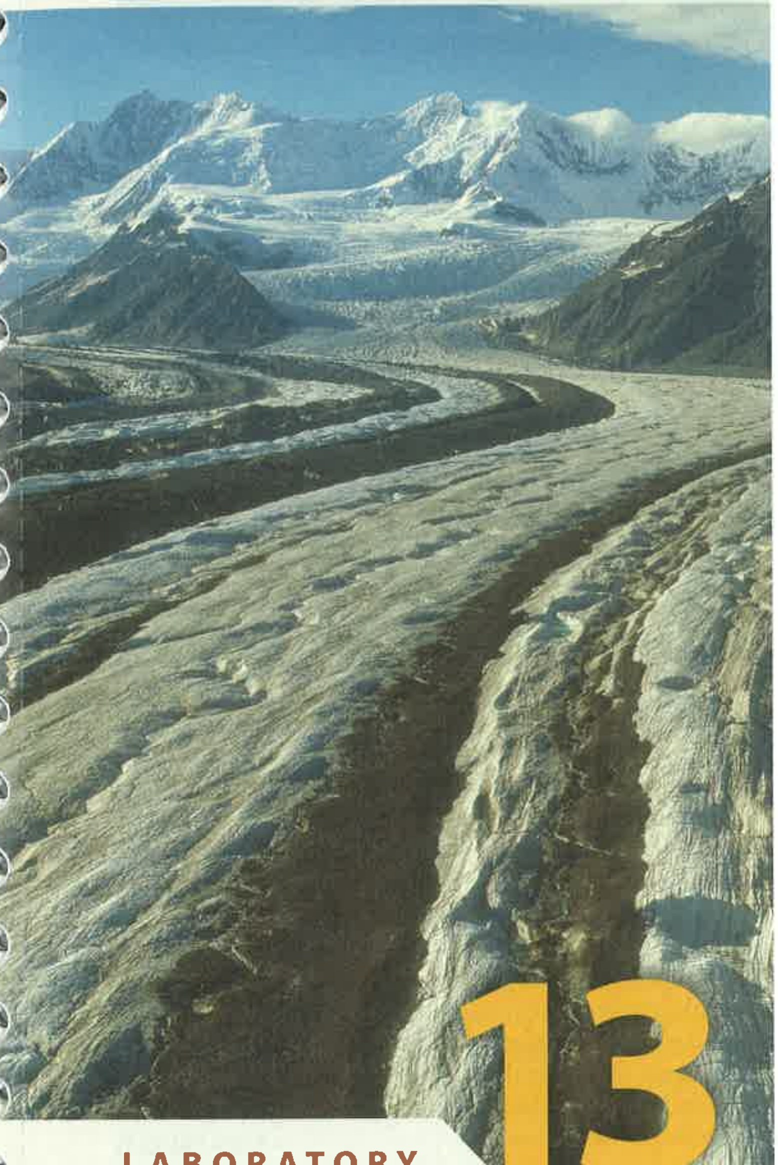

LABORATORY 13

Glaciers and the Dynamic Cryosphere

CONTRIBUTING AUTHORS
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Kennicott Glacier, a long (43 km, 27 mi) valley glacier in Alaska. Mountains in the distance are where snow and ice accumulate and form the glacier. Down valley, dark medial moraines of rocky drift are deposited from melting ice. (Photo by Michael Collier)

BIG IDEAS

Earth's crysphere is its snow and ice (frozen water), including permafrost, sea ice, mountain glaciers, continental ice sheets, and the polar ice caps. The extent of snow and ice in any given area depends on how much snow and ice accumulates during winter months and how much snow and ice melts during summer months. Glaciers are one of the best known components of the cryosphere, because they are present on all continents except Australia and have created characteristic landforms and resources utilized by many people.

FOCUS YOUR INQUIRY

THINK About It | What is the cryosphere, and how do changes in the cryosphere affect other parts of the Earth system?

THINK About It | How do glaciers affect landscapes?

THINK About It | How is the cryosphere affected by climate change?

Introduction

The **cryosphere** is all of Earth's snow and ice (frozen water). It all begins with a single snowflake falling from the sky or a single crystal of ice forming in a body of water. Over time, a visible body of snow or ice may form. Most snow and ice melts completely over summer months, providing much-needed water to communities. However, there are areas of Earth's surface where the annual amount of ice accumulation exceeds the annual amount of ice melting. Permanent masses of ice can exist there. These areas (**FIGURE 13.1**) range from places with permanently frozen ground (permafrost), to places

ACTIVITY 13.1 Cryosphere Inquiry

THINK About It What is the cryosphere, and how do changes in the cryosphere affect other parts of the Earth system?

OBJECTIVE Analyze global and regional components of the cryosphere, and then infer how they may change and ways that such change may affect other parts of the Earth system.

PROCEDURES

1. **Before you begin**, do not look up definitions and information. Use your current knowledge, and complete the worksheet with your current level of ability. Also, this is **what you will need** to do the activity:
   ____ pen
   ____ Activity 13.1 Worksheets (pp. 347–348) and pencil
2. **Complete the worksheet in a way that makes sense to you.**
3. **After you complete the worksheet**, be prepared to discuss your observations and classification with other geologists.

ACTIVITY 13.2 Mountain Glaciers and Glacial Landforms

THINK About It How do glaciers affect landscapes?

OBJECTIVE Analyze features of landscapes affected by mountain glaciation and infer how they formed.

PROCEDURES

1. **Before you begin**, read the Introduction, Glaciers, and Glacial Processes and Landforms. Also, this is **what you will need:**
   ____ ruler, calculator
   ____ Activity 13.2 Worksheets (pp. 349–350) and pencil
2. **Then follow your instructor's directions** for completing the worksheets.

where ice permanently covers the ground (glaciers and ice caps, ice sheets), to places where ice covers parts of the ocean (ice shelves, sea ice). The ice in your freezer may last for days or months, but ice in some of Earth's ice caps is thousands of years old.

ACTIVITY 13.3 Continental Glaciation of North America

THINK About It How do glaciers affect landscapes?

OBJECTIVE Analyze features of landscapes affected by continental glaciation and infer how they formed.

PROCEDURES

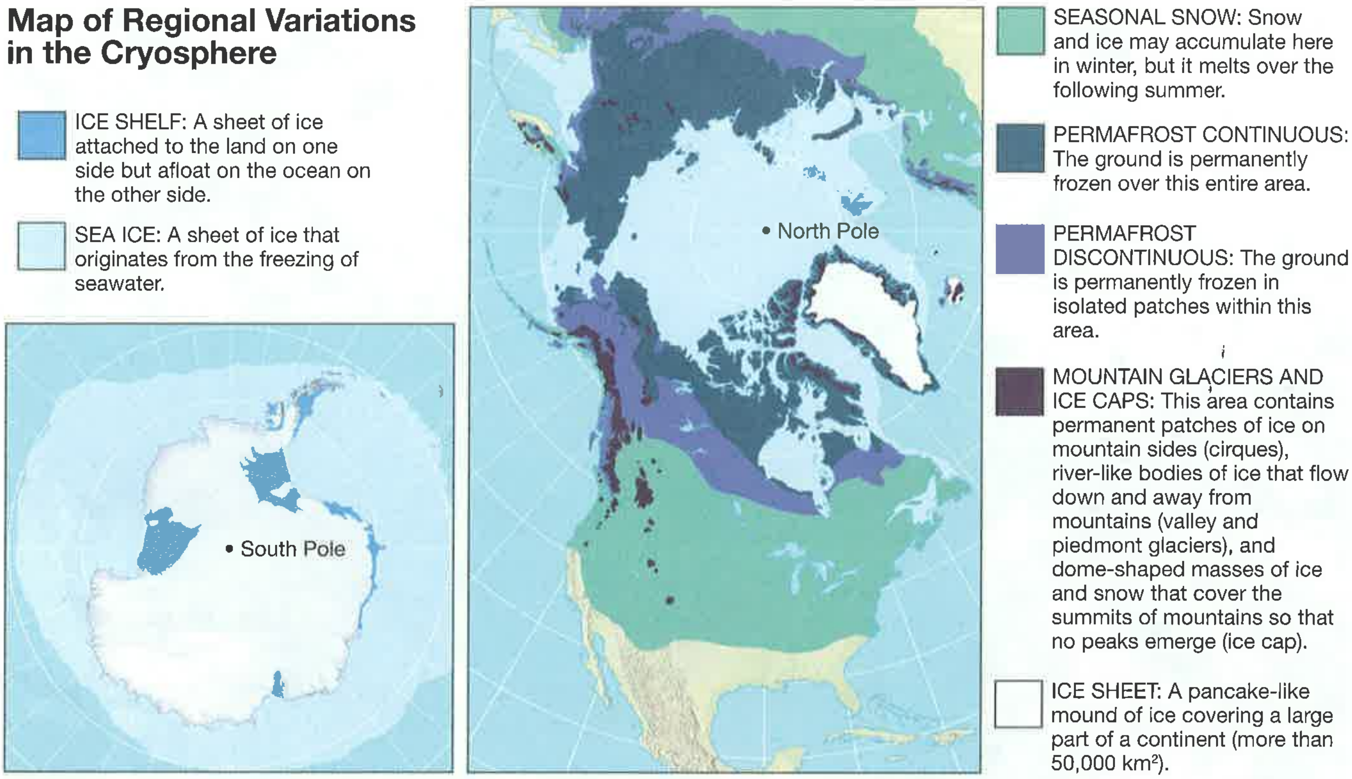
1. **Before you begin**, read the Introduction, Glaciers, and Glacial Processes and Landforms. Also, this is **what you will need:**
   ____ Activity 13.3 Worksheet (p. 351) and pencil
2. **Then follow your instructor's directions** for completing the worksheets.

Dynamic Cryosphere

The total amount of ice on Earth's surface is ever-changing due to annual variations in global patterns of air circulation and regional variations in things like ground temperature, ocean surface temperature, and the *weather* (daily to seasonal conditions of the atmosphere, such as air temperature and humidity, wind, cloud cover, and precipitation). Global and regional amounts of ice are also affected by *climate*—the set of atmospheric conditions (like air temperature, humidity, wind, and precipitaion) that prevails in a region over decades. A region's climate is generally determined by measuring the average conditions that exist there over a period of years or the conditons that normally exist in the region at a particular time of year.

Climate Change

A region's climate is based on factors like latitude, altitude, location relative to oceans (moisture sources), and location relative to patterns of global air and ocean circulation. **Climate change** refers to a significant change in atmospheric conditions of a region or the planet. This can occur due to natural factors like changing patterns of global air circulation, variations in volcanic activity, and changes in solar activity. It can also occur due to human factors like construction of regional urban centers (adding regional sources of heat energy) and deforestation (removing a transpiration source of atmospheric water vapor; adding soot and gases to the atmosphere as the forest is burned).



(Courtesy of The Cryoshphere, world map, UNEP/GRID-Arendal, www.grida.no/graphicslib/detail/the-cryosphere-world-map_e290.)

FIGURE 13.1 Cryosphere components. You can also download a complete world map of cryosphere components from this UNEP (United Nations Environment Programme) website: **http://www.grida.no/graphicslib/detail/the-cryosphere-world-map_e290**

Glaciers

Glaciers are large ice masses that form on land areas that are cold enough and have enough snowfall to sustain them year after year. They form wherever the winter accumulation of snow and ice exceeds the summer ablation (also called *wastage*). *Ablation* (wastage) is the loss of snow and ice by melting and by *sublimation* to gas (direct change from ice to water vapor, without melting). Accumulation commonly occurs in *snowfields*—regions of permanent snow cover (**FIGURE 13.2**).

Glaciers can be divided into two zones, accumulation and ablation (**FIGURE 13.2**). As snow and ice accumulate in and beneath snowfields of the **zone of accumulation,** they become compacted and highly recrystallized under their own weight. The ice mass then begins to slide and flow downslope like a very viscous (thick) fluid. If you *slowly* squeeze a small piece of ice in the jaws of a vise or pair of pliers, then you can observe how it flows. In nature, glacial ice formed in the zone of accumulation flows and slides downhill into the **zone of ablation,** where it melts or sublimes (undergoes sublimation) faster than new ice can form. The *snowline* is the boundary between the zones of accumulation and ablation. The bottom end of the glacier is the **terminus.**

It helps to understand a glacier by viewing it as a river of ice. The "headwater" is the zone of accumulation, and the "river mouth" is the terminus. Like a river, glaciers *erode* (wear away) rocks, transport their load (tons of rock debris), and deposit their load "downstream" (down-glacier).

The downslope movement and extreme weight of glaciers cause them to abrade and erode (wear away) rock materials that they encounter. They also *pluck* rock material by freezing around it and ripping it from bedrock. The rock debris is then incorporated into the glacial ice and transported many kilometers by the glacier. The debris also gives glacial ice extra abrasive power. As the heavy rock-filled ice moves over the land, it scrapes surfaces like a giant sheet of sandpaper. Rock debris falling from valley walls commonly accumulates on the surface of a moving glacier and is transported downslope. Thus, glaciers transport huge quantities of sediment, not only *in,* but also *on* the ice.

When a glacier melts, it appears to retreat up the valley from which it flowed. This is called **glacial retreat,** even though the ice is simply melting back (rather than moving back up the hill). As melting occurs (**FIGURE 13.3**), deposits of rocky gravel, sand, silt, and clay accumulate where there once was ice. These deposits collectively are called **drift.** Drift that accumulates directly from the melting ice is unstratified (unsorted by size) and is called **till.** However, drift that is transported by the meltwater becomes more rounded, sorted by size, layered, and is called **stratified drift.** Wind also can transport the sand, silt, and clay particles from drift. This wind-transported sediment can form dunes or *loess* deposits (wind-deposited, unstratified accumulations of clayey silt).

FIGURE 13.2 Mountain glaciation. This is an ASTER infrared satellite image of a 20-by-20 km area in Alaska. Vegetation appears red, glacial ice is blue, and snow is white. (Image courtesy of NASA/GSFC/METI/ERSDAC/JAROS and U.S./Japan ASTER Science Team.)

There are five main kinds of glaciers based on their size and form.

- **Cirque glaciers**—small, semicircular to triangular glaciers that form on the sides of mountains. If they form at the head (up-hill end) of a valley and grow large enough, then they evolve into valley glaciers.
- **Valley glaciers**—long glaciers that originate at cirques and flow down stream valleys in the mountains.
- **Piedmont glaciers**—mergers of two or more valley glaciers at the foot (break in slope) of a mountain range.
- **Ice sheet**—a vast, pancake-shaped ice mound that covers a large portion of a continent and flows independent of the topographic features beneath it and covers an area greater than 50,000 km^2. The Antarctic Ice Sheet (covering the entire continent of Antarctica) and the Greenland Ice Sheet (covering Greenland) are modern examples.
- **Ice cap**—a dome-shaped mass of ice and snow that covers a flat plateau, island, or peaks at the summit of a mountain range and flows outward in all directions from the thickest part of the cap. It is much smaller than an ice sheet.

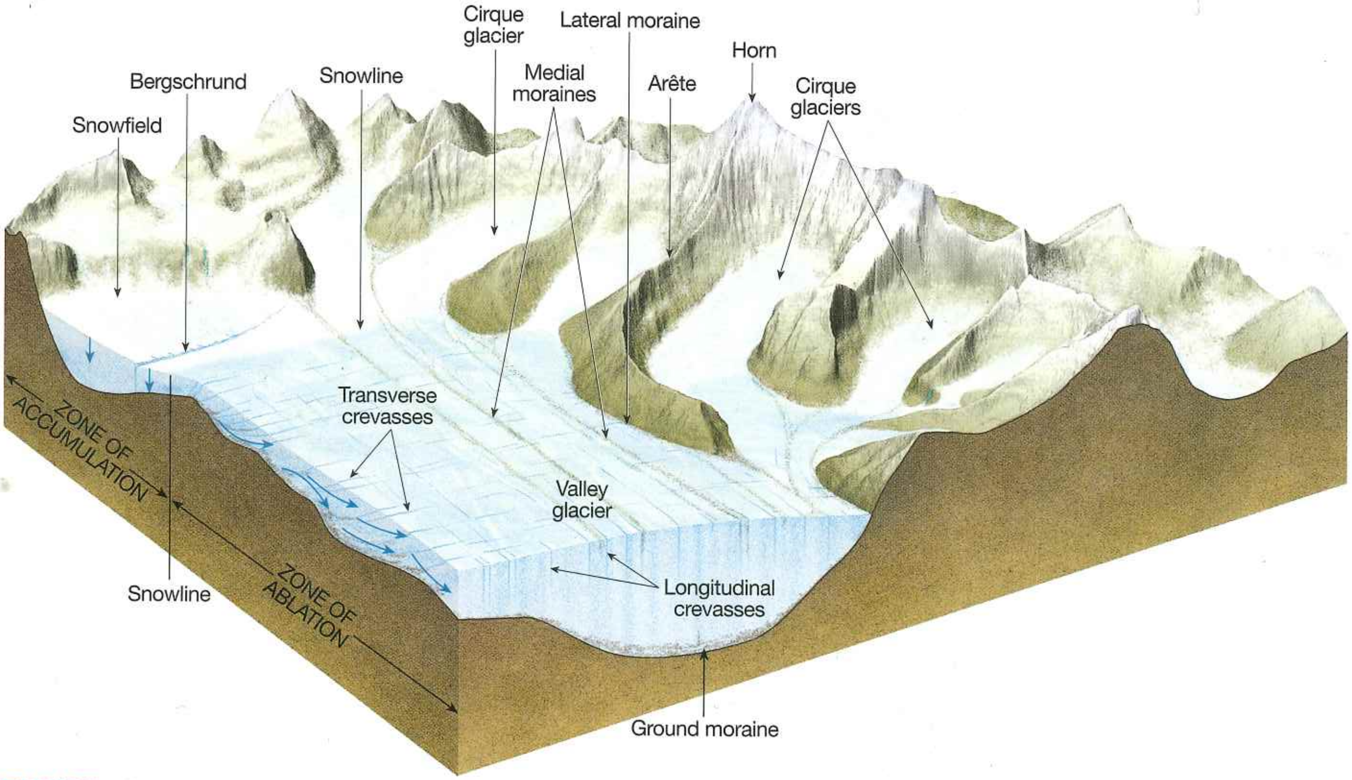


FIGURE 13.3 Active mountain glaciation, in a hypothetical region. Note the cutaway view of glacial ice, showing flow lines and direction (blue lines and arrows).

Glacial Processes and Landforms

Glaciated lands are affected by either local to regional "mountain glaciation" or more continent-wide "continental glaciation."

Mountain Glaciation

Mountain glaciation is characterized by cirque glaciers, valley glaciers, piedmont glaciers, and ice caps. Poorly developed mountain glaciation involves only cirques, but the best-developed mountain glaciation involves all three types. In some cases, valley and piedmont glaciers are so well developed that only the highest peaks and ridges extend above the ice. Ice caps cover even the peaks and ridges. FIGURE 13.2 shows a region with mountain glaciation. Note the extensive *snowfield* in the zone of accumulation. *Snowline* is the elevation above which there is permanent snow cover.

Also note that there are many cracks or fissures in the glacial ice of FIGURE 13.2. At the upper end of the glacier is the large *bergschrund* (German, "mountain crack") that separates the flowing ice from the relatively immobile portion of the snowfield. The other cracks are called **crevasses**—open fissures that form when the velocity of ice flow is variable (such as at bends in valleys). **Transverse crevasses** are perpendicular to the flow direction, and **longitudinal crevasses** are aligned parallel with the direction of flow.

FIGURE 13.3 shows the results of mountain glaciation after the glaciers have completely melted. Notice the characteristic landforms, water bodies, and sedimentary deposits. For your convenience, distinctive features of glacial lands are summarized in three figures: *erosional features* in FIGURE 13.4, *depositional features* in FIGURE 13.5, and *water bodies* in FIGURE 13.6. Note that some features are identical in mountain glaciation and continental glaciation, but others are unique to one or the other. Study the descriptions in these three figures and compare them with the visuals in FIGURES 13.2 and 13.3.

Continental Glaciation

During the Pleistocene Epoch, or "Ice Age," that ended 11,700 years ago, thick ice sheets covered most of Canada, large parts of Alaska, and the northern contiguous United States. These continental glaciers produced a variety of characteristic landforms (FIGURE 13.7, FIGURE 13.8).

Recognizing and interpreting these landforms is important in conducting work such as regional soil analyses, studies of surface drainage and water supply, and exploration for sources of sand, gravel, and minerals. The thousands of lakes in the Precambrian Shield area of Canada also are a legacy of this continental glaciation, as are the fertile soils of the north-central United States and south-central Canada.

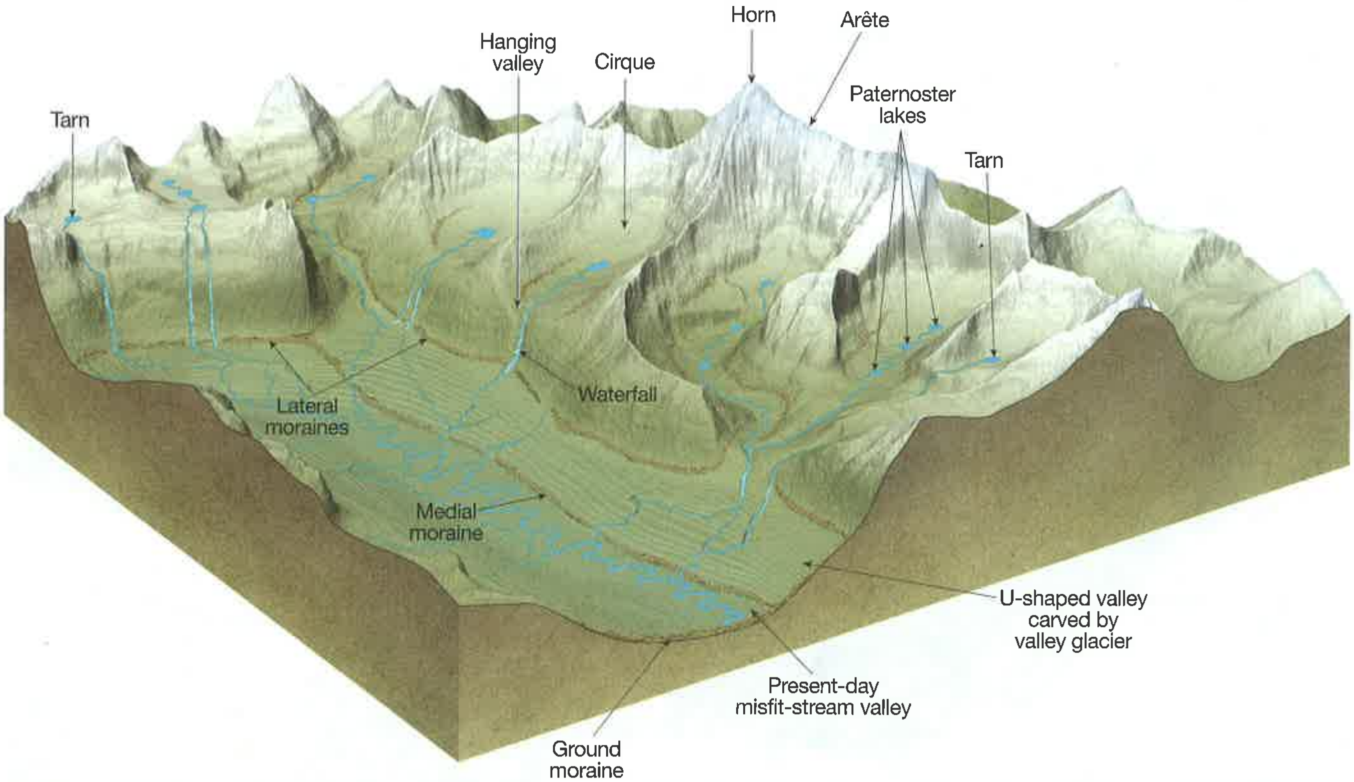


FIGURE 13.4 Erosional and depositional features of mountain glaciation. The same region as FIGURE 13.3, but showing erosion features remaining after total ablation (melting) of glacial ice.

ACTIVITY

13.4 Glacier National Park Investigation

THINK About It | **How do glaciers affect landscapes? How is the cryosphere affected by climate change?**

OBJECTIVE Analyze glacial features in Glacier National Park and infer how glaciers there may change in the future.

PROCEDURES

1. **Before you begin**, read about Glacial National Park, Montana below. Also, this is **what you will need:**
   ____ calculator
   ____ Activity 13.4 Worksheet (p. 352) and pencil
2. **Then follow your instructor's directions** for completing the worksheets.

Glacier National Park, Montana

Glacier National Park is located on the northern edge of Montana, across the border from Alberta and British Columbia, Canada. Most of the erosional features formed by glaciation in the park developed during the Wisconsinan glaciation that ended about 11,700 years ago. Today, only small cirque glaciers exist in the park. Thirty-seven of them are named, and nine of those can be observed on the topographic map of part of the park in FIGURE 13.14.

ACTIVITY

13.5 Nisqually Glacier Response to Climate Change

THINK About It | **How is the cryosphere affected by climate change?**

OBJECTIVE Evaluate the use of Nisqually Glacier as a global thermometer for measuring climate change.

PROCEDURES

1. **Before you begin**, read Nisqually Glacier—A Global Thermometer? Also, this is **what you will need:**
   ____ ruler
   ____ Activity 13.5 Worksheets (p. 353–354) and pencil
2. **Then follow your instructor's directions** for completing the worksheets.

EROSIONAL FEATURES OF GLACIATED REGIONS		MOUNTAIN GLACIATION	CONTINENTAL GLACIATION
Cirque	Bowl-shaped depression on a high mountain slope, formed by a cirque glacier	X	
Arête	Sharp, jagged, knife-edge ridge between two cirques or glaciated valleys	X	
Col	Mountain pass formed by the headward erosion of cirques	X	
Horn	Steep-sided, pyramid-shaped peak produced by headward erosion of several cirques	X	
Headwall	Steep slope or rock cliff at the upslope end of a glaciated valley or cirque	X	
Glacial trough	U-shaped, steep-walled, glaciated valley formed by the scouring action of a valley glacier	X	
Hanging valley	Glacial trough of a tributary glacier, elevated above the main trough	X	
Roche moutonnée	Asymmetrical knoll or small hill of bedrock, formed by glacial abrasion on the smooth stoss side (side from which the glacier came) and by plucking (prying and pulling by glacial ice) on the less-smooth lee side (down-glacier side)		X
Glacial striations and grooves	Parallel linear scratches and grooves in bedrock surfaces, resulting from glacial scouring	X	X
Glacial polish	Smooth bedrock surfaces caused by glacial abrasion (sanding action of glaciers analogous to sanding of wood with sandpaper)	X	X

FIGURE 13.5 **Erosional features of mountain or continental glaciation.**

Nisqually Glacier—A Global Thermometer?

Nisqually Glacier is one of many active valley glaciers that occupy the radial drainage of Mt. Rainier—an active volcano located near Seattle, Washington, in the Cascade Range of the western United States. Nisqually Glacier occurs on the southern side of Mt. Rainier and flows south toward the Nisqually River Bridge in FIGURE 13.15. The position of the glacier's terminus (downhill end) was first recorded in 1840, and it has been measured and mapped by numerous geologists since that time. The map in FIGURE 13.15 was prepared by the U.S. Geological Survey in 1976 and shows where the terminus of Nisqually Glacier was located at various times from 1840 to 1997. (The 1994, 1997, and 2010 positions were added for this laboratory, based on NHAP aerial photographs and satellite imagery.) Notice how the glacier has more or less retreated up the valley since 1840.

Sea Ice

Sea ice is frozen ocean water. The largest masses of sea ice occur in the Arctic Ocean and around the continent of Antarctica (FIGURE 13.16). In both locations, the sea

ACTIVITY

13.6 The Changing Extent of Sea Ice

THINK About It | **How is the cryosphere affected by climate change?**

OBJECTIVE Measure how the extent of sea ice has changed annually in the past, predict how it may change in the future, and infer what benefits or hazards could result if Arctic sea ice continues to decline.

PROCEDURES

1. **Before you begin**, read Sea Ice. Also, this is **what you will need**:
   ____ 30 cm (12 in.) length of thread or thin string
   ____ ruler, calculator
   ____ Activity 13.7 Worksheets (pp. 355–356) and pencil
2. **Then follow your instructor's directions** for completing the worksheets.

DEPOSITIONAL FEATURES OF GLACIATED REGIONS		MOUNTAIN GLACIATION	CONTINENTAL GLACIATION
Ground moraine	Sheetlike layer (blanket) of till left on the landscape by a receding (wasting) glacier.	X	X
Terminal moraine	Ridge of till that formed along the leading edge of the farthest advance of a glacier.	X	X
Recessional moraine	Ridge of till that forms at terminus of a glacier, behind (up-glacier) and generally parallel to the terminal moraine; formed during a temporary halt (stand) in recession of a wasting glacier.	X	X
Lateral moraine	A body of rock fragments at or within the side of a valley glacier where it touches bedrock and scours the rock fragments from the side of the valley. It is visible along the sides of the glacier and on its surface in its ablation zone. When the glacier melts, the lateral moraine will remain as a narrow ridge of till or boulder train on the side of the valley.	X	
Medial moraine	A long narrow body of rock fragments carried in or upon the middle of a valley glacier and parallel to its sides, usually formed by the merging of lateral moraines from two or more merging valley glaciers. It is visible on the surface of the glacier in its ablation zone. When the glaciers melt, the medial moraine will remain as a narrow ridge of till or boulder train in the middle of the valley.	X	
Drumlin	An elongated mound or ridge of glacial till (unstratified drift) that accumulated under a glacier and was elongated and streamlined by movement (flow) of the glacier. Its long axis is parallel to ice flow. It normally has a blunt end in the direction from which the ice came and long narrow tail in the direction that the ice was flowing.		X
Kame	A low mound, knob, or short irregular ridge of stratified drift (sand and gravel) sorted by and deposited from meltwater flowing a short distance beneath, within, or on top of a glacier. When the ice melted, the kame remained.		X
Esker	Long, narrow, sinuous ridge of stratified drift deposited by meltwater streams flowing under glacial ice or in tunnels within the glacial ice		X
Erratic	Boulder or smaller fragment of rock resting far from its source on bedrock of a different type.	X	X
Boulder train	A line or band of boulders and smaller rock clasts (cobbles, gravel, sand) transported by a glacier (often for many kilometers) and extending from the bedrock source where they originated to the place where the glacier carried them. When deposited on different bedrock, the rocks are called erratics.	X	X
Outwash	Stratified drift (mud, sand and gravel) transported, sorted, and deposited by meltwater streams (usually muddy braided streams) flowing in front of (down-slope from) the terminus of the melting glacier.	X	X
Outwash plain	Plain formed by blanket-like deposition of outwash; usually an outwash braid plain, formed by the coalescence of many braided streams having their origins along a common glacial terminus.	X	X
Valley train	Long, narrow sheet of outwash (outwash braid plain of one braided stream, or floodplain of a meandering stream) that extends far beyond the terminus of a glacier.	X	
Beach line	Landward edge of a shoreline of a lake formed from damming of glacial meltwater, or temporary ponding of glacial meltwater in a topographic depression.		X
Glacial-lake deposits	Layers of sediment in the lake bed, deltas, or beaches of a glacial lake.		X
Loess	Unstratified sheets of clayey silt and silty clay transported beyond the margins of a glacier by wind and/or braided streams; it is compact and able to resist significant erosion when exposed in steep slopes or cliffs.		X

FIGURE 13.6 Depositional features of mountain or continental glaciation.

ice reaches its maximum thickness and extent during the winter months, then it melts back to a minimum extent and thickness during the summer months. In the northern hemisphere, Arctic sea ice reaches its minimum thickness and extent by September. Sea ice helps moderate Earth's climate, because its bright white surface reflects sunlight back into space. Without sea ice, the ocean absorbs the sunlight and warms up. Sea ice also provides the ideal environment for animals like polar bears, seals, and walruses to hunt, breed, and migrate as survival dictates. Some Arctic human populations rely on subsistence hunting of such species to survive.

WATER BODIES OF GLACIATED REGIONS		MOUNTAIN GLACIATION	CONTINENTAL GLACIATION
Tarn	Small lake in a cirque (bowl-shaped depression formed by a cirque glacier). A melting cirque glacier may also fill part of the cirque and may be in direct contact with or slightly up-slope from the tarn.	X	
Ice-dammed lake	Lake formed behind a mass of ice sheets and blocks that have wedged together and blocked the flow of water from a melting glacier and or river. Such natural dams may burst and produce a catastropic flood of water, ice blocks, and sediment.	X	X
Paternoster lakes	Chain of small lakes in a glacial trough.	X	
Finger lake	Long narrow lake in a glacial trough that was cut into bedrock by the scouring action of glacial ice (containing rock particles and acting like sand paper as it flows downhill) and usually dammed by a deposit of glacial gravel (end or recessional moraine).	X	X
Kettle lake or kettle hole	Small lake or water-saturated depression (10s to 1000s of meters wide) in glacial drift, formed by melting of an isolated, detached block of ice left behind by a glacier in retreat (melting back) or buried in outwash from a flood caused by the collapse of an ice-dammed lake.	X	X
Swale	Narrow marsh, swamp, or very shallow lake in a long shallow depression between two moraines.		X
Marginal glacial lake	Lake formed at the margin (edge) of a glacier as a result of accumulating meltwater; the upslope edge of the lake is the melting glacier itself.	X	X
Meltwater stream	Stream of water derived from melting glacial ice, that flows under the ice, on the ice, along the margins of the ice, or beyond the margins of the ice.	X	X
Misfit stream	Stream that is not large enough and powerful enough to have cut the valley it occupies. The valley must have been cut at a time when the stream was larger and had more cutting power or else it was cut by another process such as scouring by glacial ice.	X	X
Marsh or swamp	Saturated, poorly drained areas that are permanently or intermittently covered with water and have grassy vegetation (marsh) or shrubs and trees (swamp).	X	X

FIGURE 13.7 Water bodies resulting from mountain or continental glaciation.

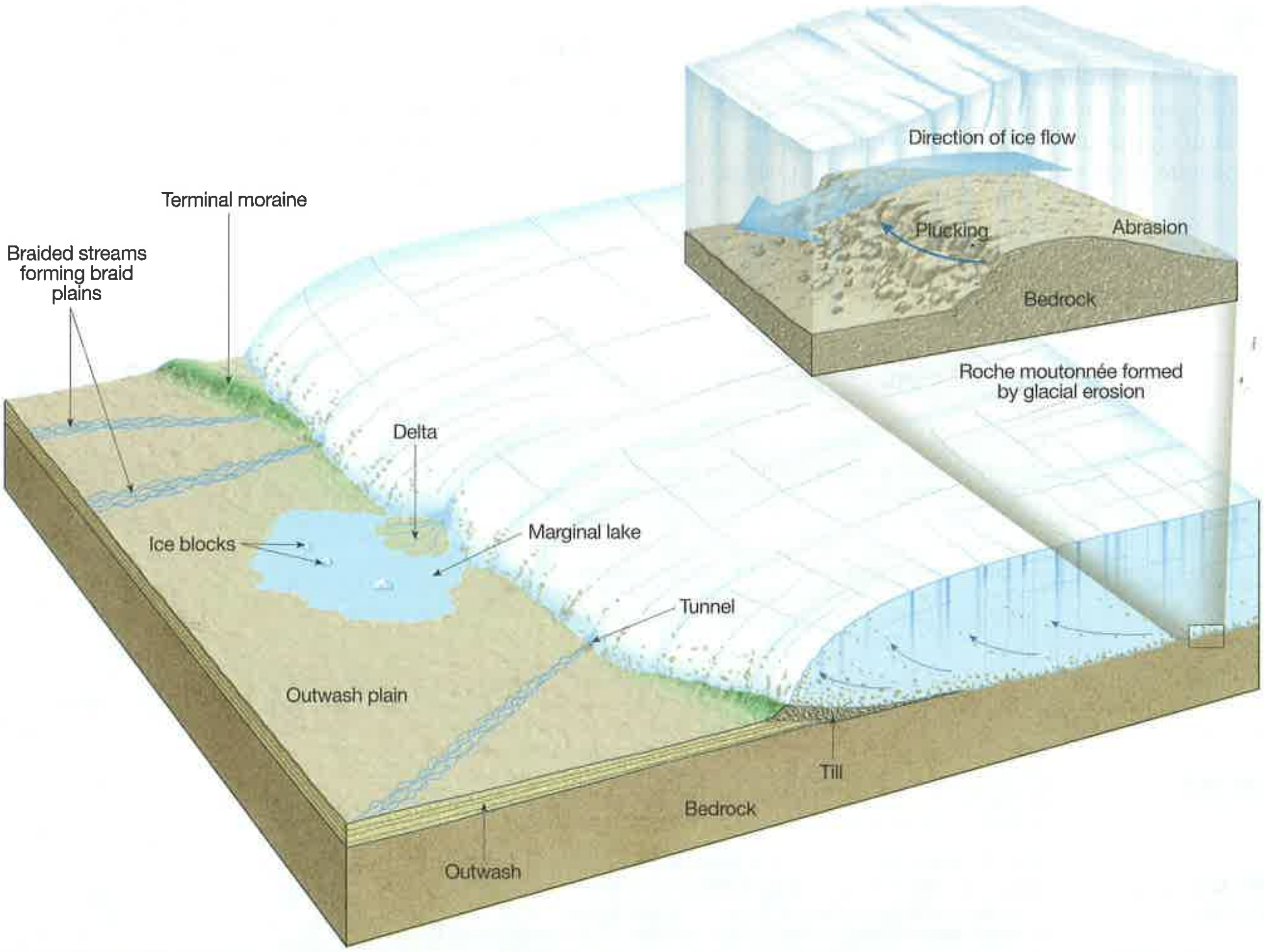


FIGURE 13.8 Continental glaciation in a hypothetical region. Continental glaciation produces these characteristic landforms at the beginning of ice wastage (decrease in glacier size due to severe ablation).

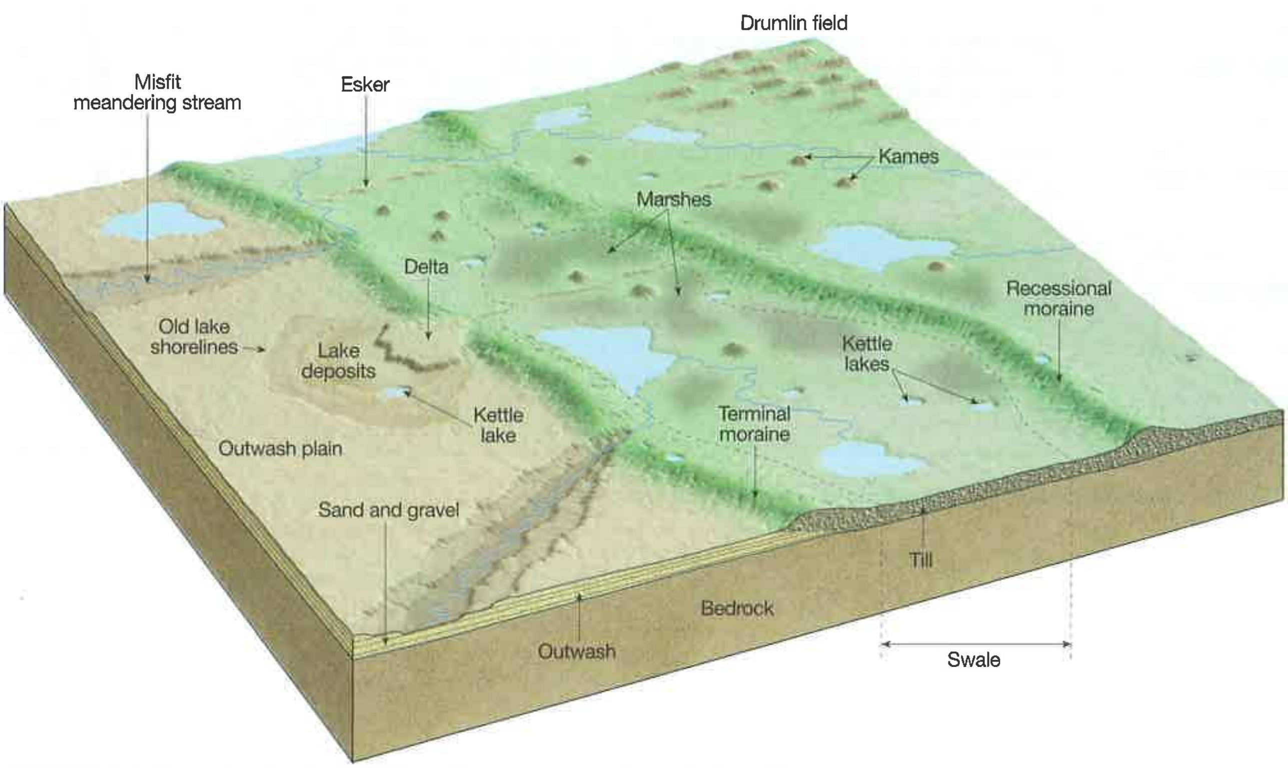


FIGURE 13.9 Erosional and depositional features of continental glaciation. Continental glaciation leaves behind these characteristic landforms after complete ice wastage. (Compare to FIGURE 13.8.)

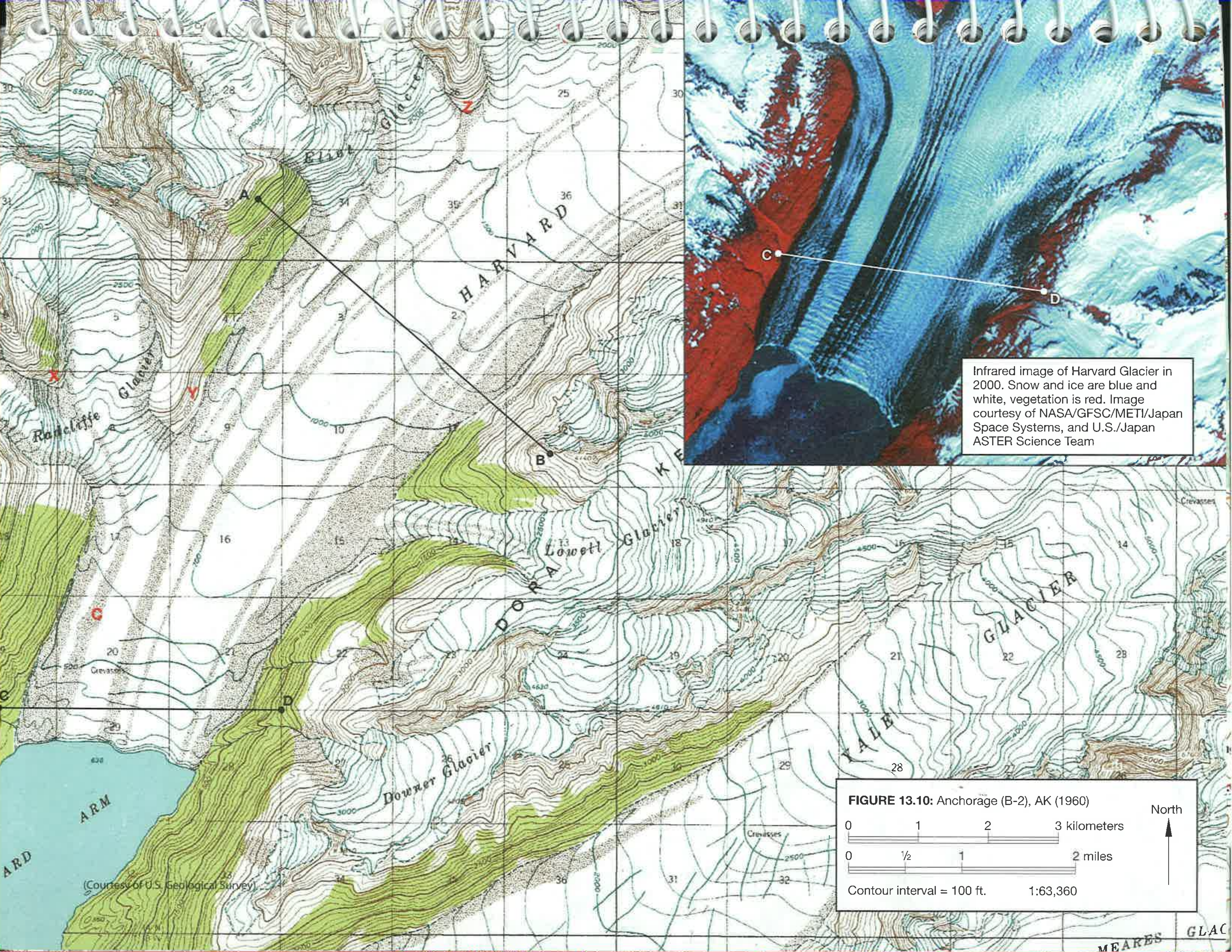


FIGURE 13.10: Anchorage (B-2), AK (1960)

Infrared image of Harvard Glacier in 2000. Snow and ice are blue and white, vegetation is red. Image courtesy of NASA/GFSC/METI/Japan Space Systems, and U.S./Japan ASTER Science Team

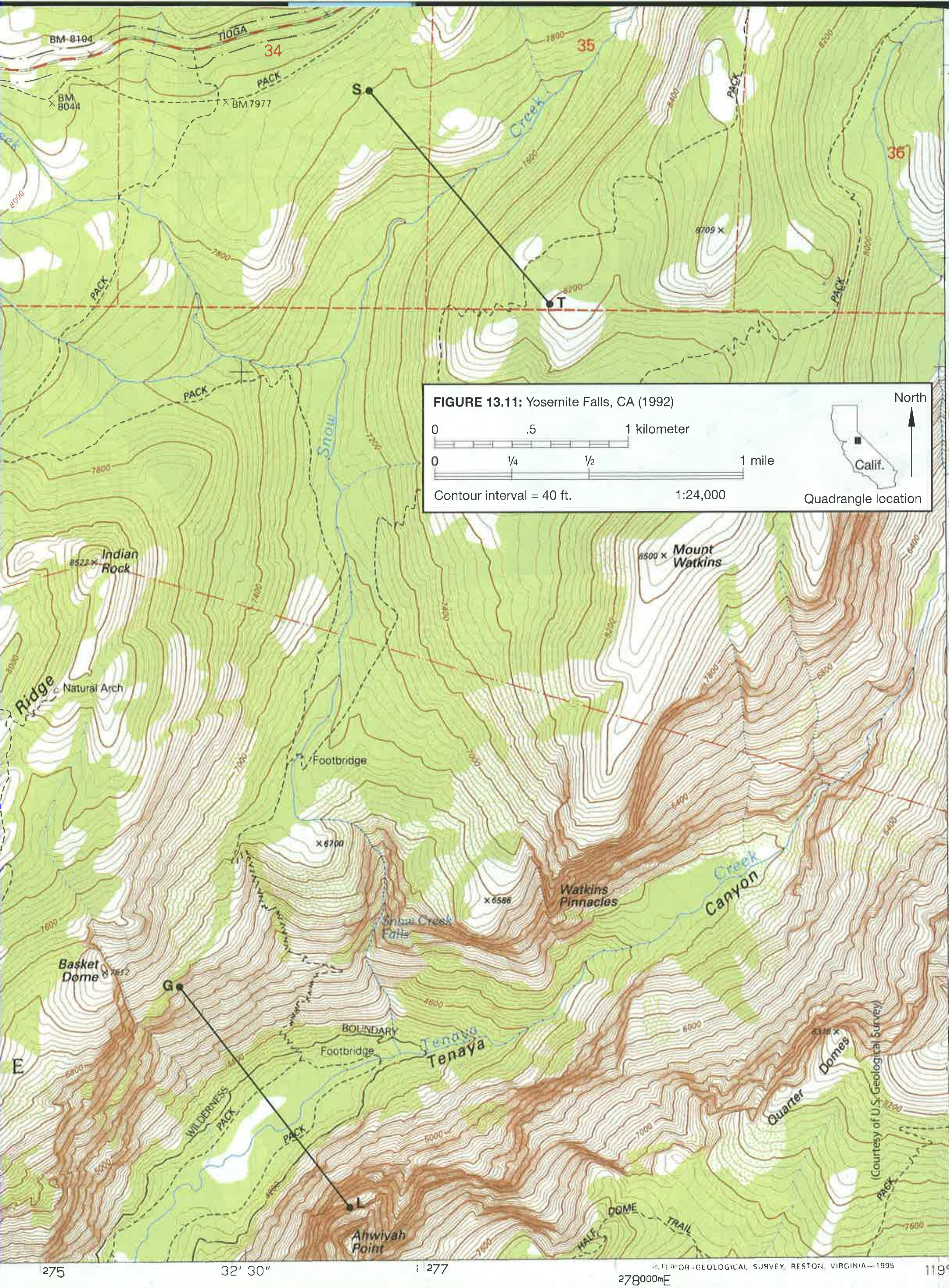


FIGURE 13.11: Yosemite Falls, CA (1992)

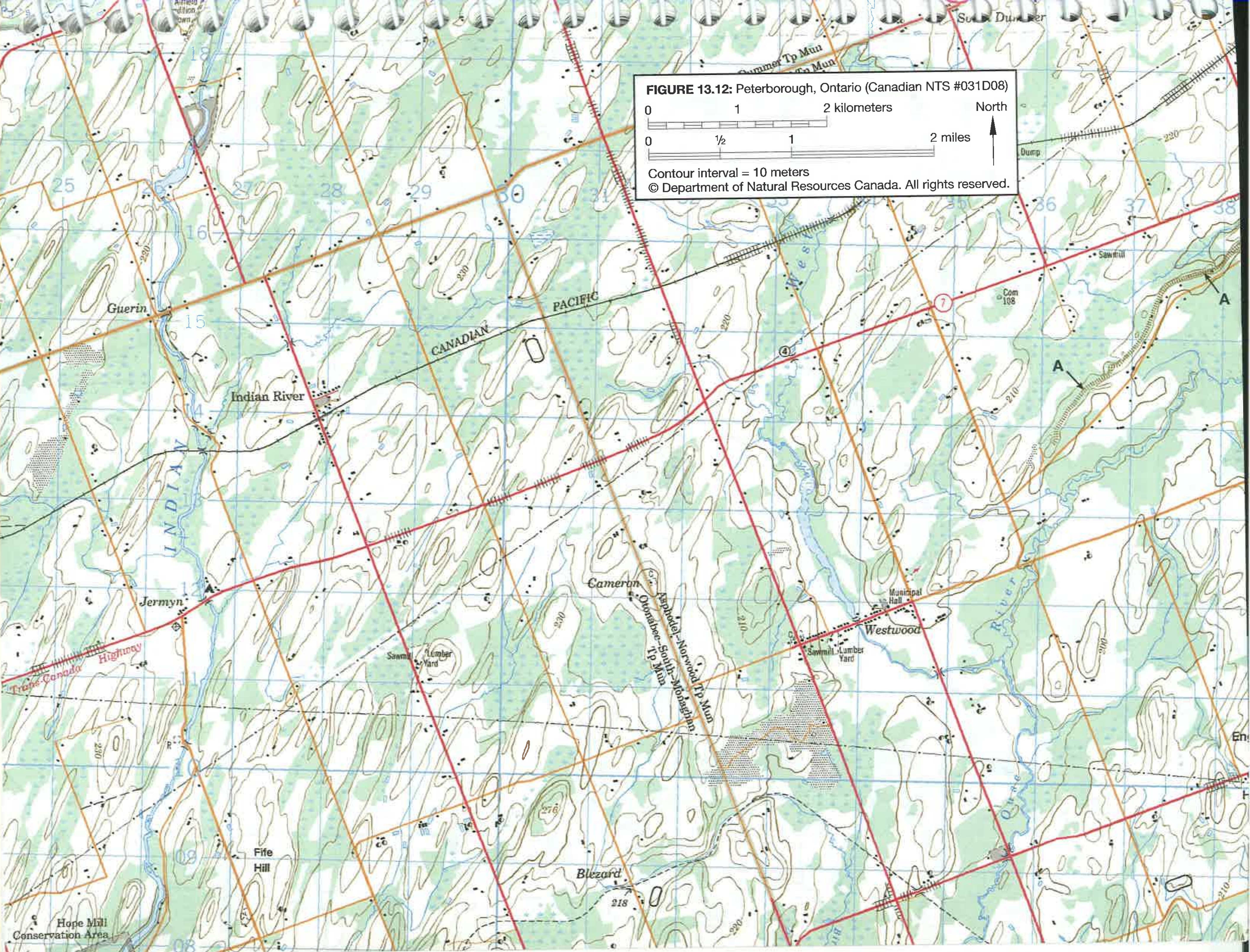


FIGURE 13.12: Peterborough, Ontario (Canadian NTS #031D08)

0 1 2 kilometers

0 ½ 1 2 miles

North

Contour interval = 10 meters

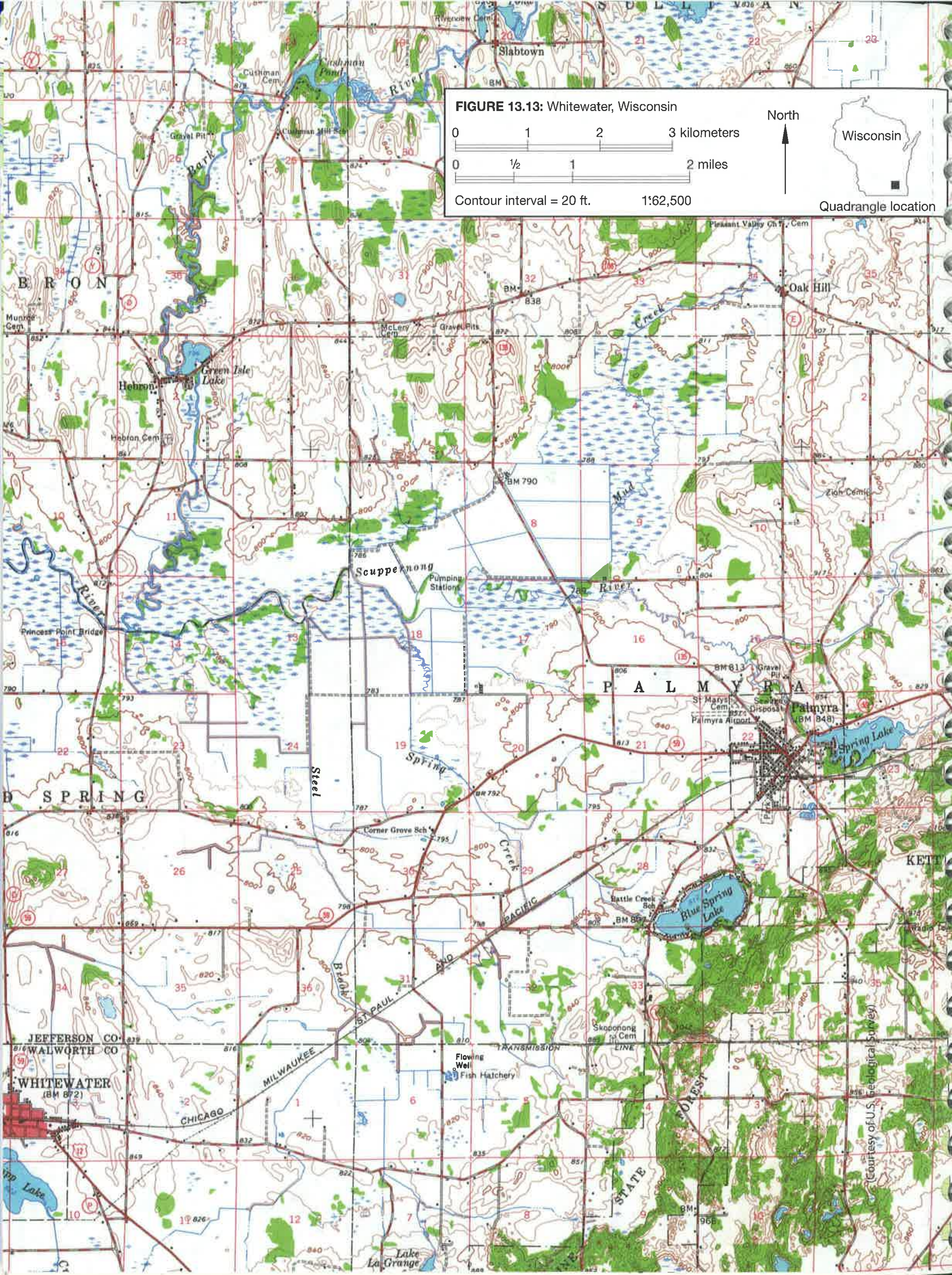


FIGURE 13.13: Whitewater, Wisconsin

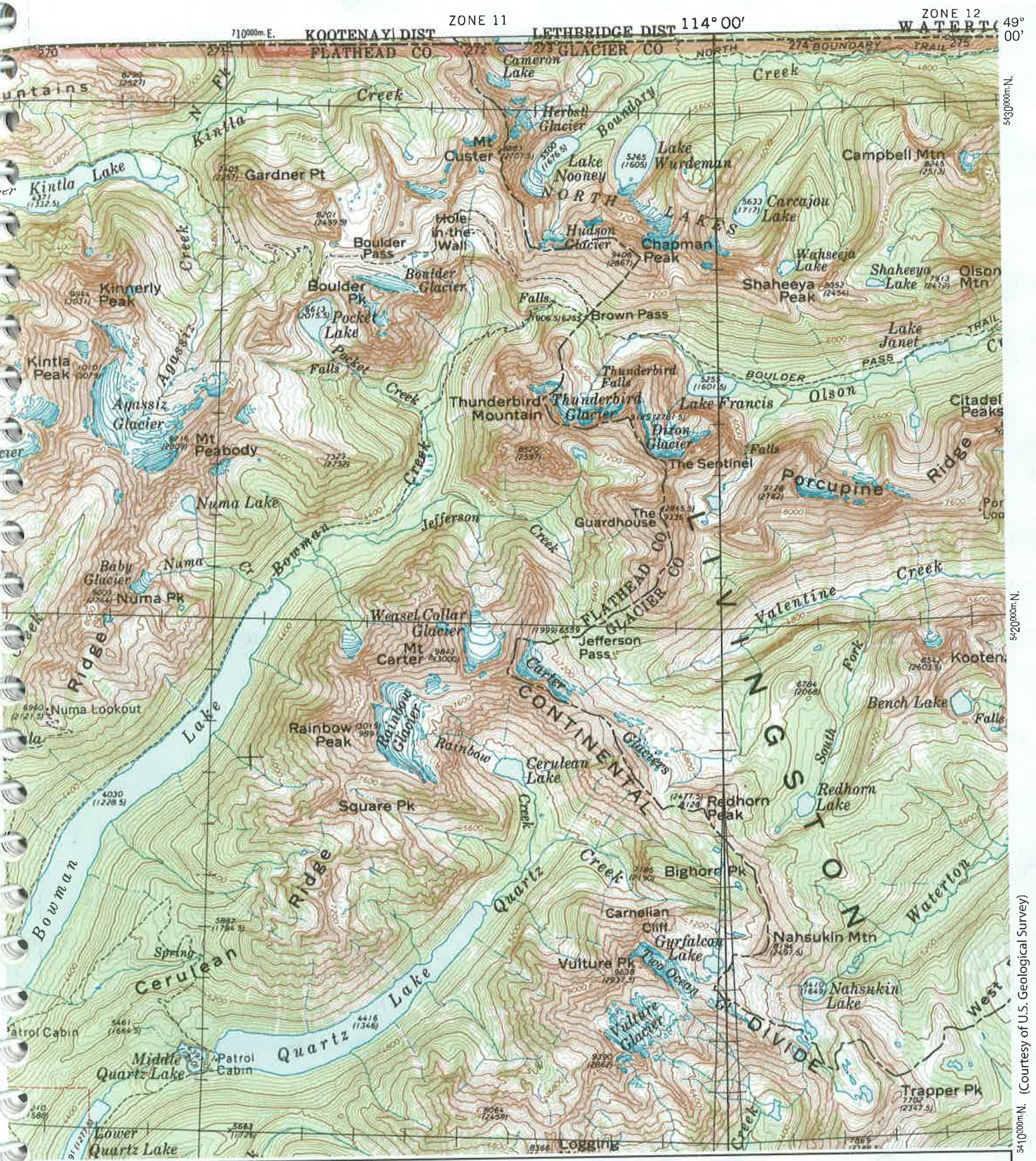
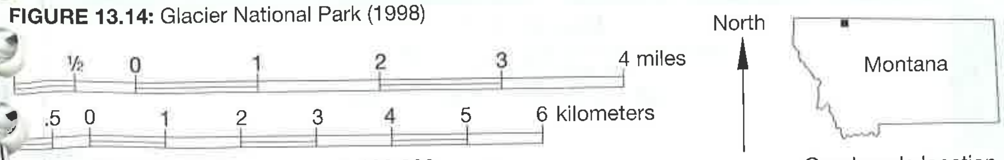


FIGURE 13.14: Glacier National Park (1998)



Contour interval = 80 ft. 1:100,000

North American Datum of 1927 (NAD27) grid.

Glacier Data				
Name	1850 Area (km²)	1966 Area (km²)	1993 Area (km²)	2005 Area (km²)
Agassiz	4.06	1.59	1.02	1.04
Vulture	0.77	0.65	0.21	0.32

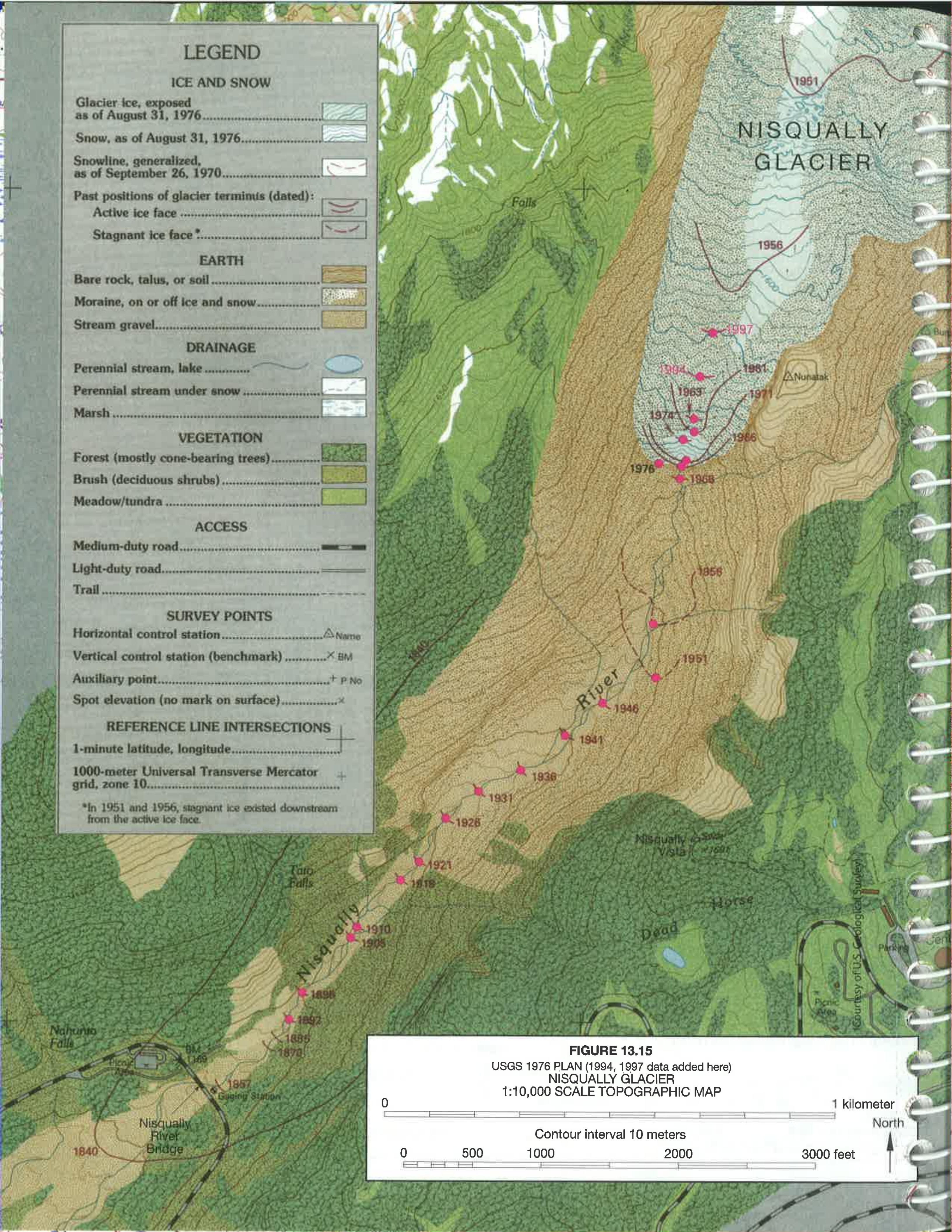


FIGURE 13.15
USGS 1976 PLAN (1994, 1997 data added here)
NISQUALLY GLACIER
1:10,000 SCALE TOPOGRAPHIC MAP

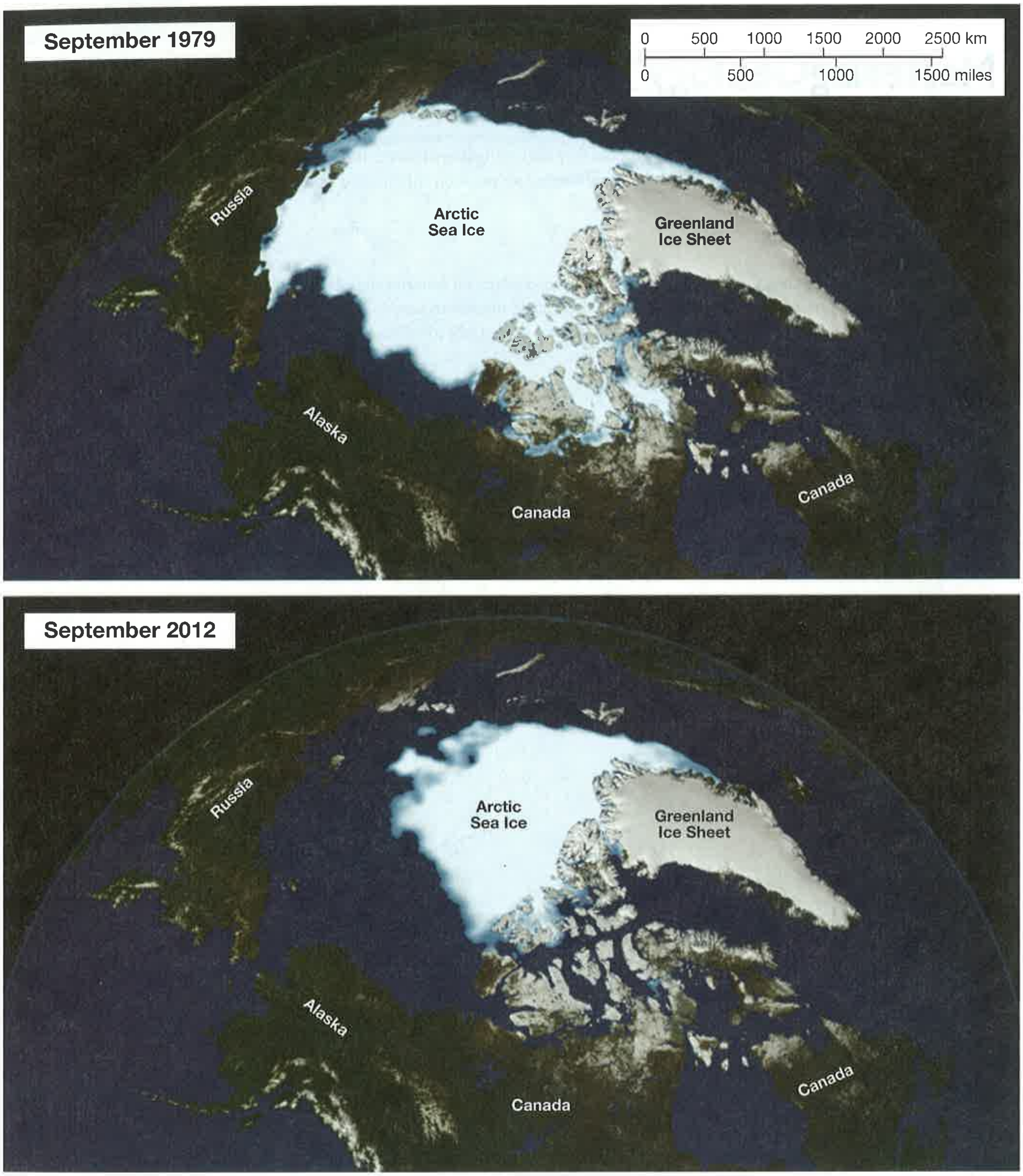


FIGURE 13.16 Extent of Arctic Sea Ice: 1979 and 2012. Sea ice covers essentially all of the Arctic Ocean in winter months, but it melts back to a minimum thickness and extent by the end of summer (September). These NASA satellite images reveal the minimum extent of Arctic sea ice at times 33 years apart. Dark blue areas are ocean; gray areas are mountain glaciers and the Greenland Ice Sheet. White and light blue areas are the Arctic sea ice.

ACTIVITY 13.1 Cryosphere Inquiry

Name: ______________________ **Course/Section:** ______________________ **Date:** __________

A. The cryosphere is all of Earth's snow and ice.

1. In **FIGURE 13.1**, what is the sequence of cryosphere regions that you would encounter on the ground if you traveled from Mexico (a beige- to yellow-colored region with no snow or ice) to the North Pole?

2. Notice in **FIGURE 13.1** that mountain glaciers and ice caps occur in parts of Greenland, Canada, Russia, Alaska, and the western conterminous United States. Some mountain glaciers also exist very close to the equator (not shown in **FIGURE 13.1**). How do you think it is possible for glaciers to exist at the equator?

3. If the temperature of Earth's atmosphere were to rise, then how do you think it would affect the cryosphere, hydrosphere, and biosphere?

4. If the temperature of Earth's atmosphere were to cool, then how do you think it would affect the cryosphere, hydrosphere, and biosphere?

B. Snow and glaciers are two of the best known parts of the cryosphere. Notice the snow and glaciers in the satellite image on the next page. It is a perspective view, looking north, of part of the Himalayan Mountains and was made by draping an ASTER natural color satellite image over a digital elevation model (by the NASA/GSFC/METI/ERSDAC/JAROS and U.S./Japan ASTER Science Team). You can view the same region in Google Earth™ by searching for coordinates 28 09 38 N, 90 03 05 E.

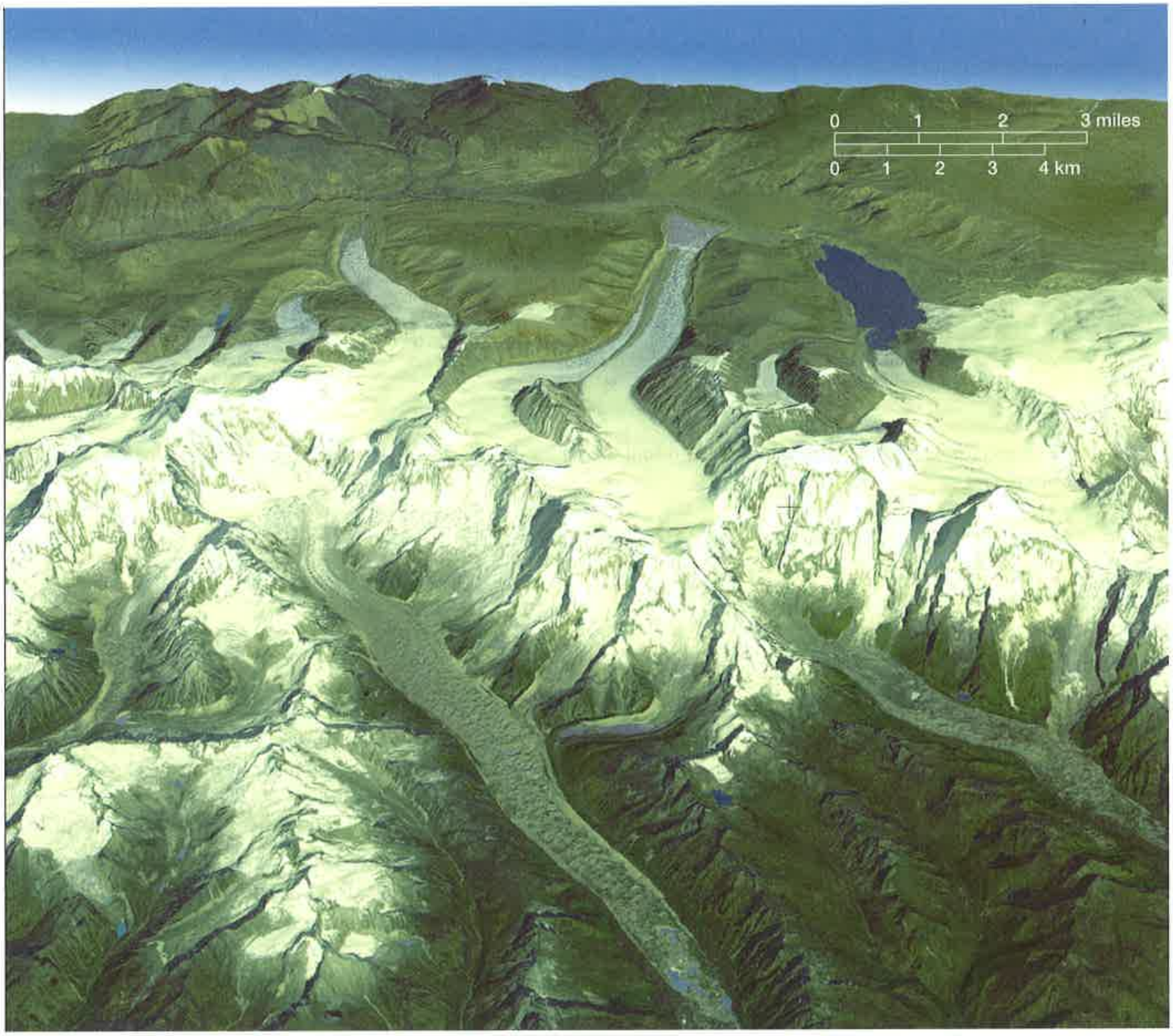
The glaciers in the satellite image formed by compaction and recrystallization of snow at higher elevations. Then they flowed downhill, where they eventually melt. A glacier's **mass balance** is the difference between the mass of its ice that is accumulating and the mass of ice that is melting. If a glacier has more ice accumulating than melting, then it has a positive mass balance and will advance downhill. If a glacier melts faster than it accumulates ice, then it has a negative mass balance and will retreat (melt back).

1. The satellite image was acquired in summer of 2009, after most of the seasonal snow had melted. Using a pen, draw a line along the **snowline**—the line between areas with snow (higher elevations) and areas with no snow.
2. Place arrows on the glaciers to show their direction of flow, like a river of ice.
3. Label the "area of snow and ice accumulation" and two "areas of ablation" (glacial melting).
4. Label the area where the glaciers have "positive mass balance" and the areas where the glaciers have a "negative mass balance."
5. Is the mass balance of the snowline that you drew in part B1 positive, negative, or neither? Why?

C. Refer to **FIGURE 13.2**, an ASTER satellite image of a 20-by-20 km area of southern Alaska. It is an infrared image, so vegetation appears red, glacial ice is blue, and snow is white.

1. Where is the zone of ablation in this image, and how can you tell?

2. Name two resources (used by humans) that were created by the glaciers in **FIGURE 13.2**?



D. **REFLECT & DISCUSS** In what ways have the glaciers affected the landscape in the above image, and what does it suggest about how extensive these glaciers must have been in the past?

ACTIVITY 13.2 Mountain Glaciers and Glacial Landforms

Name: ______________________ **Course/Section:** ______________ **Date:** ________

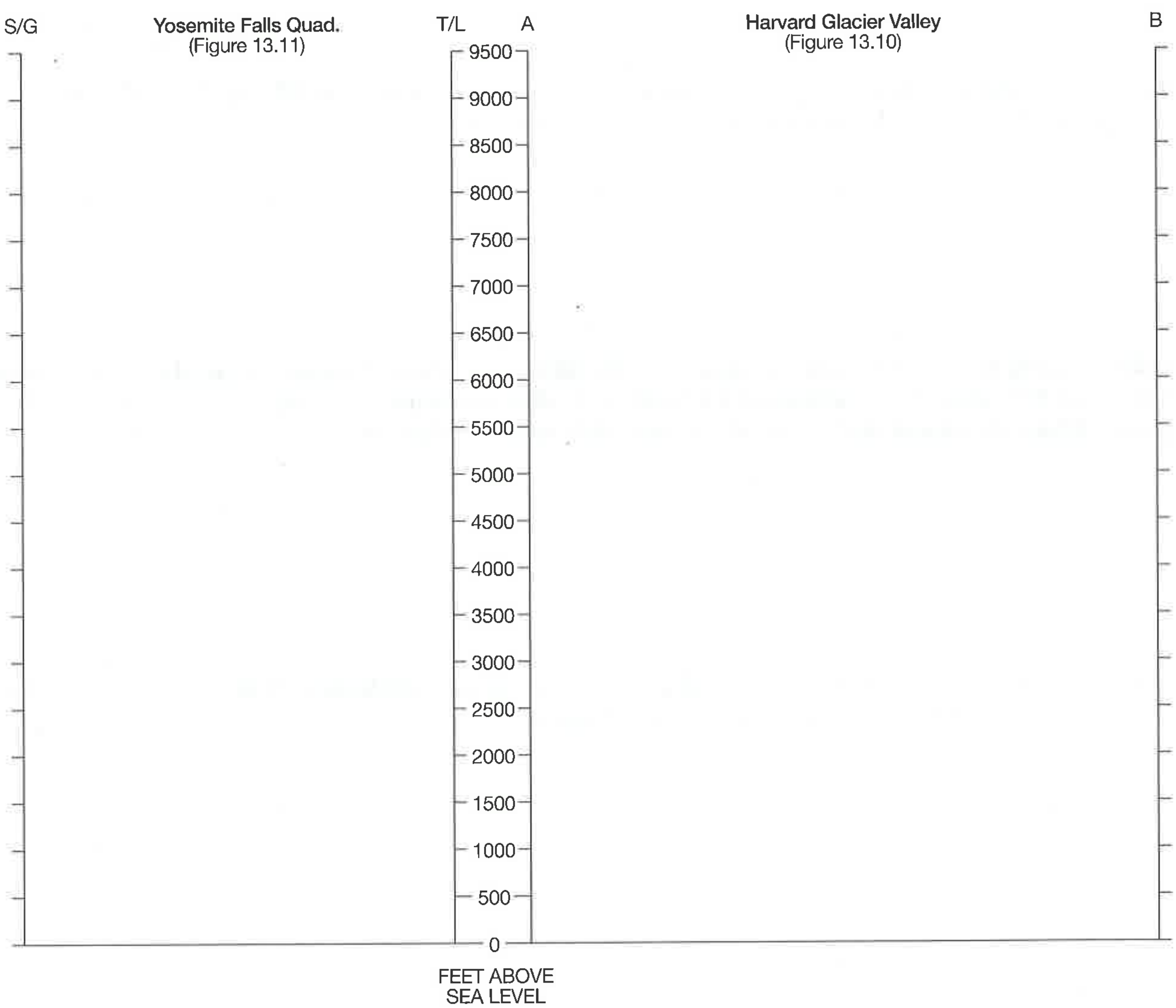
A. FIGURE 13.10 is a topographic map of modern mountain glaciation near Anchorage, Alaska. FIGURE 13.11 is a topographic map of the southeast part of the Yosemite Falls, California quadrangle (Yosemite National Park), which was shaped by Pleistocene glaciers (that have since melted away) and modern streams.

1. On the left-hand side of the graph below, construct and label a topographic profile for line ***S–T*** *across a valley on* FIGURE 13.11 *that is being cut by a modern river.* Refer to FIGURE 9.16 (Topographic Profile Construction), if needed.
2. On the left-hand side of the graph below, also construct and label a topographic profile for line ***G–L*** *across a valley on* FIGURE 13.11 *that was scoured and shaped by a Pleistocene valley glacier.*
3. Which of the above cross sections (river or glacial) is "V" shaped: ______________

   Describe the erosional process that you think causes this shape.

4. Which of the above cross sections (river or glacial) is "U" shaped: ______________

   Describe the erosional process that you think causes this shape.



5. On the right-hand side of the graph on page 349, complete the topographic profile for line ***A–B** across the Harvard Glacier* (**FIGURE 13.10**).

   a. Label the part of the profile that is the top surface of the glacier.

   b. Using a dashed line, draw where you think the rock bottom of the valley is located under the Harvard Glacier. (Your drawing may extend slightly below the figure.)

   c. Based on the profile that you just constructed, what is the maximum thickness of Harvard Glacier along line **A–B?**

B. Refer back to **FIGURE 13.10**, a portion of the Anchorage (B-2), Alaska, quadrangle, for the following questions. In the southwestern corner, note the Harvard Arm of Prince William Sound. The famous *Exxon Valdez* oil spill occurred just south of this area (it did not affect Harvard Arm).

1. Lateral and medial moraines in/on the ablation zone of Harvard Glacier are indicated by the stippled (finely dotted) pattern on parts of the glacier. If a hiker found gold in rock fragments on the glacier at location **C,** then would you look for gold near location **X, Y,** or **Z?** Explain your reasoning.

2. Notice the crevasses (blue line segments) within a mile of Harvard Glacier's terminus. What specific kind of crevasses are they, and why do you think they formed only on this part of the glacier?

C. Refer back to the Yosemite Falls, California quadrangle (**FIGURE 13.11**) and locate the small steep-sided valley upstream from Snow Creek Falls (about 1.5 km northeast of line **G–L**). Such valleys are common on the sides of valleys carved by valley glaciers. What is the name of this kind of valley (**FIGURE 13.4**), and how did it form?

D. REFLECT & DISCUSS Compare the topographic map and satellite image of Harvard Glacier. Does Harvard Glacier have a positive mass balance or a negative mass balance? Explain your reasoning.

ACTIVITY 13.3 Continental Glaciation of North America

Name: ______________________ **Course/ection:** ______________________ **Date:** ____________

A. Refer to **FIGURE 13.12**, part of the Peterborough, Ontario, quadrangle, for the following questions. This area lies north of Lake Ontario.

1. Study the size and shape of the short, oblong rounded hills. Fieldwork has revealed that they are made of till. What type of feature are they and how did they form?

2. Find the long narrow hill labeled **A**. It is marked by a symbol made of a long line of tiny pairs of brown dots. What would you call this linear feature, and how do you think it formed?

3. Towards what direction did the glacial ice flow here, and how can you tell?

B. The most recent glaciation of Earth is called the *Wisconsinan glaciation.* It reached its maximum development about 18,000 years ago, when a "*Laurentide Ice Sheet*" covered central and eastern Canada, the Great Lakes Region, and the northeastern United States. It ended by about 11,700 years ago, at the start of the Holocene Epoch. Refer to **FIGURE 13.13**, a portion of the Whitewater, Wisconsin, quadrangle.

1. List the features of glaciated regions from **FIGURES 13.8** and **13.9** that are present in this region.

2. Describe in what direction the ice flowed over this region. Cite evidence for your inference.

3. What kinds of lakes are present in this region, and how did they form? (Refer to **FIGURE 13.7**.)

4. In the southeastern corner of the map, the northwest-trending forested area is probably what kind of feature?

5. Note the swampy and marshy area running from the west-central edge of the map to the northeastern corner. Describe the probable origin of this feature (more than one answer is possible).

C. **REFLECT & DISCUSS** How are the glaciated areas of **FIGURES 13.12** and **13.13** different from areas affected by mountain glaciation and how are they they same?

ACTIVITY 13.4 Glacier National Park Investigation

Name: ______________________ **Course/Section:** ______________________ **Date:** __________

Refer to the map of Glacier National Park in **FIGURE 13.14**.

A. List the features of glaciation from **FIGURES 13.3, 13.4, 13.8,** or **13.9** that are present in **FIGURE 13.14**.

B. Locate Quartz Lake and Middle Quartz Lake in the southwest part of the map. Notice the Patrol Cabin located between these lakes. Describe the chain of geologic/glacial events (steps) that led to formation of Quartz Lake, the valley of Quartz Lake, the small piece of land on which the Patrol Cabin is located, and the cirque in which Rainbow Glacier is located today.

C. Based on your answers above, what kind of glaciation (mountain versus continental) has shaped this landscape?

D. Locate the Continental Divide and think of ways that it may be related to weather and climate in the region. Recall that weather systems generally move across the United States from west to east.

1. Describe how modern glaciers of this region are distributed in relation to the Continental Divide.

2. Based on the distribution you observed, describe the weather/climate conditions that may exist on opposite sides of the Continental Divide in this region.

E. Describe how the size (area in km^2) of Agassiz Glacier changed from 1850 to 2005.

F. Describe how the size (area in km^2) of Vulture Glacier changed from 1850 to 2005.

G. **REFLECT & DISCUSS** What do you expect the area (km^2) of Agassiz and Vulture Glaciers to be in 2020? Explain.

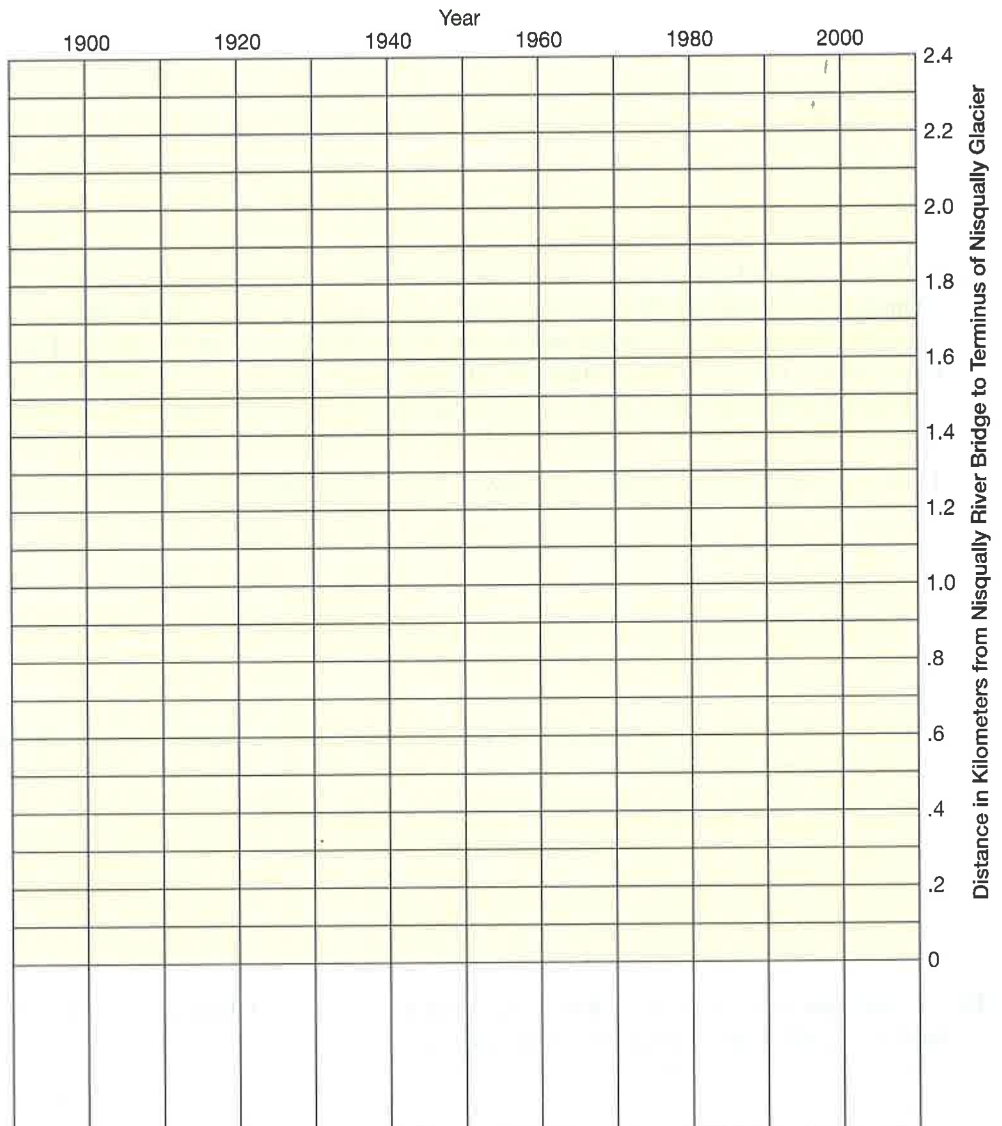
Nisqually Glacier Response to Climate Change

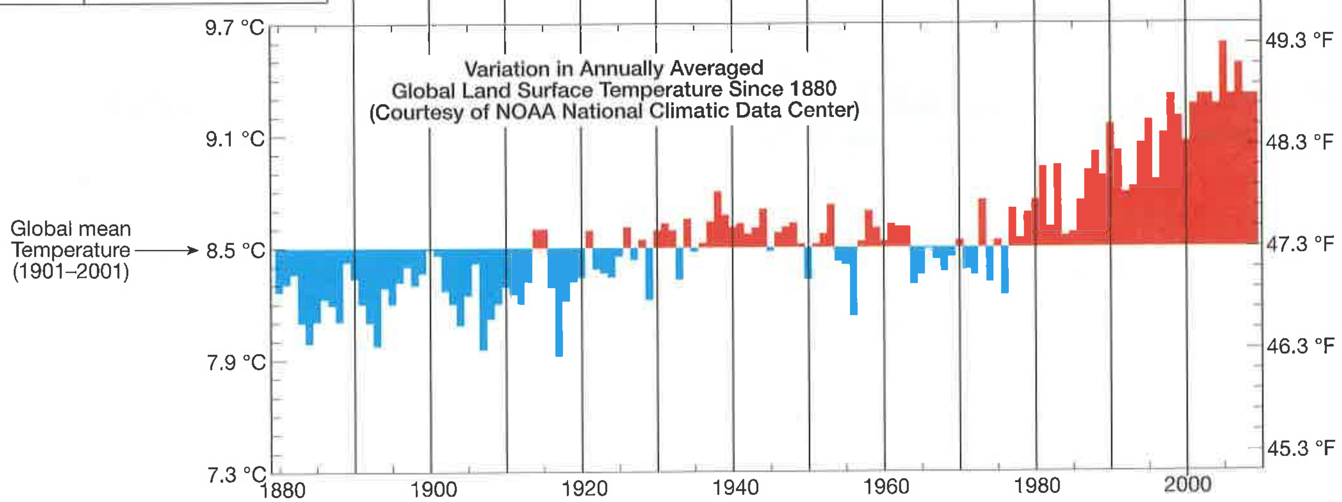
Name: ______________________ **Course/Section:** ______________________ **Date:** ______________

A. **Refer to FIGURE 13.15 and fill** in the Nisqually Glacier Data Chart below. To do this, use a ruler and the map's bar scale to measure the distance in kilometers from Nisqually River Bridge to the position of the glacier's terminus (red dot) for each year of the chart. Be sure to record your distance measurements to two decimal points (hundredths of km).

NISQUALLY GLACIER DATA CHART

Year	Distance in kilometers from Nisqually River Bridge to terminus of Nisqually Glacier
•2010	
•1997	
•1994	
•1976	
•1974	
•1971	
•1968	
•1966	
•1963	
•1961	
•1956	
•1951	
•1946	
•1941	
•1936	
•1931	
•1926	
•1921	
•1918	
•1910	
•1905	
•1896	
•1892	





B. Plot your data from part A (Nisqually Glacier Data Chart) in the graph to the right of the data chart. After plotting each point of data, connect the dots with a smooth, light pencil line. Notice that the glacier terminus retreated up the valley at some times, but advanced back down the valley at other times. Summarize these changes in a chart or paragraph, relative to specific years of the data.

C. Notice the blue and red graph of climatic data at the bottom of your graph (part B) provided by the NOAA National Climatic Data Center (NCDC). NCDC's global mean temperatures are mean temperatures for Earth calculated by processing data from thousands of observation sites throughout the world (from 1880 to 2009). The temperature data were corrected for factors such as increase in temperature around urban centers and decrease in temperature with elevation. Although NCDC collects and processes data on land and sea, this graph only shows the variation in annually averaged global land surface temperature since 1880.

1. Describe the long-term trend in this graph—how averaged global land surface temperature changed from 1880 to 2005.

2. Lightly in pencil, trace any shorter-term pattern of cyclic climate change that you can identify in the graph. Describe this cyclic shorter-term trend.

D. Describe how the changes in position of the terminus of Nisqually Glacier compare to variations in annually averaged global land surface temperature. Be as specific as you can.

E. **REFLECT & DISCUSS** Based on all of your work above, do you think Nisqually Glacier can be used as a global thermometer for measuring climate change? Explain.

ACTIVITY 13.6 The Changing Extent of Sea Ice

Name: ______________________________ **Course/Section:** ______________________ **Date:** __________

A. Refer to the satellite images of Arctic sea ice in **FIGURE 13.16** on page 345. These images were both taken in the month of September, when sea ice is at its minimum thickness and extent. "Extent" refers to how far the ice extends in all directions: its total area without regard for tiny ice free areas within the overall body of sea ice. It is easy to see that there was less sea ice in September of 2012 than in September of 1979, but how much less? To find out, you need to measure the extent of the sea ice in 1979 and 2012 by following these directions.

Step 1. Start by using a piece of thin string or thread about 30 cm (12 in.) long to measure the circumference of the sea ice. Carefully lay the string along the edge of the body of sea ice so that the string totally surrounds it as perfectly as possible. Then lay that length (segment) of string along the bar scale to determine the circumference of the sea ice in kilometers.

Step 2. Assume that the circumference of sea ice that you just measured is like the circumference of a circle. Circumference of a circle is equal to 2 times ∏ (3.14) times radius, so radius (r) equals circumference divided by 2 times ∏. So, determine the radius of the ice sheet by dividing the circumference (Step 1) by 6.28.

Step 3. Area of a circle is equal to ∏ (3.14) times the square of its radius. So determine the area of the ice sheet by multiplying the radius from step 2 by itself (to get radius squared), and then multiply that number by 3.14. Your answer will be in square kilometers (km^2).

1. Using the three steps above, what was the extent of Arctic sea ice in September of 1979, in millions of km^2? Show your work below.

2. Using the three steps above, what was the extent of Arctic sea ice in September of 2012, in millions of km^2? Show your work below.

3. Based on your limited set consisting of just two years of data, what has been the rate of Arctic sea ice decline from 1979 to 2012 (in km per year)? Show your work.

B. Scientists at the National Snow and Ice Data Center (NSIDC) have measured the annual September extent of Arctic and Antarctic sea ice in more exact ways. Arctic sea ice fills the Arctic Ocean, which is confined by land masses like Asia (Russia), North America, and Greenland (**FIGURE 13.1**). A table of the NSIDC data is provided on the next page.

1. Graph all of the data for extent of Arctic sea ice from 1979 to 2013, then use a ruler to draw a "best fit" line through the points so that the number of, and distance to, points above and below the line is similar. Label the line as "Arctic."

2. What was the average annual extent of Arctic sea ice from 2000 to 2007, in millions of km^2? Show your work.

3. What was the average annual extent of Arctic sea ice from 2008 to 2013, in millions of km^2? Show your work.

4. Based on your graph and calculations above, would you say that the annual amount of Arctic sea ice is decreasing, increasing, or staying about the same? Explain.

5. What do you predict the extent of Arctic sea ice will be in 2015?

6. Graph all of the data for extent of Antarctic sea ice from 1979 to 2013, then use a ruler to draw a "best fit" line through the points. Label the line as "Antarctic."

7. What was the average annual extent of Antarctic sea ice from 2000 to 2007, in millions of km^2? Show your work.

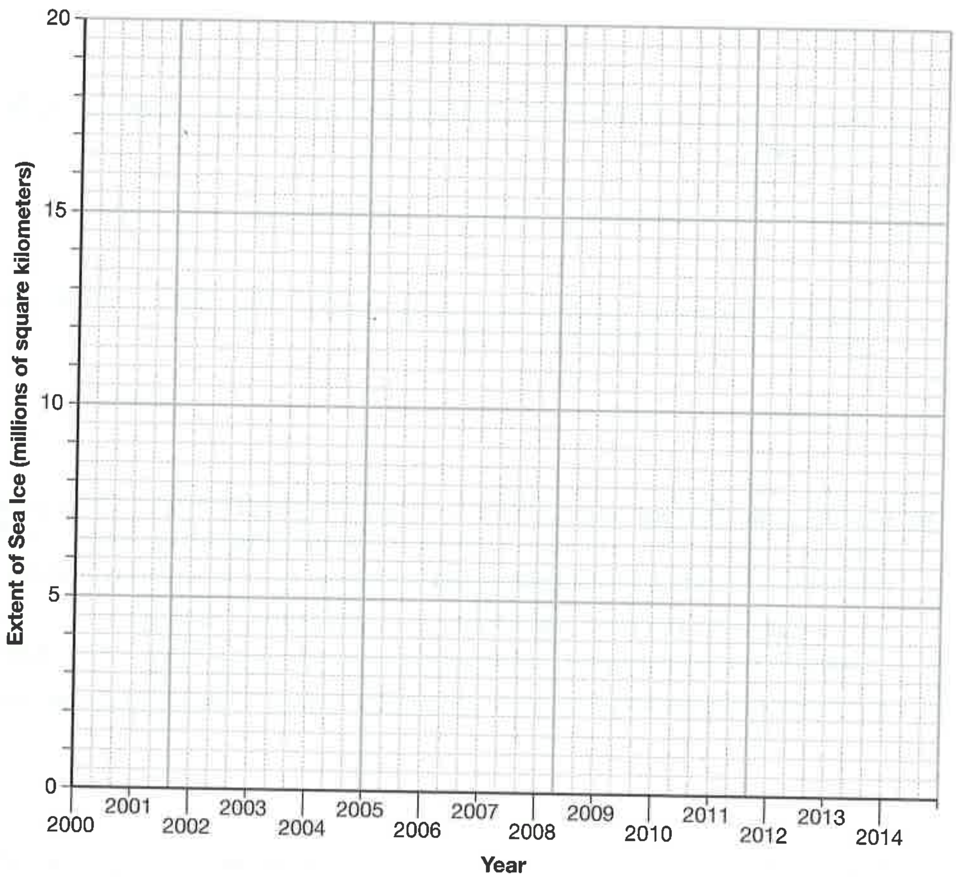
8. What was the average annual extent of Antarctic sea ice from 2008 to 2013, in millions of km^2? Show your work.

9. Based on your graph and calculations above, would you say that the annual amount of Antarctic sea ice is decreasing, increasing, or staying about the same? Explain.

Summer Extent of Sea Ice

Year	Arctic Extent in millions of square kilometers	Antarctic Extent in millions of square kilometers
2000	3.4	19.1
2001	3.5	18.4
2002	6.0	18.2
2003	6.2	18.6
2004	6.1	19.1
2005	5.6	19.2
2006	6.0	19.3
2007	4.3	19.2
2008	4.7	18.5
2009	5.4	19.1
2010	4.9	19.2
2011	4.6	18.9
2012	3.6	19.4
2013	5.4	19.8

(Courtesy of National Snow and Ice Data Center (NSIDC))



C. **REFLECT & DISCUSS** The changes in Arctic sea ice extent over time are not the same as the Antarctic changes. Why do you think the two bodies of sea ice are so different, and what benefits or hazards could result if the Arctic sea ice continues to decline?