1 ***Glaciers***

Earth – Chapter 18

2 ***Chapter 18 – Glaciers & Glaciation***

3 **Glaciers: A Part of Two Basic Cycles**

- 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 Earth cycles:
  - Hydrologic cycle
    - Water can be trapped in a glacier for many to tens of thousands of years
  - Rock cycle

4 **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 valley from an accumulation center
- Ice Sheets
  - Ice sheets exist on a larger scale than valley glaciers, currently exist at both poles
    - Greenland and Antarctica

5 **Valley Glacier**

6 **Ice Sheets**

7 **Glaciers: A Part of Two Basic Cycles**

- Ice Age Ice Sheets
  - 18,000 years ago, ice sheets covered large portions of North America, Europe, and Siberia
    - Known as the *Last Glacial Maximum*
  - Over the past 2.6 million years, ice sheets have advanced and retreated multiple times
    - Alternating glacial and interglacial periods

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9 **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
      - Sea ice expands and contracts with the seasons
    - Glaciers form on land (*continental ice sheets*)
      - Greenland (60º – 80º N. latitude)
        - » Ice sheet covers 1.7 square million kilometers, avg. ~1500 meters thick
      - Antarctica in the southern hemisphere
        - » Ice sheet covers 13.9 square million kilometers
    - Ice flows out in all directions from one or more snow accumulation centers

10 **Glaciers: A Part of Two Basic Cycles**

- 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
    - Sustained by ice flow from the adjacent ice sheet
  - Some ice shelves are unstable and starting to break apart
    - Breakup of ice shelves attributed to the trend related to accelerated climate change

11 **Ice Shelves**

12 **Ice Shelves**

13 **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
    - Essentially these are valley glaciers connecting ice caps/sheets to the sea
  - Piedmont glaciers form when one or more alpine glacier emerges from the valley and spreads out in a broad lobe, occupying broad lowlands at the base of steep mountains

14 **Iceland's Vatnajökull Ice Cap**

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16 **Piedmont Glacier**

17 **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
    - Extremities of crystals evaporate
    - Snowflakes become smaller, thicker, and more spherical
  - 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

18 **Transformation of snow to glacial ice**

19 **Formation and Movement of Glacial Ice**
- Movement of a Glacier
  - Glacial ice moves as a *flow*
  - The solid flows in two ways:
    - 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

20 **Movement of a Glacier**

21 **Formation and Movement of Glacial Ice**
- Movement of a Glacier
  - Ice behaves as a brittle solid until subjected to pressure due to the weight of at least 50 meter of overlying ice
  - In contrast with the lower plastic portion, the upper 50 meter 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

22 **Crevasses**

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24 **Formation and Movement of Glacial Ice**
- Rates of Glacial Movement
  - Movement of glacial ice is not obvious
  - Like a river, glacial ice does not all move at the same rate
    - Flow is fastest in the center of the glacier
    - Valley walls and floor slow the base and sides, causing drag
  - Glacial velocity ranges from extremely slow to several meters per day
    - Some glaciers exhibit extremely rapid movements called surges
    - Rates of movement have been measured using markers in the past, and time-lapse photography more recently

25 **Measuring Glacial Movement**

26 **Movement of Antarctic Ice**

27 **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
    - Loss of ice by a glacier is called ablation
      - Melting
      - Calving
        - »the breaking off of large pieces of ice
        - » creates icebergs where the glacier has reached the sea

28 **Zones of a Glacier**

29 **Glacial Ablation**

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31 **Iceberg**

32 **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
    - If accumulation exceeds loss, the glacial front advances
    - If ablation increases and/or accumulation decreases, the ice front will retreat
- Because glaciers are sensitive to changes in temperature and precipitation, they provide clues about changes in climate

33 **The glacial budget**

34 **Retreating Glaciers**

35 **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
    - Occurs when meltwater penetrates the cracks and joints of bedrock beneath a glacier and freezes
  - Rocks in the glacier also act like sandpaper to smooth and polish a rock surface in a process called abrasion

36 **Evidence of Glacial Erosion**

37 **Glacial Erosion**

- Glacial abrasion produces:
  - Rock flour (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

38 **Glacial Abrasion**

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42 **Rock Flour**

43 **Landforms Created By Glacial Erosion**

- Landforms created by valley glaciers and ice sheets are very different
  - While ice sheets subdue most topography, valley glaciers create sharp and angular topography
    - Valley 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

44 **Erosional Landforms Created by Alpine Glaciers**

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49 **U-Shaped Glacial Trough**

50 **Landforms Created By Glacial Erosion**

- 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
    - After the glacier has melted away, the cirque basin is sometimes occupied by a small lake called a tarn
  - When two glaciers exist on opposite sides of a mountain, the dividing ridge erodes away, creating a gap called a col

51 **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

52 **The Matterhorn *(in Switzerland, not Anaheim…)***

53 **The Matterhorn**

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57 **Landforms Created By Glacial Erosion**

- Roches Moutonnées
  - An asymmetrical knob of bedrock produced by continued glacial erosion is called a roches moutonnées
    - Glacial abrasion smoothens the gentle slope facing the oncoming glacier and plucking steepens the opposite side as the ice sheet rides over it
- Fiords
  - Deep, steep-sided inlets of the sea
    - Drowned glacial troughs that form when sea level rises
    - Depths may exceed 1000 meters

58 **Roches Moutonnées**

59 **Fiords**

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61 **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*

62 **Glacial Till**

63 **Glacial till is typically unstratified and unsorted**

64 **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

65 **Glacial Erratic**

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67 **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 as a medial moraine

68 **Formation of a Medial Moraine**

69 **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 glacier will retreat to a point where it is in balance, the ice front stabilizes, and a new end moraine forms
      - The very first end moraine signifies the farthest advance of the glacier and is called the *terminal end moraine*
      - End moraines that form as the ice front occasionally stabilizes are termed *recessional end moraines*
    - A ground moraine is a rock-strewn plain created as the glacier retreats

70 **Glacial depositional features**

71 ***My favorite glacier:***
Athabaska Glacier, Alberta, 1976

72 ***"Geology Guy" on his favorite glacier in 1976***

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76 **End Moraines of the Great Lakes**

77 **Two Significant End Moraines in the Northeast**

78 **Landforms Made of Till**

- Drumlins
  - Drumlins are streamlined asymmetrical hills composed of till and formed from ice sheets
  - Range in height from about 15 to 50 meters and may be up to 1 kilometer long
    - The steep side of the hill faces the direction from which the ice advanced
    - The gentler, longer slope points in the direction the ice moved

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80 **A drumlin in upstate New York**

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82 **Landforms Made of Stratified Drift**

- Two basic categories of features composed of *stratified drift*:
  - *Ice-contact deposits* accumulate on, within, or immediately adjacent to a glacier

– *Outwash sediment* is material deposited by meltwater streams

83 **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
      - Often are pockmarked with basins or depressions known as kettles

84 **Landforms Made of Stratified Drift**

- 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 composed largely of sand and gravel

85 **Common Depositional Landforms**

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88 **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
    - Atlantic coast of the United States lay more than 100 kilometers east of New York City!
  - If the Antarctic Ice Sheet melted, sea level would rise 60 or 70 meters

89 **Crustal Subsidence and Rebound**

90 **Changing Sea Level**

91 **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
      - Prior to the Ice Age, a significant part of the Missouri River drained north toward Hudson Bay
    - New York's Finger Lakes
      - 11 long, narrow, roughly parallel water bodies oriented north–south
      - Prior to the Ice Age, they were a series of river valleys, glacial erosion transformed them into deep, steep-walled lakes

92 **Changing Rivers**

93 **New York's Finger Lakes**

94 **Other Effects of Ice-Age Glaciers**

- Ice Dams Create Proglacial Lakes
  - Ice sheets and alpine glaciers can act as dams to create proglacial lakes
    - Examples: Lake Agassiz, Lake Missoula
    - The failure of ice dams can release large volumes of water very quickly

95 **Glacial Lake Agassiz**

96 **Glacial Lake Missoula**

97 **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
- Example: Lake Bonneville

98 **Pluvial Lakes**

99 **The Glacial Theory and *this* 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 and 3 million years ago
    - ~20 of these cycles spanned the Ice Age
  - The Antarctic ice sheet formed at least 30 million years ago

100 **Where Was The Ice?**

101 **Maximum extent of ice during the Ice Age**

102 **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
  - Rock evidence of earlier ice ages
- 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

103 **Tillite**

104 **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

105 **A Late Paleozoic Ice Age**

106 **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*)

107 **Orbital Variations**

108 **Causes of Ice Ages**

- Other Factors
  - Changes in Earth's atmosphere
  - Changes in ocean circulation
  - Changes in the reflectivity of Earth's surface

109 **Ice Cores**

110 **End of Chapter 18**