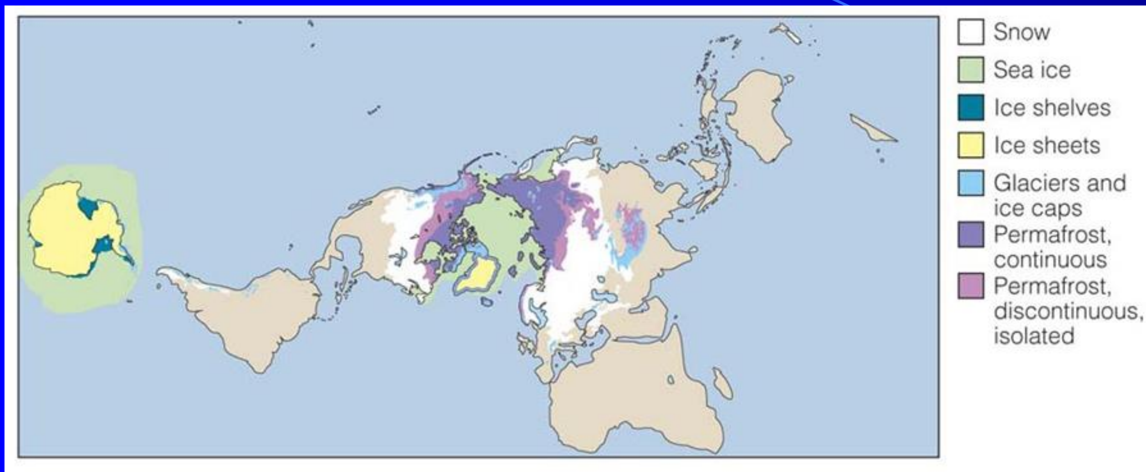
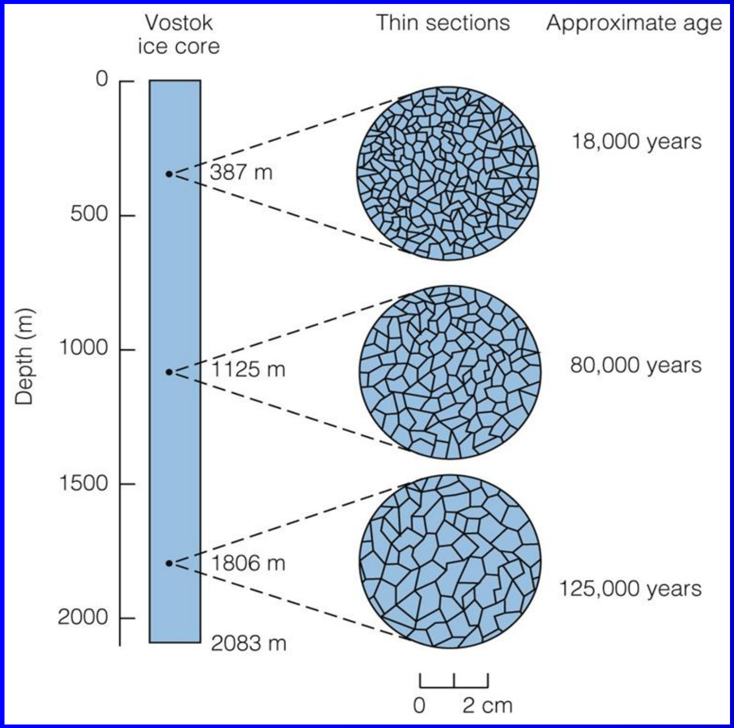
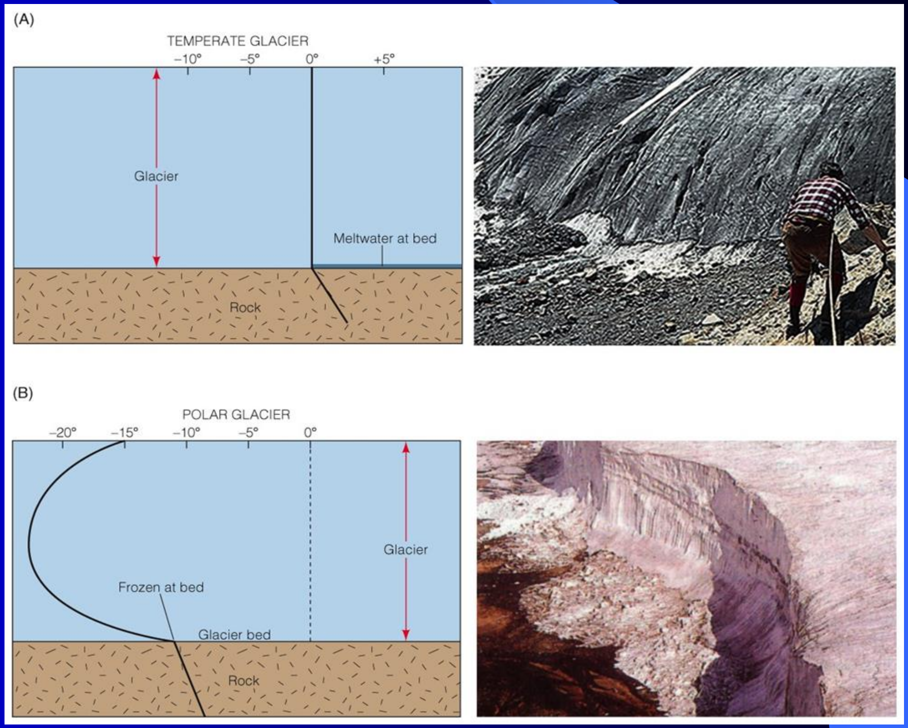
The Cryosphere

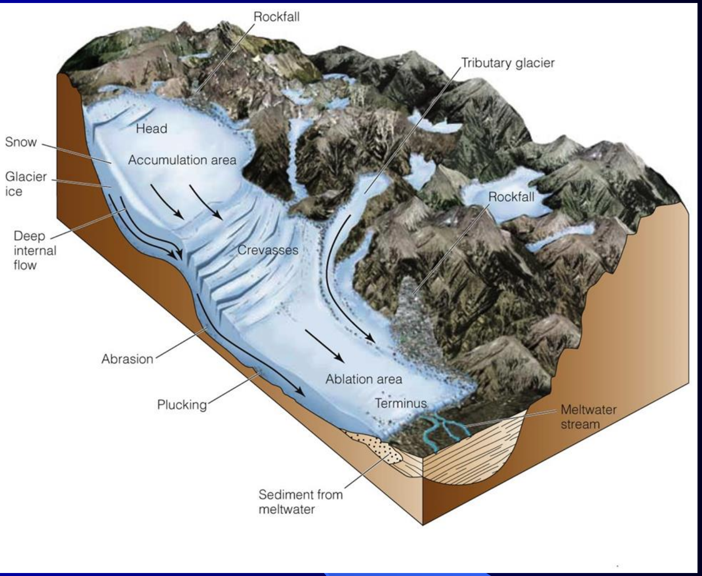


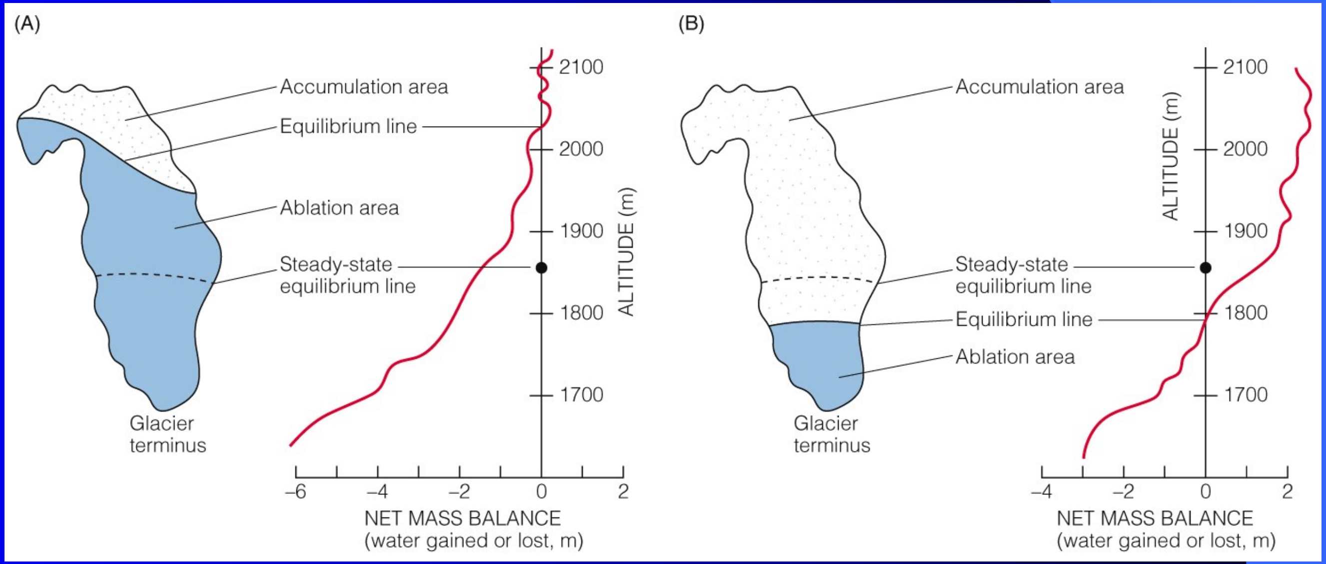
- Glaciers form wherever snow and ice can accumulate
  - High latitudes
  - High mountains at low latitudes
- Ice temperatures vary among glaciers
  - Warm (temperate) glaciers: at pressure melting point, can coexist with water
  - Cold (polar) glaciers: below pressure melting point





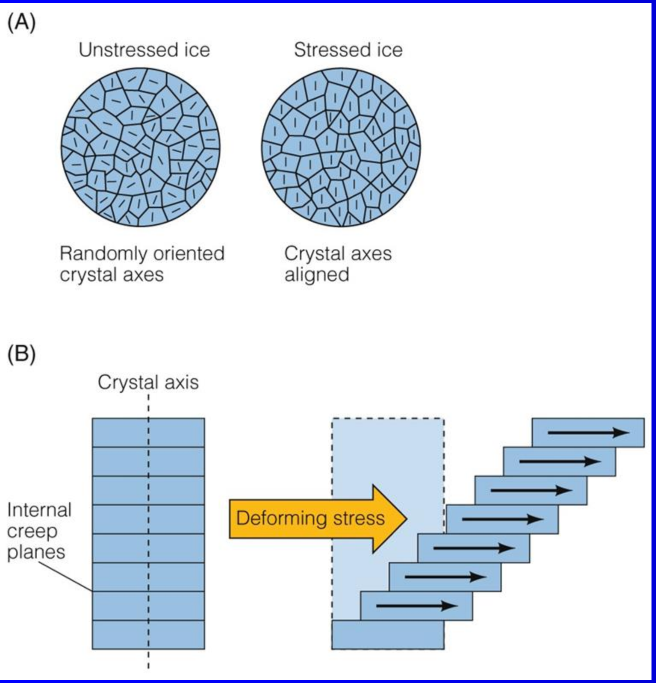
- A glacier's advance or retreat is the balance of the amount of snow and ice added (accumulation) and lost (ablation)
  - Upper zone is the accumulation area
  - Below this is the ablation area
  - Between these is the equilibrium line
  - The front of the glacier is called the terminus



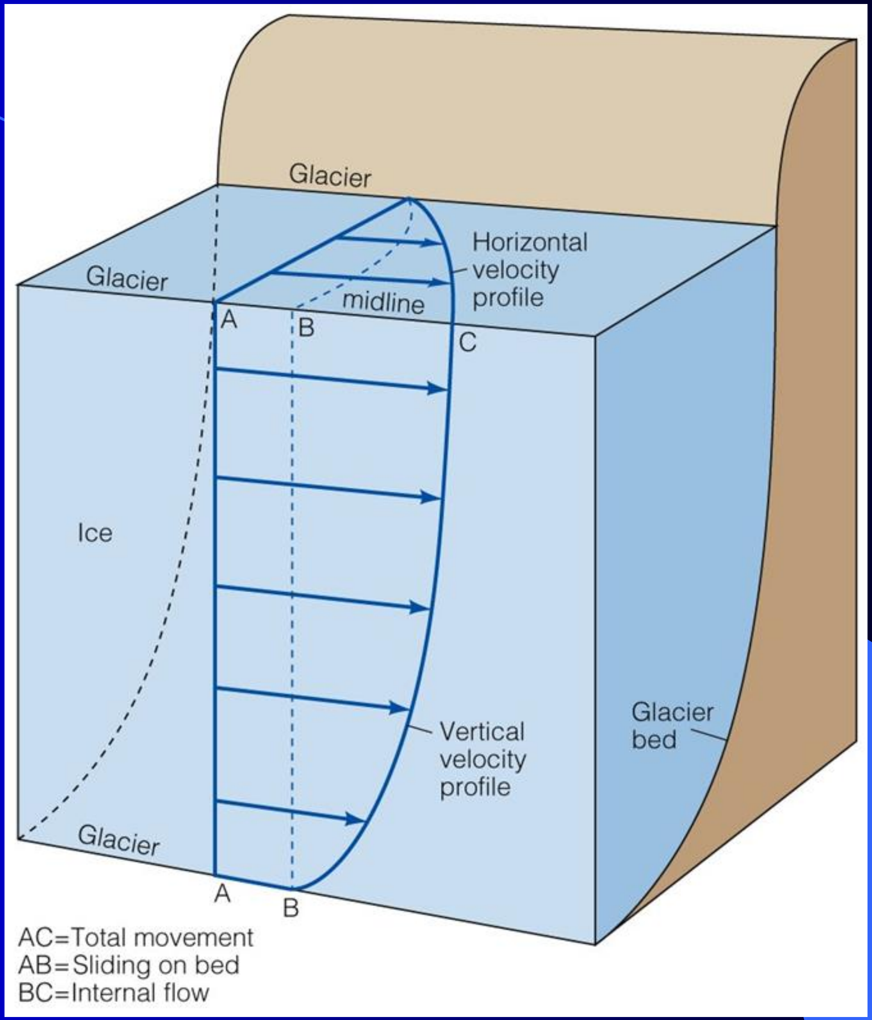


- The terminus of a glacier responds to changes in mass balance
- The movement of glacier ice occurs by

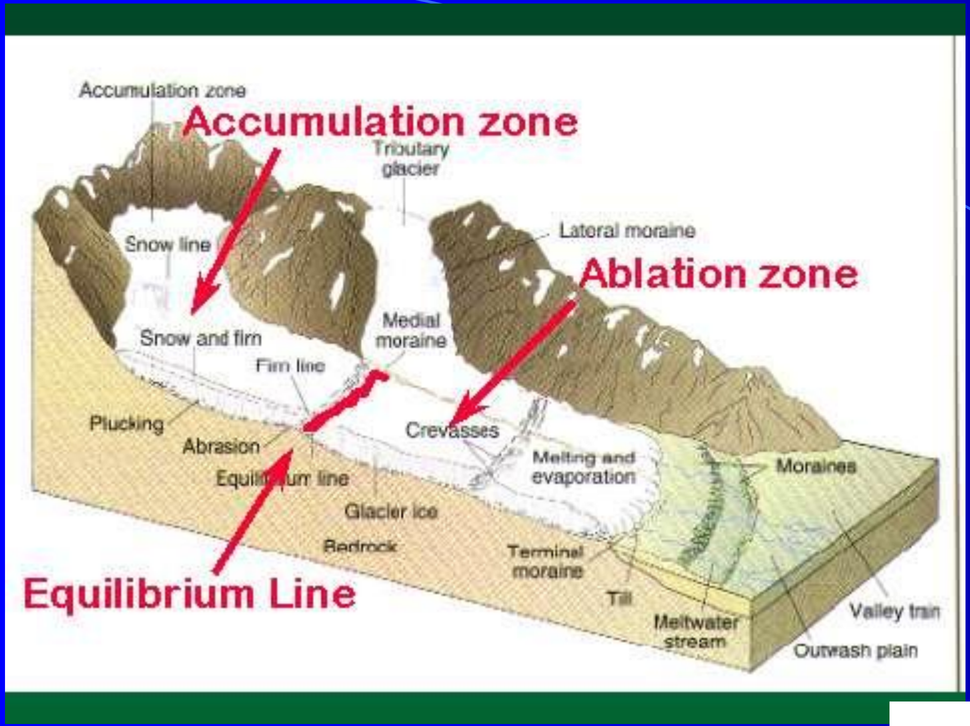
1. Internal flow
    - Ice at critical thickness deforms and is pulled downslope by gravity
    - Occurs within individual ice crystals under stress
    - The surface is brittle, cracks under tension, forms crevasses, <50 m deep
2. Basal sliding
    - Meltwater at the base acts as lubricant

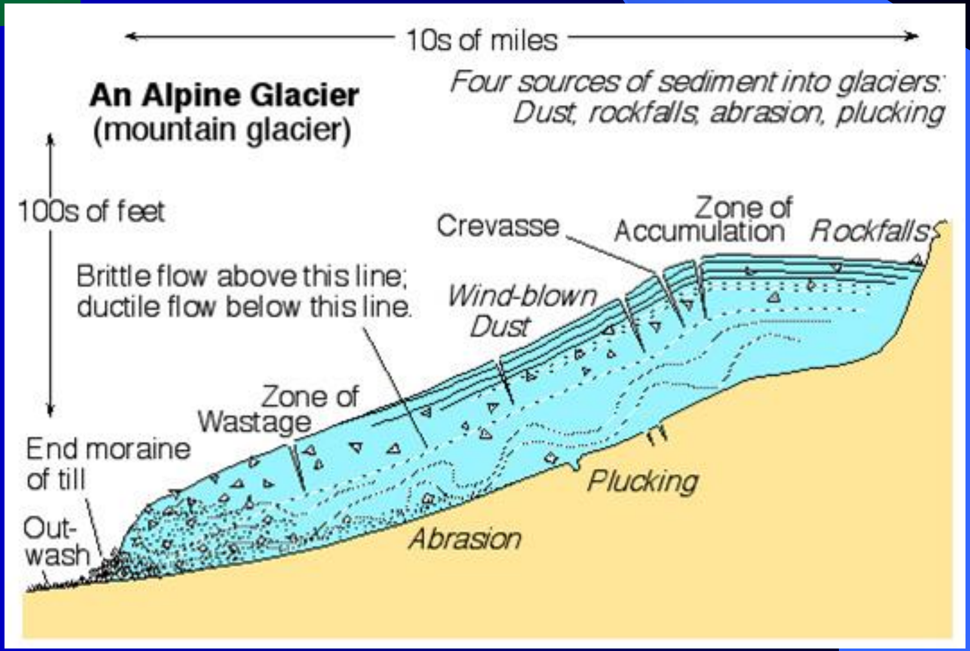


- The uppermost ice in the central part of a glacier flows faster than the sides and the base - similar to a river
- Flow velocities vary from cm to m per day
- Even as a terminus is retreating, down-glacier flow of ice continues
- The response lag is the time for effects of change in accumulation to be transferred through the glacier to the terminus



Alpine (Mountain) Glaciers





Alpine Glaciers – Erosional Features

Cirques

U-shaped valley

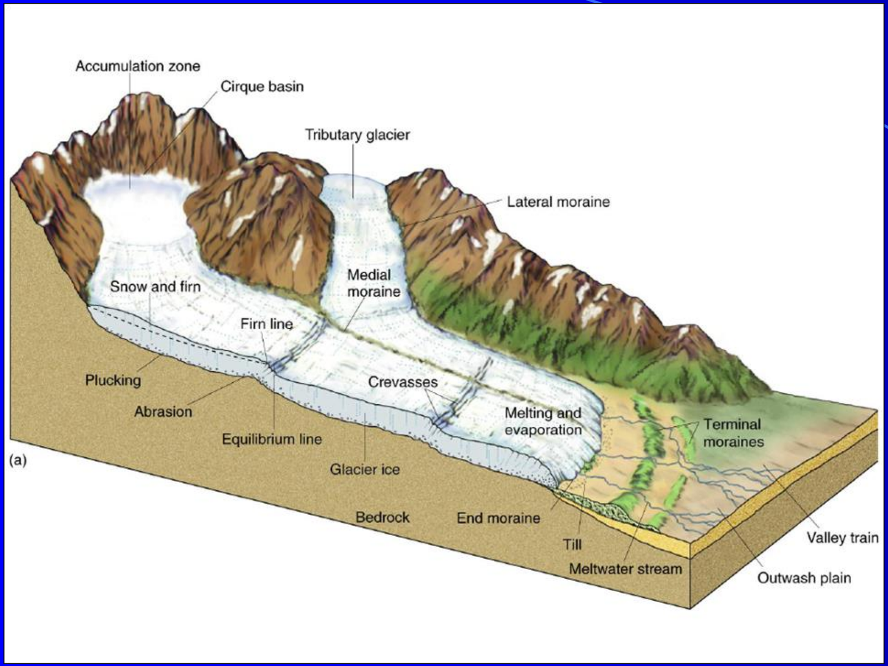
Col

Hanging valley

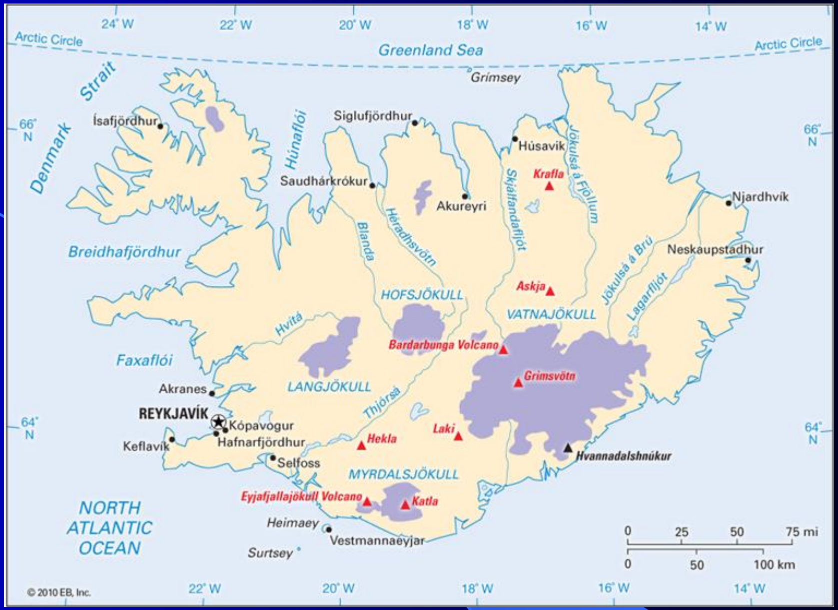
Aretes

Horn

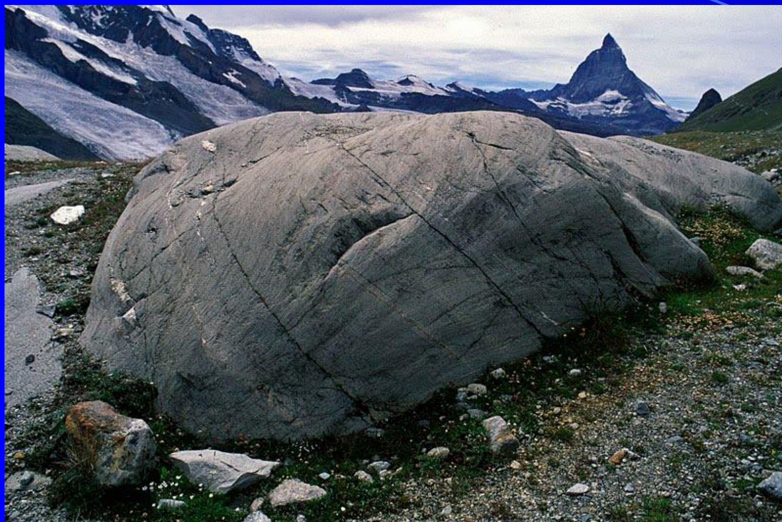
Alpine glaciers – depositional features



Ice Cap and Continental Glaciers

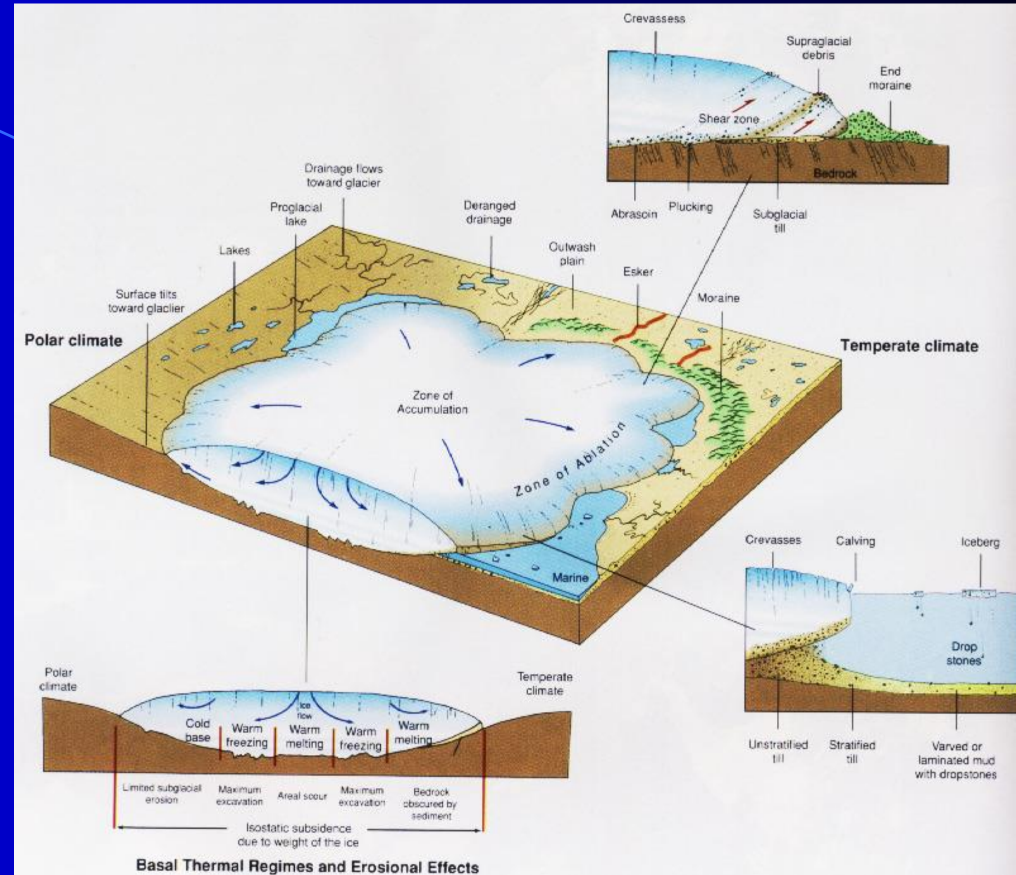


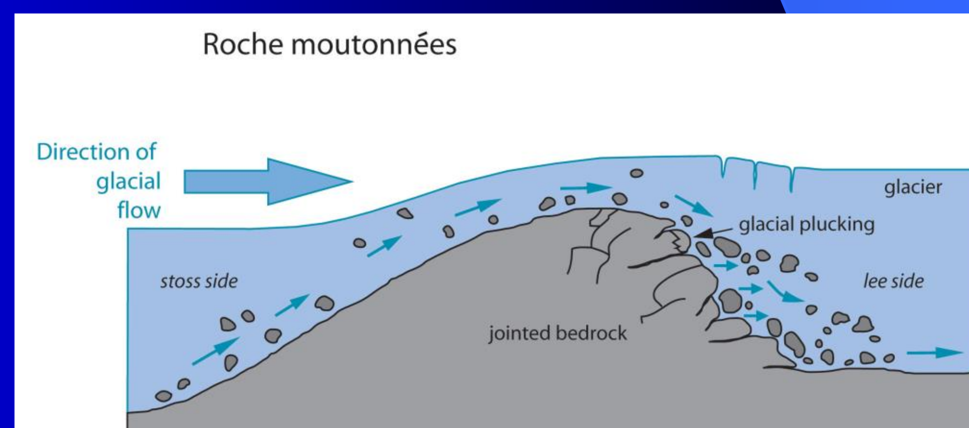
Erosional Features



Rock drumlin

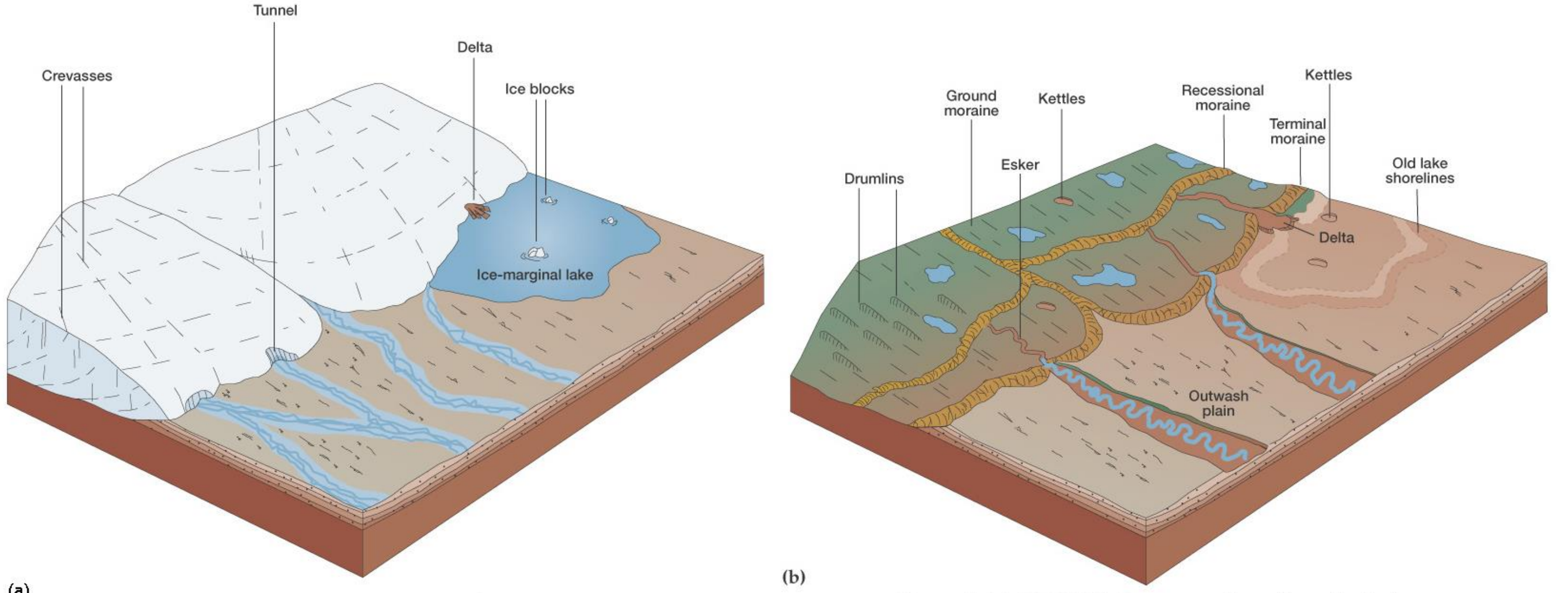
Grooves and striations



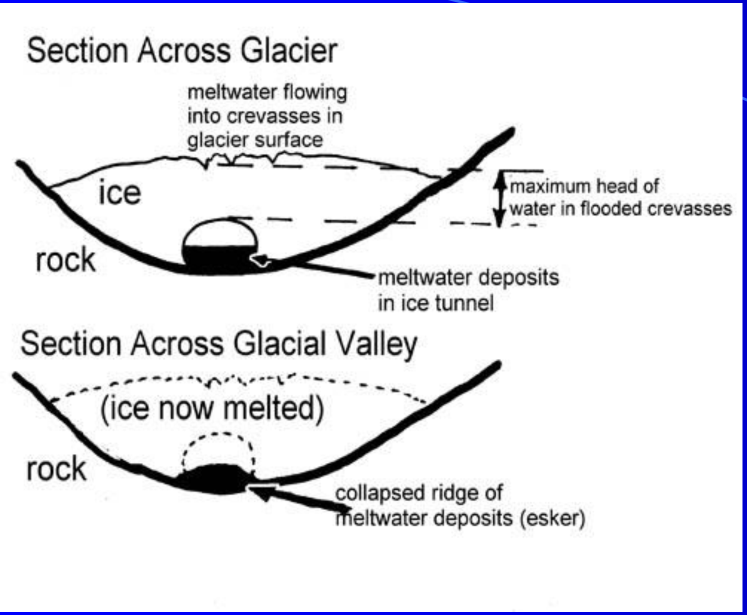


- The debris carried by the glacier eventually gets deposited
  - Till: unsorted glacial debris deposited by glacial ice
  - Outwash: debris reworked, transported and deposited by meltwater
  - Moraines: glacially bulldozed ridges of sediment
  - Esker: curved ridge of sand and gravel
  - Kettle: closed basin

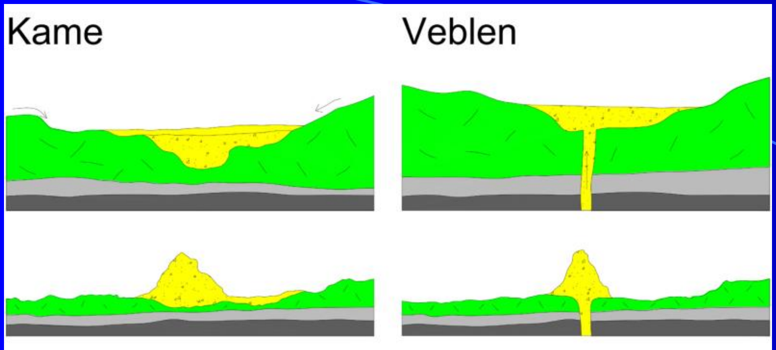
Depositional Features



Ground moraine (till)
Terminal moraine
Recessional moraines

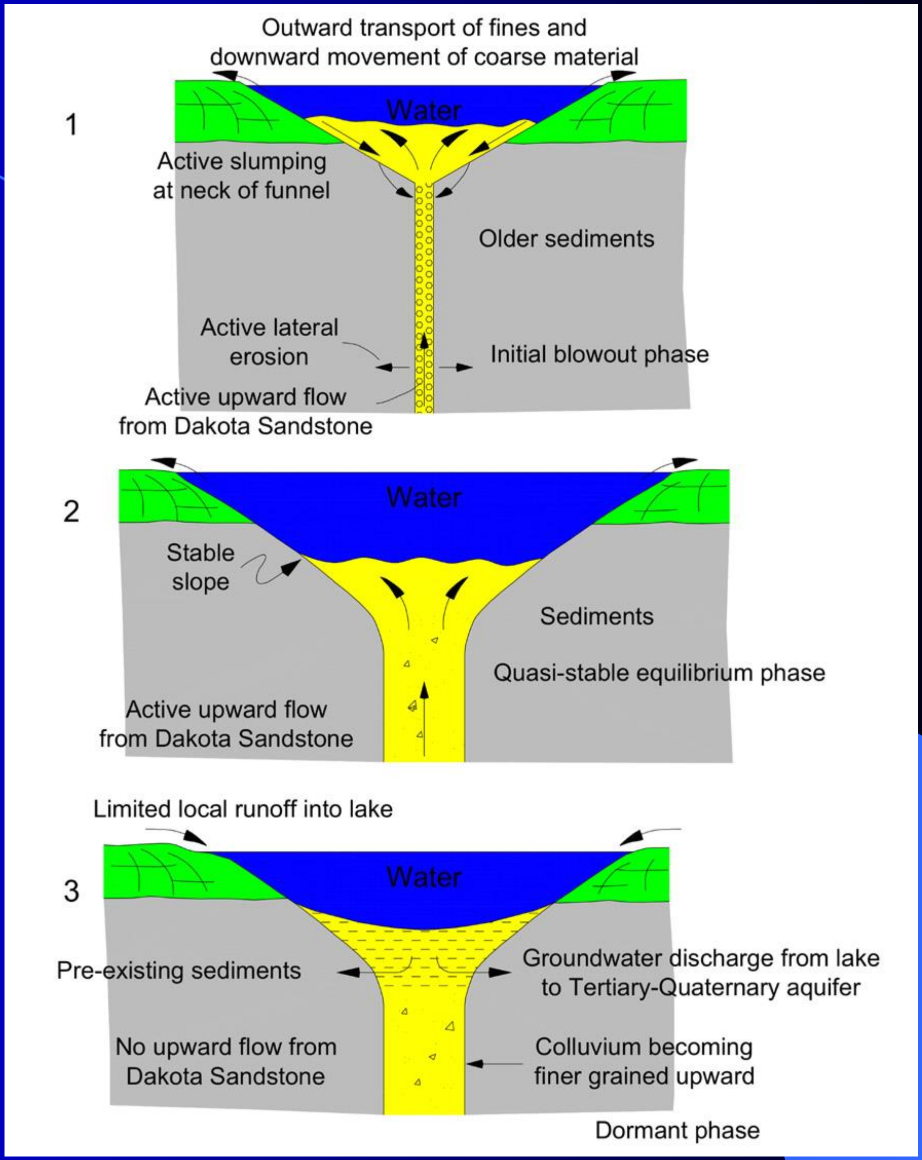

Section Across Glacier
meltwater flowing
into crevasses in
glacier surface
ice
maximum head of
water in flooded crevasses
rock
meltwater deposits
in ice tunnel
Section Across Glacial Valley
(ice now melted)
rock
collapsed ridge of
meltwater deposits (esker)

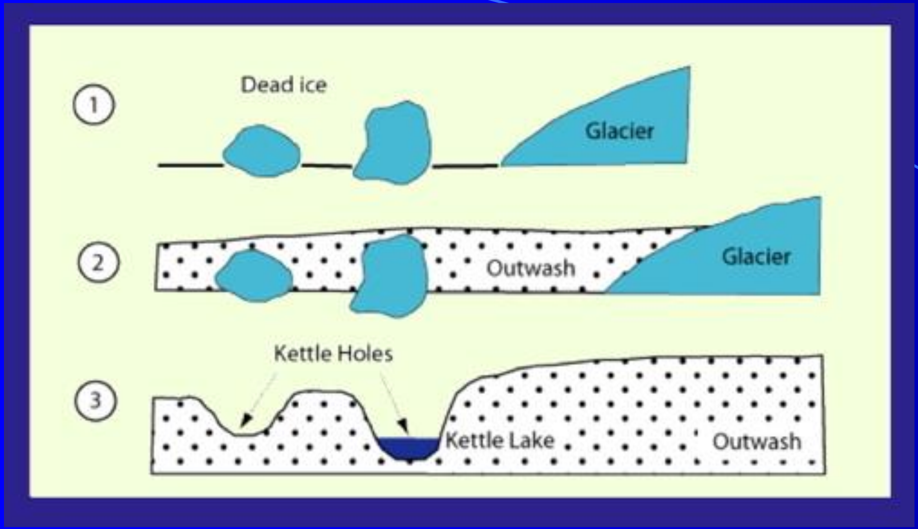
Eskers


Kame
Veblen

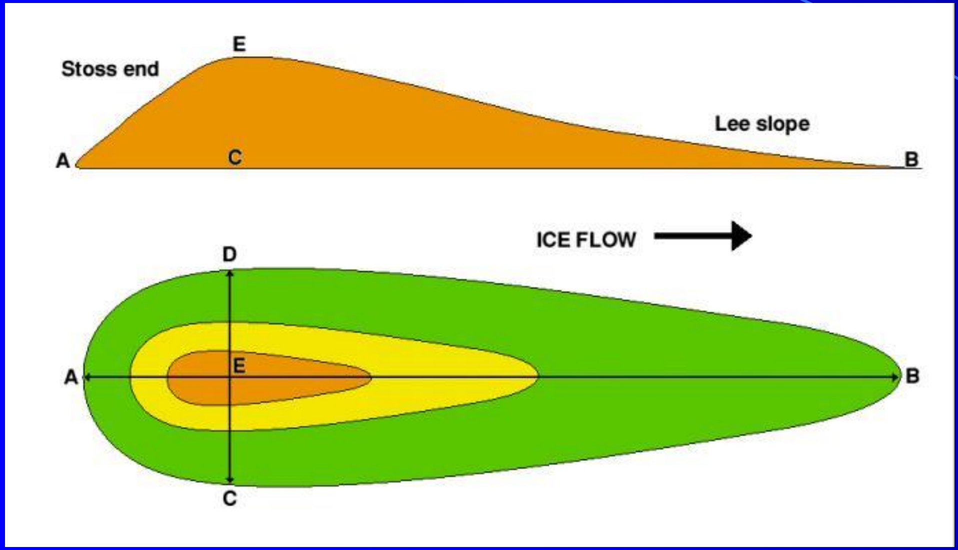

Kame


Veblen


Outward transport of fines and
downward movement of coarse material
1
Water
Active slumping
at neck of funnel
Older sediments
Active lateral
erosion
Initial blowout phase
Active upward flow
from Dakota Sandstone
2
Water
Stable
slope
Sediments
Quasi-stable equilibrium phase
Active upward flow
from Dakota Sandstone
Limited local runoff into lake
3
Water
Pre-existing sediments
Groundwater discharge from lake
to Tertiary-Quaternary aquifer
No upward flow from
Dakota Sandstone
Colluvium becoming
finer grained upward
Dormant phase

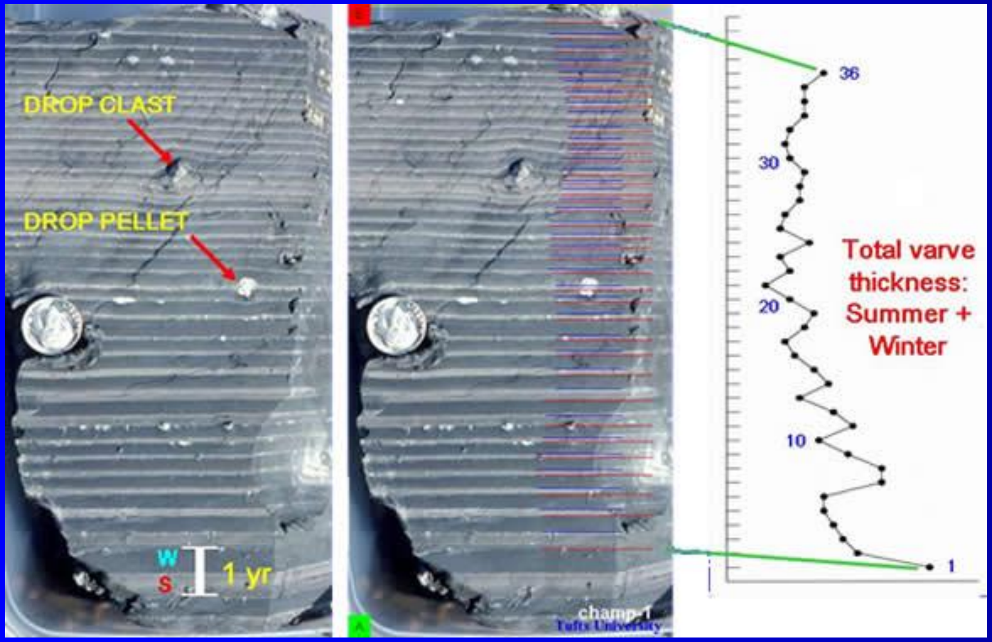

1
Dead ice
Glacier
2
Outwash
Glacier
3
Kettle Holes
Kettle Lake
Outwash

Drumlins

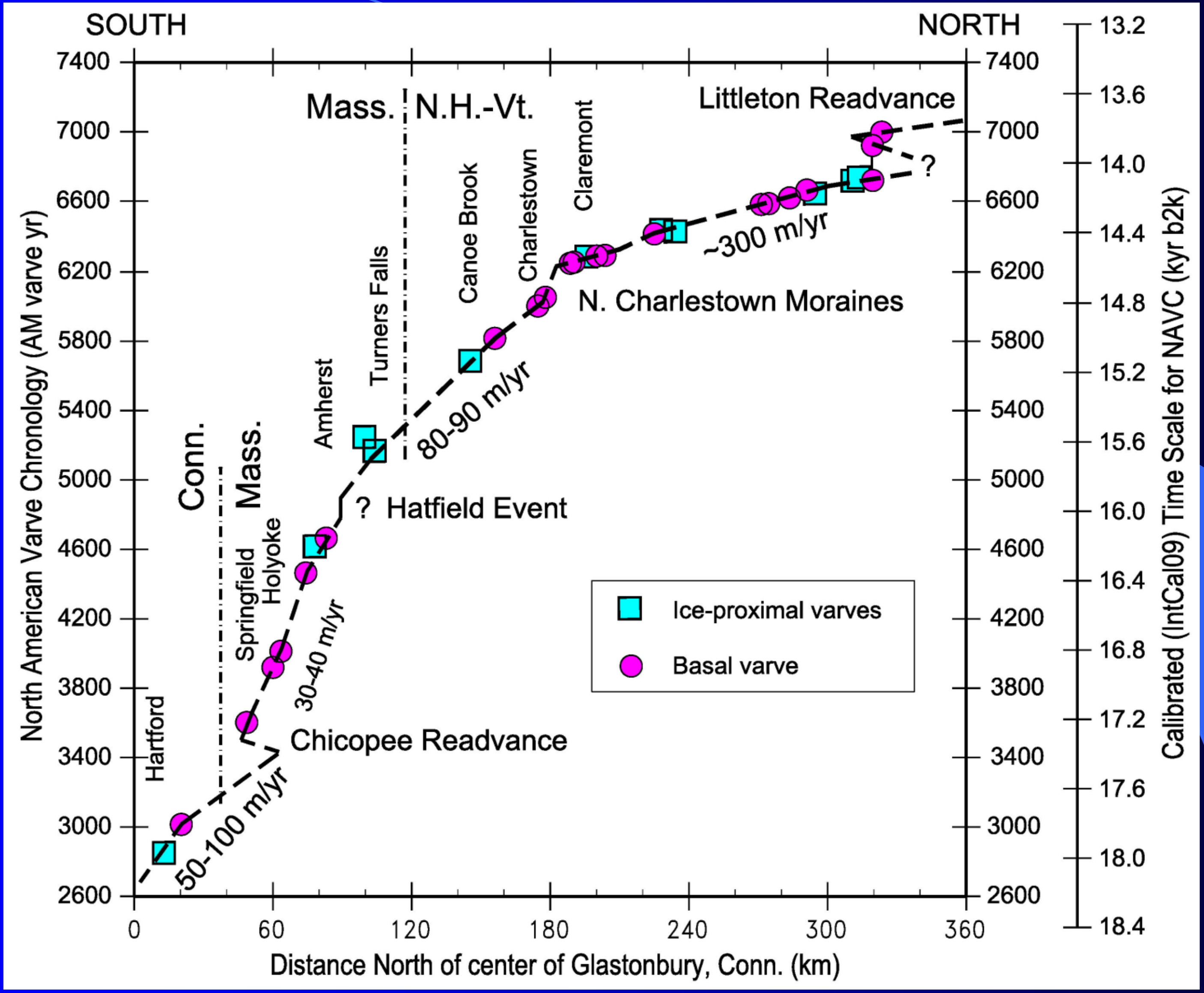


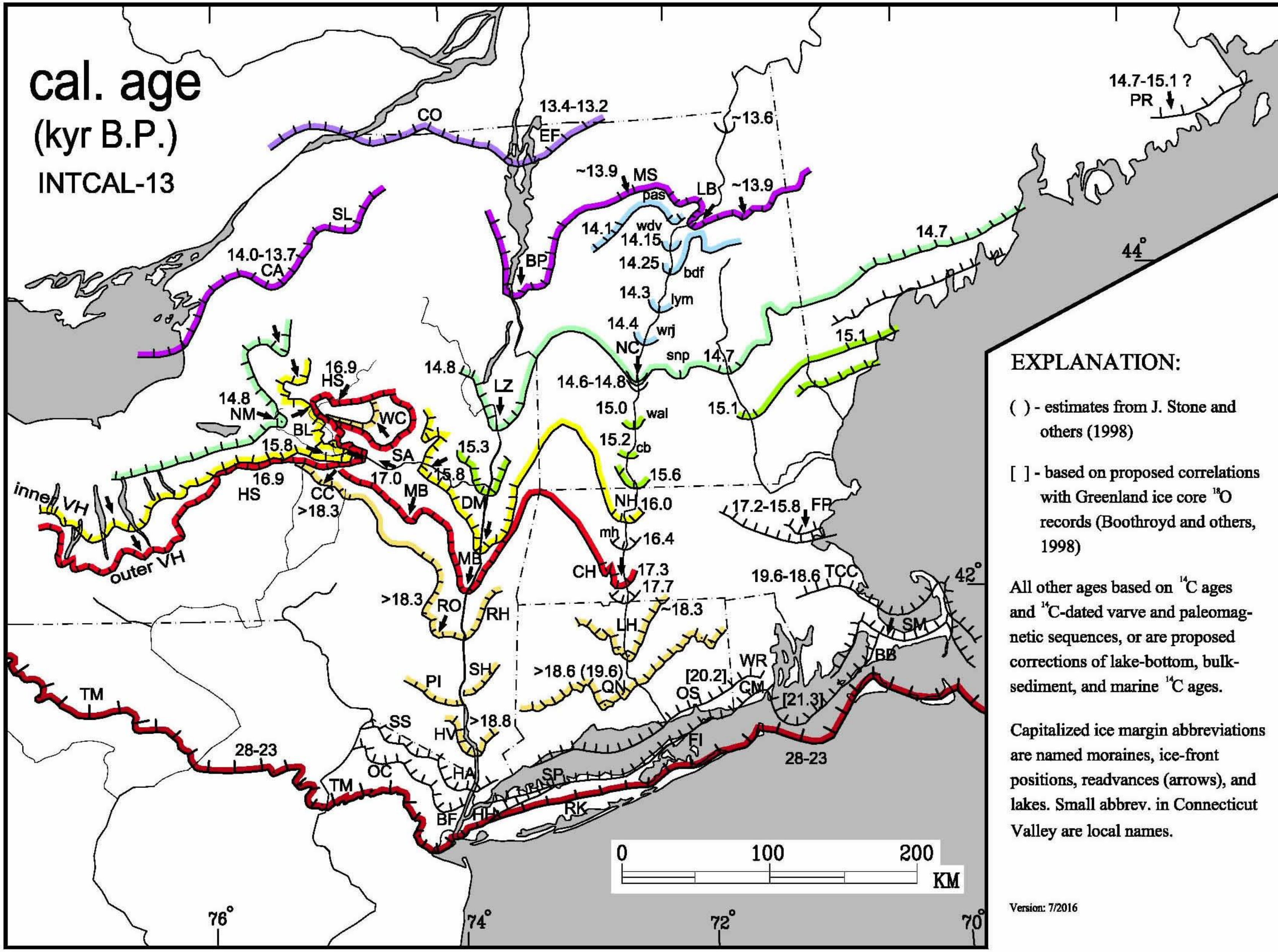
Proglacial lake varves

- Varves are found in the deposits of glacial lakes. Each varve consists of two distinct layers of sediment, a lower layer of light colored sandy material and an upper layer of darker silt.
- Most melting of the glacier occurs in spring and early summer, so at these times the meltwater streams flow fastest and carry their greatest loads. Fine material is held in suspension in the lake whilst heavier material is deposited.
- As autumn and winter approach, the capacity and competence of the meltwater streams is reduced because there is less melting and less meltwater. This allows the finer material, that has been kept in suspension, to settle out and be deposited. Thus, each year, a new set of coarse and fine beds are formed. By counting the number of varves in the lake sediments it is possible to establish the age of the lake.
- The varying thicknesses of the varves provides information about climatic conditions. Thick varves are the result of increased deposition, caused by warmer temperatures and increased melting. Thin varves suggest little deposition because of reduced melting and outwash.

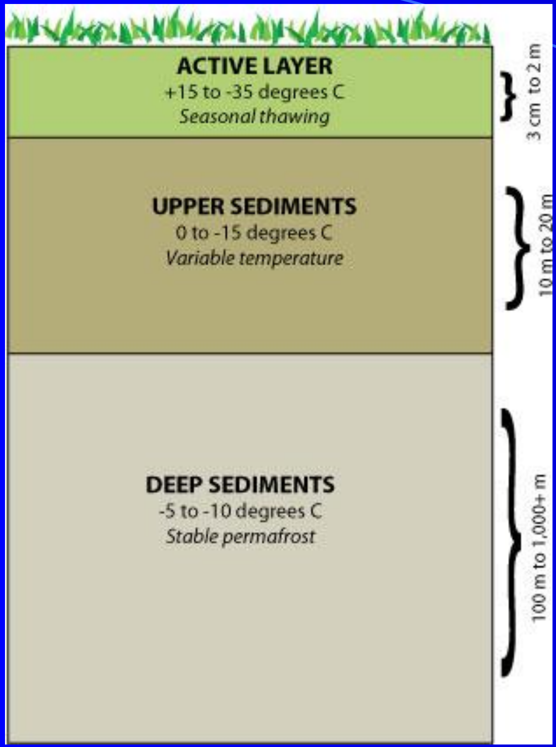


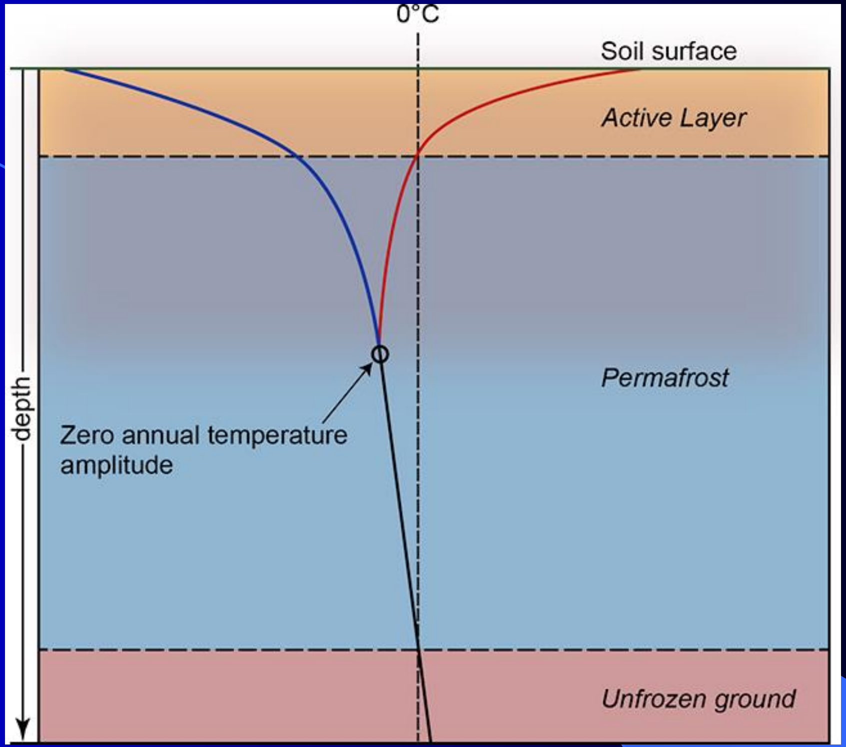
Basal varve localities are places where the bottom of the varve sequence can be found resting on till, bedrock, or a non-varved ice-proximal sand and gravel deposit. The oldest or bottom-most varve in the sequence represents the first fine-grained lacustrine sediment deposited at the receding glacier front and very closely approximates the time of deglaciation.


SOUTH
NORTH
Mass.
N.H.-Vt.
Littleton Readvance
Claremont
Charlestown
Canoe Brook
Turners Falls
Amherst
Conn.
Mass.
Springfield
Holyoke
Hartford
N. Charlestown Moraines
~300 m/yr
80-90 m/yr
? Hatfield Event
30-40 m/yr
Chicopee Readvance
50-100 m/yr
?
Ice-proximal varves
Basal varve
North American Varve Chronology (AM varve yr)
Calibrated (IntCal09) Time Scale for NAVC (kyr b2k)
Distance North of center of Glastonbury, Conn. (km)

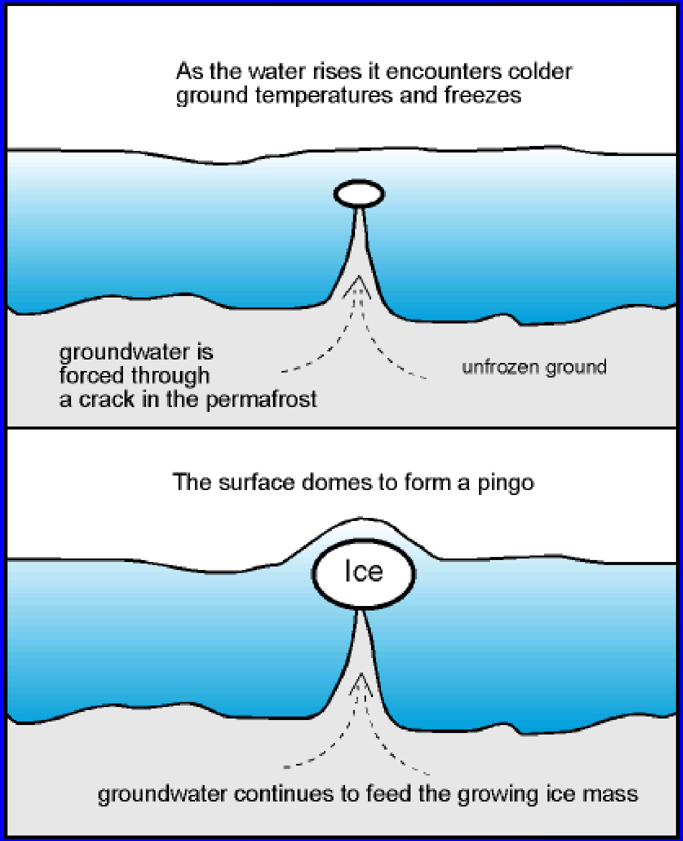

cal. age
(kyr B.P.)
INTCAL-13
EXPLANATION:
( ) - estimates from J. Stone and others (1998)
[ ] - based on proposed correlations with Greenland ice core 18O records (Boothroyd and others, 1998)
All other ages based on 14C ages and 14C-dated varve and paleomagnetic sequences, or are proposed corrections of lake-bottom, bulk-sediment, and marine 14C ages.
Capitalized ice margin abbreviations are named moraines, ice-front positions, readvances (arrows), and lakes. Small abbrev. in Connecticut Valley are local names.
Version: 7/2016
CO
13.4-13.2
EF
~13.6
14.7-15.1 ?
PR
~13.9
MS
pas
LB
SL
14.0-13.7
CA
BP
14.1
wdv
14.15
14.25
bdf
14.3
lym
14.4
wrj
NC
snp
14.7
15.1
44°
14.8
LZ
14.6-14.8
15.0
wal
15.2
cb
15.6
NH
16.0
mh
16.4
CH
17.3
17.7
~18.3
LH
16.9
HS
WC
NM
BL
15.8
SA
15.3
17.0
MB
DM
inner VH
outer VH
CC
>18.3
RO
RH
17.2-15.8
FP
19.6-18.6
TCC
42°
SM
BB
WR
CM
[20.2]
OS
[21.3]
>18.6 (19.6)
QN
PI
SH
>18.8
HV
SS
OC
HA
BF
HH
SP
FI
RK
TM
28-23
0
100
200
KM
76°
74°
72°
70°

- Land beyond the limit of glaciers is called periglacial and is mainly found in circumpolar regions
  - Characterized by permafrost
    - The active layer of this thaws in summer, becoming unstable, and refreezes in winter
    - When it melts, ground collapses
  - Patterned ground: ice-wedge polygons
  - Pingoes: frost-heaved hills
  - Geliflunction: mass wasting

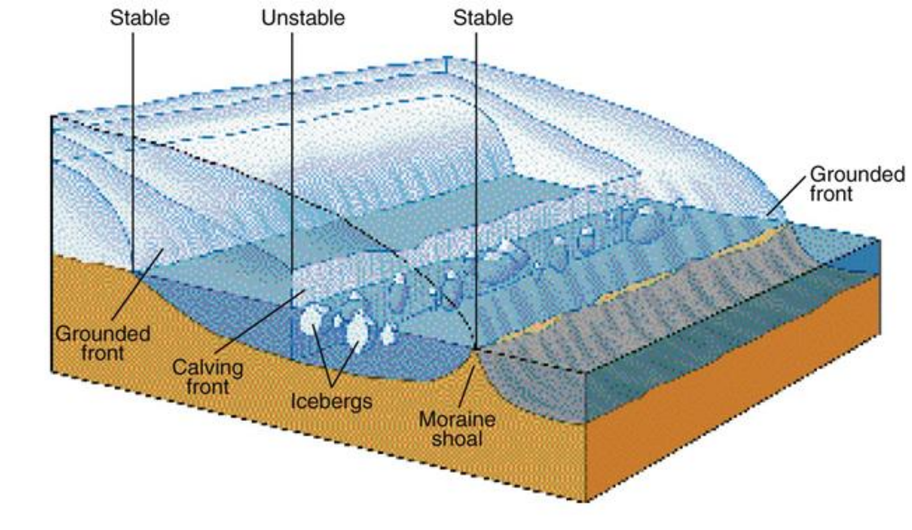

ACTIVE LAYER
+15 to -35 degrees C
Seasonal thawing
3 cm to 2 m
UPPER SEDIMENTS
0 to -15 degrees C
Variable temperature
10 m to 20 m
DEEP SEDIMENTS
-5 to -10 degrees C
Stable permafrost
100 m to 1,000+ m


0°C
Soil surface
Active Layer
Permafrost
Zero annual temperature amplitude
depth
Unfrozen ground

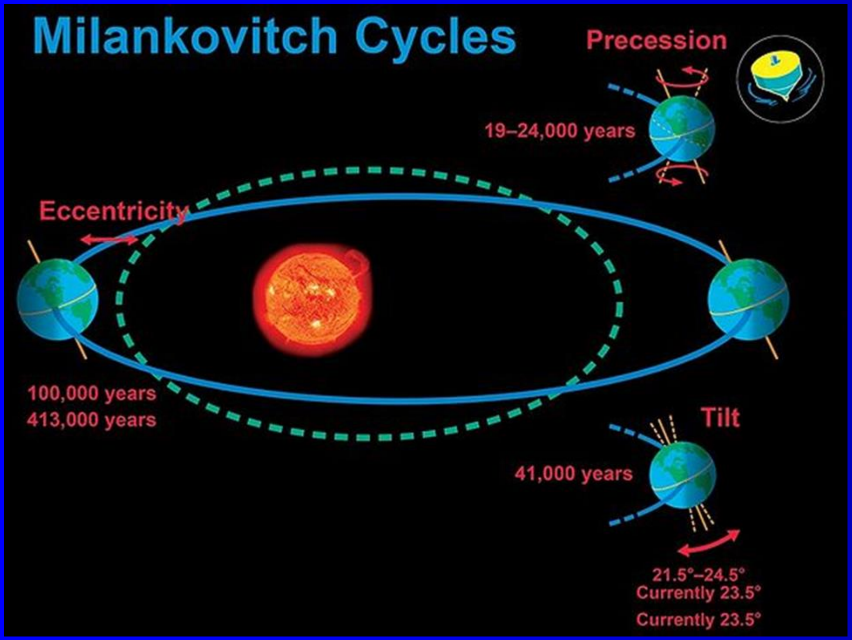
Pingos

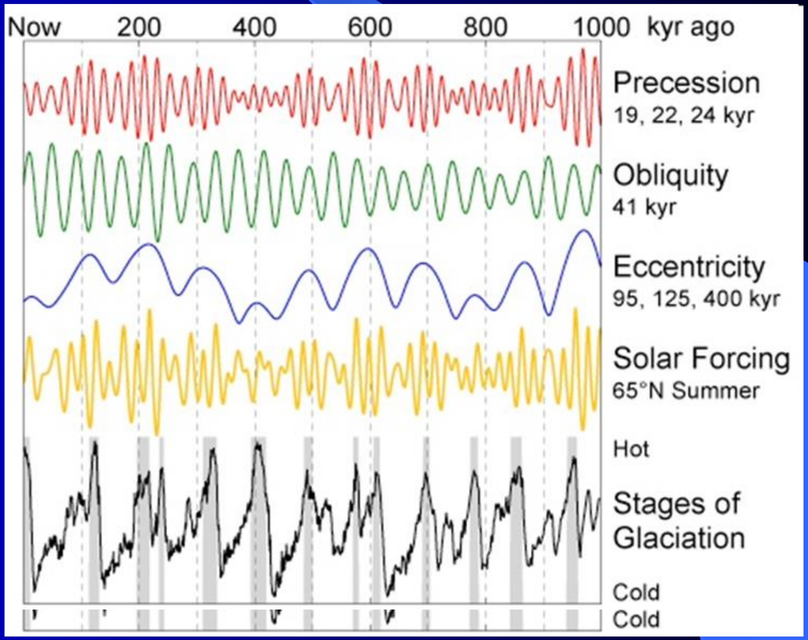

As the water rises it encounters colder ground temperatures and freezes
groundwater is forced through a crack in the permafrost
unfrozen ground
The surface domes to form a pingo
Ice
groundwater continues to feed the growing ice mass

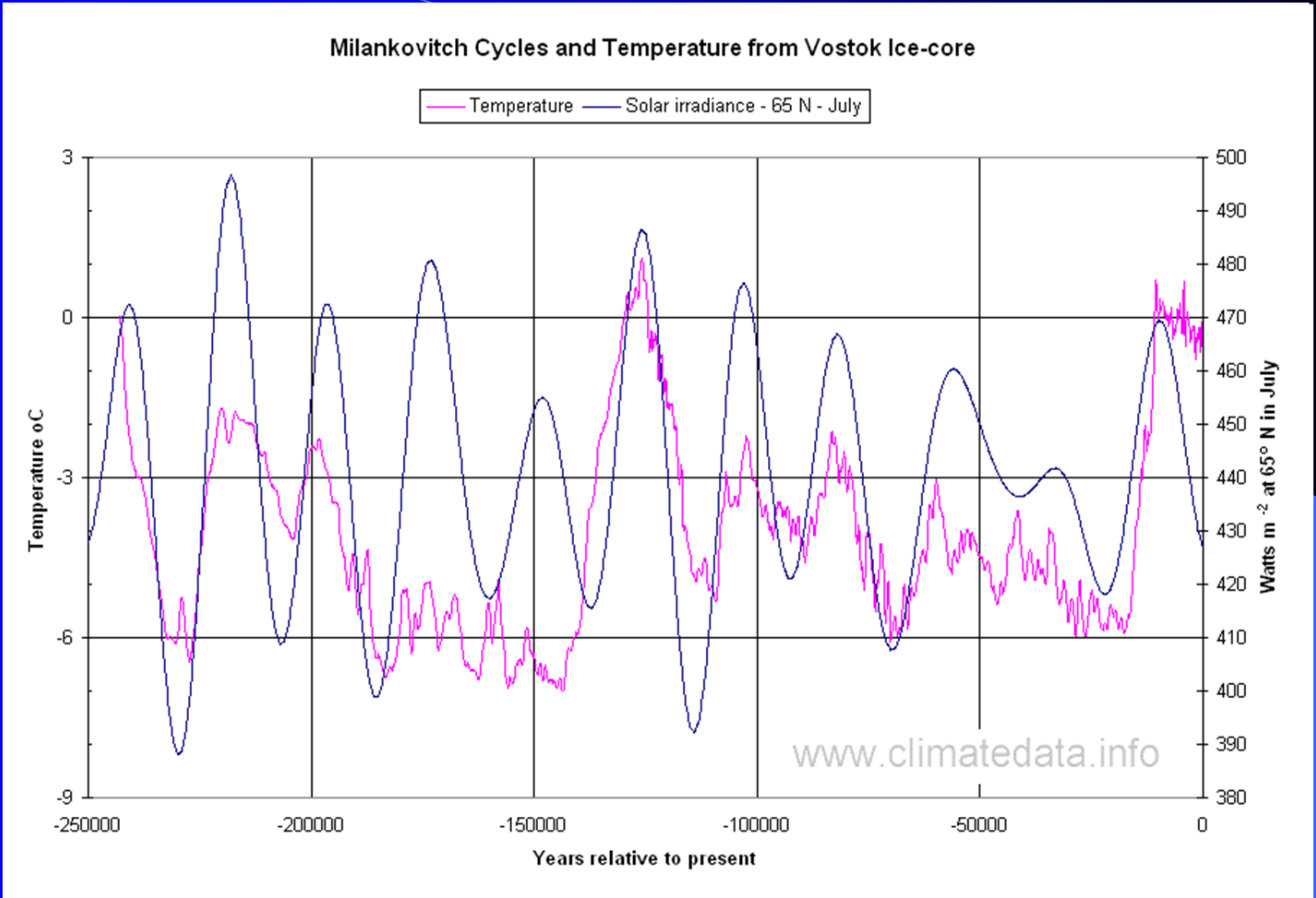
- Coastal glacier retreat is characterized by frontal calving
  - Where the terminus is in deep water
  - Front breaks off to form icebergs
- Fjord glacier termini may remain grounded on a shoal, preventing calving

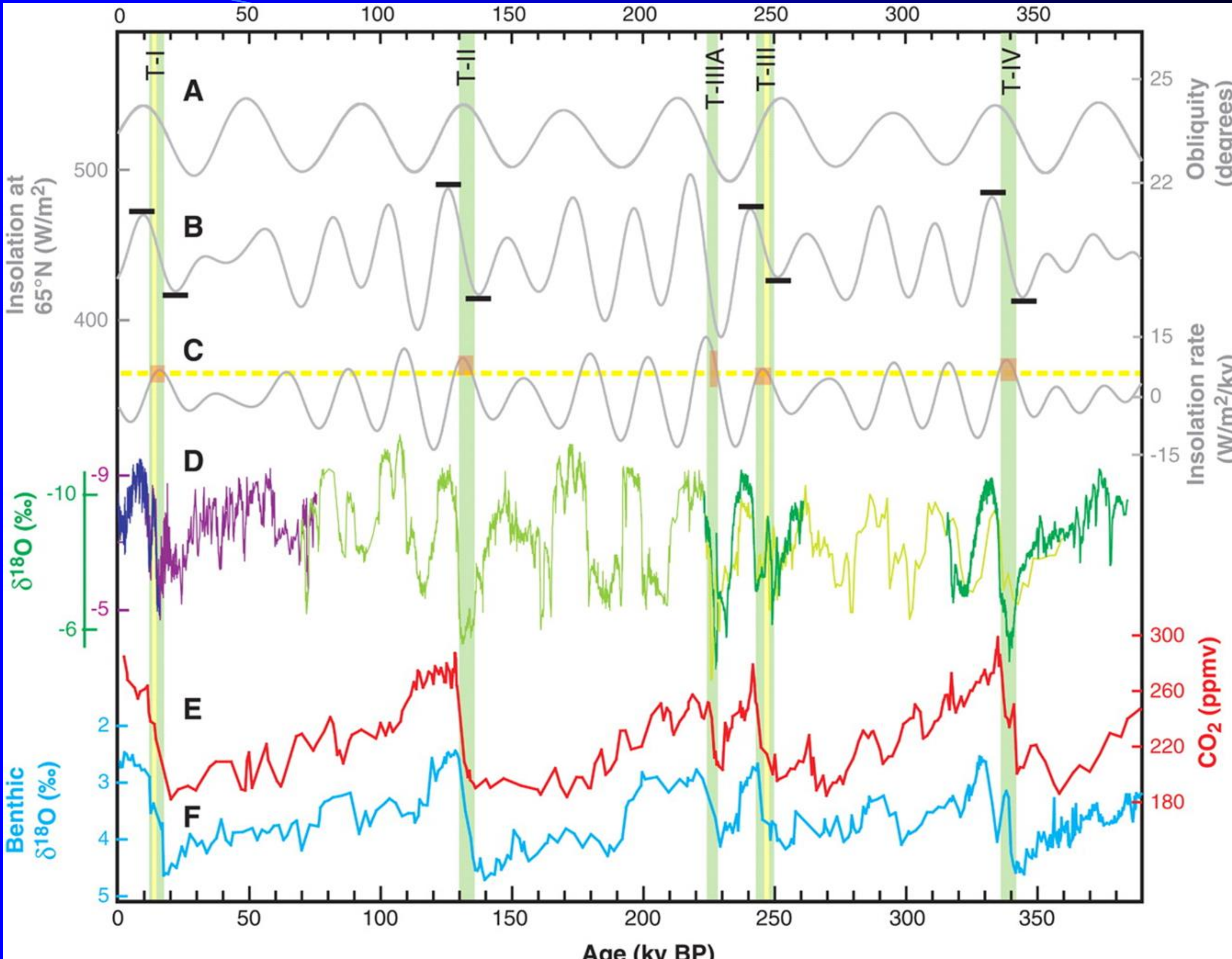


- The Earth fluctuates between periods of extended cooler and warmer temperatures
  - Glaciations: glaciers expand, and new ones form
  - Interglacials: ice sheets retreat, sea level rises
- We are in an interglacial period

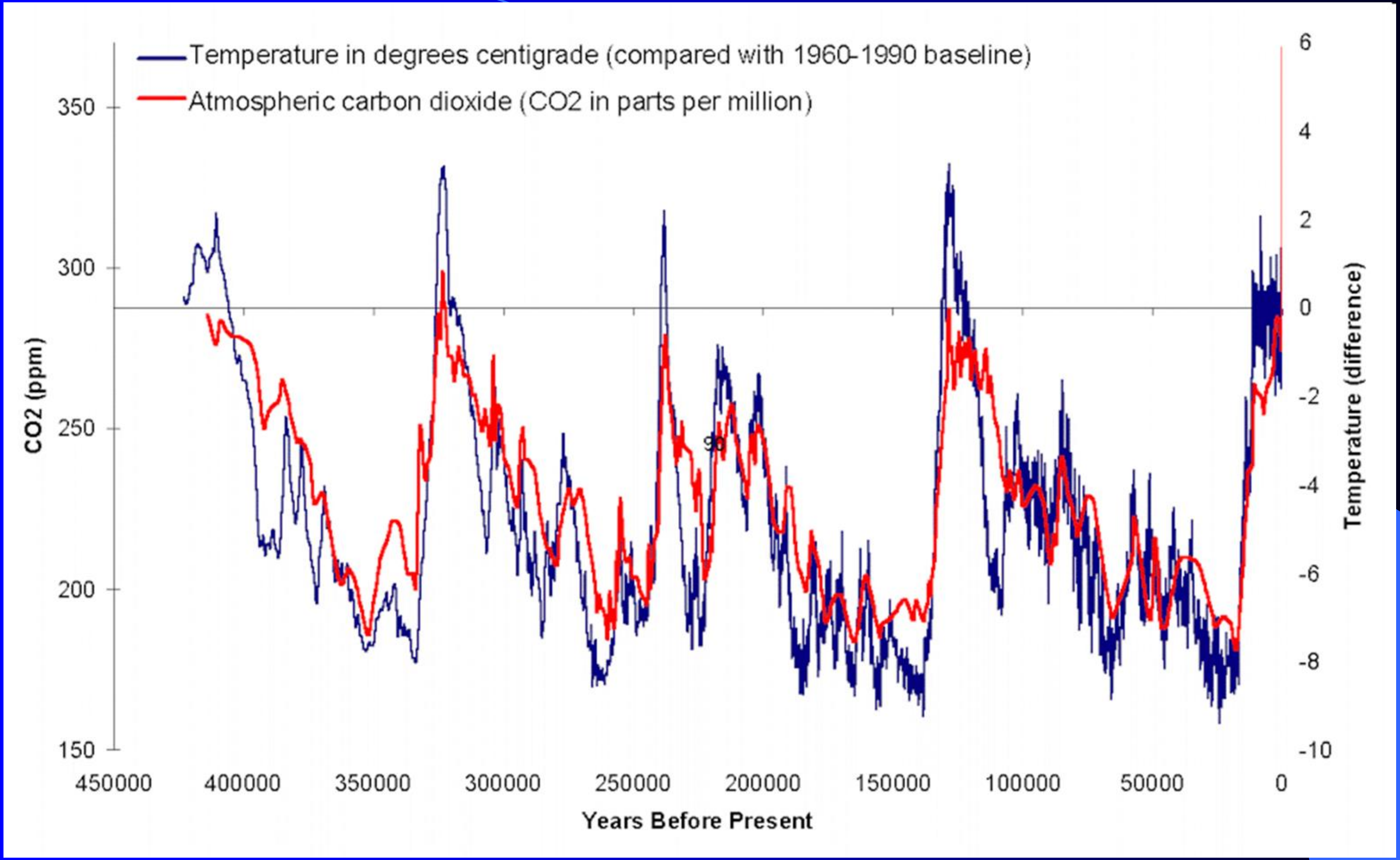





Milankovitch Cycles and Temperature from Vostok Ice-core
Temperature
Solar irradiance - 65 N - July
Temperature oC
Watts m -2 at 65° N in July
Years relative to present
3
0
-3
-6
-9
500
490
480
470
460
450
440
430
420
410
400
390
380
-250000
-200000
-150000
-100000
-50000
0
www.climatedata.info

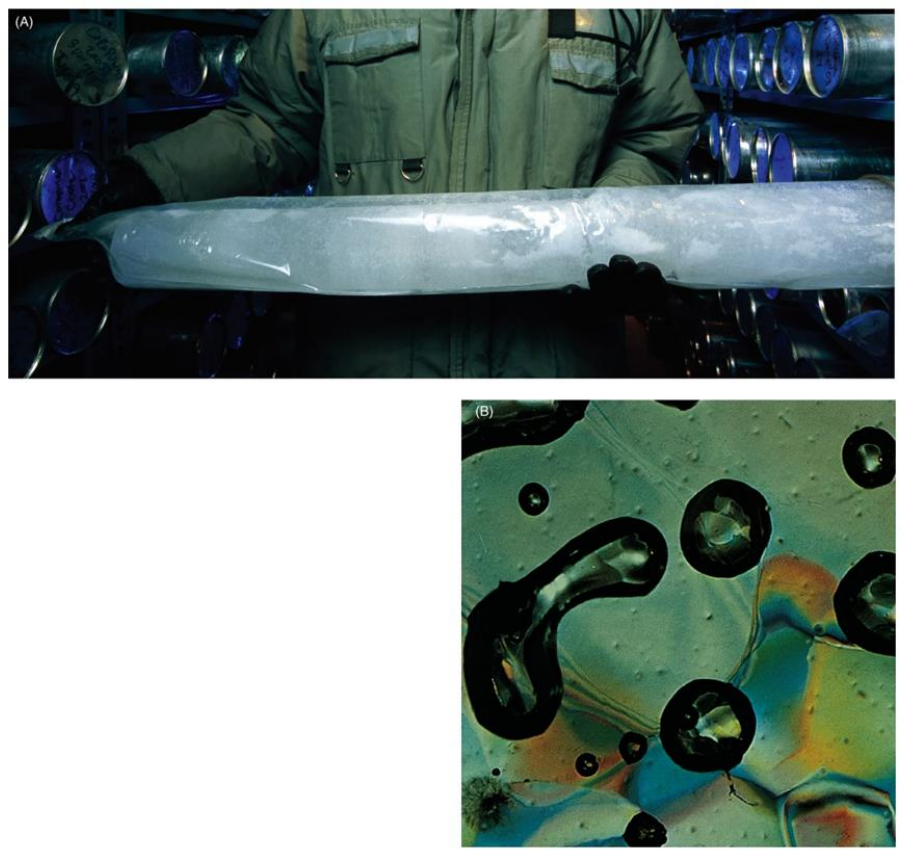


T-I
T-II
T-IIIA
T-III
T-IV
A
B
C
D
E
F
Obliquity (degrees)
Insolation at 65°N (W/m2)
Insolation rate (W/m2/ky)
δ18O (‰)
CO2 (ppmv)
Benthic δ18O (‰)
Age (ky BP)



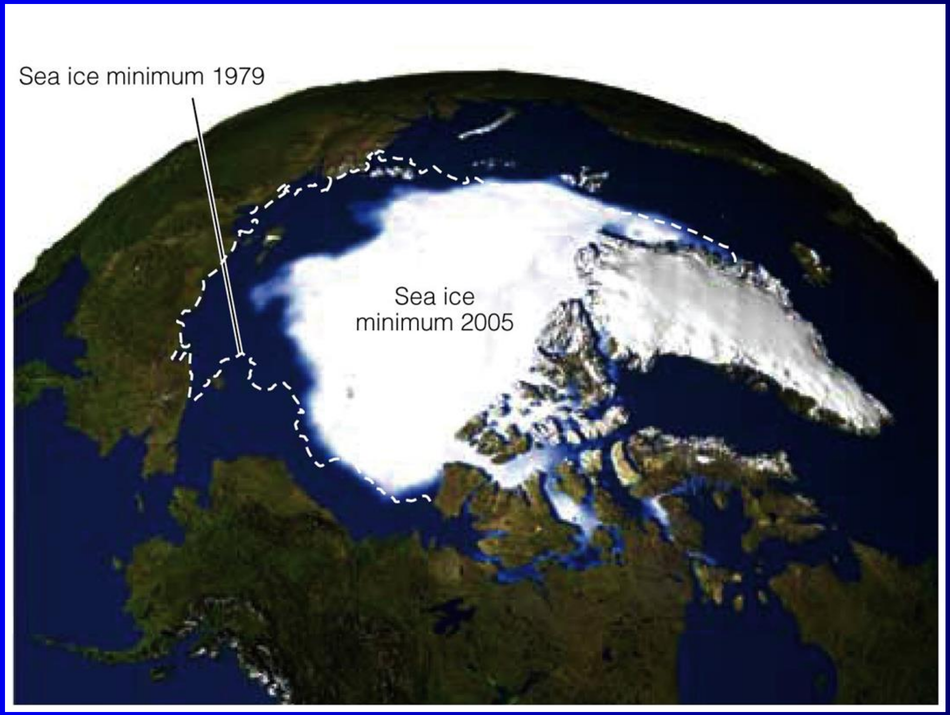
Temperature in degrees centigrade (compared with 1960-1990 baseline)
Atmospheric carbon dioxide (CO2 in parts per million)
CO2 (ppm)
350
300
250
200
150
Temperature (difference)
6
4
2
0
-2
-4
-6
-8
-10
450000
400000
350000
300000
250000
200000
150000
100000
50000
0
Years Before Present

- Trapped in the snow that accumulates each year on a glacier is evidence of local and global environmental conditions
- The oldest ice in most cirque and valley glaciers is several hundred to several thousand years old
- Large ice sheets contain ice that dates far back into the ice ages
- This can be examined through ice cores

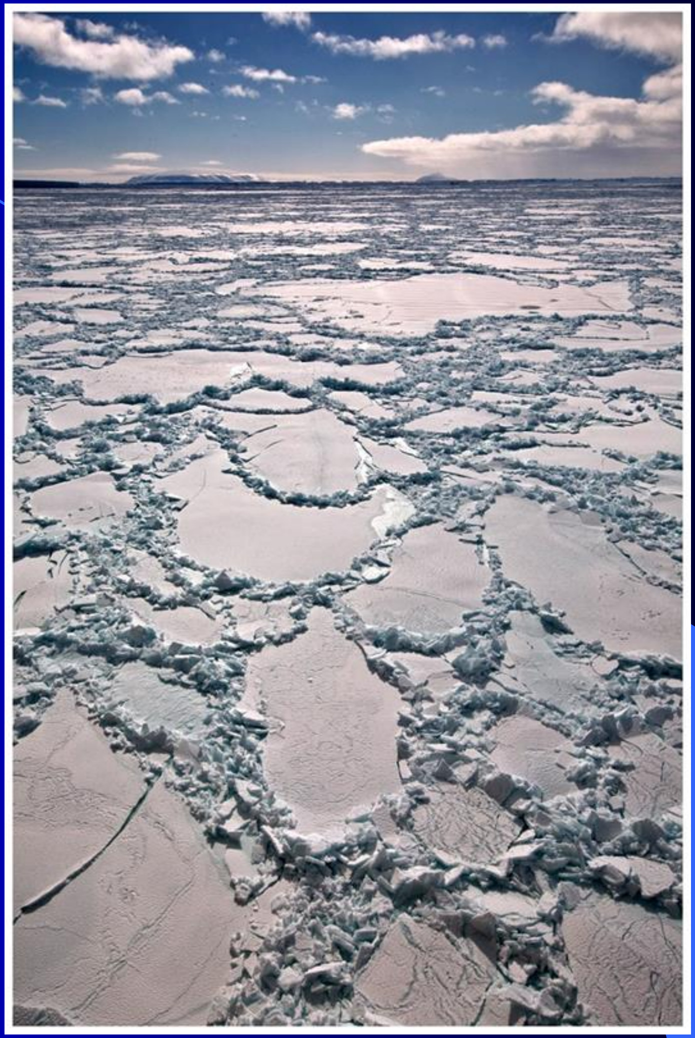


Sea Ice

- Forms by the solidification of fresh water at the ocean surface, not by precipitation, salt crystals are excluded
  - In glacial periods, the ocean becomes saltier, during interglacials, sea ice melts and it becomes less salty
- 2/3 of Earth's persistent ice cover floats as a thin veneer on polar oceans
- But it only comprises 1/1000 of Earth's total volume of ice



- Once the ocean surface cools to the freezing point of sea water, slight additional cooling leads to ice formation
  - First small platelets or needles called frazil
  - Then a soupy mixture at the surface
  - Without waves, crystals freeze together to form a 1-10 cm thick blanket of ice
  - With waves, crystals form 3 cm diameter pancake-like ice masses



Ice in the Earth System

- Influence on ocean salinity and circulation
  - Interactions among ice, water and atmosphere influence ocean structure, salinity and circulation
  - Sea ice is very sensitive to temperature change, and the exclusion of salt as it forms leads to the production of dense, cold saline water on the continental shelves
  - This produces deep bottom ocean water

- Influence on atmospheric circulation and climate
  - Floating ice isolates the ocean surface from the atmosphere, cutting off heat exchange
  - Ice has high albedo, reflecting incoming solar radiation rather than absorbing it
  - This results in a steep temperature gradient between the equator and poles, driving atmospheric circulation

- Ice cover and environmental change
  - If the climate became colder and ice over expanded, the result would be a positive feedback due to raised albedo
  - If the climate warms and ice cover shrinks or disappears, a similar but opposite effect of positive feedback warming would occur as the Earth's overall albedo decreases
    - While melting of sea ice would contribute little to ocean levels, however melting of land ice would contribute significantly to water volume
    - Both would drastically affect ocean salinity