Glaciers and Glaciation
A glacier is a thick mass of ice that forms, over hundreds and thousands of years, by the accumulation, compaction, and recrystallization of snow.

Glaciers are parts of two basic cycles:
- Hydrologic cycle
  - Water can be trapped in a glacier for many years
- Rock cycle
Glaciers: A Part of Two Basic Cycles

• Valley (Alpine) Glaciers
  – Glaciers that exist in valleys of mountainous areas are called valley or alpine glaciers
    • Flow down the valley

• Ice Sheets
  – Ice sheets exist on a larger scale than valley glaciers
    • Examples: Greenland and Antarctica
Greenland’s ice sheet occupies 1.7 million square kilometers (663,000 square miles), about 80 percent of the island.

The area of the Antarctic Ice Sheet is almost 14 million square kilometers (5,460,000 square miles). Ice shelves occupy an additional 1.4 million square kilometers (546,000 square miles).
Glaciers: A Part of Two Basic Cycles

• Ice Sheets
  – Ice Age ice sheets
    • 18,000 years ago, ice sheets covered large portions of North America, Europe, and Siberia
    • Over the past 2.6 million years, ice sheets have advanced and retreated multiple times
Glaciers: A Part of Two Basic Cycles

• Ice Sheets
  – Greenland and Antarctica
    • The Arctic Ocean is covered with sea ice (frozen seawater), not glacial ice
      – Sea ice is up to 4 meters thick while glaciers are hundreds to thousands of meters thick
    • Glaciers form on land
      – Greenland in the northern hemisphere
      – Antarctica in the southern hemisphere
    • Ice flows out in all directions from one or more snow accumulation centers
Glaciers: A Part of Two Basic Cycles

- Ice Sheets
  - Ice shelves
    - Along parts of Antarctica, glacial ice flows into the sea, creating ice shelves
      - In shallow water, the ice touches bottom and is grounded
      - In deep water, the ice shelf floats
    - Thickest on landward side and thin seaward
    - Some ice shelves are unstable and starting to break apart
      - Breakup of ice shelves attributed to regional global warming
Ice Shelves

In shallow water, the ice shelf is grounded.

In deeper water the ice shelf floats.

As ice melts, material transported by the glacier is released and falls to the ocean floor. The rocks are called dropstones.
Glaciers: A Part of Two Basic Cycles

• Other Types of Glaciers
  – Ice caps cover some uplands and plateaus
  – Ice caps and ice sheets feed outlet glaciers, which are tongues of ice extending outward from the large masses
  – Piedmont glaciers form when one or more alpine glacier emerges from the valley and spreads out in a broad lobe
Ice caps completely bury the underlying terrain but are much smaller than ice sheets.
When a valley glacier is no longer confined, it spreads out to become a piedmont glacier.
Formation and Movement of Glacial Ice

- Glaciers form in areas where more snow falls in winter than melts during the summer
  - Snow above the snowline does not melt in the summer
- Glacial Ice Formation
  - Air infiltrates snow
    * Snowflakes become smaller, thicker, and more spherical
Formation and Movement of Glacial Ice

• Glacial Ice Formation
  • Air is forced out
    – Snow is recrystallized into a much denser mass of small grains called firn
    – Once the thickness of the ice and snow exceeds 50 meters, firn fuses into a solid mass of interlocking ice crystals—glacial ice
Formation and Movement of Glacial Ice

• Movement of a Glacier
  – Glacial ice moves as flow
    • Plastic flow involves movement within the ice
      – Under pressure, ice behaves as a plastic material
    • Along the ground, the entire ice mass slides along the ground as basal slip
      – Meltwater acts as lubricant
Ice in the zone of fracture is carried along "piggyback" style.

Below a depth of about 50 meters (160 feet), ice behaves plastically (deforms without breaking) and gradually flows.

Basal slip occurs episodically. Ice in contact with the valley floor remains fixed as stress builds to the point that the glacier lurches forward.
Formation and Movement of Glacial Ice

• Movement of a Glacier
  – The upper 50 meters of a glacier is brittle and called the **zone of fracture**
  • Crevasses (cracks in the ice) are present in the zone of fracture but sealed off by plastic flow at depth
Crevasses
• Rates of Glacial Movement
  – Like a river, glacial ice does not all move at the same rate
    • Flow is fastest in the center of the glacier
  – Glacial velocity ranges from extremely slow to several meters per day
    • Some glaciers exhibit extremely rapid movements called surges
Movement of Antarctic Ice

- The slowest movement occurs along divides.
- Area of more rapid movement.
- Divide separating glacier basins.
- Divides are generally over mountains that shape the flow of ice.

Lambert Glacier drains about 900,000 square kilometers (500,000 square miles) of East Antarctica.
Formation and Movement of Glacial Ice

• Budget of a Glacier
  – Glacial zones
    • The *zone of accumulation* is the area where a glacier forms
      – Is located above the snowline
    • The *zone of wastage* is the area where there is a net loss of glacial ice
      – Melting
      – *Calving*—the breaking off of large pieces of ice (icebergs where the glacier has reached the sea)
Zones of a Glacier

ZONE OF ACCUMULATION
More snow falls each winter than melts each summer

ZONE OF WASTAGE
All the snow from the previous winter melts along with some glacial ice

Snowline
Crevasses
Braided streams
Formation and Movement of Glacial Ice

• Budget of a Glacier
  – Glacial budget
    • The glacial budget is the balance, or lack of balance, between accumulation and loss of ice
      – Loss of ice at the lower end of the glacier is called ablation
      – If accumulation exceeds loss, the glacial front advances
      – If ablation increases and/or accumulation decreases, the ice front will retreat
Glacial Erosion

- Glaciers are capable of great erosion and sediment transport
- Glaciers erode the land primarily in two ways:
  - As a glacier flows over a bedrock, it loosens and lifts blocks in a process called **plucking**
  - Rocks in the glacier also act like sandpaper to smooth and polish a rock surface in a process called **abrasion**
Glacial Erratic
Glacial Erosion

• Glacial abrasion produces:
  – Rock flours (pulverized rock)
  – Glacial striations (grooves in the bedrock)

• Glacial erosion is controlled by:
  – Rate of movement
  – Thickness of the ice
  – Types of rock fragments trapped in the ice
  – The erodibility of the surface below the glacier
Glacial Abrasion

A. Glacial abrasion created the scratches and grooves in this bedrock.

B. Glacially polished granite in California’s Yosemite National Park.
Landforms Created By Glacial Erosion

- Landforms created by valley glaciers and ice sheets are very different
  - Valley glaciers create sharp and angular topography
  - Ice sheets subdue most topography
Landforms Created By Glacial Erosion

• Glaciated Valleys
  – Glaciers widen and deepen valleys, creating U-shaped glacial troughs
  – Glaciers tend to straighten valleys, removing sharp curves and creating truncated spurs
  – Glaciers in a main (trunk) valley typically erode more than tributary glaciers, creating hanging valleys
Erosional Landforms Created by Alpine Glaciers

A. Un glaciated topography
- V-shaped valley
- Medial moraine
- Arête
- Horn
- Cirques

B. Region during period of maximum glaciation
- Main glacier
- Arête
- Tarn
- Horn
- Cirques

C. Glaciated topography
- Glacial trough
- Truncated spurs
- Hanging valley
- Pater noster lakes
U-Shaped Glacial Trough
• **Glaciated Valleys**
  
  – A *pater noster lake* forms after parts of the bedrock (lifted and plucked by the glacier) fill with water
  
  – A *cirque* (a bowl-shaped depression) is typically found at the head of a glacial valley
    
    • When two glaciers exist on opposite sides of a mountain, the dividing ridge erodes away, creating a gap called a *col*
Landforms Created By Glacial Erosion

• Glaciated Valleys
  – **Fiords** are deep, steep-sided inlets
    • Drowned glacial troughs that form when sea level rises
Fiords
Landforms Created By Glacial Erosion

• Arêtes and Horns
  – Some features form from the continued glacial erosion of cirques
    • An arête is a sharp-edged ridge
    • A horn is a pyramid-like peak
• **Roches Moutonnées**
  – An asymmetrical knob of bedrock produced by continued glacial erosion is called a *roches moutonnées*
  • Glacial abrasion smoothes the gentle slope facing the oncoming glacier and plucking steepens the opposite side as the ice sheet rides over it
Roches Moutonnées
Glacial Deposits

• As glaciers melt, the rocks and sediments in the glaciers are deposited
  – Glacial drift refers to all sediments of glacial origin
    • Two types of glacial drift
      – Till is material that is deposited directly by the ice
      – Sediments laid down by glacial meltwater are called stratified drift
Glacial till is an unsorted mixture of many different sediment sizes.

A close examination of glacial till often reveals cobbles that have been scratched as they were dragged along by the ice.
Glacial Deposits

• Glacial Till
  – Till is deposited as glacial ice melts and drops its load of rocks
    • Glacial erratics are boulders in the till or lying on the surface

• Stratified Drift
  – Sediment that is sorted by size and weight of the particles is called stratified drift
    • Deposited by glacial meltwater rather than the glacier itself
Landforms Made of Till

• Lateral and Medial Moraines
  – A moraine is a landform made of glacial till
    • A lateral moraine is an accumulation of debris on the side of the glacial till
    • A medial moraine is created when two alpine glaciers converge
      – The lateral moraines of each glacier converges in the center of the new glacier
Formation of a Medial Moraine

Geologist’s Sketch

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Landforms Made of Till

• End and Ground Moraines
  – A glacier is similar to a conveyor belt – regardless of the movement, sediments are constantly moved forward and dropped at the terminus
    • An end moraine is an accumulation of debris that forms at the terminus of a glacier
    • A ground moraine is a rock-strewn plain created as the glacier retreats
Formation of an End Moraine

When accumulation equals ablation, the terminus of a glacier is stationary and an end moraine forms.
Two Significant End Moraines in the Northeast
Landforms Made of Till

• Drumlins
  – Drumlins are smooth, elongate, parallel hills composed of till and formed from ice sheets
    • Example: Bunker Hill
Landforms Made of Stratified Drift

• Outwash Plains and Valley Trains
  – Glacial melt water, choked with sediment, flows onto a flat surface, drops its load, builds a broad, ramp like surface, and creates braided streams
    • Outwash plains are associated with ice sheets
    • Valley trains are associated with mountain valleys
• Ice-Contact Deposits
  – Meltwater flows over, within, and at the base of motionless ice deposits, stratified drifts that remain once the ice melts away
    • A kame is steep-sided mound formed from ice-contact stratified drift
      – Kame terraces occur when glacial ice occupies a valley
    • An esker is a narrow, sinuous ridge
Common Depositional Landforms

- Esker
- Drumlin field
- Retreating glacier
- Braided river
- Kame
- Ground moraine
- Braided river
- Outwash plain
- End moraine
- Bedrock
- Kettle lake
Other Effects of Ice-Age Glaciers

• **Crustal Subsidence and Rebound**
  – Ice sheets cause downwarping of the crust
  • After the glacier melts, the crust gradually rebounds

• **Sea-Level Changes**
  – During the last glacial maximum, sea level was 100 meters lower than present level
  – If the Antarctic Ice Sheet melted, sea level would rise 60 or 70 meters
In northern Canada and Scandinavia, where the greatest accumulation of glacial ice occurred, the added weight caused downwarping of the crust.

Ever since the ice melted, there has been gradual uplift or rebound of the crust.
Changing Sea Level

During the Last Glacial Maximum, about 18,000 years ago, sea level was nearly 100 meters (330 feet) lower than it is today.

During the Last Glacial Maximum, the shoreline extended out onto the present day continental shelf.
Other Effects of Ice-Age Glaciers

• Changes to Rivers and Valleys
  – The advance and retreat of the North American ice sheets changed the routes of rivers and modified the size and shape of many valleys
    • Upper Mississippi Drainage Basin
    • New York’s Finger Lakes
Changing Rivers

A. This map shows the Great Lakes and the familiar present-day pattern of rivers. Quaternary ice sheets played a major role in creating this pattern.

B. Reconstruction of drainage systems prior to the Ice Age. The pattern was very different from today, and the Great Lakes did not exist.

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Other Effects of Ice-Age Glaciers

• Ice Dams Create Proglacial Lakes
  – Ice sheets and alpine glaciers can act as dams to create proglacial lakes
    • Example: Lake Agassiz
    • The failure of ice dams can release large volumes of water very quickly
Other Effects of Ice-Age Glaciers

• Pluvial Lakes
  – The growth of ice sheets can cause the temperatures and evaporation to decrease in semi-arid regions
  • If precipitation occurs, pluvial lakes form
Pluvial Lakes

The Great Salt Lake is a remnant of Lake Bonneville.

Lake Bonneville was nearly the size of present-day Lake Michigan.
The Glacial Theory and the Ice Age

• Glaciers were once more extensive than they are today
  – Looking at glacial deposits and using the principle of uniformitarianism

• Glacial/Interglacial cycles occur every 100,000 years
  – The Northern Hemisphere Ice Ages began between 2–3 million years ago
  – The Antarctic ice sheet formed at least 30 million years ago
Causes of Ice Ages

• The Quaternary Ice Age is not the only ice age in Earth’s history
  – Tillite is a sedimentary rock formed from glacial till

• Any successful theory about the causes of ice ages must include:
  – Causes of the onset of glacial conditions
  – Causes of alteration between glacial and interglacial stages
Causes of Ice Ages

• Plate Tectonics
  – Continents shift and move through geologic time
    • Change ocean circulation
    • Continents move toward or away from the poles
    • Climate change triggered by plate tectonics is extremely gradual
      – Happens on a scale of millions of years
A Late Paleozoic Ice Age

The supercontinent Pangaea showing the area covered by glacial ice near the end of the Paleozoic era.

The continents as they appear today. The white areas indicate where evidence of the late Paleozoic ice sheets exists.
Causes of Ice Ages

• Variations in Earth’s Orbit
  – Changes in Earth’s orbit can vary the amount of solar radiation received
    • Variations in the shape of Earth’s orbit around the Sun (eccentricity)
    • Changes in the angle of Earth’s axis (obliquity)
    • The wobbling of Earth’s axis (precession)
Orbital Variations

The shape of Earth's orbit changes during a cycle that spans about 100,000 years. It gradually changes from nearly circular to more elliptical and then back again. This diagram greatly exaggerates the amount of change.

Today the axis of rotation is tilted about 23.5 degrees to the plane of Earth's orbit. During a cycle of 41,000 years, this angle varies from 21.5 to 24.5 degrees.

Earth's axis wobbles like a spinning top. Consequently, the axis points to different spots in the sky during a cycle of about 26,000 years.
Causes of Ice Ages

• Other Factors
  – Changes in Earth’s atmosphere
  – Changes in ocean circulation
  – Changes in the reflectivity of Earth’s surface
End of Chapter 18