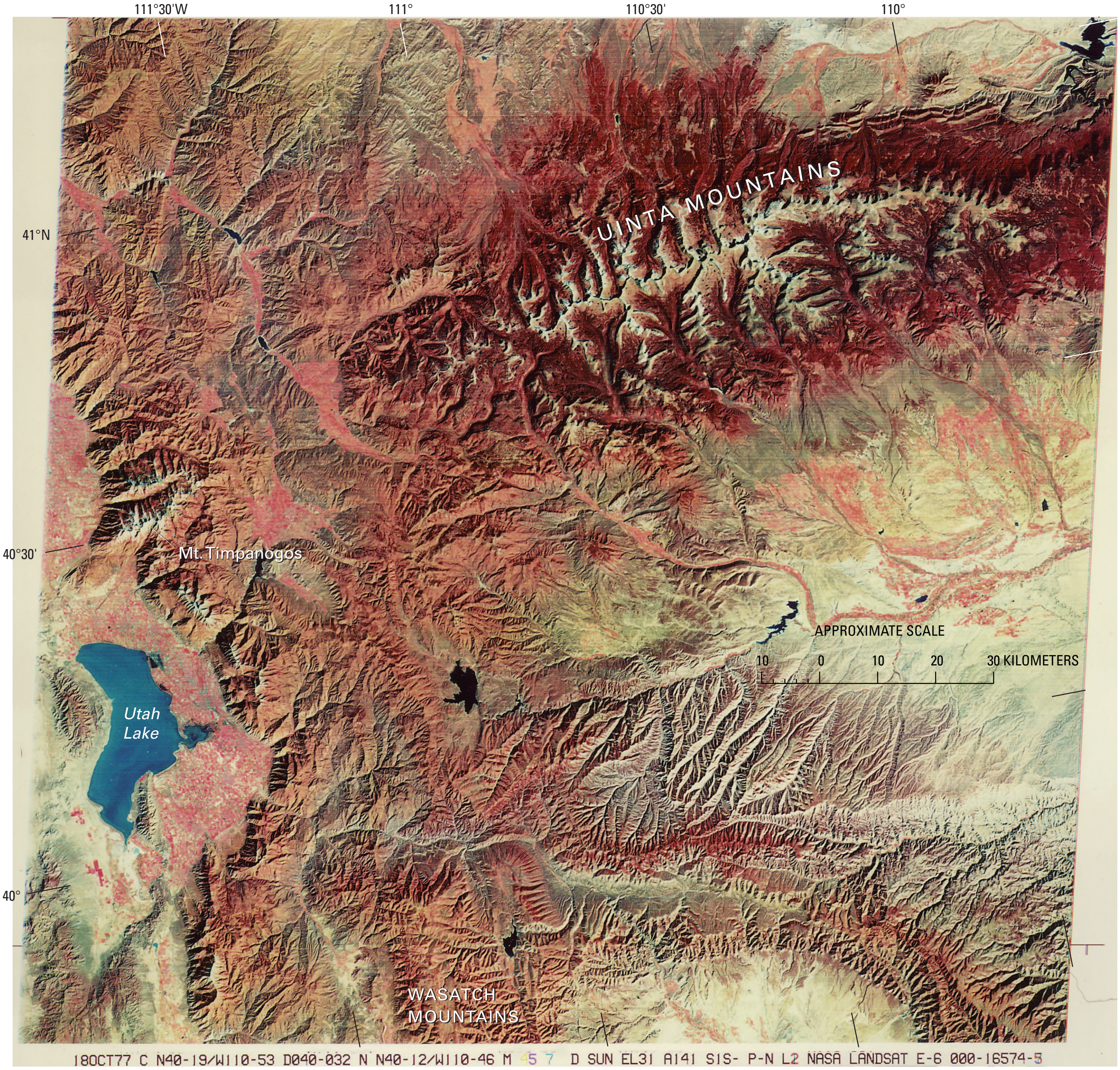


***Figure 22.**—Excellent snowfree Landsat 2 MSS false-color composite image (6000–16574, bands 4, 5, and 7; 18 October 1977; Path 40, Row 32) covering an area in north-central Utah. The only glacier reported in Utah occupies a deep cirque on the east side of Mount Timpanogos (3,582 m) in the Wasatch Range (extreme west-central part of image) about 22 km north of Utah Lake. No glaciers are indicated on 1:24,000-scale USGS quadrangle maps in the Uinta Mountains (northeast quadrant of image), which are more extensive and higher (up to 4,100 m in elevation). Glacial moraines are clearly seen extending 40 km to the north and south of the crest of the Uinta Mountains.*

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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[6] U.S. Geological Survey, Glacier National Park, West Glacier, MT 59936.
[7] U.S. National Park Service, Glacier National Park, West Glacier, MT 59936.

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.

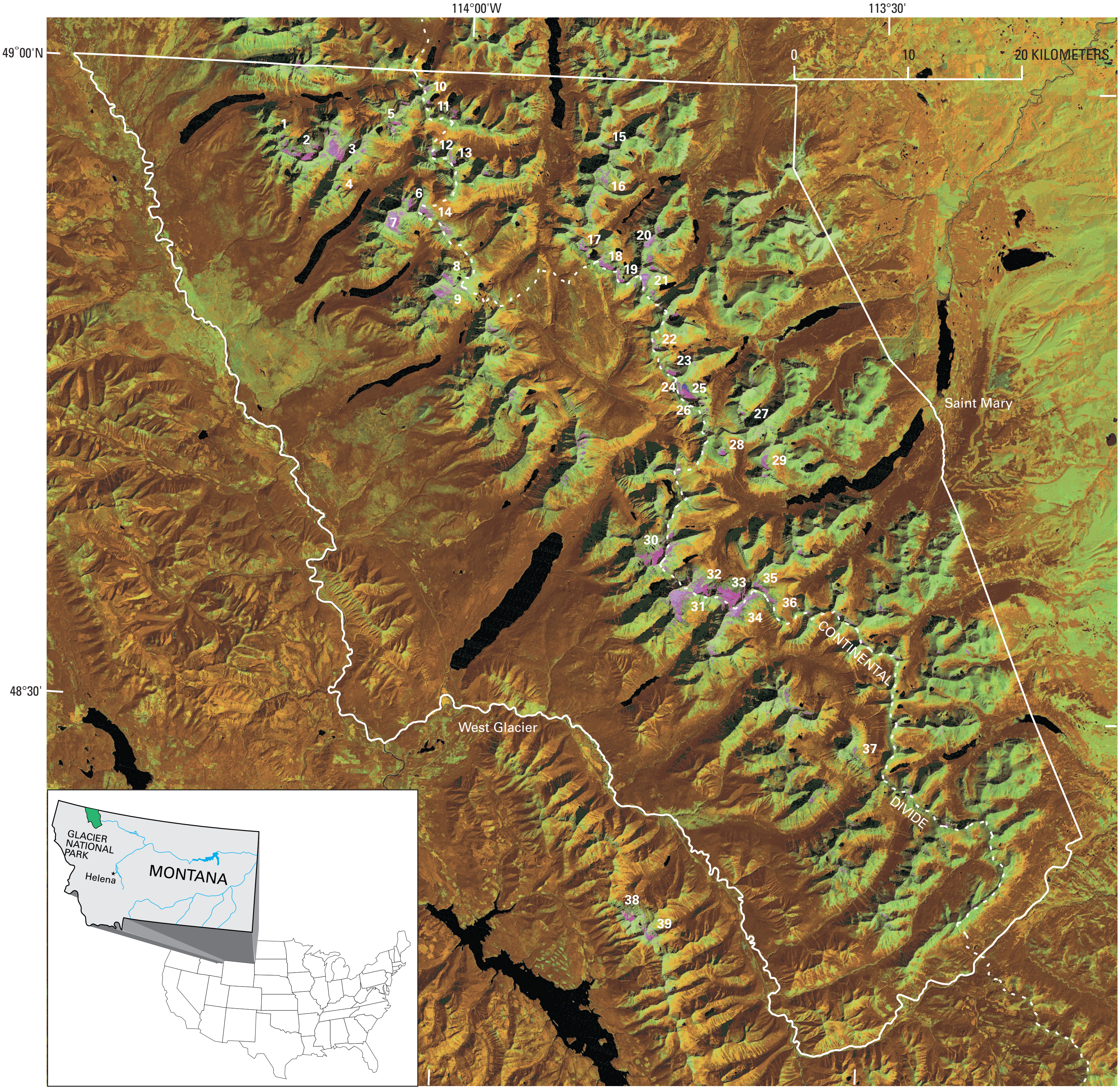


Figure 23.—*Computer-generated, unsupervised spectral classification of a Landsat TM scene (LT50410260095244, bands 3, 4, 5, Path 41, Row 26) of Glacier National Park and vicinity, Montana, collected on 1 September 1995. The image, which shows the boundary of Glacier National Park, has been rectified 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.

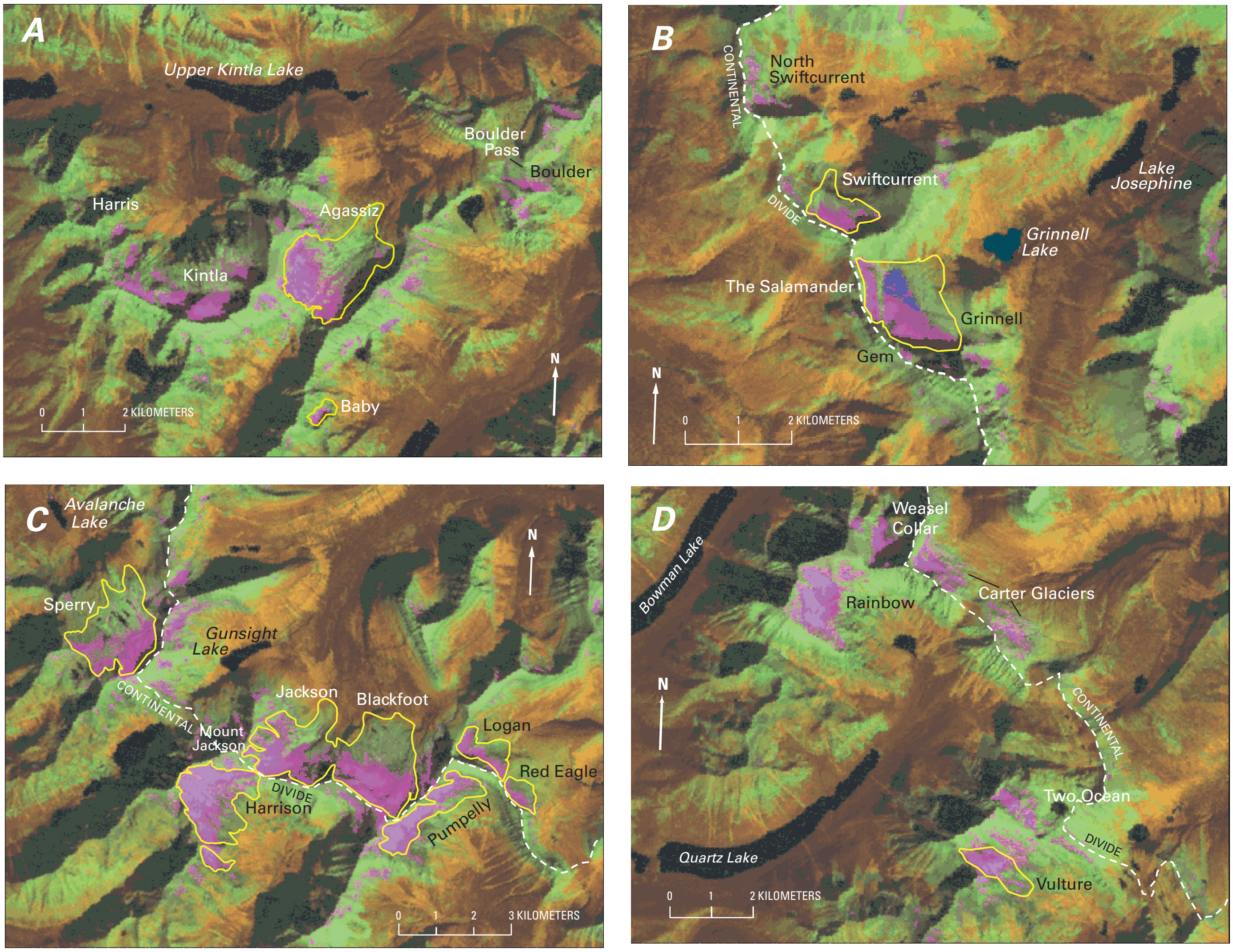
The Little Ice Age comprised a several-hundred-year-long cool period (about 1400 to about 1850 in North America), during which Glacier National Park glaciers formed and expanded. This continued until a warming climate initiated glacier retreat after the middle 1800's. Figure 25 illustrates the magnitude 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

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. 25C).

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 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.

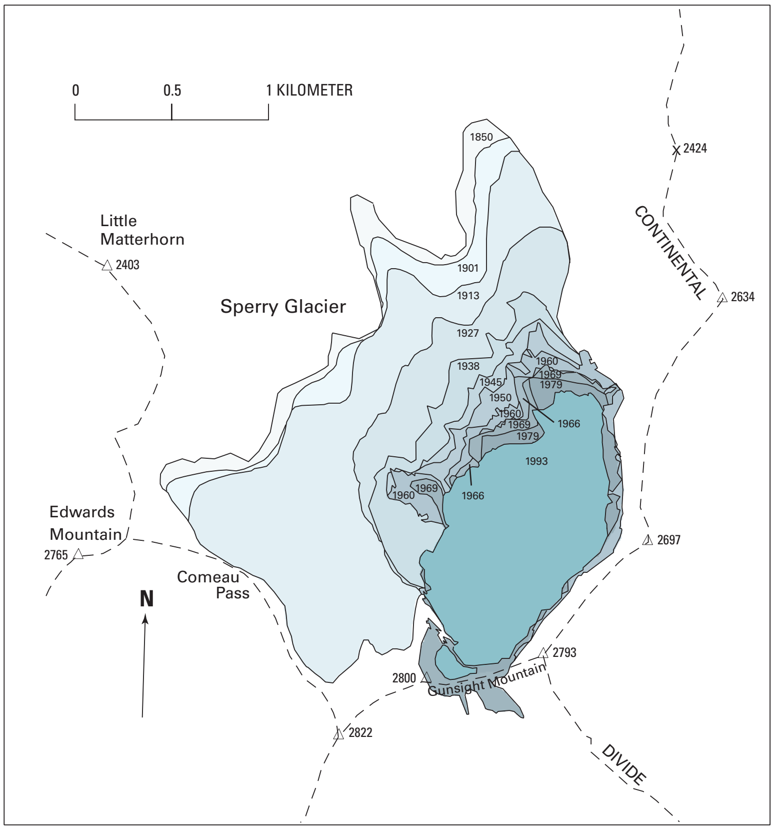
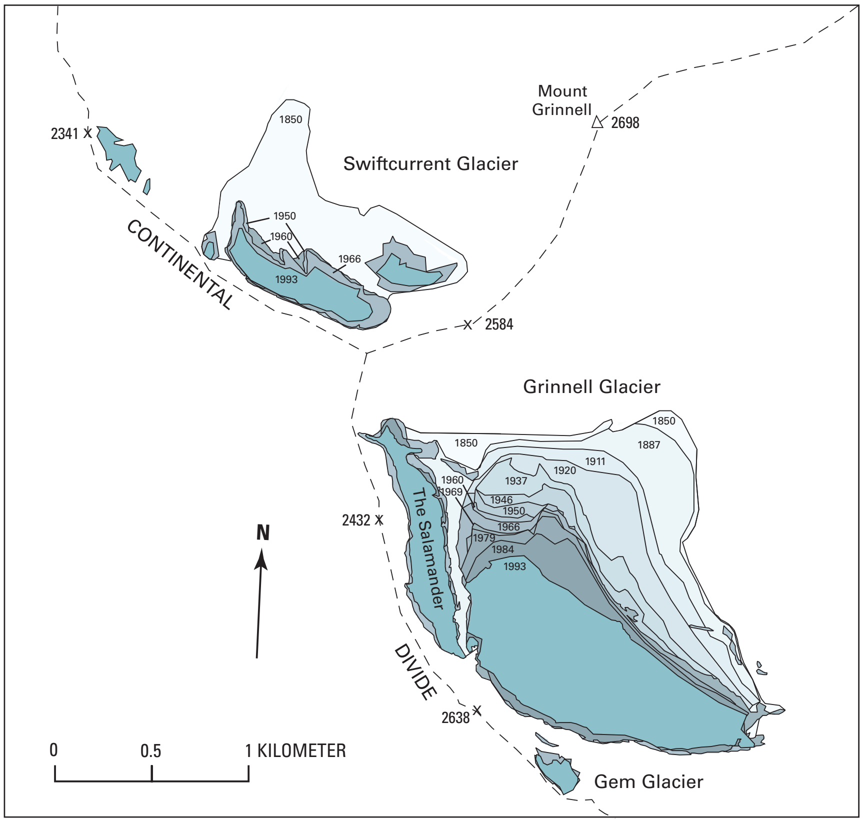


Figure 28.—Neoglacial recession chronology of Grinnell and Swiftcurrent Glaciers showing the series of termini mapped since the middle 19th century. Grinnell Glacier, along with Sperry Glacier (fig. 27), is relatively accessible and has been frequently observed, so it has yielded a fairly complete record 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.

Recent Glacier Trends

An often asked question is, "How have glaciers changed in area, length, or volume with time?" The answer must be qualified. It is relatively simple to observe specific glaciers for several decades, as has been done at the Nisqually and South Cascade Glaciers, as well as at several other glaciers. In all cases, these long records have shown general recession. As the observation frequency is increased, however, some of these records have shown periods of advance within the general retreat, and these periods of advance do not always correlate from glacier to glacier. In fact, glaciers that are side by side geographically sometimes behave differently. These short advances in the overall trend are a result of the complex interaction between the effects of elevation, latitude, exposure, basin area-elevation distribution, the variables of climate, and the individual glacier's dynamic-response characteristics. A strategy for monitoring glaciers of the United States and other glacierized regions is discussed by Fountain and others (1996) and was the subject of a 1996 workshop on long-term monitoring of glaciers of North America and northwestern Europe (Williams and Ferrigno, 1997).

An apparent contradiction exists in this general long-term recession. Table 1 gives glacier areas from Meier (1961a) and from more recent sources, where available. Many of the recent sources show an increase in total ice during the last 10 to 20 years. An incorrect conclusion is that glacier cover has increased. The correct conclusion is that more glacier cover has been recorded as a result of better source material, mainly maps and vertical aerial photographs. Had the same quality of source material been available and the same methodology been applied for the earlier determinations of area, the apparent trend of glacier increase seen in table 1 would almost certainly be reversed.

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