G202 Class Notes - Glacial Processes and Climate

I. Introduction / Basic Processes

A. Glacier- a thick mass of flowing / moving ice

1. glaciers originate on land from the compaction and recrystallization of snow, thus are generated in areas favored by a climate in which seasonal snow accumulation is greater than seasonal melting
   a. polar regions
   b. high altitude/mountainous regions

B. Snowfield- a region that displays a net accumulation of snow
1. snowline- imaginary line defining the limits of snow accumulation in a snowfield.

C. Water balance- in general the hydrologic cycle involves water evaporated from sea, carried to land, precipitation, water carried back to sea via rivers and underground

1. water becomes locked up or frozen in glaciers, thus temporarily removed from the hydrologic cycle

   a. > global glacial ice, < global sea leve
   b. < global ice, > global sea level

D. Formation of glacial ice:
1. snow crystallizes from atmospheric moisture, accumulates on surface of earth. As snow is accumulated,
2. snow crystals become compacted > in density, with air forced out of pack.
   a. Firn: compacted snow with D = 0.5D water
   b. >compaction, density >, snow ---------ice
      (1) compaction = recrystallization
      (2) with greater compaction, ice crystals increase in size

E. Glacial Types

1. Alpine Glaciers- glaciers generally confined to mountain valleys
   a. cirque glaciers- confined to basins at head of valley.
   b. Valley glaciers- extend down drainage/valley
   c. Piedmont glaciers- valley glaciers that extend to mouth of valley, where ice spreads out broadly over the flat land.

   d. presently found in Pacific Northwest, Canadian Rockies, Swiss Alps, and other mountainous regions (Hawaii?)

2. Continental Glaciers- massive accumulations of ice that cover extensive areas of the earth's surface.

   a. Ice Sheets - continent-scale ice mass

(1) present examples include: Greenland and Antarctica
(2) pre-historic examples: Canada-norther U.S., northern Europe

3. Highland Icefields- occur in mountain areas, ice accumulates in a relatively unconfined sheet through coalescence of valley glaciers (e.g. western Canada and Alaska)

4. Ice Shelf - floating, slab-like glaciers in coastal ocean areas

5. Temperate vs. Polar Glaciers (classification based on ice temperature)

a. Polar glacier - ice is well below melting point year round
(1) permanently frozen year round
(2) no seasonal melting
(3) dry-based glaciers

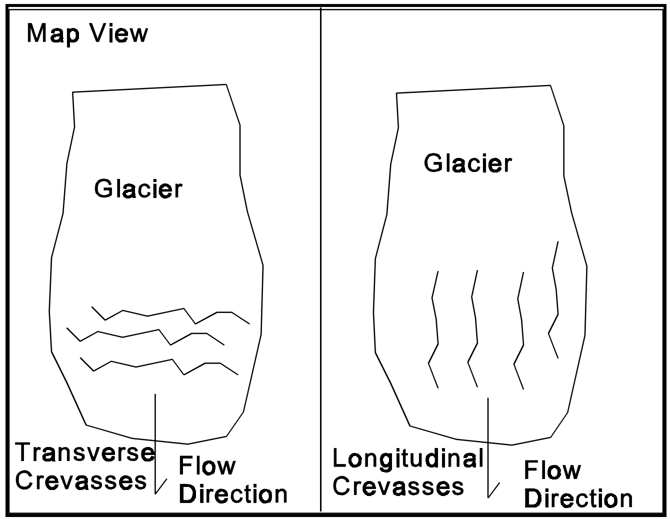
b. Temperate Glaciers - ice goes through seasonal melt cycles
(1) wet-based glaciers
(2) seasonal freeze-thaw cycles

II. Glacial Movement: Process of Ice Movement

A. Ice Flow- movement of glacial ice is primarily by means of plastic deformation/flow and/or by shear/slip

1. Internal Deformation at Molecular Level-ice behaves brittly until a thickness of 150-200 ft in which the weight of ice causes it to deform plastically and flow

2. Basal Slip: the interface between the ice and underlying stratum is most often the site of shear/slip (exception: in polar regions where ice is frozen to underlying stratum).

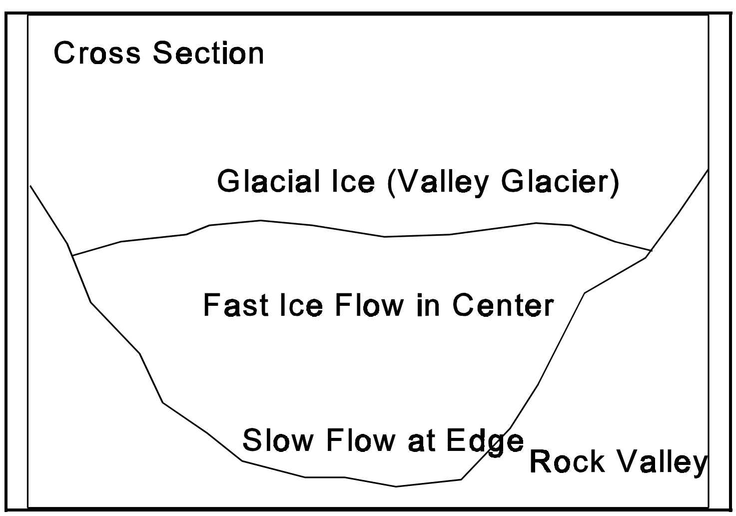


B. Zone of Fracture- uppermost portion of glacier nearest the surface where the ice deforms brittly.

1. crevassing- process of ice brittly fracturing into cracks (tensional stress/bending stress)
   a. transverse crevasses - cracks perpendicular to ice flow direction
   b. longitudinal crevasses - cracks parallel to ice flow direction

C. Areal distribution of ice flow

1. glacial ice flows fastest in central portions of valley glaciers and slowest along valley walls due to friction



D. Rates of ice flow- from very slow (cm's per 10's of years) to very rapid (several meters/day)

1. glacial surging- periods of time in which glaciers flow very quickly (up to 180 ft/day!).

    a. possibly results from hydroplaning/sliding along bottom of glacier- due to increase in hydraulic/lift pressure reducing friction at base of glacier.

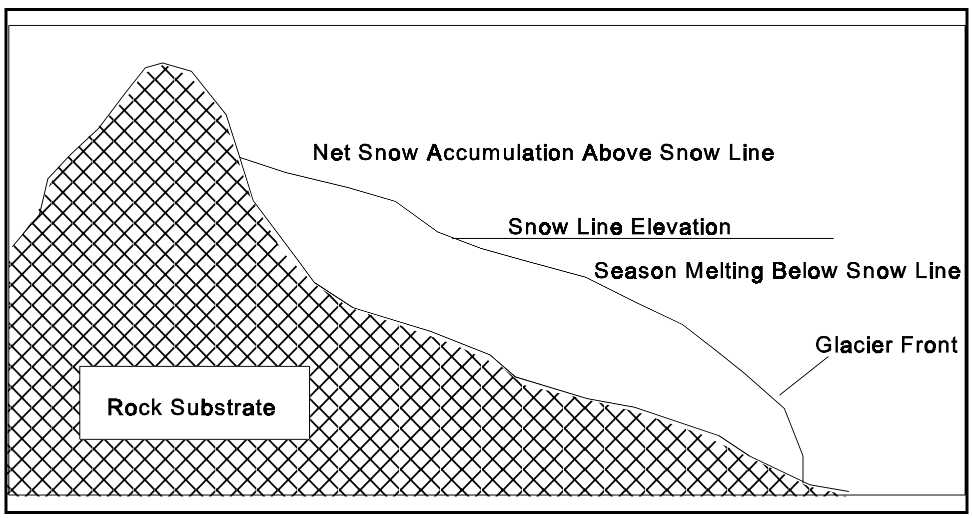
E. Mass Balance Relationships for Glaciation

1. Snow line- the elevation above which the temperature is cool enough for some winter snow to show a net accumulation.

    a. equatorial regions: snow line above 20,000 feet grades downward with > latitude
    b. polar regions: snowline @ sealevel.

2. function of rate of snow accumulation above snowline vs. rate of ice melting below snow line

    a. rate of snow accumulation high above snowline
    b. ablation or snow melting occurs below snowline



        (1) calving- blocks of glacial ice break off from glacial at snout of glacier, may form ice bergs in cases of snout at water/ocean front.

3. Mass Balance of Ice

If rate accumulation > rate of ablation = ice advance
If rate accumulation < rate of ablation = glacial retreat
If rate accumulation = rate of ablation = static equilibrium

4. important note, in all cases above ice continually flows downslope, but in case of retreat, downslope movement can not keep pace with melting of glacial snout.

III. Glacial Erosion (glaciers = natures bull dozers)

A. The movement of ice and the pressure exerted on the underlying earth surface result in capability of glaciers to perform great amounts of erosion and earth sculpturing.

B. Glacial Erosion Process-

1. Plucking Process- as ice flows over fractured bedrock surface, the ice/movement loosens and lifts blocks of rock/debris and incorporates them into the ice via a freeze/thaw process. Meltwater from ice generated via friction and temperature, water fills cracks of rock, frost wedging breaks and pulverizes rock.

2. Abrasion - ice as a belt sander- ice incorporates rock fragments at its base and operates as a rasp on underlying rock strata

    a. may produce Rock Flour - finely pulverized clay-sized sediment
    b. Glacial striations on polished bedrock surfaces- linear scratches on bedrock surface that preserve clues as to the direction of glacial motion

C. Erosional Landforms in Alpine Glacial Areas

1. U-shaped valleys- flat valley bottoms and steep valley walls. Through Glacial erosion, they tend to:

    a. widen a valley, deepen a valley, straighten valleys

    b. depth of valley modification dependent upon thickness of glacial ice

2. hanging valleys- tributary valleys left hanging high above the main glacial trough upon melting of glacial ice.

    a. result from glaciers cutting main valleys deeper than tributary valleys due to greater accumulations of icen in main valleys, upon melting, tributary valleys were not cut as deep as main valley, thus leaving them hanging.

3. paternoster lakes- a string of glacial lakes in line along a glaciated valley

4. cirque- a bowl shaped depression located at the head of a glacial valley, steep walls on three sides of cirque, with open end leading down valley

    a. cirque- represents the cradle of the glacier where snow accumulated most with ice formation, glaciers flowing away from cirque.

    b. bowl shaped depression results from plucking rock from sides, and scooping out at base of glacier.

5. Fiords - glacial valleys which have been inundated by the sea (i.e. a drowned U-shaped valley).

6. Aretes- saw-toothed ridge which separates two glacial valleys (a glacial valley divide)

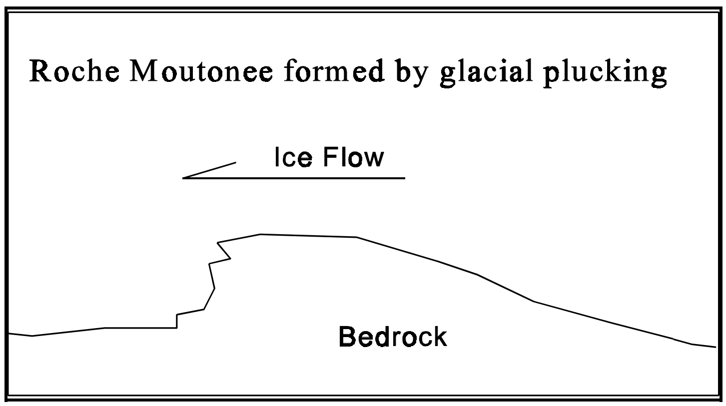
    a. Col- A sharped-edge pass or saddle between two adjacent cirques. Occurs when two adjacent cirques cut back to remove part of arete between them resulting in col.

7. Horn- 3-sided pyramid shaped mountain peaks, produced by the adjoinment of 3 cirques on each side of the peak.

    a. result as erosional remnant from the plucking and frost wedging action at the head of glacial tributary valleys.

D. Erosional Landscape in Continental Glaciation areas

1. Roche Moutonnee- phenomena in which pre-existing bedrock hills are sheared off and rounded by moving ice, with plucking dominant on lee side forming a smooth sloping stoss side and more steeply inclined irregular lee side.



2. Striated Glacial Pavements on Bedrock via the abrasion process.

IV. Glacial Depositional Features

A. Deposition of eroded debris occurs when glacial ice melts, sediment may be deposited directly by the glacial ice or by melt waters flowing away from the glacial ice.

B. Sediment produced by Glaciers

1. Drift- any sediment derived from a glacial origin
2. Till- sediment deposited directly by glacial ice

    a. Deposited by ice when it melts
    b. unsorted mixture of sediment of many sizes (clay to boulder)
    c. Glacial erratics- large boulders found in glacial till

3. Outwash- sediment deposited by melt water from the glacier.
    a. well sorted sediment that is sorted according to its size and weight

        (1) (coarsest sediment deposited closer to glacial front, finest generally carried farther from the glacial front)

C. Moraines - layers or ridges of till (unsorted glacial deposits) deposited from glacial ice

1. lateral moraines- associated only with alpine glaciers, moraine/till deposited along valley walls.

2. Medial moraines- till deposited at the juncture of two alpine glaciers which coalesce as tributaries (i.e. lateral moraines which merge as medial moraines)

3. end moraines- may be applied to both continental and valley glaciers-

    a. till deposited at the terminus of a glacier at any given time (thus may be later bull dozed by the glacier)

    b. terminal moraine- deposited at the point of furthest advance of a glacier

    c. recessional moraine- deposited at the terminus of a glacial as it recedes back up the valley

4. Ground Moraine- applied to continental glaciers- till deposited irregulary as the glacier recedes forming a gently undulating surface, fills in low spots.

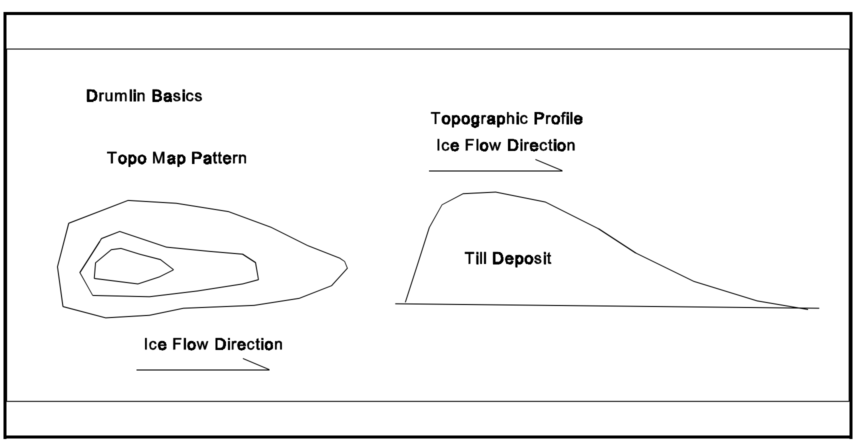
5. Glacial erratics- anomalously large boulders that have been glacially derived, transported large distances, now forming an exotic rock type not indiginous to the site of depostion.

D. Outwash plain (continental and/or alpine glaciers)- melt water from the glacier flows over end moraines, eroding them and carrying sediment further downslope, sediment becomes sorted and deposited downslope of most end moraines.

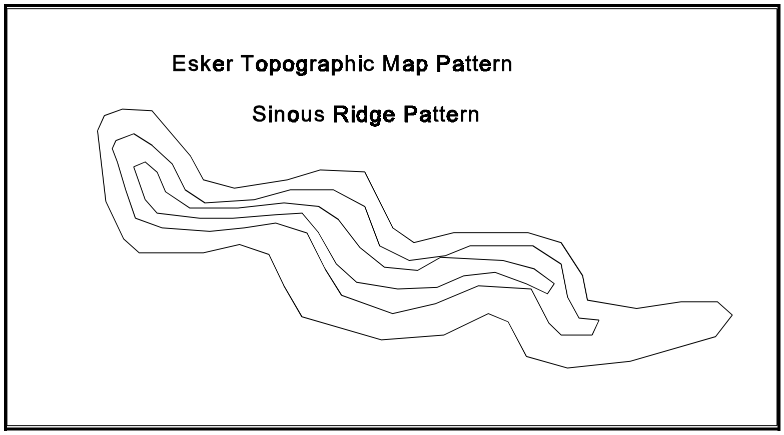
E. Kettle Holes (term applied to continental glaciers)- depressions found in deposits- represents situation where an isolated block of ice became buried in drift, subsequently melted, leaving a pit in the glacial sediment.

F. Drumlins (continental glaciers)- streamlined, tear-drop shaped, asymetrical hills composed of till, the tail of the drumlin points in direction of ice movement, round/wide steep side points in opposite direction of flow.

1. Drumlins often found in clusters, possibly related to re-advance of a glacier over end moraine, resulting in bulldozing and shaping drumlins into the forms.



G. Eskers-(continental glaciers)- sinuous ridges composed of semi-sorted sand and gravel, deposited by sub-glacial streams flowing in tunnels beneath the ice, near the terminus of the glacier.



H. Kames- (continental glaciers) steep-sided hills that are composed of sand and gravel, thought to represent sediment deposited in hollows within glacial ice.

1. Ice-margin contact deposits
2. sorted and stratified

V. Glaciation in Geologic Past

A. Periods of extensive glacial activity are evident from preserved rock/glacial record, field investigations have provided proof that many ice ages have existed in past.

1. Evidence of more recent glaciations come from geomorphological evidence reflecting glacial-related landscape modifications.

a. Geomorphological evidence is somewhat limited in longevity as glacial geomorphic phenomena are readily destroyed by subsequent weathering and fluvial surface erosion as well as subsequent glacial modifications.

(1) most recent ice advances are best preserved

2. Geologic evidence of ancient glacial periods comes from the sedimentary rock record.

B. Ice ages- characterized by complex periods of glacial advance and retreat, separated by periods of warm climates

1. Pleistocene Epoch- geologic time period between 10,000 years and 2.0 million years ago.

a. Character of Pleistocene: refrigeration of high latitude and high altitude portions of earth, and subsequent development of extensive ice sheets and alpine glaciers.

b. Glacial/interglacial relations: Find evidence for over 20 major glacial events in the past 2.0 million years. Each period was separated by a warm time known as an interglacial period.

(1) Wisconsinan glaciation most recent: from 30,000 yr B.P. to 5,000-10,000? year B.P.

(2) Presently we are in the Holocene (the last 10,000 years), more specifically we are in the late Holocene

(a) Holocene = interglacial climate period

(3) Historical Ice Advances / Retreat

(a) Little Ice Age: 1600's through 1900's

i) build-up of alpine glaciers world wide, with maximum ice advance in the mid-1800s.

(b) Recent trend - global warming and ice retreat since the mid-1800's.

c. Extent of Pleistocene Glaciation

(1) Total of 1/3 land area of earth with ice thickness ranging from 10's of feet to several thousands of feet.

(2) Pleistocene glaciation grew out from poles to lower latitudes

(a) covering most of Canada, extending down into the northern tier states of the U.S. (northern Washington, Idaho, Montana, North Dakota, Eastern South Dakota/Nebraska, Wisconsin, Minnisota, Illinois, Michigan, Ohio, Indiana, Iowa, northern Pennsylvania, New York and the New England/Maritime states).

(b) In Europe, glaciers covered all of the scandinavian countries, northern Russia, Great Britain, Ireland, Denmark, Sweden, Poland.

(c) High Mountain areas also were significantly impacted by Pleistocene glaciation: Cascade Range, Sierra Nevada Mountains, the northern Rockies of Montana, Wyoming and Idaho, the intermountain west of Utah/Nevada, and the southern Rockies of Colorado and New Mexico. As well as the Alps, and Pyrenees of Europe.

C. Large-scale Influences of Glaciation on Earth's Crust:

1. Landscape modification: both in the glaciated regions as well as in "periglacial zones"

    a. Periglacial zones- areas lying in the foreland of the glaciers, areas that were never covered by ice, but received extensive modification by erosional/depositional processes of meltwater. As well as sites of cold climate weathering/mass wasting processes (freeze/thaw, and permafrost conditions).

2. Glacio-eustatic Sea Level Fluctuations-
    a. ice buildup on continents removes water from the hydrologic cycle, most of which comes from evaporation of sea water.
    b. Net result is lowering of sea level during glacial periods, and raising of sea level during interglacial periods.

3. Global Glacio-eustatic sea level curve:
    a. based on the examination of oxygen isotope ratios found in skeletal tests of microfossils in sea deposits.

    b. Examines the ratio of O^{16}/O^{18} in skeletal tests (which fix oxygen from the ocean, and are presumed to be a reflection of oxygen isotopic ratios present in past seawater).

        (1) O^{16} - "normal" light oxygen (8 protons, 8 neutrons in atom)
        (2) O^{18} - "heavy" oxygen (8 protons, 10 neutrons in atom)

    c. Under evaporative process, only O^{16} in H_2O molecules is evaporated from sea water, subsequently moved inland to form snow/ice

        (1) O^{18} is left behind in the ocean water. Hence, during glacial periods, one would expect a $<$ in the ratio of O^{16}/O^{18} as the relative proportion of O^{18} has increased due to evaporation/locking of O^{16} up in glacial ice.

        (2) Vice-versa during interglacials. Examining the record of oxygen isotopes can provide a record of glacial/interglacial periods.

            (a) O^{16}/O^{18} ratio from the marine record represents a "climate proxy"

4. Crustal depression- under the weight of a great thickness of ice, the earth's crust in depressed downward into the asthenosphere. After the ice melts and the weight is removed, the crust is subsequently uplifted back to equilibrium.

    a. "Isostatic" Depression - subsidence of Earth's crust due to glacial ice loading
    b. "Isostatic" Uplift - uplift and rebound of Earth's crust due to melting and removal of glacial ice

5. Glacial/Pluvial Lake development- concomitant with increased moisture/evaporation during glacial periods, along with melt water, more water was available on continents, thus large glacial lakes often form.

    a. The Great Lakes are a remnant of glacio-pluvial processes.
    b. e.g. Glacial Lake Bonneville in Utah
        (1) Great Salt Lake is remnant of much larger Pluvial Lake

VI. Causes of Glaciation
  A. Any model must accommodate two givens:
    1. climatic changes that lead to lower average temperatures and increased precipitation

    2. the alternation of glacial and interglacial stages on orders of 10's to 100's of thousands of years

  B. Possible Models

    1. Plate Tectonics- ice can only accumulate on continents when they are located at the higher latitudes, thus only when plate locations are favorable can glaciation occur.

        a. Provides explanation for large scale occurrence of glaciation

        b. Glacial Climates as Related to Continental Positions
            (1) High Latitude Contienent Positions (colder climates)
            (2) High Altitude Mountain Building Events

    2. Milankovitch theory of climate oscillation
        a. based on premise that variations in climate are associated with incoming solar radiation.

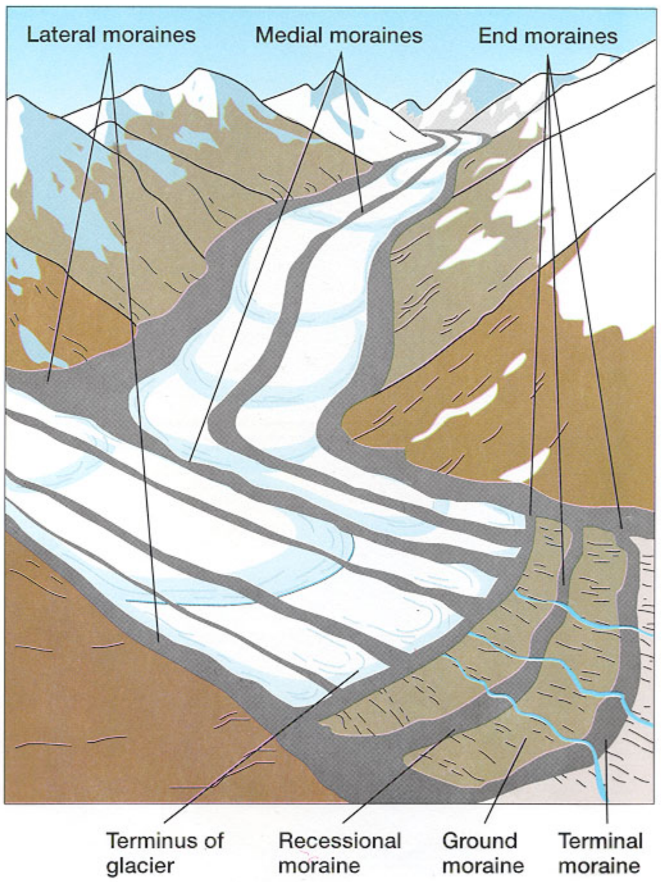
        b. solar radiation may be influenced by eccentricity or shape of earth's orbit about the sun

        c. solar radiation may be influenced by obliquity, or changes in angle that earth's axis is oriented with plane of orbit.

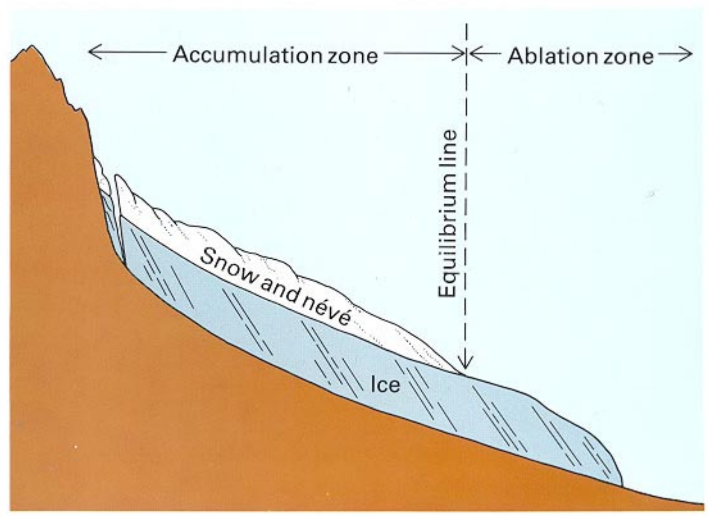
        d. solar radiation may be indluenced by precession or wobbling of the earth's axis.

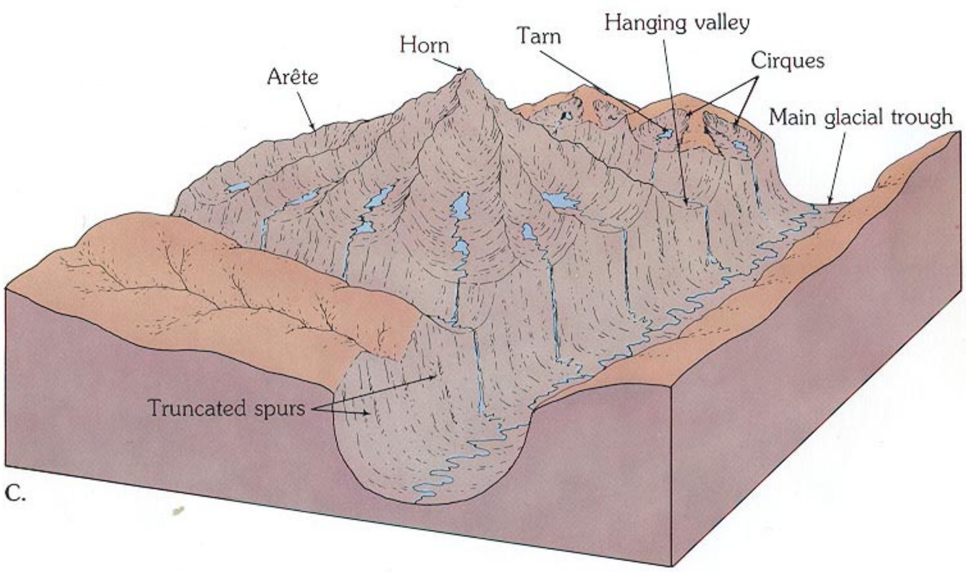
  C. Other Considerations to Climate Change
    1. Global Warming / Greenhouse Effect
    2. Changes in Ocean Circulation Patterns
        a. cool ocean currents promote cool dry air
        b. El Nino / La Nina Cycles
    3. Volcanic Eruptions / Decrease in Solar Radiation due to Dust Blocking
        a. e.g. Mt. Pinatubo eruption in early 1990's

Alpine Glaciation



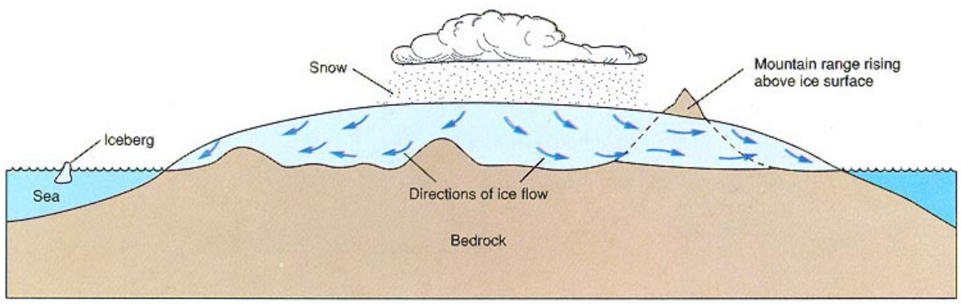
Schematic longitudinal cross section of an alpine glacier

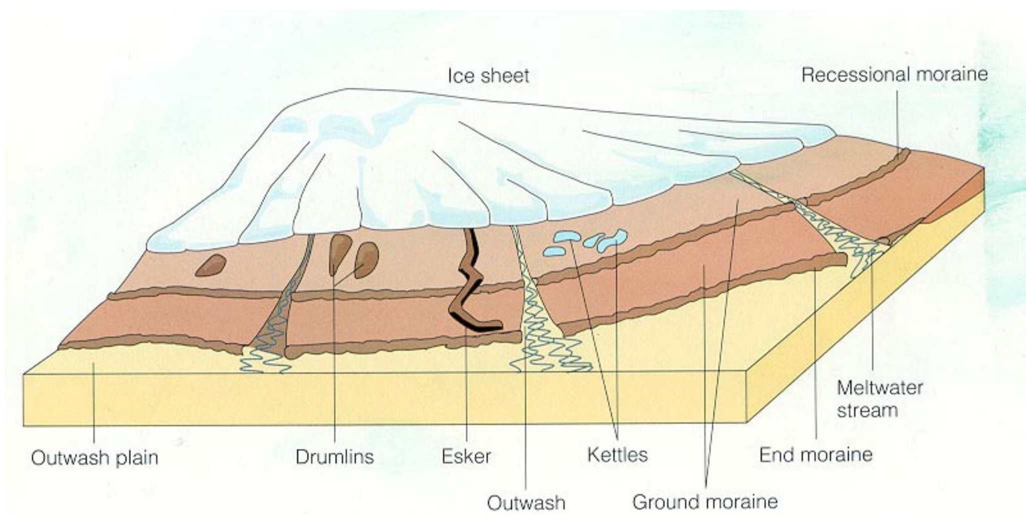




C.

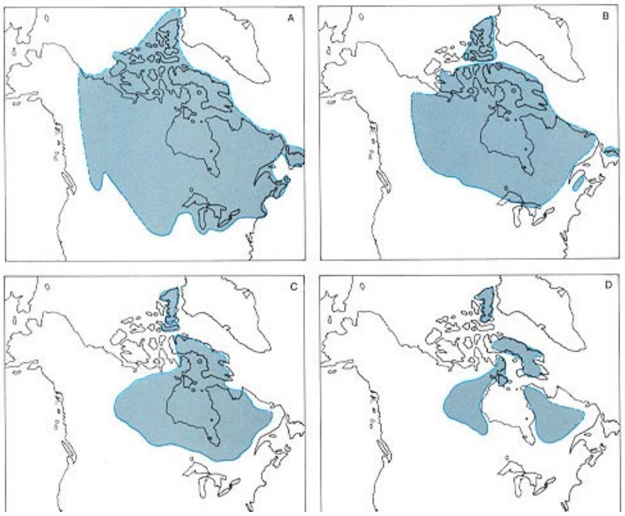
Continental Glaciation



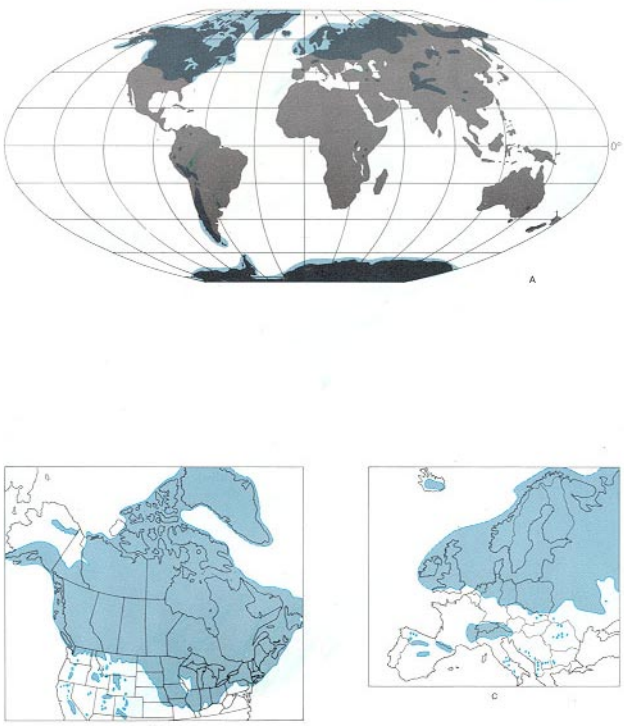


Pleistocene Glaciation

Probable decline of the Laurentide ice sheet during the most recent deglaciation



The maximum extent of Pleistocene glaciation T74



Distribution of contemporary ice sheets and glaciers in the Northern Hemisphere T76