Prepared in cooperation with the
Departments of Geology and Geography,
Portland State University, Portland, Oregon

Digital Outlines and Topography of the Glaciers of the American West

Open-File Report 2006–1340

U.S. Department of the Interior
U.S. Geological Survey

Cover. Map showing distribution of glaciers in the American West.

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Digital Outlines and Topography of the Glaciers of the American West

By Andrew G. Fountain[1], Matthew Hoffman[1], Keith Jackson[1], Hassan Basagic[1], Thomas Nylen[1], and David Percy[1]

Introduction

Alpine glaciers have generally receded during the past century (post-“Little Ice Age”) because of climate warming (Oerlemans and others, 1998; Mann and others, 1999; Dyurgerov and Meier, 2000; Grove, 2001). This general retreat has accelerated since the mid 1970s, when a shift in atmospheric circulation occurred (McCabe and Fountain, 1995; Dyurgerov and Meier, 2000). The loss in glacier cover has had several profound effects. First, the shrinkage of glaciers results in a net increase in stream flow, typically in late summer when water supplies are at the lowest levels (Fountain and Tangborn, 1985). This additional water is important to ecosystems (Hall and Fagre, 2003) and to human water needs (Tangborn, 1980). However, if shrinkage continues, the net contribution to stream flow will diminish, and the effect upon these benefactors will be adverse. Glacier shrinkage is also a significant factor in current sea level rise (Meier, 1984; Dyurgerov and Meier, 2000). Second, many of the glaciers in the West Coast States are located on stratovolcanoes, and continued recession will leave oversteepened river valleys. These valleys, once buttressed by ice are now subject to failure, creating conditions for lahars (Walder and Driedger, 1994; O’Connor and others, 2001). Finally, reduction or loss of glaciers reduce or eliminate glacial activity as an important geomorphic process on landscape evolution and alters erosion rates in high alpine areas (Hallet and others, 1996). Because of the importance of glaciers to studies of climate change, hazards, and landscape modification, glacier inventories have been published for Alaska (Manley, in press), China (*http://wdcdgg.westgis.ac.cn/DATABASE/Glacier/Glacier.asp*), Nepal (Mool and others, 2001), Switzerland (Paul and others, 2002), and the Tyrolian Alps of Austria (Paul, 2002), among other locales.

To provide the necessary data for assessing the magnitude and rate of glacier change in the American West, exclusive of Alaska (fig. 1), we are constructing a geographic information system (GIS) database. The data on glacier location and change will be derived from maps, ground-based photographs, and aerial and satellite images. Our first step, reported here, is the compilation of a glacier inventory of the American West. The inventory is compiled from the 1:100,000 (100K) and 1:24,000 (24K)-scale topographic maps published by the U.S. Geological Survey (USGS) and U.S. Forest Service (USFS). The 24K-scale maps provide the most detailed mapping of perennial snow and ice features. This report informs users of the data about the challenges we faced in compiling the data and discusses its errors and uncertainties.

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Figure 1. Distribution of glaciers (dark purple) in the American West.

We rely on the expertise of the original cartographers in distinguishing “permanent snow and ice” from seasonal snow, although we know, through personal experience, of cartographic misjudgments. Whether “permanent” means indefinite or resident for several years is impossible to determine within the scope of this study. We do not discriminate between “glacier,” defined as permanent snow or ice that moves (Paterson, 1994), and stagnant snow and ice features. Therefore, we leave to future users the final determination of seasonal versus permanent snow features and the discrimination between true glaciers and stagnant snow and ice bodies. We believe that future studies of more regional focus and knowledge can most accurately refine our initial inventory. For simplicity we refer to all snow and ice bodies in this report as glaciers, although we recognize that most probably do not strictly meet the requirements; many may be snow patches.

Data

In this project we acquired digital data electronically from the World Wide Web, although some data were provided directly to us by agency data custodians. We did not digitize from the original source maps except to edit the digital data. The validity of the glacier inventory is based on the assumption that published topographic maps identified all the glaciers on the landscape.

1:24,000-Scale Maps

For elevations, the 1 arc second (~30 m) "seamless" National Elevation Data were downloaded from the USGS (*http://ned.usgs.gov/*). Rather than rewrite the metadata descriptions for data like these, we copied the text into this report and italicized the font. The following is from *http://seamless.usgs.gov/website/seamless/products/1arc.asp*.

> *The National Elevation Data set (NED) 1 Arc Second is a raster product assembled by the U.S. Geological Survey (USGS). NED is designed to provide National elevation data in a seamless form with a consistent datum, elevation unit, and projection. Data corrections are made in the NED assembly process to minimize, but not eliminate, artifacts, perform edge matching, and fill sliver areas of missing data. NED has a resolution of one arc-second (approximately 30 meters) for the conterminous United States, Hawaii, and Puerto Rico and a resolution of two arc-seconds for Alaska.*
>
> *NED data sources have a variety of elevation units, horizontal datums, and map projections. In the NED assembly process the elevation values are converted to decimal meters as a consistent unit of measure, NAD83 is consistently used as horizontal datum, and all the data are recast in a geographic projection. Older DEM's produced by methods that are now obsolete have been filtered during the NED assembly process to minimize artifacts that are commonly found in data produced by these methods. Artifact removal greatly improves the quality of the slope, shaded-relief, and synthetic drainage information that can be derived from the elevation data.*

Assessment of elevation accuracy (*http://ned.usgs.gov/Ned/accuracy.asp*) is currently under development.

The elevation accuracy cannot exceed the accuracy of the original paper, 7½-minute quadrangle maps. According to the Federal Geographic Data Committee (FGDC) National Map Accuracy Standards (NMAS; USGS, 1999), the horizontal accuracy requirement is that 90 percent of all points tested must be accurate within 12.2 m. For vertical accuracy, 90 percent of all points tested are correct to one-half contour interval. Stated exceptions include surfaces covered by dense woodland, obscured by fog or clouds, or those that cannot provide enough detail for precise mapping. Presuming that the cartographers worked with fog and cloud-free photographs, which is typically the case, significant errors still occur over bright snowcover common to the upper elevations on glaciers. The uniform surface of bright snow often contains insufficient texture, and cartographic methods lose the parallax required for relative vertical surface position. The result is significant differences with field measured values (Echelmeyer and others, 1996). In steep relief, common to glacierized[2] and glaciated[3] areas, small errors in horizontal position lead to large errors in elevation, which make NMAS essentially void. Therefore, we regard NMAS as a minimum estimate of the error.

The source of the digital outlines for the glaciers, also based on topographic quadrangle paper maps, is one of two Federal agencies, either the USFS or the USGS. In 1993 the USGS and USFS began a joint mapping program to deliver maps (paper and digital products) to the general public (USGS, 1998). The lead agency for distributing these joint digital topographic maps appears to be the USFS, although many of the products are also available from the USGS

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[2] Glaciers are present.

[3] No glaciers are present, but glaciers were present in the past and modified the landscape.

Web site. To the best of our understanding, the USGS produced 24K digital maps and vector products well past 1993, perhaps as late as 2000.

The paper maps, known by the USFS as a Primary Base Series, and 7.5-minute standard series by the USGS (table 1), were digitally scanned and georeferenced and are known as a PBS Softcopy by the USFS and a digital raster graphic (DRG) by the USGS. The digital vector outlines of map features, such as the hydrographic features (lakes, glaciers, permanent snow, wetlands, rivers, etc.), roads, or administrative boundaries, are digitally abstracted from the PBS/DRG as themes. The digital features are known as cartographic feature files (CFF) by the USFS and as digital line graphs (DLG) by the USGS. To minimize confusion with acronyms we identify all digital georeferenced maps as "scanned maps" and outlines of landscape features, such as glaciers, as "derived vector data" without regard to data source in the USGS or USFS.

Table 1. Lineage and naming conventions for paper and digital products from USGS and USFS.

Agency	Paper product name	Scanned map product name	Derived vector data product
USFS	Primary Base Series (PBS)	Softcopy	Cartographic feature file (CFF)
USGS	7.5-minute standard series	Digital raster graphic (DRG)	Digital line graph (DLG)

The digital processes to create the derived vector data and related accuracy are summarized here. We assume that the processes and accuracy of the products from either agency are the same and we rely on the USFS metadata found on the FSGeodata Clearinghouse Web page for descriptions of the digitization process and resulting accuracy. Rather than reword the metadata descriptions, we copied them into this report as italicized text. The metadata for the softcopy maps are obtained from *http://fsgeodata.sc.egov.usda.gov/products/pbsmetasample.html.*

A softcopy map description.

> *Softcopy Primary Base Series data are raster images produced from CFF and PBS map sources. PBS maps are large-scale Forest Service topographic maps produced in cooperation with the U.S. Geological Survey (USGS).*
>
> *The Softcopy Primary Base Series (PBS) is a raster image of the USDA Forest Service topographic map, including the collar information, georeferenced to the UTM grid. It is very similar to the Digital Raster Graphic (DRG) product. The image is generated from the digital file; it is not scanned, except for the contours. . . There are two versions of the file, one with full map collar, and one clipped at the neat line. The files are in Tagged Image File Format (TIFF). . . .*

The process of creating a softcopy map.

> *1. Production of a Softcopy PBS begins with the scanning of the contour layer (MAP1) on stable base material. The scanning resolution is 25 microns (1016 dpi). 2. Noise is removed from the contour image file. The contour image file is expanded to fit the map size with white pixels using the ISCAN utility in Intergraph. 3. The contour image file is warped to fit the neat line on the PBS Text File (TEXT1) using a helmert transformation using the IRAS utility*

> *in Intergraph. 4. The Cartographic Feature File (CFF1) is symbolized in Microstation. 5. All three files (PBS Text, CFF, and contour) are converted and merged into a single TIFF (Tagged Image File Format) file. 6. The TIFF file is georeferenced in UTM using the register and rectify commands in ARC/INFO. This process creates a .tfw file containing the six parameters of an affine transformation. The entire project is georeferenced in the same UTM zone. Therefore, this UTM zone may be different from where the quad is actually located and different from the UTM Zone Number calculated below. 7. Two products are created: unclipped and clipped. The unclipped files contain the full map collar and legend information. The clipped files do not contain the legend information and are clipped at the map neat line. 8. The unclipped files are registered to the quad's respective UTM ground coordinates. 9. The clipped files are registered to the quad's respective UTM ground coordinates and the pixels are rectified to the UTM grid from true north.*

The softcopy horizontal positional accuracy.

> *Although the datum of the published map is retained, in order to be consistent with other digital data, this image is cast on the UTM and may therefore be INCONSISTENT with the credit note on the image collar. Softcopy PBS meet the accuracy standards of the published map scale only in the area of the softcopy PBS that falls within the neatline of the published map, excluding insets. Overedge areas fall outside the transformation boundary area (map neatline). As a result, areas outside the neatline and beyond control point extent can exhibit anomalies or discrepancies. These anomalies will also appear in the map inset area and in the map collar.*

The softcopy vertical positional accuracy.

> *Refer to the Softcopy PBS collar for information about the vertical positional accuracy.*

The metadata for CFF data were derived also from the USFS FSGeodata Clearinghouse Web site, (*http://svinetfc4.fs.fed.us/*). The CFF data can be described as follows:

> *CFF data were initially collected by digitizing Forest Service Primary Base Series (PBS) maps. They are revised using standard topographic mapping techniques, including the addition of updated information provided by National Forests and Grasslands. The feature categories contained in the CFF are: transportation (roads and trails), streams and water bodies, political and administrative boundaries, land ownership, and other cultural features. Elevation contours, vegetation, and text (geographic names, labels, etc.) are not included in the CFF. CFFs are produced and maintained by the Forest Service Geospatial Service and Technology Center.*
>
> *Cartographic Feature File (CFF) data are digital representations, in vector format, of cartographic information. Map features are converted to digital form from maps, aerial photography, global positional systems and related sources. CFF data are used to publish 1:24,000-scale 7.5 minute topographic quadrangle maps. CFF data contain feature attributes, can be topologically structured in a GIS, and have passed certain quality-control checks. The files are supplied on the Forest Service intranet (FSWEB) as two files in ARC/INFO export format: a line and a point file.*

The process creating a CFF from a PBS.

The original cartographic feature file (CFF) was digitized from either the Primary Base Series (PBS) quadrangle or, if not available, U.S. Geological Survey (USGS) topographic map series quadrangle. Digitizing was performed by GSTC personnel or through contracting. PBS maps are created from USGS topographic maps used as sources (bases), then modified and/or updated to meet Forest Service needs. The original digital data were produced by one of the following methods: - scanning a stable-based copy of the graphic materials. The scanning process captured the digital data at a scanning resolution of 0.001 inch or less; the resulting raster data were then manually digitized and attributed on an interactive computer editing station. - manually digitizing from a stable-based copy of the graphic material using a digitizing table to capture the digital data at a resolution of 0.001 inch or less; attribution was performed as the data were digitized or on an interactive edit station after digitizing was completed. Four control points corresponding to the four corners of the quadrangle were used for registration during data collection. A four-parameter affine transformation was performed from the processing software internal coordinates to State Plane grid coordinates. The CFF data were checked for position and attributes by one or more of the following processes: - comparing plots of the digital data to the graphic source. - comparing the digital data to the digital raster scan. - comparing the digital data to the graphic source. The file may have undergone a basic revision. The update revision uses a variety of sources, including monoscopic imagery, stereoscopic imagery, cadastral information or other ancillary image or data sources, with field correction guides.

The CFF attribute accuracy.

The accuracy is estimated to be 98.5 percent. Attribute accuracy was tested by one or more of the following methods in accordance with the data vintage: - color display of CFF on interactive computer graphic system - manual comparison of the source with hard-copy plots - symbolized display of CFF on an interactive computer graphic system - selected attributes that could not be visually verified on plots or on screen were interactively queried and verified on screen. All attribute data conform to the attribute codes as of the date of digitizing. Vintage of this data set is: Vintage 11.

Vintage 11 Description: September 1996 to present. Revised to Single Edition Standards; data run through the TACS process (an in-house editing and database system); revision projects followed by the hardcopy process receive additional edits; polygons requiring screened or patterned fills have centroids and a segmented neatline for the open window layer process. Multilinking: Coincident lines digitized once, with multiple codes linked to them, except for roads with landnet; automatic valid multilink check now part of process. Edit Methodology: On-screen, and using automatic feature code checks and two different types of plots with improved correct attribution, and proper multilinking.

The CFF horizontal positional accuracy.

> *Accuracy of these digital data meets accuracy specifications in the National Map Accuracy Standards (NMAS). It also meets the standards of Vintage 11 for tracking and edgematching. Tracking: Collection and editing standards ensure consistently smooth linework. Edgematching: Features edgematched to adjoining quads within the project, as well as to any adjoining projects that have been through the TACS process and which reside in the TACS database, using an imaginary neatline drawn between the quads to eliminate "overshoots/undershoots."*

The CFF vertical positional accuracy.

> *Accuracy of these digital data meets accuracy specifications in the National Map Accuracy Standards (NMAS). This file does not contain the contour information. However, it may contain benchmark control point locations.*

Although the original producers of the 24K scanned maps and derived vector data were the USGS and USFS, we actually obtained the digital data from a variety of sources. For the National Parks, Mount Rainier, Glacier, Rocky Mountain, and Olympic, the data were obtained directly from each park. For glaciers in California, the data are from the California Geospatial Clearinghouse and from similar sites for parts of Colorado (table 2). The data for the remaining glacier-populated regions were downloaded from the USFS FSGeodata Clearinghouse.

Table 2. Source of digital data.

[Original refers to the ultimate source of the data. Agency refers to where the data were acquired (Web site). If no Web site is given, the data were provided by a person at the agency. Scanned map data are digital images of the paper maps; derived vectors are the polygons that define the shape and position of all the glaciers; NED is the National Elevation Data set; USFS, U.S. Forest Service; USGS, U.S. Geological Survey; WGIAC, Wyoming Geographic Information Advisory Council; MT-NRIS, Montana Natural Resource Information System; CaSIL, California Spatial Information Library; CoGIS, Colorado GIS data; GNP, Glacier National Park; NOCA North Cascades National Park; ONP, Olympic National Park; MORA Mount Rainier National Park]

Scale	Data type	Original	Agency	Web site
1:24,000	Scanned map	USFS	USFS	*http://svinetfc4.fs.fed.us/*
1:24,000	Scanned map	USGS	WGIAC	*wgiac2.state.wy.us/html/aboutDRG.asp*
1:24,000	Scanned map	USGS	MT-NRIS	*nris.state.mt.us/gis/default.htm*
1:24,000	Scanned map	USGS	CoGIS	*dola.colorado.gov/demog/gis/*
1:24,000	Derived vector	USFS	USFS	*fsgeodata.sc.egov.usda.gov/*
1:24,000	Derived vector	USGS	CaSIL	*gis.ca.gov/*
1:24,000	Derived vector	USGS	CoGIS	*dola.colorado.gov/demog/gis/*
1:24,000	Derived vector	USGS	MT-NRIS	*nris.state.mt.us/gis/default.htm*
1:24,000	Derived vector	USGS	GNP	
1:24,000	Derived vector	USGS	NOCA	
1:24,000	Derived vector	USGS	ONP	
1:24,000	Derived vector	USGS	MORA	
1:24,000	NED	USGS	USGS	*ned.usgs.gov/*
1:100,000	Derived vector	USGS	USGS	*edc.usgs.gov/products/*
1:100,000	Scanned map	USGS	USGS	*topomaps.usgs.gov/drg*

1:100,000-Scale Maps

For use as a preliminary product and as a means of testing our methods prior to acquiring the more detailed 24K data, we downloaded and processed the DLG data and DRG maps at the 100K scale from the USGS (table 2). The 100K hydrography files (USGS) contained 30- by 60-minute quadrangles. The DLG do not carry accuracy statements, but prior to release the USGS checks them for fidelity completeness, attribute accuracy, topological fidelity, and edge matching with other maps (USGS, 1996). Each 100K map is divided into eight downloadable files from the USGS Web site. The resulting vector data were merged, queried for glacier features, and converted to polygons.

Methods

Our first challenge was to find the location of the glacierized regions. While most of the areas were evident to us (for example, Mount Rainier, North Cascades, WA; Sierra Nevada, CA), other areas were not. We used the 100K data as an initial guide, because all the data files were available and coded. From these data we defined which 24K topographic quadrangles were needed and downloaded them from the USFS and USGS. We quickly realized that many glaciers were not included at the 100K scale, and we had to search further. One important guide was a general inventory of glacierized areas in the American West (Krimmel, 2002). In addition, we searched seamless scanned 24K maps available digitally on the World Wide Web (for example, topozone.com, terraserver.microsoft.com) of all known mountain ranges above alpine treelines looking for glacier features, which were depicted as white patches with blue contour lines and blue perimeters. The search led to the “discovery” of glacier populations elsewhere (for example, Seven Devils Mountains, ID; Gore Range, CO).

The hydrography layer of each area was downloaded and subsampled for the glacier outlines. To check the accuracy of the derived vector depiction of glacier outlines, we merged the files into one of 18 study zones that represented concentrated glacier populations (for example, North Cascades, northwestern Montana, Wind River Range). For each study zone, the derived vector data were superimposed on the scanned maps and visually checked to determine whether the derived vector data accurately represented the glacier boundary depicted on the scanned maps. As stated earlier, this approach assumes that the scanned maps are correct. We are only testing the fidelity of the derived vector data against their source. If the offset between the two was equal to or less than one line width, that is, no space between boundary lines, no change was made. If the offset was greater than one line width, the derived vector data were manually edited. If the outline was missing, it was digitized. This stage of the process was carried out with a group of 5–7 individuals working in the same room, to help ensure a common approach to corrections. After all the study zones were corrected, each was examined again but by an individual different from the one who completed the original edits. Once the derived vector data were corrected, the area of each glacier (polygon) and position of its centroid (latitude/longitude in decimal degrees) were calculated. Each study zone was superimposed on the digital elevation model (DEM), and the topographic characteristics of each glacier polygon were calculated, including, maximum, minimum, and mean elevation, average aspect, and average slope.

Because glaciers are time-variable landscape features, the time of mapping is important. Maps commonly identify several time values, including year of original photography, year of field checking, and year of map publication, photorevisions, and republication. All photographic dates were collected from the collars of the scanned maps and from hard copy maps where scanned map collars could not be found.

Results

1:24,000-Scale Data

Glacier Size. It became immediately clear, particularly with the 24K data, that many small glacier features (<0.001 km^2) were included. This challenges the definition of a glacier—permanent snow or ice that moves. Of course, we cannot determine movement, but for small ice patches on gently sloping surfaces it is unlikely that they exhibit motion. Additionally, we do not have the resources to field check even a small fraction of these features. Defining any minimal size threshold below which features would not be a glacier and eliminating them from the database was considered arbitrary, and the extensive analysis required to adequately define minimal conditions is beyond the scope of this report. Consequently, we included all features on the scanned maps that were color-coded as snow or ice (white background, blue contour lines and perimeters) in the database. Technically, this database is composed of glaciers and permanent snow and ice bodies, although we will refer to all as glaciers. This may be an advantage from a hydrologic perspective, as the small features may play an important hydrologic role in the high alpine watersheds in late summer when the seasonal snow has disappeared and commonly little precipitation occurs.

One wonders if these features are merely transient features captured only that year when the aerial photography was acquired. In high alpine regions it is often difficult to distinguish between a glacier margin and late seasonal snow. It would be nearly impossible to distinguish between a late seasonal snow patch and a permanent one. A separate project assessing glacier change examined a time series of aerial photographs for select regions, and in some cases the small snow and ice patches are indeed transitory features mistakenly included by the cartographers (fig. 2). In other cases, the features seem quite persistent and were observed on aerial photographs for over 40 years; ground-based photography revealed them to be composed of ice (fig. 3). In short, it is difficult to discern the permanence of these features. Furthermore, it is possible that the scanned maps do not include some other permanent snow/ice features thought to be seasonal by the original cartographers. In any case, we leave it to the user to more finely define the features of interest.

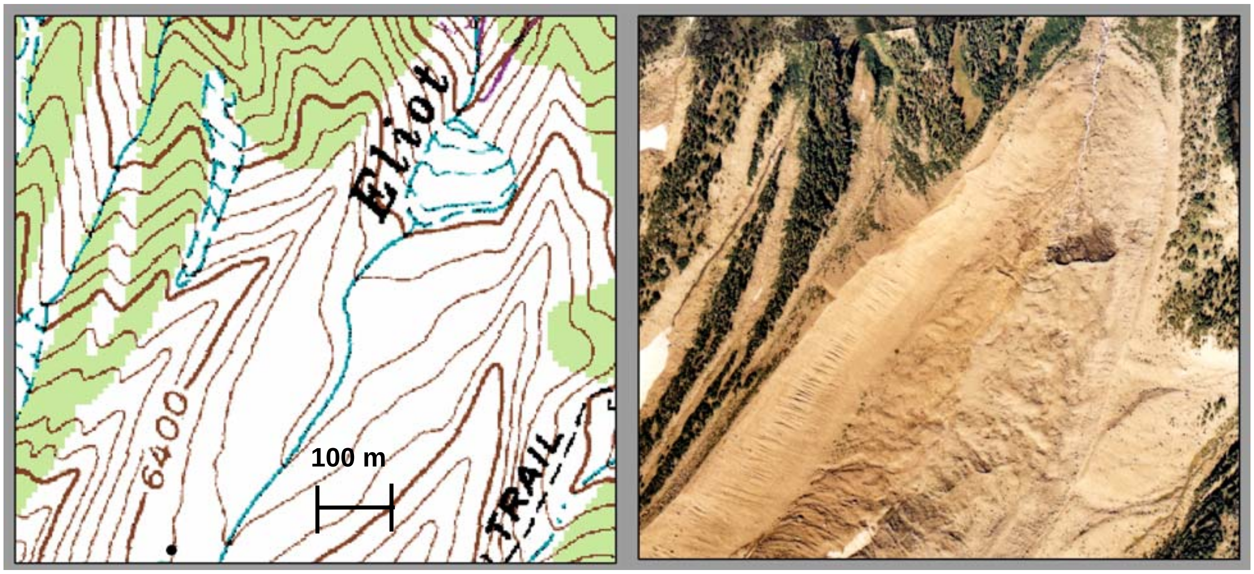


Figure 2. Eliot Glacier, Mount Hood, OR. Note the snow depicted on the 1956 scanned map at left, which we would include as permanent snow and ice, and the absence of snow in the 1989 aerial photograph on the right. Also, the rock-covered ice is not shown (mottled texture in the center of the photograph). The width of the largest snowpack on the map is about 200 m.

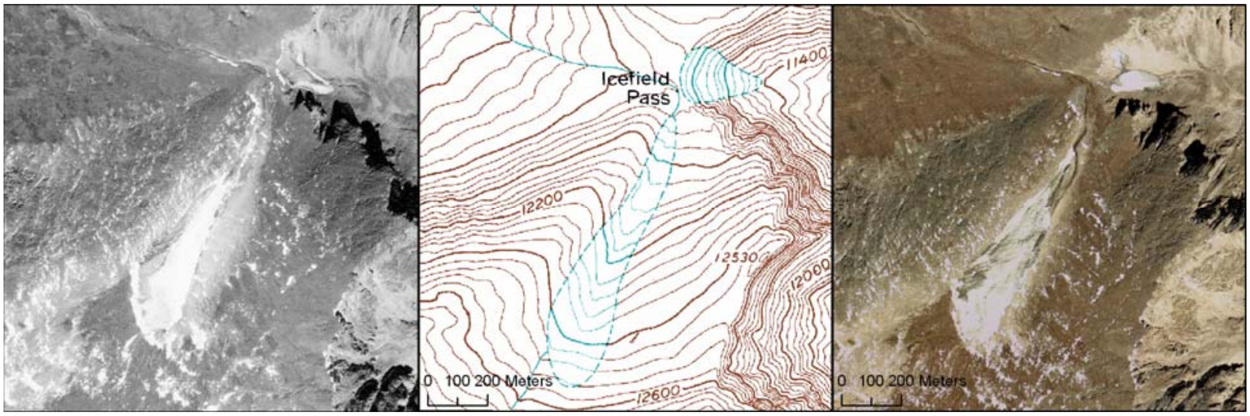


Figure 3. Icefield Pass, Colorado Front Range. An example of a perennial snow/ice patch that is included in our database. Leftmost aerial photograph was taken in 1946, the center topographic map is based on photographs taken in 1958, and the rightmost aerial photograph is from 2001. The left photograph is from the University of Colorado Map Library Collection, the center map is from the USGS 1:24,000 quadrangle map series, and the rightmost photograph is from Rocky Mountain National Park.

As mentioned, there can be problems in defining a glacier perimeter as opposed to one that includes marginal patches of late seasonal snow. We know of numerous cases where seasonal snow is included as part of the glacier. To test the fidelity of topographic quadrangle representations of glacier outlines, Granshaw and Fountain (2006) compared a hand-constructed glacier inventory exhaustively compiled by glaciologists using vertical and oblique aerial photography and some ground-based field work (Post and others, 1971) to a digital inventory derived from topographic quadrangles over the same time period. The comparison showed considerable variability for some glacier outlines, but the differences were compensatory when the glacier area was summed over the region such that the hand-constructed total glacier-covered area differed by only 1.5 percent (estimated error of the digital inventory was 0.9 percent) over a total glacier area of 116 km^2. It was unclear, however, as to the actual cause of the differences because the hand-constructed outlines exhibited a smooth generalized shape rather than a normally rougher outline.

Glacier outlines. We were somewhat surprised with the attribute coding of glaciers within the hydrography attributes of the USGS 100K maps. They seemed to have different codes for glaciers in different areas and in some cases had no codes whatsoever. For the 24K USFS/USGS data we found numerous errors (table 3). Some features, such as lakes, were coded as glaciers (fig. 4A), moraines as glaciers, and vice versa. These problems underscored the importance of checking the derived vector data against the scanned maps. Occasionally we found missing glacier outlines in the derived vector data (fig. 4B). Errors in digitizing were found such that the polygon outlining the glacier did not conform to the perimeter on the scanned map and needed to be edited or completely redone (fig. 5A), or that two or more glaciers were combined in one polygon rather than split into individual glaciers (fig. 5B). We never encountered two spatially separate glacial outlines contained within the same polygon. Rather, we found two adjacent glaciers connected at higher elevations that formed separate lobes at lower elevations, as commonly found on glacierized volcanoes. We used two criteria for splitting glaciers. The first was cultural. If separate lobes were differently named, the ice mass was split along the logical division between lobes, usually a flow divide. The second was physical. If the ice mass clearly diverged and flowed into separate valleys, it was split along the flow divide as determined from contour lines from the scanned maps.

On occasion, glacier outlines were complete on one quadrangle map, but where the glacier extended across to the adjacent quadrangle, the outline may not have continued and had to be digitized (fig. 6A). Another common error was ice-free islands surrounded by a glacier (doughnuts) but not digitized. We digitized these islands and deleted their area to create a “doughnut hole” in the glacier (fig. 6B). Finally, we found and deleted spurious lines in the derived vector data. In some cases these lines had no relation to the glaciers and were found in the ice-free landscape. In other cases these lines split glaciers but had no relation to a flow divide or the cultural name of the glacier. In this case, the lines were often straight and appeared to be artifacts in the data perhaps left over from other mapping efforts.

Finally, we had significant problems calculating the average aspect of the glaciers. We did not appreciate the fact that the GIS (ESRI, Inc.) calculated aspect without regard to map projection. The GIS always calculated aspect using “up” grid as north, and for some projections this produced an increasingly large error with longitude away from the central meridian. For other projections the error was subtle. We finally projected the data into the local Universal Transverse Mercator (UTM) zone and performed the aspect calculation. There is no error in aspect at the centerline of the UTM zone, where grid north and projection north are the same, and a small error (a maximum of 2° 13’ within our study area) at the edge of the UTM zone and grid north.

Table 3. Errors found in the derived vector data at 1:24,000-scale scanned maps.

[NG, not a glacier but a polygon that typically identifies another landscape feature such as a lake; E/R, polygon edited to conform to the shape on the scanned map because polygon was very poorly drawn (entirely redigitized), not closed, or needed a line added to split glaciers; M, a glacier that had to be digitized because it appeared on the scanned map but was missing from the derived vector data; H, a non-glacierized area surrounded by glacier ice (a doughnut hole) that was missing from the derived vector data and digitized; L, a spurious line in the derived vector data that does not correspond to any feature, or a line that divided a glacier in two, apparently an artifact of a map merge, in either case, deleted]

State	NG	E/R	M	H	L
California	0	0	3	10	0
Colorado	0	0	0	0	9
Idaho	1	2	2	0	1
Montana	1	392	79*	1	0
Nevada	0	0	0	0	0
Oregon	16	15	6	0	0
Washington	30	101	324	22	21
Wyoming	0	1	265	20	0

* Of these, 63 were white patches with blue perimeters with no contour lines and listed as “snowfields” on the scanned maps. These were unique to Montana and to the Seven Devils Mountains, ID.

Photographic dates. We had some problems in defining the photographic dates for each scanned map. We originally used a combination of USGS and USFS scanned maps to check our glacier outlines. However, because of ambiguity in the map dates reported on the collars of the USFS maps, we used only the USGS scanned map collar data for all 335 quadrangles that contain glaciers. In the cases examined we did not encounter a difference between USGS and USFS glacier outlines on the scanned maps.

Some map quadrangles were created from photographs acquired over multiple years. In some cases, coverage of the quadrangle required photographic surveys flown in different years, and the years are generally close in time (for example, 1976 and 1978). In other cases, quadrangles are updated by “photo-revision” and often occur decades after first publication. In both situations there are no indications from the map collar whether part or the entire quadrangle was revised. We use the earliest date of aerial photography as the date for the glacier outline. This choice is arbitrary for the first case, when multiple years are required for the photographic surveys. For the second case, photo-revised maps, we have yet to find a case in which glacier extent has been revised. We compared glacier extents on the same quadrangle for several different publication and revision dates; the glacier outlines have always conformed to the earliest mapping date. In several cases, we examined the original photography at the USGS Rocky Mountain Mapping Center in Lakewood, CO, where the photographic archives are housed. We found that the glacier outlines conformed to the original map date. We also searched for USGS photography on the USGS Earth Explorer Web page (*http://edcsns17.cr.usgs.gov/EarthExplorer/*). Where we found photographs for the same year as the photographic year on the map collar, we compared glacier outlines and again found the outlines conformed to the earliest photography.

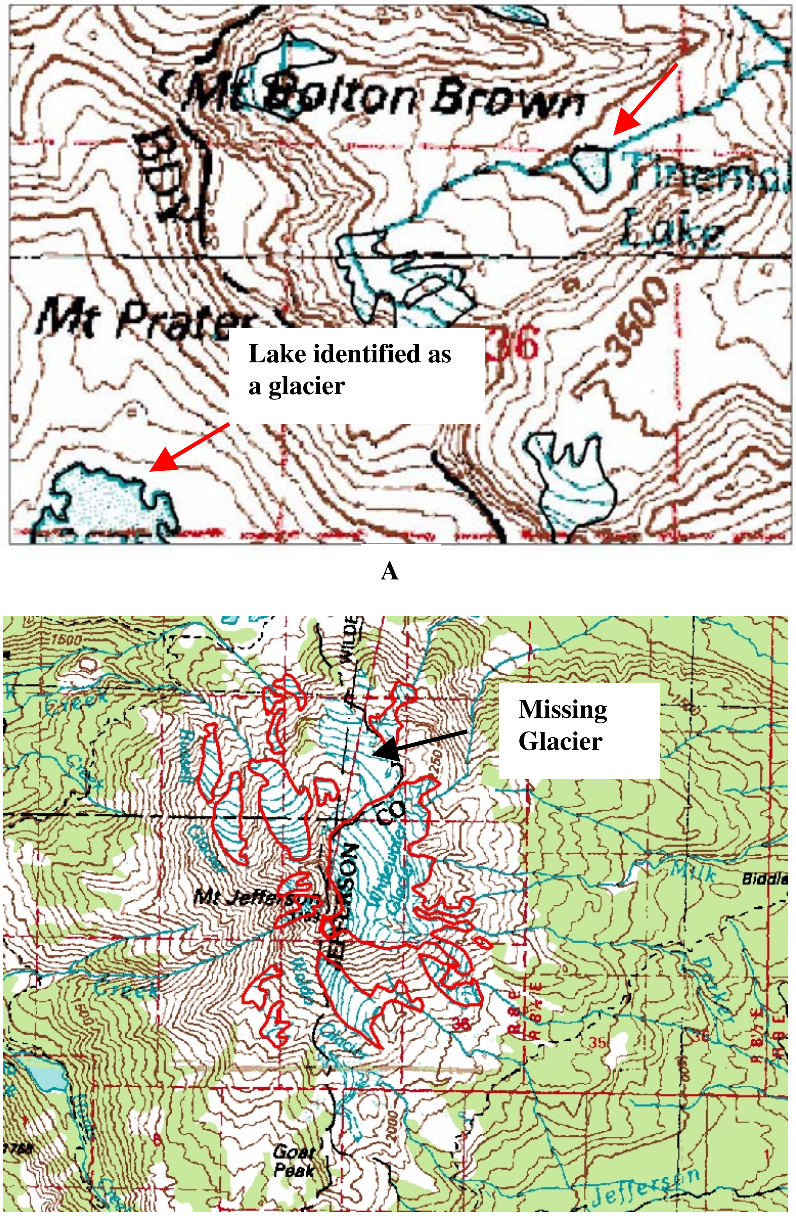


Figure 4. Errors in the derived vector files compared to the original scanned maps, which are their source. (*A*) Portion of map from Sierra Nevada, CA, with derived vector outlines in black. Note two lakes identified as glaciers. (*B*) Portion of map from Cascades, OR, with derived vector outlines in red. Note the missing glacier.

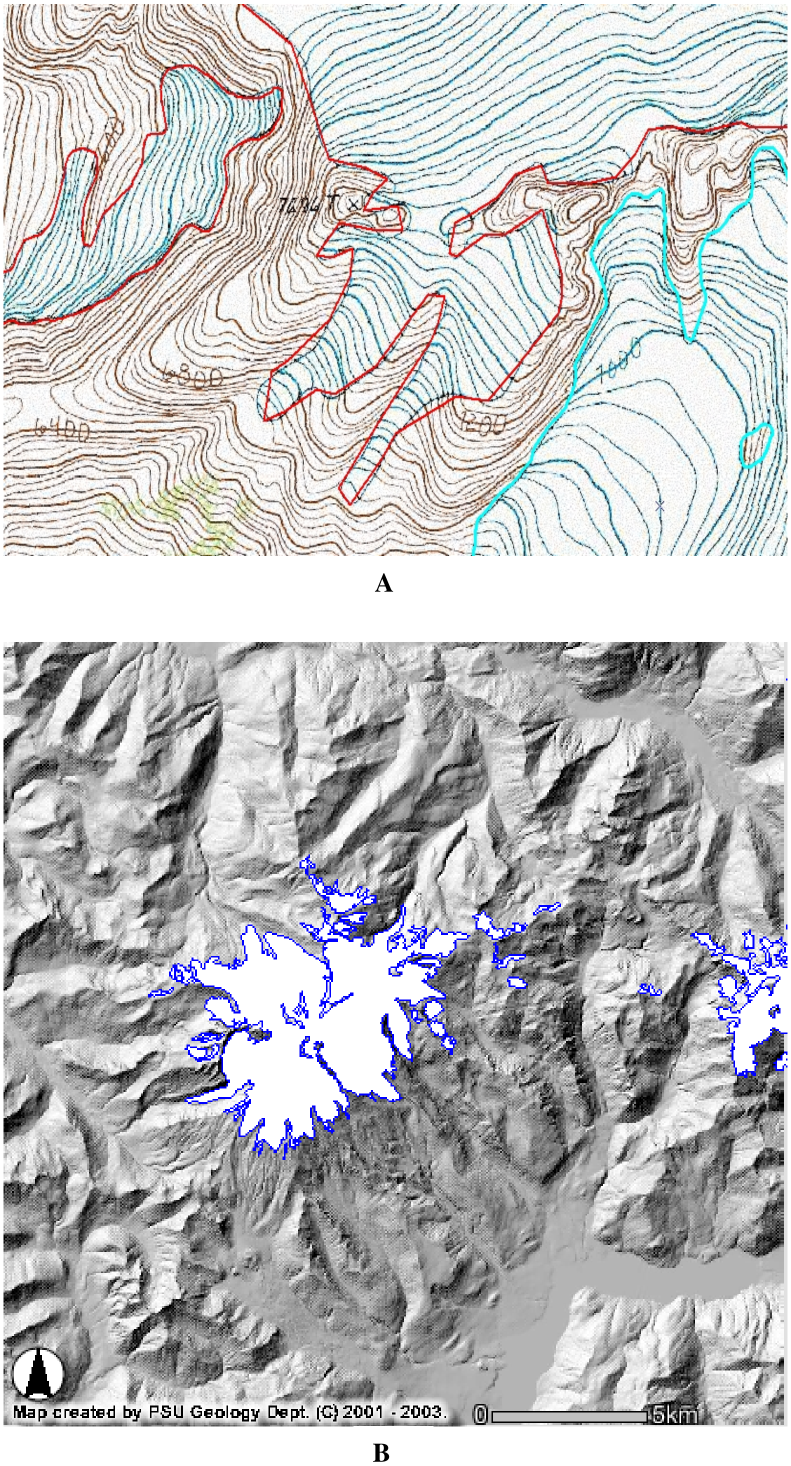
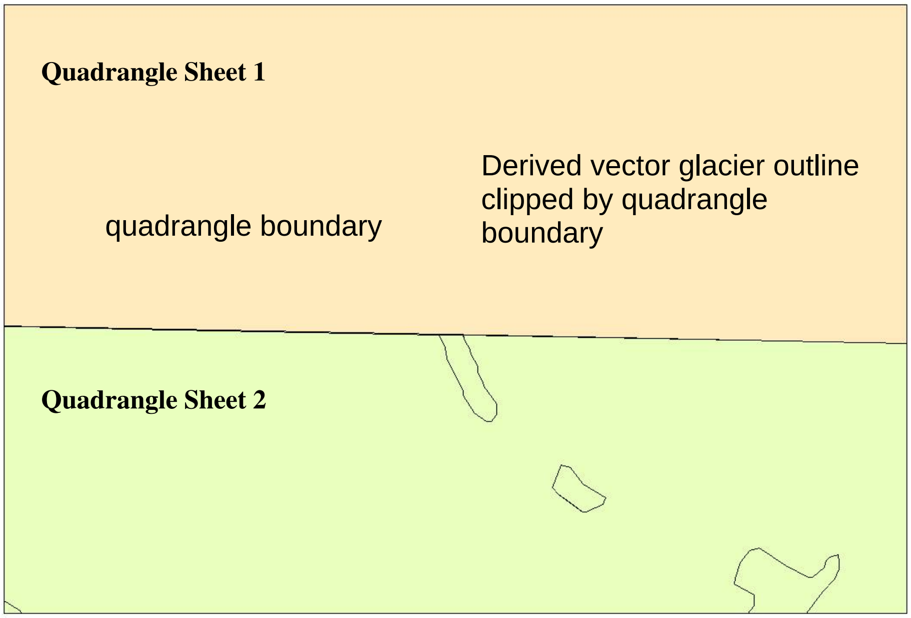
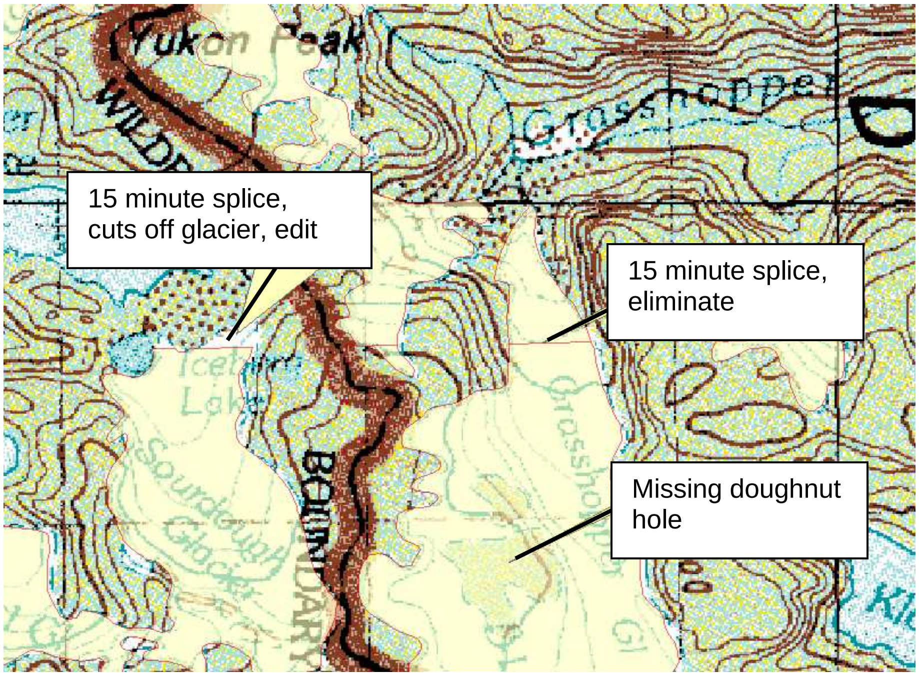


Figure 5. Errors in the derived vector files compared to the original scanned maps from which the files are derived. (*A*) Portion of map from North Cascades, WA, with vector outlines in red. Note how poorly the digitized outline matches the glacier perimeter. (*B*) Portion of map from Mount Baker, WA. Note that the derived vector glacier outlines (blue) are not split into individual glaciers.



A



B

Figure 6. Errors in the derived vector files compared to the original scanned map. (*A*) Portion of map from Sierra Nevada, CA, with vector outlines in black. Note glacier outline clipped by quadrangle boundary and missing in sheet 1. (*B*) Portion of map from Wind River Range, WY, with vector glacier outlines filled with light transparent yellow. Note glacier splits due to relict, 15-minute map (1:63,360) boundaries. Also note the covered doughnut hole, which should be ice free.

For the 335 quadrangles that contain glaciers, 255 have one photographic date, 70 have two dates, and 10 have three dates. Of the 80 quadrangles with multiple photographic dates, 33 have a range in dates greater than 10 years, the largest range being 33 years. Earliest photographic dates range from 1943 to 1987, but most minimum dates occur during the 1960s, '70s, and '80s (table 4).

Table 4. Earliest photographic date listed for all quadrangles and glaciers.

Earliest date	Number of quadrangles	Number of glaciers
1940–49	4	42
1950–59	54	1214
1960–69	109	2463
1970–79	81	2658
1980–89	87	1926

Data. We found 8,303 glaciers on the 24K maps. The largest was 10.59 km^2 and the smallest was 347 m^2. Table 5 shows the number of glaciers within different size categories (fig. 7).

Table 5. Number of glaciers in the 1:24,000-scale inventory for each area category.

[Number refers to the number of glaciers that are equal to or smaller than the area on the same row and larger than the area of the previous row]

Area (m^2)	Number	Cumulative number	Cumulative percent
316	0	0	0.00
1000	36	36	0.43
3162	793	829	9.98
10000	2447	3276	39.46
31623	2598	5874	70.75
100000	1501	7375	88.82
316228	605	7980	96.11
1000000	194	8174	98.45
3162278	99	8273	99.64
10000000	29	8302	99.99
31622777	1	8303	100.00

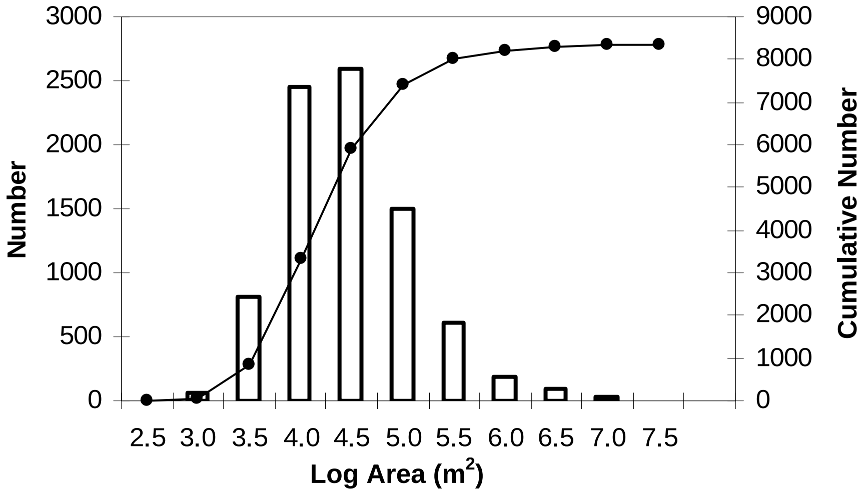


Figure 7. Histogram of the number of glaciers in the 1:24,000-scale glacier inventory as a function of area. Bars show the number and the line with symbols is the cumulative number.

Glacier attributes and description. For each glacier we generated 24 different descriptive and topographic attributes. They are as follows:

GLACNUM:	Unique identification number for each glacier
X_COORD:	Longitude of glacier centroid in NAD83 datum
Y_COORD:	Latitude of glacier centroid in NAD83 datum
AREA:	Area of glacier in square meters
GLACNAME:	From the USGS Geographic Names Information System (GNIS)
CLASSIFICA:	All features are classified as “snow or ice body”
SOURCE_SCA:	Source scale of data. All features are 1:24,000.
SOURCE:	Source of data, USFS PBS, USGS DRG, or National Park Service
USGS_QD_ID:	USGS 7.5’ quadrangle ID
REGION:	Mountain range in which the glacier is located
STATE:	Abbreviation of State in which the glacier is located
STATENAME:	Full name of State in which the glacier is located
QUADNAME:	USGS 7.5’ quadrangle name
FILENAME:	Name of scanned map image file used to generate glacier outline
PUBLICATIO:	Year of publication of quadrangle; not populated for all glaciers
PHOTODATE1:	Earliest aerial photography date (year) as shown on map collar
SLP_D_MEAN:	Mean glacier slope, degrees, calculated from 1 arc second NED
SLP_D_MAX:	Maximum slope of glacier in degrees from 1 arc second NED

SLP_D_MIN:	Minimum slope of glacier in degrees from 1 arc second NED
ELEV_MEAN:	Mean elevation of glacier in meters from 1 arc second NED
ELEV_MAX:	Maximum elevation of glacier in meters from 1 arc second NED
ELEV_MIN:	Minimum elevation of glacier in meters from 1 arc second NED
ASP_MEAN:	Mean aspect of glacier from 1 arc second NED in UTM NAD83.

1:100,000-Scale Data

Glacier outlines. We found similar errors as with the 24K-derived vector data (table 6).

Mapping inconsistencies. A comparison of the 100K and 24K data sets exhibits a number of mapping inconsistencies, especially among smaller glaciers. This is an understandable result given the difference in scales. As expected, most of the smallest glaciers are not present in the 100K data. A number of regions that contain only very small glaciers and are found within the 24K data are missing from the 100K data (table 7). In some cases, small, culturally significant (named) glaciers are missing from the 100K data (for example, Andrews Glacier, Tyndall Glacier, CO), while remote, unnamed glaciers are mapped nearby (Gore Range, CO). Because of differences in mapping the subtleties of the glacier outlines, especially ice-free islands, snow and ice patches, and other ice appendages, the area of many glaciers differs significantly between the two data sets. One other inconsistency we noted between the two data sets was in the interpretation of moraine and rock glacier deposits. One good example is Galena Creek Rock Glacier, Absaroka Range, WY, where the entire feature is mapped as a glacier in the 100K data set but is not present at all in the 24K data set (fig. 8).

Table 6. Errors found in the derived vector data at the 1:100,000-scale.

[NG, not a glacier but a polygon that typically identifies another landscape feature such as a lake; E/R, polygon edited to conform to the shape on the scanned map because polygon was very poorly drawn (entirely redigitized), not closed, or needed a line added to split glaciers; M, a glacier that had to be digitized because it appeared on the scanned map but was missing from the derived vector data; H, a non-glacierized area surrounded by glacier ice (a doughnut hole) that was missing from the derived vector data and digitized; L, a spurious line in the derived vector data that does not correspond to any feature, or a line that divided a glacier in two, apparently an artifact of a map merge, in either case, deleted]

State	NG	E/R	M	H	L
California	0	4	5	0	0
Colorado	0	0	0	0	0
Idaho	0	0	0	0	0
Montana	4	6	41	65	0
Nevada	0	0	0	0	0
Oregon	13	8	11	0	0
Washington	22	156	138	1	0
Wyoming	2	15	29	12	13

Table 7. Glacierized regions in the 1:24,000-scale mapping but not in the 1:100,000-scale mapping.

State	Glacierized region
California	Lassen Peak, Trinity Alps
Colorado	Medicine Bow Range, Park Range, San Miguel Mountains, Sawatch Range, Tenmile Range
Idaho	Seven Devils
Montana	Madison Range
Oregon	Mount Thielsen, Wallowas

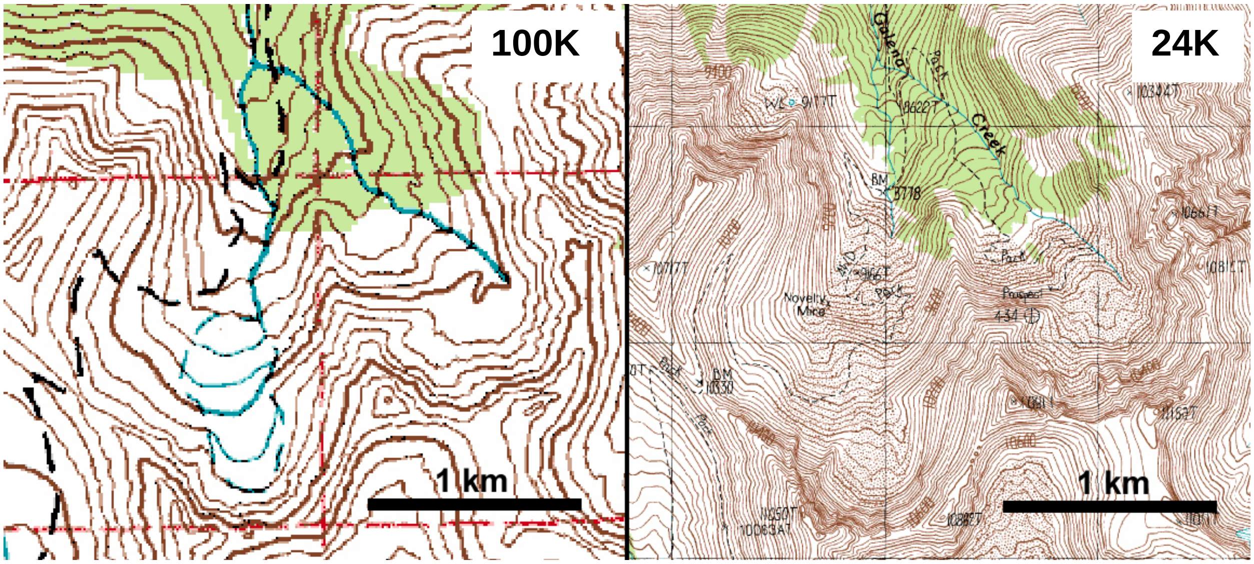


Figure 8. Galena Creek Rock Glacier, Absaroka Range, WY, as represented in the 1:100,000-scale (100K) and 1:24,000-scale (24K) data sets.

Data. The 100K glacier inventory includes 1,523 glaciers, of which the smallest was 3,070 m^2 and the largest is 13.6 km^2 (table 8). The distribution of areas is shown in figure 9.

Table 8. Number of glaciers for each area category.

[Number refers to the number of glaciers that are equal to or smaller than the area on the same row and larger than the area of the previous row]

Area (m^2)	Number	Cumulative number	Cumulative percent
1000	0	0	0.0
3162	1	1	0.1
10000	12	13	0.9
31623	120	133	8.7
100000	538	671	44.1
316228	524	1195	78.5
1000000	222	1417	93.0
3162278	69	1486	97.6
10000000	34	1520	99.8
31622777	3	1523	100.0

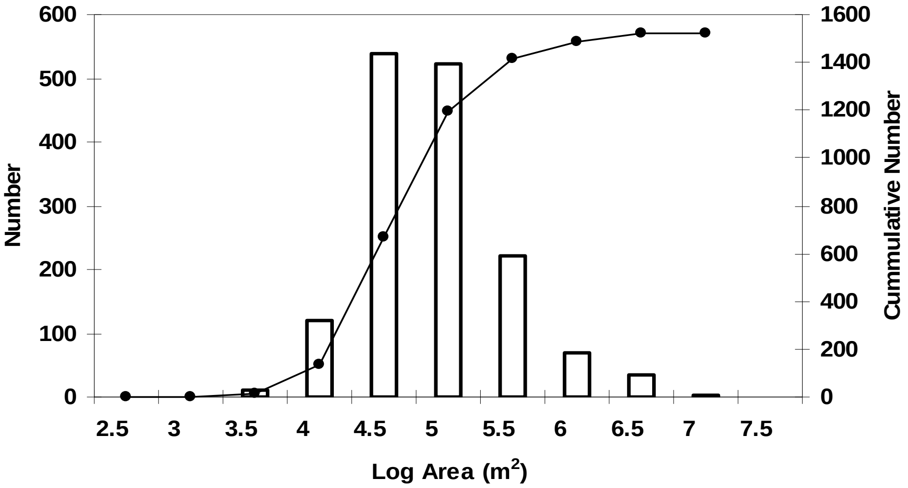


Figure 9. Histogram of the number of glaciers in the 1:100,000-scale glacier inventory as a function of area. Bars show the number and the line with symbols is the cumulative number.

Data Attributes. For each glacier we generated nine different descriptive attributes. They are as follows:

GLACNUM:	Unique identification number for each glacier
AREA:	Area of glacier in square meters
PERIMETER:	Perimeter of glacier in meters
X_COORD:	Longitude of glacier centroid in NAD83 datum
Y_COORD:	Latitude of glacier centroid in NAD83 datum
CLASSIFICA:	All features are classified as “snow or ice body”
SOURCE:	Source of data; all features are from USGS DRG
SRC_SCALE:	Source scale of data; all features are 1:100,000

Summary

We believe that the 24K data inventory is the most comprehensive inventory of glaciers in the American West. Although problems exist in the original data and specific glaciers might have some error in their outline and elevation, we believe the aggregate effect of the errors is small because they are compensating. At minimum, these data provide a basis for future improvements motivated by detailed studies within our relatively small glacier-covered regions. These data provide a snapshot of the glacier cover of the American West. Perhaps the most startling feature of the data, especially at the 24K scale, is the number of glaciers (>8,300). Most of the glaciers, as figure 7 shows, are small, 39.5 percent being equal to or smaller than 0.01 km^2. Whether these small features are truly glaciers, patches of perennial snow and ice, or patches of seasonal snow is unknown. We know that small patches of permanent ice exist, but whether this database is a true representation of these small features is unclear.

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