GLACIAL PROCESSES AND LANDFORMS

Glaciers affected landscapes directly, through the movement of ice & associated erosion and deposition, and indirectly through

- changes in sealevel (marine terraces, river gradients, climate)
- climatic changes associated with changes in atmospheric & oceanic circulation patterns
- resultant changes in vegetation, weathering, & erosion
- changes in river discharge and sediment load

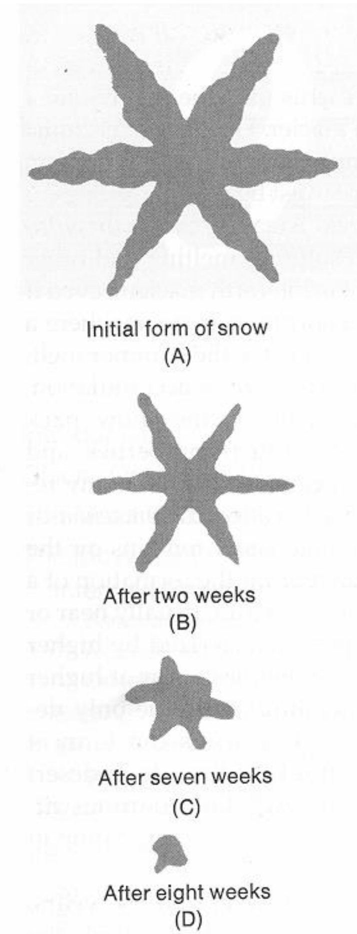
Many high-latitude regions are dominated by glacially-produced landforms

Glacial origin

Glacier: body of flowing ice formed on land by compaction & recrystallization of snow

Accreting snow changes to glacier ice as snowflake points preferentially melt & spherical grains pack together, decreasing porosity & increasing density ($0.05\ g/cm^3 \longrightarrow 0.55\ g/cm^3$): becomes firn after a year, but is still permeable to percolating water

Over the next 50 to several hundred years, firn recrystallizes to larger grains, eliminating pore space (to $0.8\ g/cm^3$), to become glacial ice



Mont Blanc, France


Mont Blanc
Google Earth
Image © 2018 DigitalGlobe
N
10 km

Glacial mechanics

Creep: internal deformation of ice

creep is facilitated by continuous deformation; ice begins to deform as soon as it is subjected to stress, & this allows the ice to flow under its own weight

Sliding along base & sides is particularly important in temperate glaciers

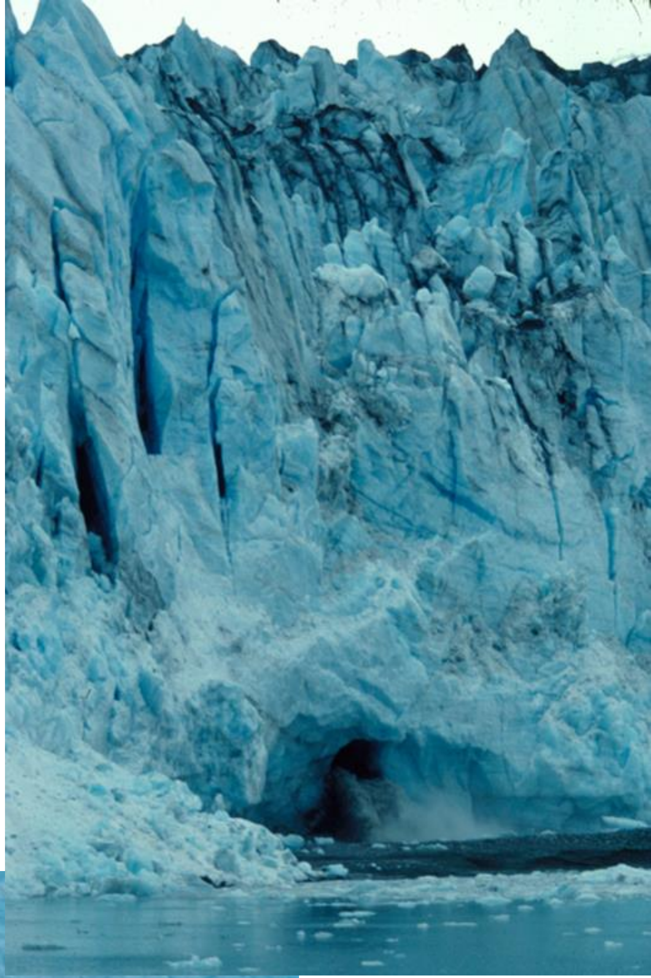
two components of slide are

regelation slip – melting & refreezing of ice due to fluctuating pressure conditions

enhanced creep

Cavell Glacier, Jasper National Park, Canada

supraglacial
stream, Alaska

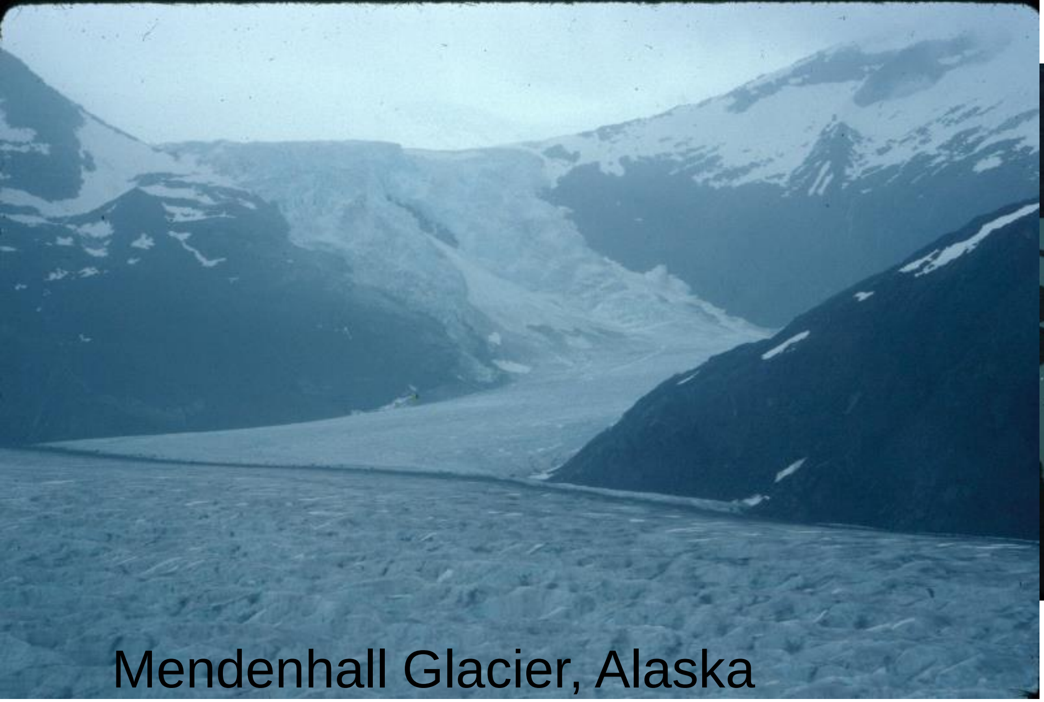


subglacial stream,
Alaska

Velocity along glacier

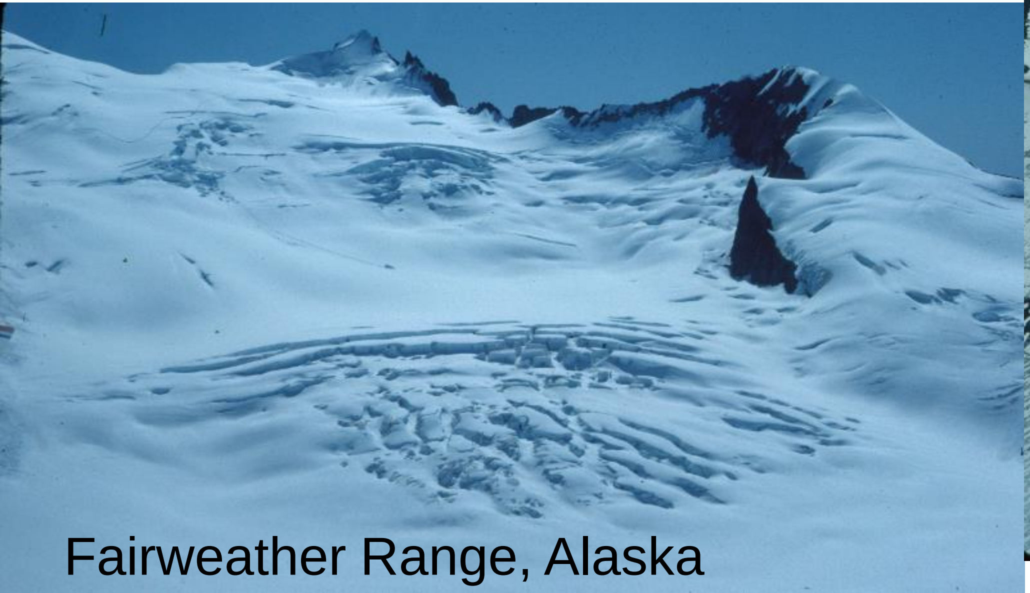
- increases to the equilibrium line as discharge increases
  - (Q = w d v), & decreases after this line as ablation becomes active
- decreases from the surface to the bedrock & from the center to
  - the edges as a result of boundary resistance and internal mechanics

As ice flows, it thickens through compressive flow when the bed is concave upward or addition of ice is low, or thins through extending flow



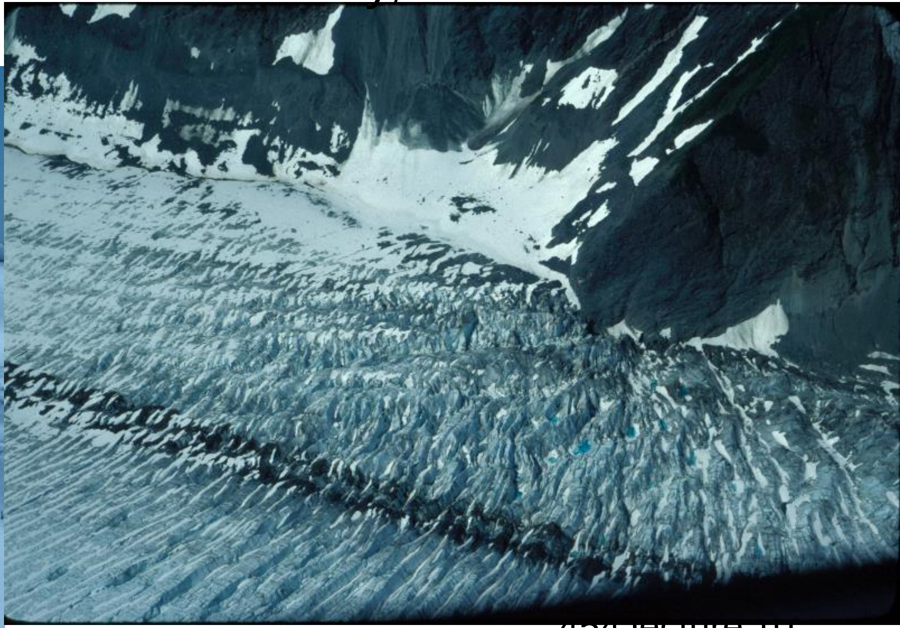
Mendenhall Glacier, Alaska

Glacier Bay, Alaska



Fairweather Range, Alaska

Glacier Bay, Alaska



Glacier Bay, Alaska

Surging glacier: movement may have characteristics similar to kinematic wave, but does not require external stimuli such as mass addition

- sudden, brief, large-scale ice displacements periodically occur
- move 10-100 times faster than normal
- periodicity at 15-100 years
- probably due to unique conditions creating cyclic instability within the glacier
- fairly common phenomenon
- surge chaotically breaks surface
- key may lie in mechanics of basal sliding (eg. meltwater lowers basal shear stress)

Types of glaciers

Morphological: based on glacier size & environment of growth

- cirque glaciers
- valley glaciers
- piedmont glaciers
- ice sheets

Dynamic: based on observed activities of glaciers

- active – continuous movement of ice from accumulation zones to edges
- passive – not enough new snow, or low slopes; very low velocity
- dead – no internal transfer of ice from accumulation zone

Thermal: based on temperature of ice

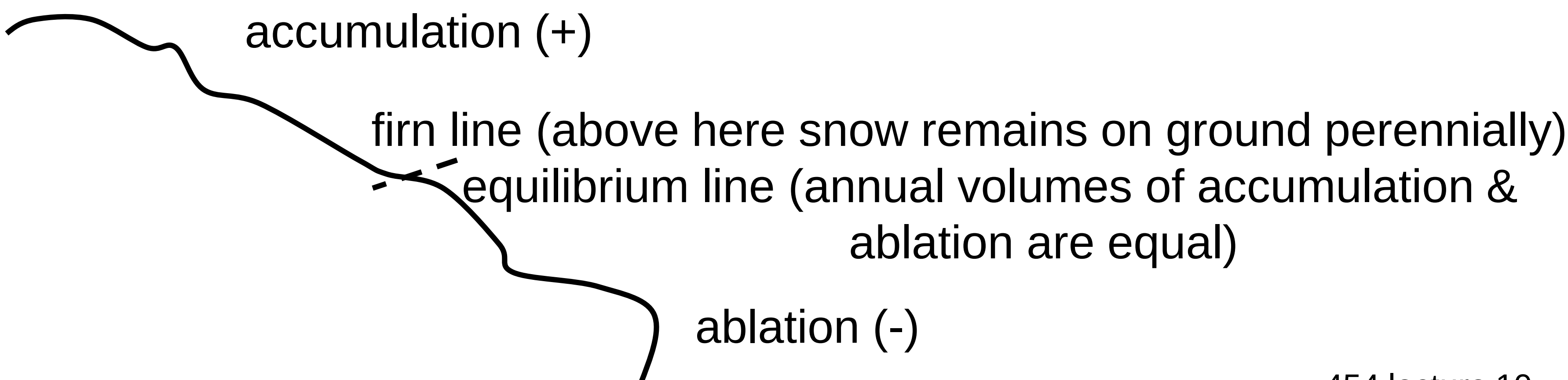
- temperate – ice throughout mass is at pressure-melting point, abundant meltwater; high velocity & erosive action
- polar or cold – absence of meltwater means ice at base is frozen to underlying rock – slippage can't occur (movement is internal) – erosive action much less

Generally, valley glaciers are active, & temperate ice sheets are polar and passive

Glacial budget: mass balance of glacier; budgeting of gains & losses of mass on glacier during specific time interval

accumulation	ablation	
snow	melting	sublimation
rain & other water	evaporation	calving
avalanches	wind erosion	

Usually consider one budget year (time between two successive stages) when ablation attains maximum yearly value – usually end of summer



+ mass balance: advance; steep or vertical front

-- mass balance: recede; gently sloping, partially buried snout

rates of accumulation & ablation matter, as well as overall balance

temperate glaciers – high accumulation & ablation rates, move rapidly

polar glaciers – low accumulation & ablation rates, passive

} both may have 0 net balance

Ice structures

Primary

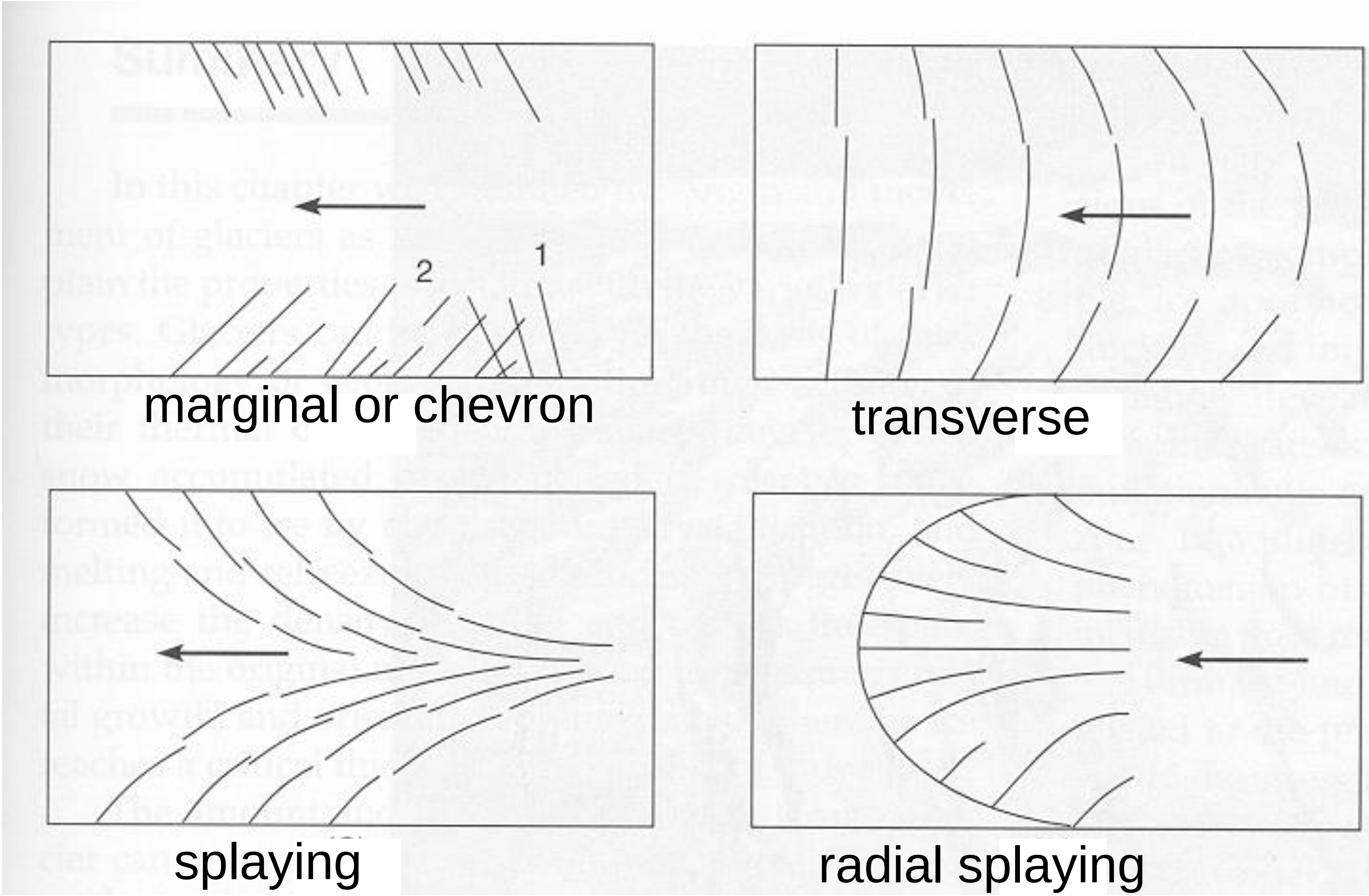
stratification: layers or bands within ice due to annual cycle of snow accumulation & ablation – debris & textural differences separate bands

Secondary

foliation: layering produced by shear during ice motion, produces alternating clear blue & white bubble-rich ice

crevasses: cracks in ice surface; reflect tensional stress, usually perpendicular to direction of maximum elongation, although also

- splay or radial crevasses near centerline where spreading exerts component of lateral extension
- chevron/en echelon crevasses near ice margins where shear stress parallels valley walls and crevasses form diagonal to valley sides
- transverse crevasses where ice extends in longitudinal direction (eg ice falls)


2
1
marginal or chevron
transverse
splaying
radial splaying


Google Earth
Image © 2018 DigitalGlobe
800 m
N

ogives: at base of ice fall crevasses are closed by compression & band of dirt-stained ice forms in summer – in winter the ice descending the fall reconstitutes into clear, bubbly ice; the annual down-valley flow produces a series of alternating white & dark bands called ogives

Taku Valley, Alaska

Erosional Processes and Features

Glacial erosion occurs via

- abrasion: scraping from debris carried in ice, depends on relative hardness of debris & bedrock; amount of debris; and velocity of flow; about 0.06-5 mm/yr
- quarrying/plucking: ice exerts shear force on rock loosened by fractures & meltwater freezes to rock as glacier thickness/ velocity/meltwater fluctuate

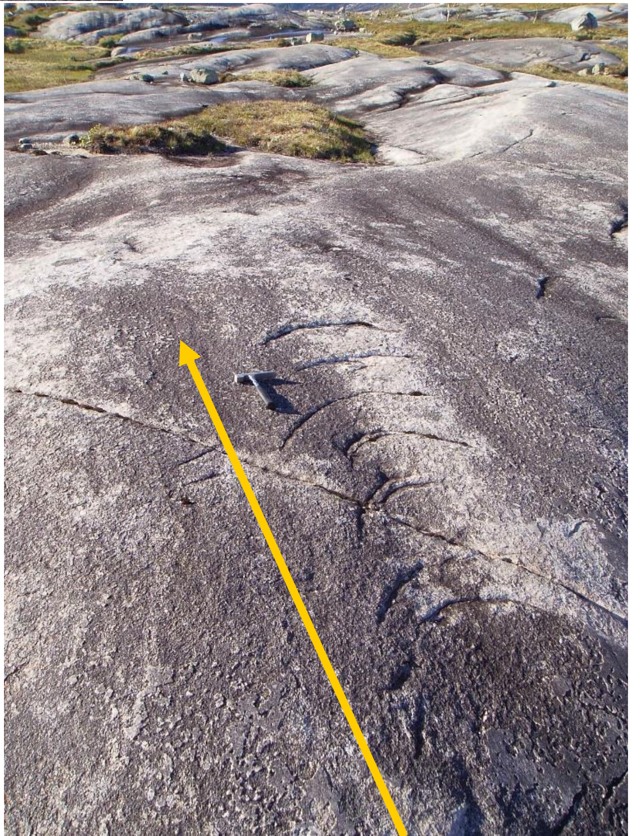
Abrasion features

- striations: mm deep, continuous only for short distances
- grooves: 1-2 m deep, 50-100 m long, boulders carried along
- crescentic marks: chipping of underlying rock

striations, Athabaska Glacier, Canada

glacial polish, Yosemite, CA

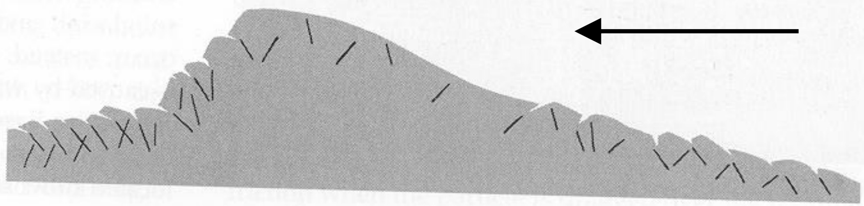
crescentic gouges,
northern Norway

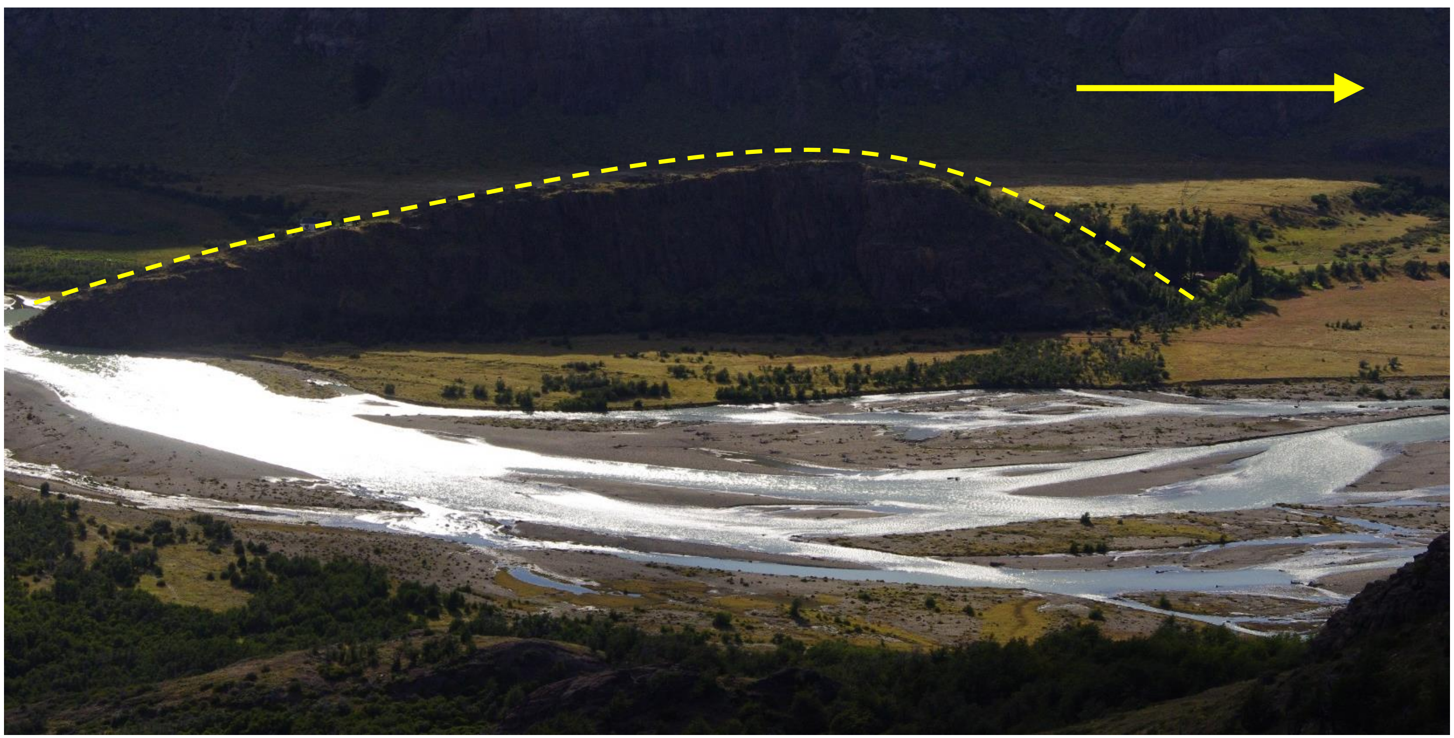


Plucking features

roche moutonnee: abrasion upstream & plucking downstream, promoted by irregular spacing of bedrock fractures

FIGURE 10.3
Relationship between joint spacing and roche moutonnée development in Yosemite Valley.
(After Matthes 1930)

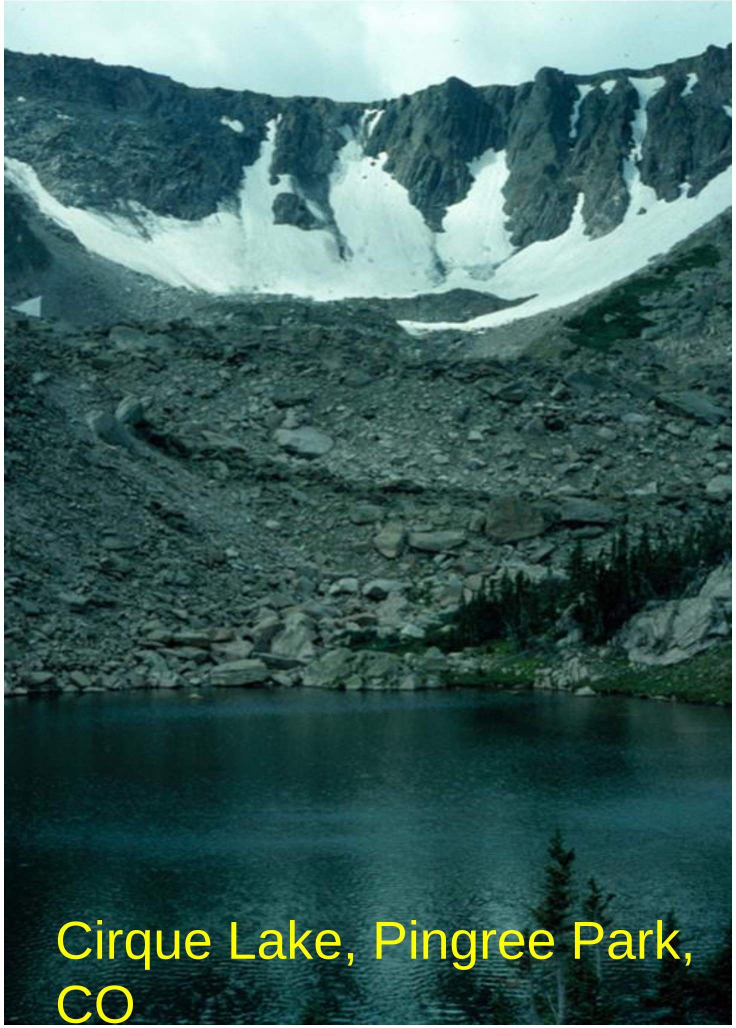




Patagonia, Argentina

Other features

cirque: deep, erosional recess with steep & shattered walls at the head of a mountain valley, semicircular in plan view like ampitheater; bowl may contain lake called tarn dammed by rock lip with moraines



Cirque Lake, Pingree Park, CO

cirque & tarn, Glacier National Park, MT


Google Earth
Alle
N
5 km

Size & shape of cirque are a function of

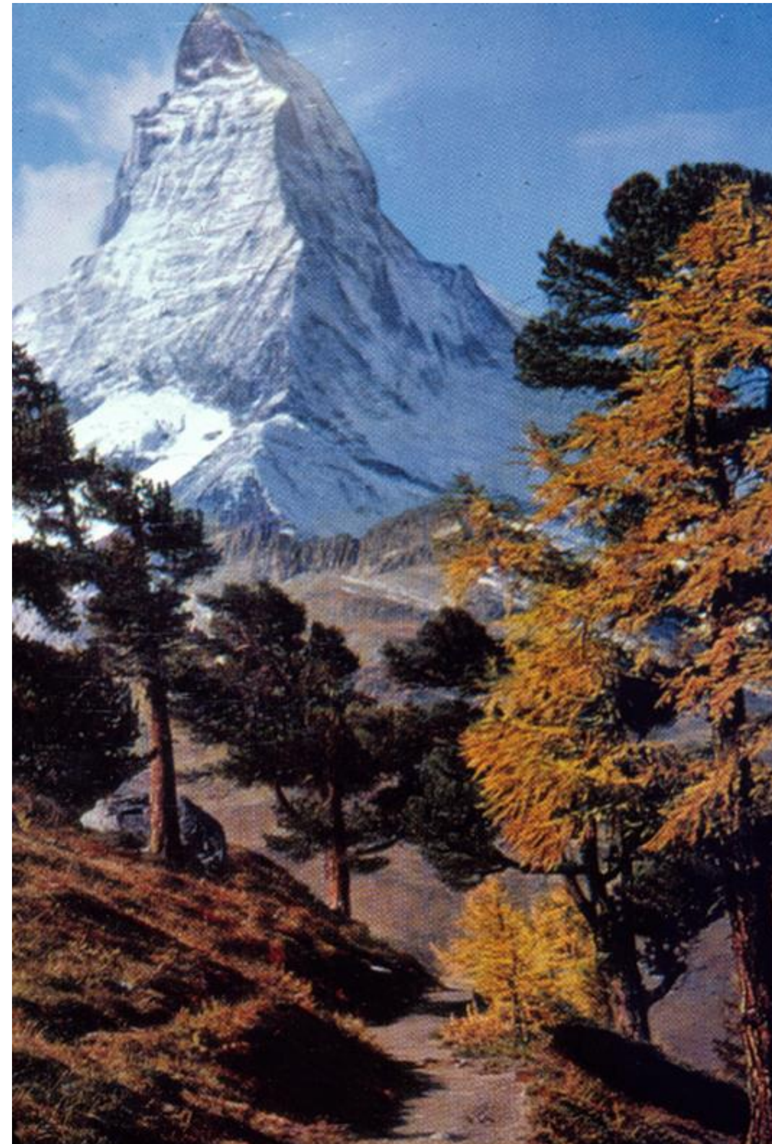
- rock type (larger & more well-developed in igneous or highly metamorphosed rocks)
- rock structure
- preglacial relief
- time span of glaciation

Elevation is controlled by snowline elevation at time of formation, orientation with respect to solar radiation & prevailing winds

Cirques grow headward & laterally to form horns and arretes

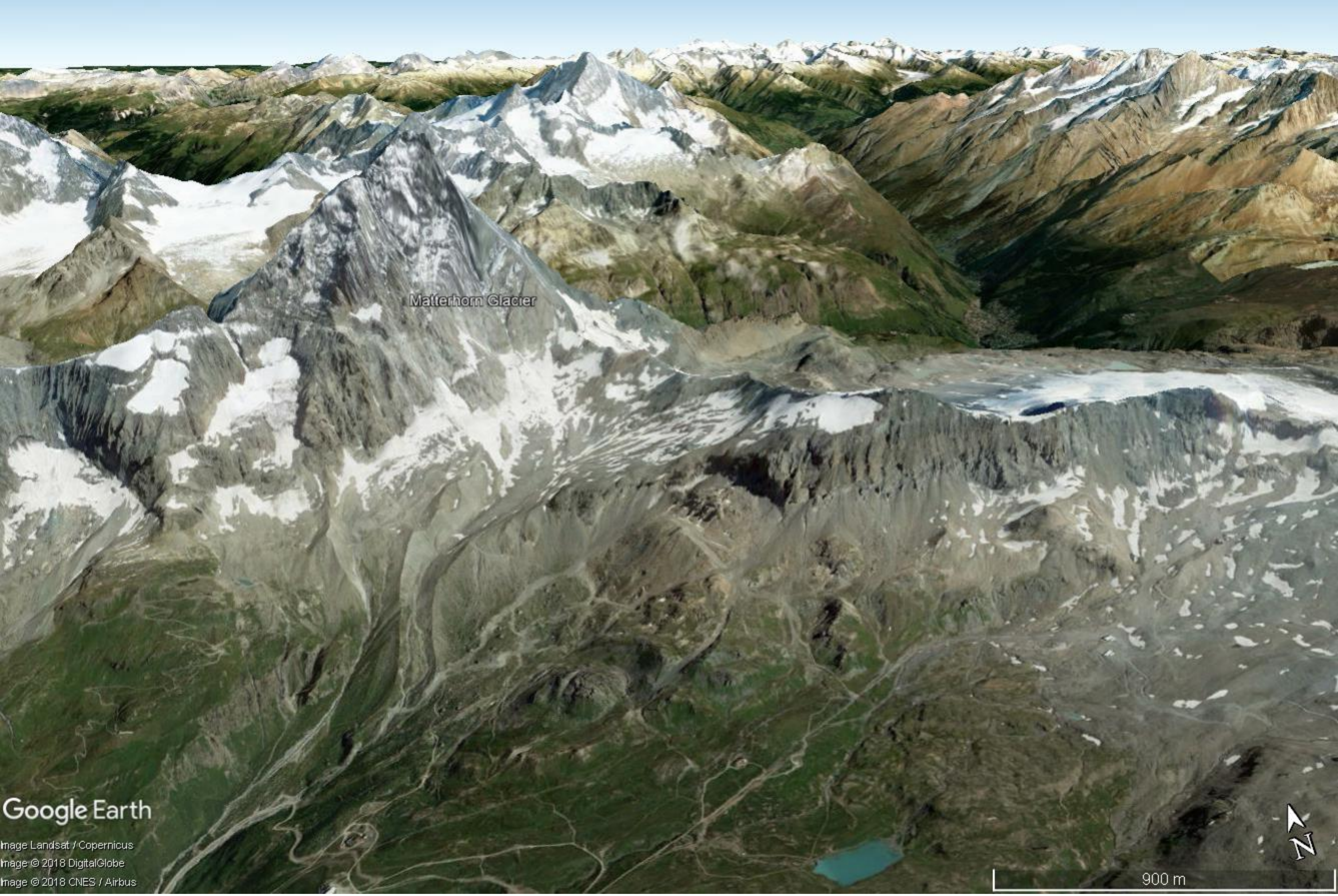
horn, Glacier National Park, MT

Matterhorn, Switzerland



Machapuchre, Nepal (horn)


Matterhorn Glacier
Google Earth
Image © 2018 DigitalGlobe
N
3 km


Matterhorn Glacier
Google Earth
Image Landsat / Copernicus
Image © 2018 DigitalGlobe
Image © 2018 CNES / Airbus
900 m
N

Cirques develop through

mechanical weathering & mass wasting: accumulating snow & firn percolate into rock fractures – pressure fluctuates during freeze & thaw, and particles move downslope by creep – nivation

erosion by cirque glaciers: move by rotational sliding as ice slides and rotates

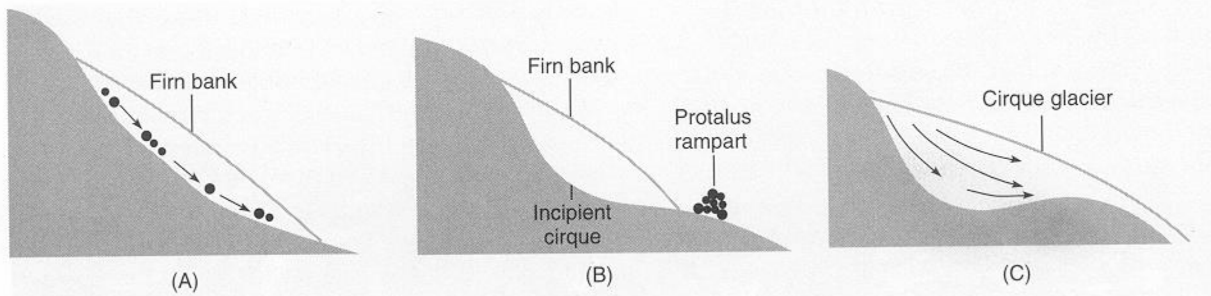


FIGURE 10.7

Stages of cirque development. (A) Nivation beneath firn bank. (B) Nivation cirque. (C) Cirque with fully developed cirque glacier.

rounded, glaciated topography,
Acadia National Park, Maine

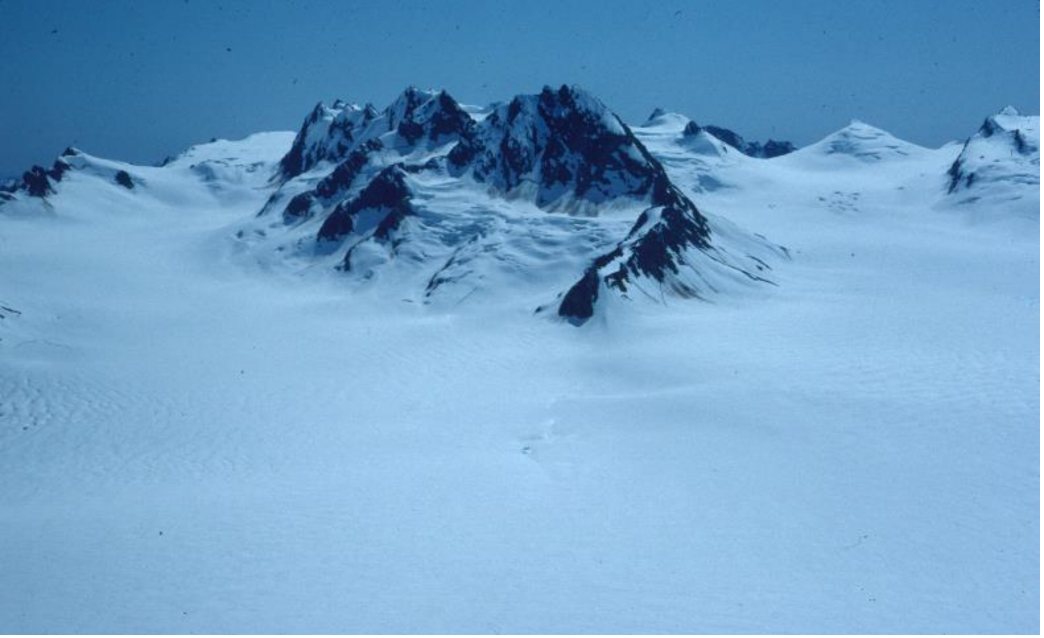
glaciated landscape, Kings Canyon National Park, CA

Nunataks: residual peaks of rock above ice when cirque glaciers merge to form ice cap

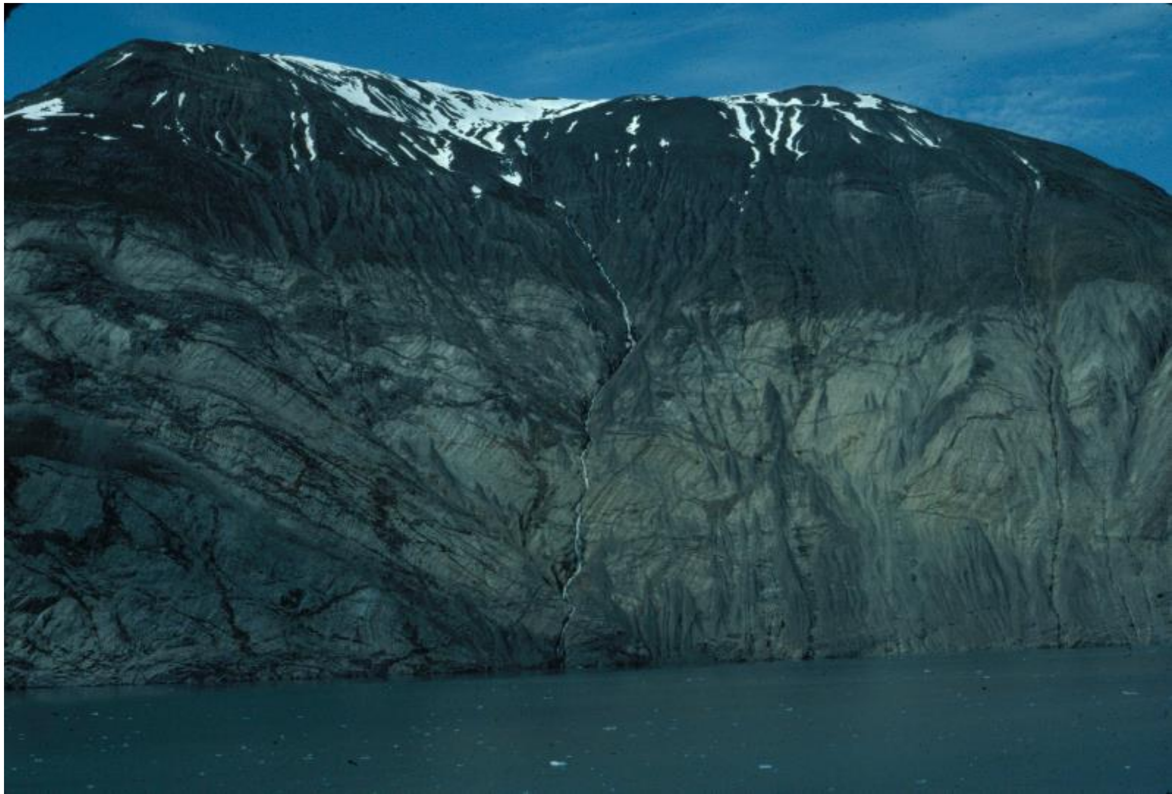
Glacial trough: steep, near-vertical sides & wide, flat bottoms; u-shaped valley created from v-shaped river valley through lateral and vertical erosion; tend to have irregular longitudinal profiles of basins with paternoster lakes & steps; also hanging valleys where tributary glaciers with less ice join the main valley

Fjords: glacial trough partially submerged by ocean; development occurred when ice was physically beneath ocean (too deep for sealevel drop)

hanging valley glacier, Jasper National Park, Canada



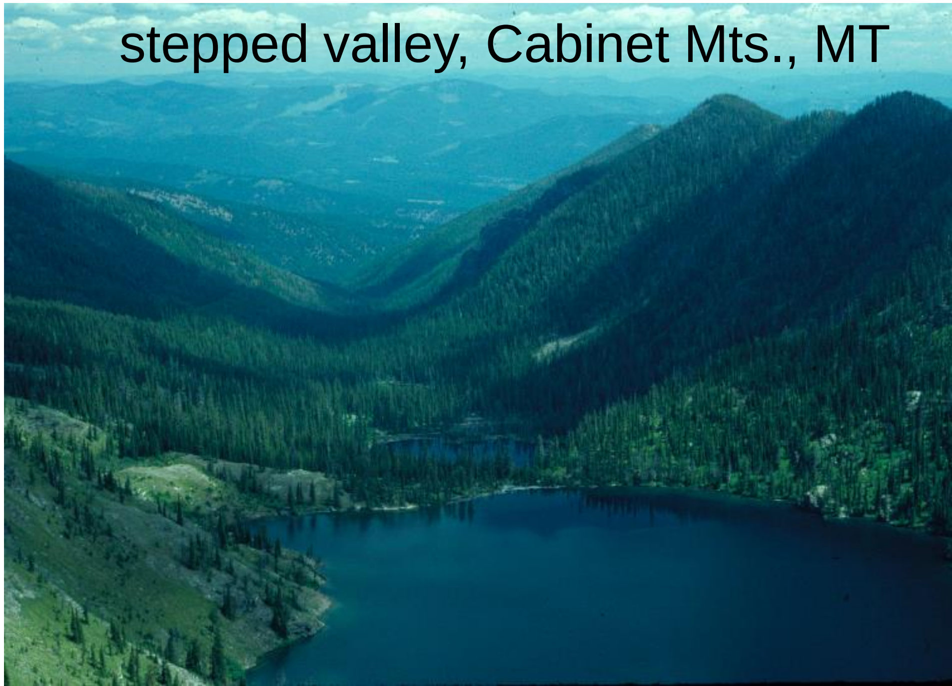
nunatak, Fairweather Range, Alaska



glacial trim line, Glacier Bay, Alaska

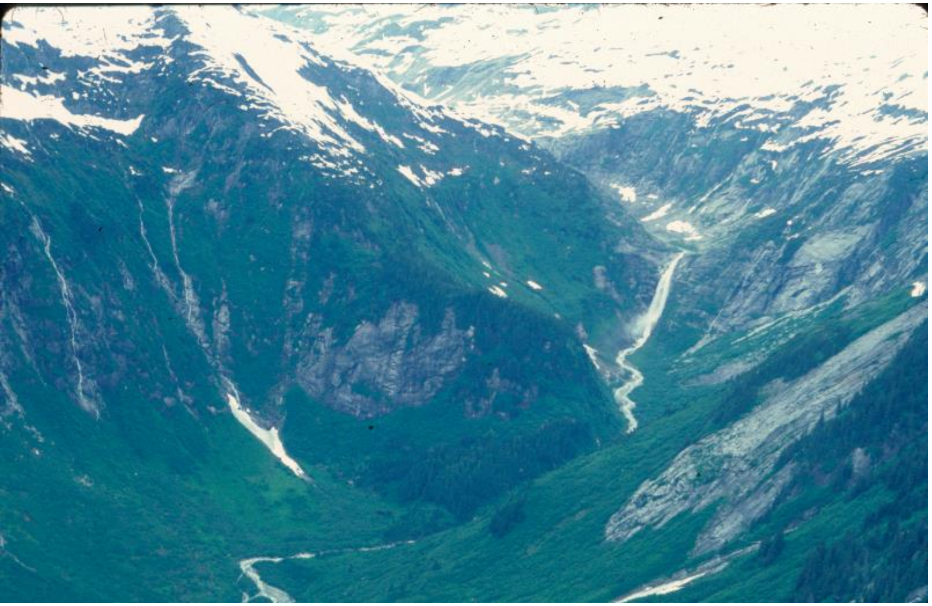
glacial tarn, Bighorn Mts., WY

u-shaped valley, Glacier N.P., MT

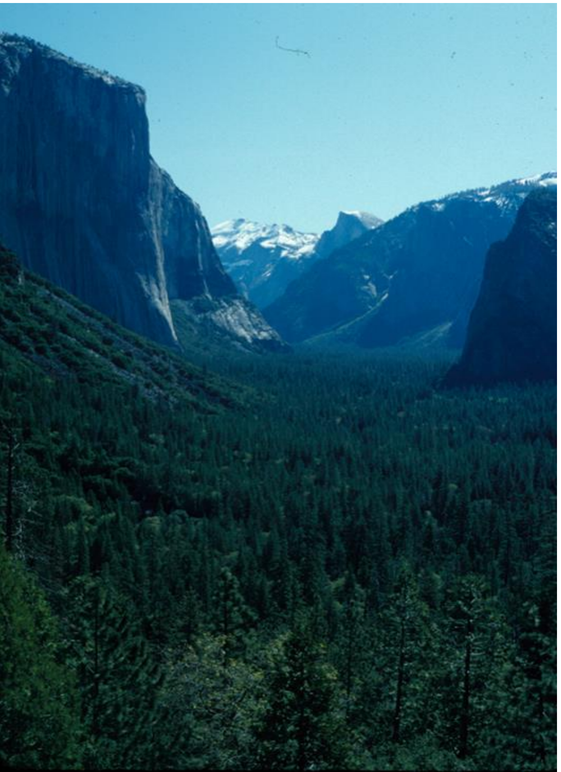


stepped valley, Cabinet Mts., MT

upper Taku Valley, Alaska



lower Taku Valley, Alaska



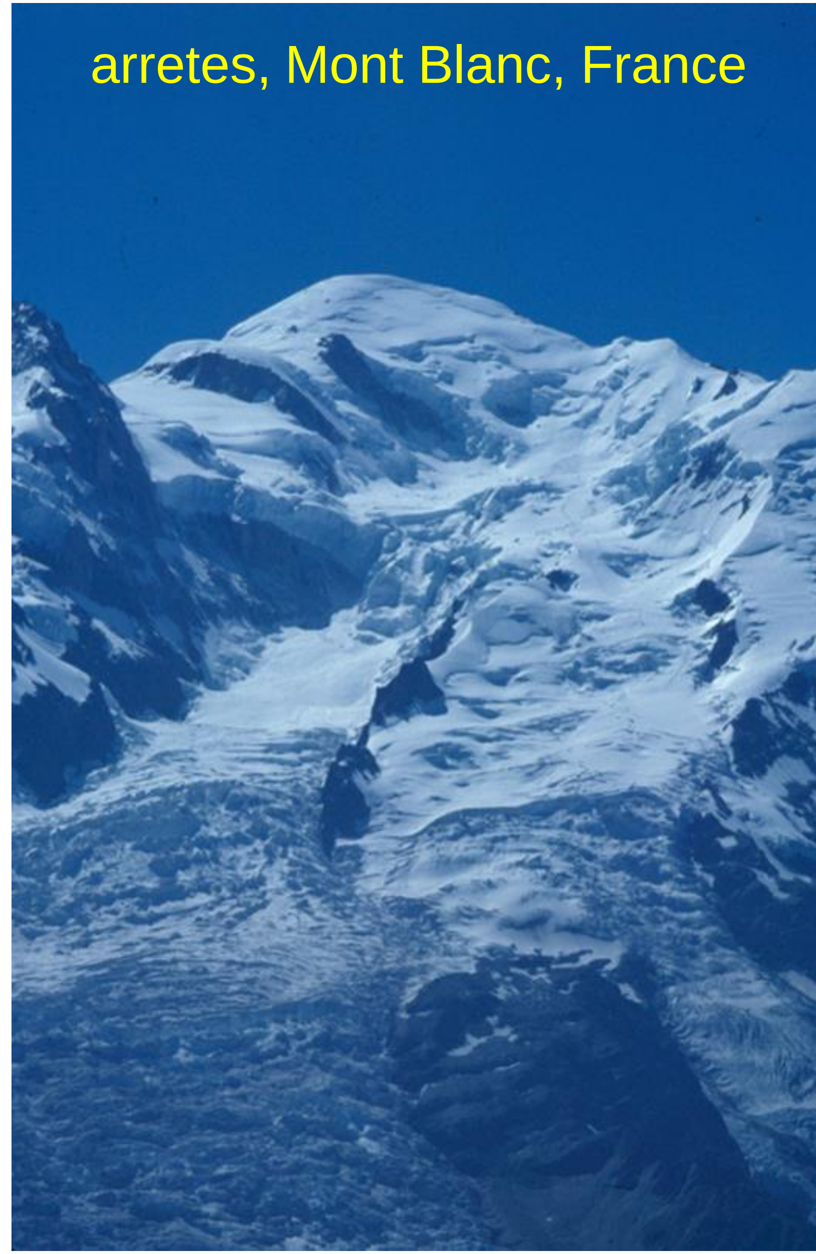
Yosemite Valley, CA


fjord, Norway


u-shaped valley, Norway


Thunersee, Switzerland


arretes, Southern Patagonia Icefield


arretes, Mont Blanc, France


Prince William Sound, Alaska

Glacial depositional features

glacial drift: all deposits associated with glaciation; covers 8% of Earth's surface above sealevel, and 25% of North America

i) *nonstratified drift*

till: transported & deposited by ice itself; unsorted; many lithologies; angular

basal or lodgement till: deposited in subglacial environment under pressure of overlying ice

ablation till: debris concentrated at or near the surface & dropped as ice melts

Type of till & mode of emplacement are determined from texture of deposit & arrangement of particles, or fabric (eg. orientation of clasts through motion = lodgement till)


Pinedale till over Bull Lake till, MT

ii) *stratified drift*

sediment transported by moving water before final deposition & thus stratified, sorted, & rounded; also called fluvioglacial

sediments deposited beyond the terminal margin of the ice in the proglacial environment form outwash – well sorted, rounded sands & gravels from bedload of stream channels

Also classify drift & depositional landforms by location relative to ice:

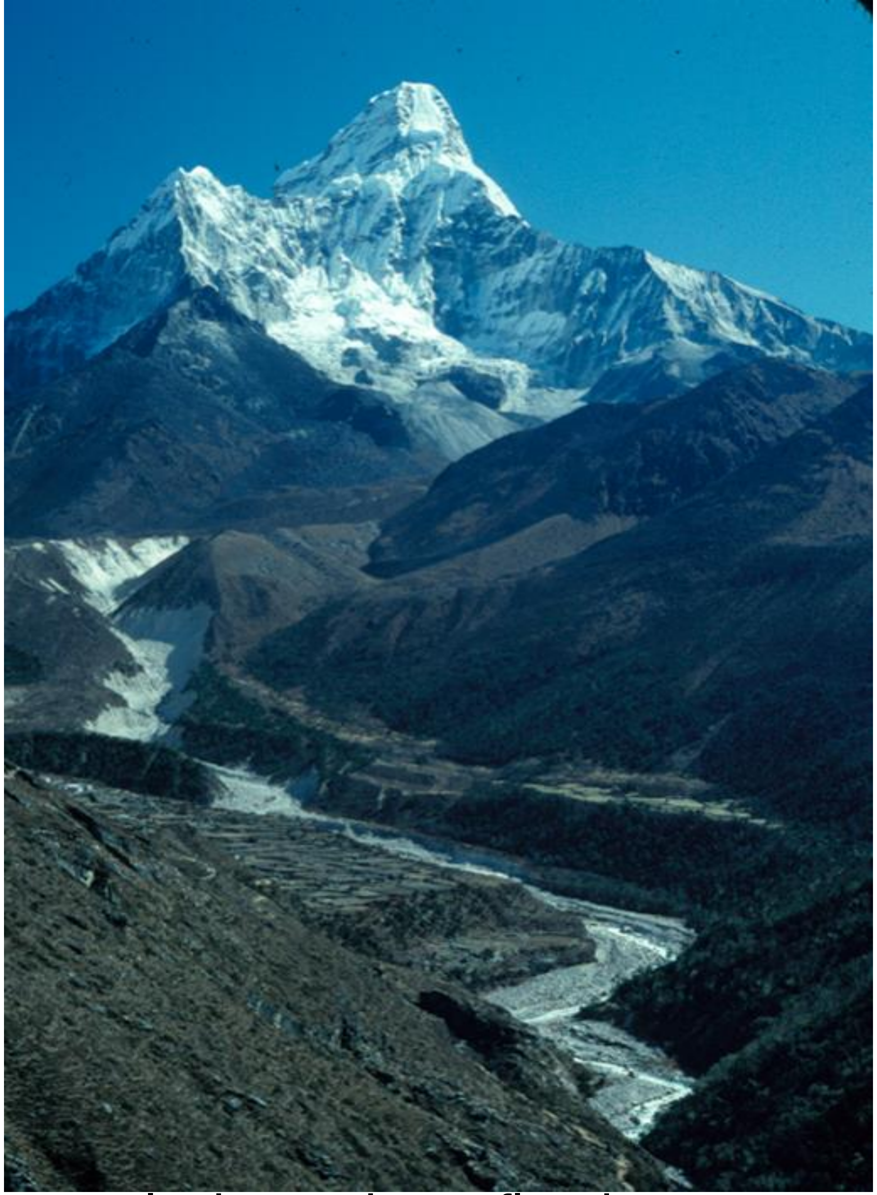
ice-contact environment: stratified, non-stratified, or combination

marginal: stagnant ice in front of active glacial zone & end moraines

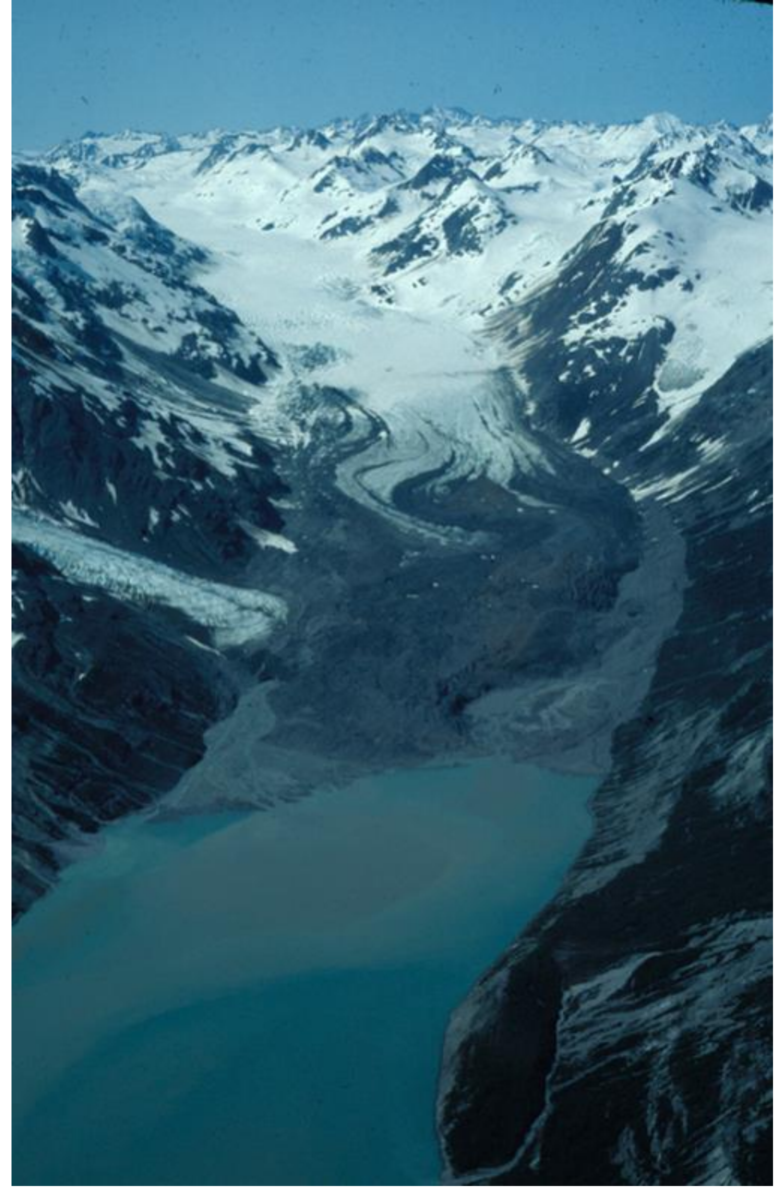
interior

moraines: depositional features with form independent of subjacent topography, constructed by accumulation of drift which is mostly ice-deposited

proglacial: stratified



glacier-outburst flood & mass movements from cirque,
Ama Dablam, Nepal



outwash fans, Glacier Bay, Alaska


Ama Dablam
Google Earth
Image © 2018 CNES / Airbus
4 km
N

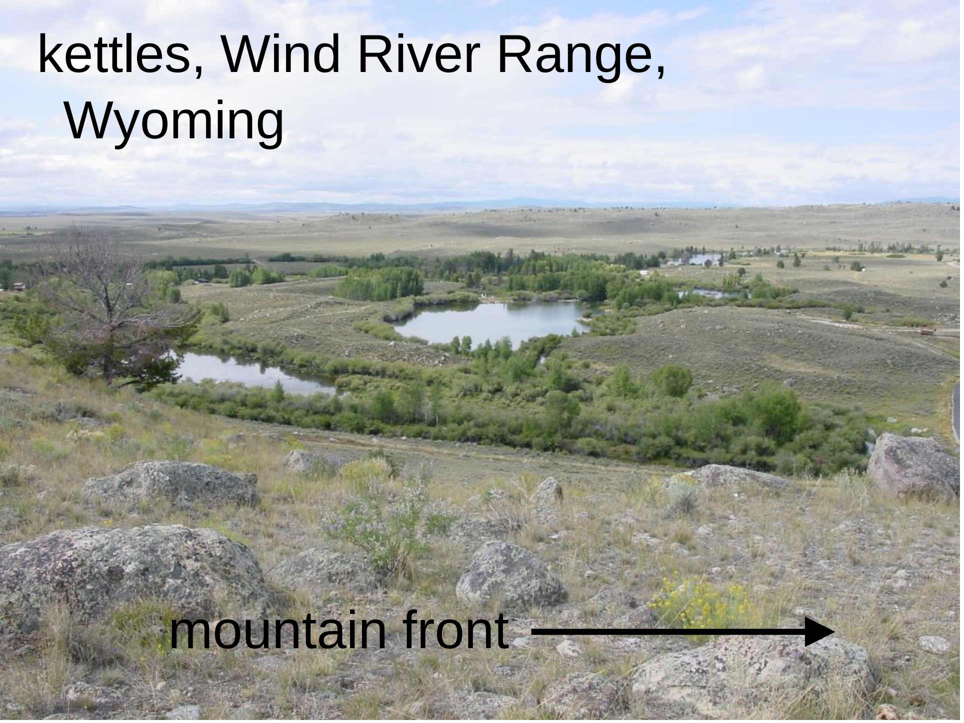
Stratified Marginal Features

kames: moundlike hills of layered sand & gravel from minor swells to 50 m high

kame terraces: drift deposited in narrow lake or stream channels between the valley side & lateral edge of stagnating ice

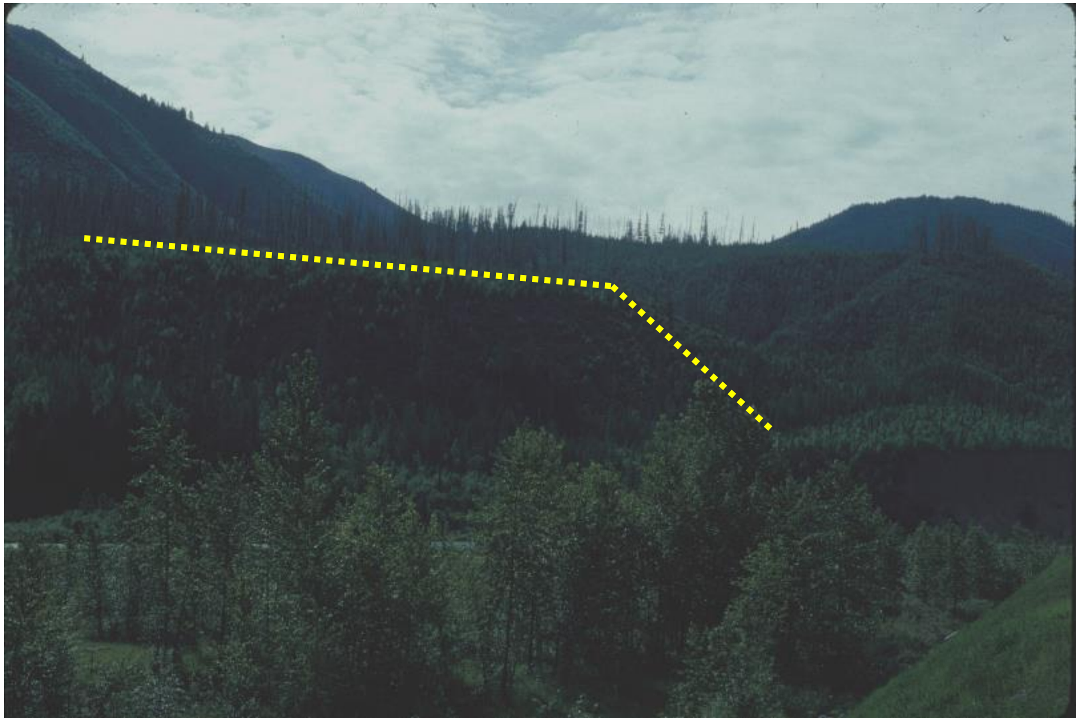
kettle holes: circular depressions from burial of isolated ice blocks by stratified drift; ice melts & drift collapses

esker: ridges of fluvioglacial drift formed in tunnels beneath the ice, in crevasses, or in supraglacial channels



kame terrace, Scotland

kame terrace,
nw MT



Moraines (marginal)

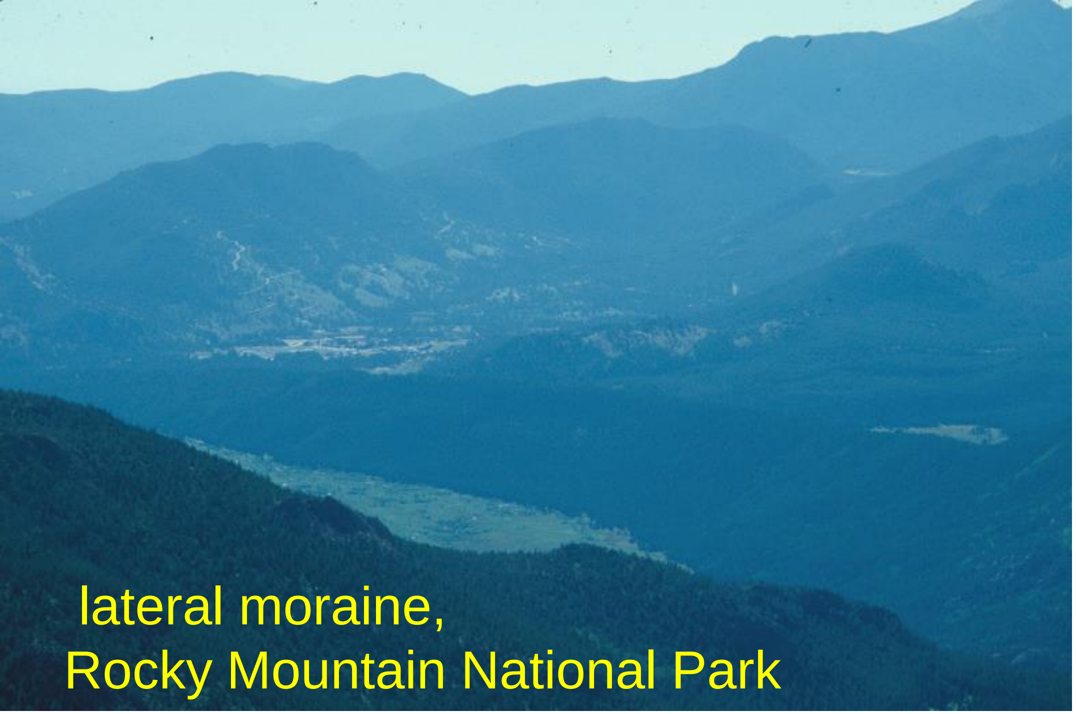
end: at or near edges of active glaciers
terminal: end moraine at farthest point of advance
lateral: sides of valley
interlobate: at junction of two lobes
medial: at junction of two valley glaciers
ground: beneath glacier

Interior features

ground moraine: smoothly undulating plains < 10 m total relief
fluted surfaces: narrow, regularly spaced, parallel ridges & grooves < 5m high & several hundred m long
drumlins: elongated parallel to ice flow, 1-2 km long, 400-600 m wide, 5-50 m high, tend to cluster together; may be erosional (streamline pre-existing drift), or depositional (ice deposits & molds material as it moves)

Glacier Bay, Alaska


Google Earth
Image © 2018 DigitalGlobe
N
10 km


lateral moraine,
Rocky Mountain National Park

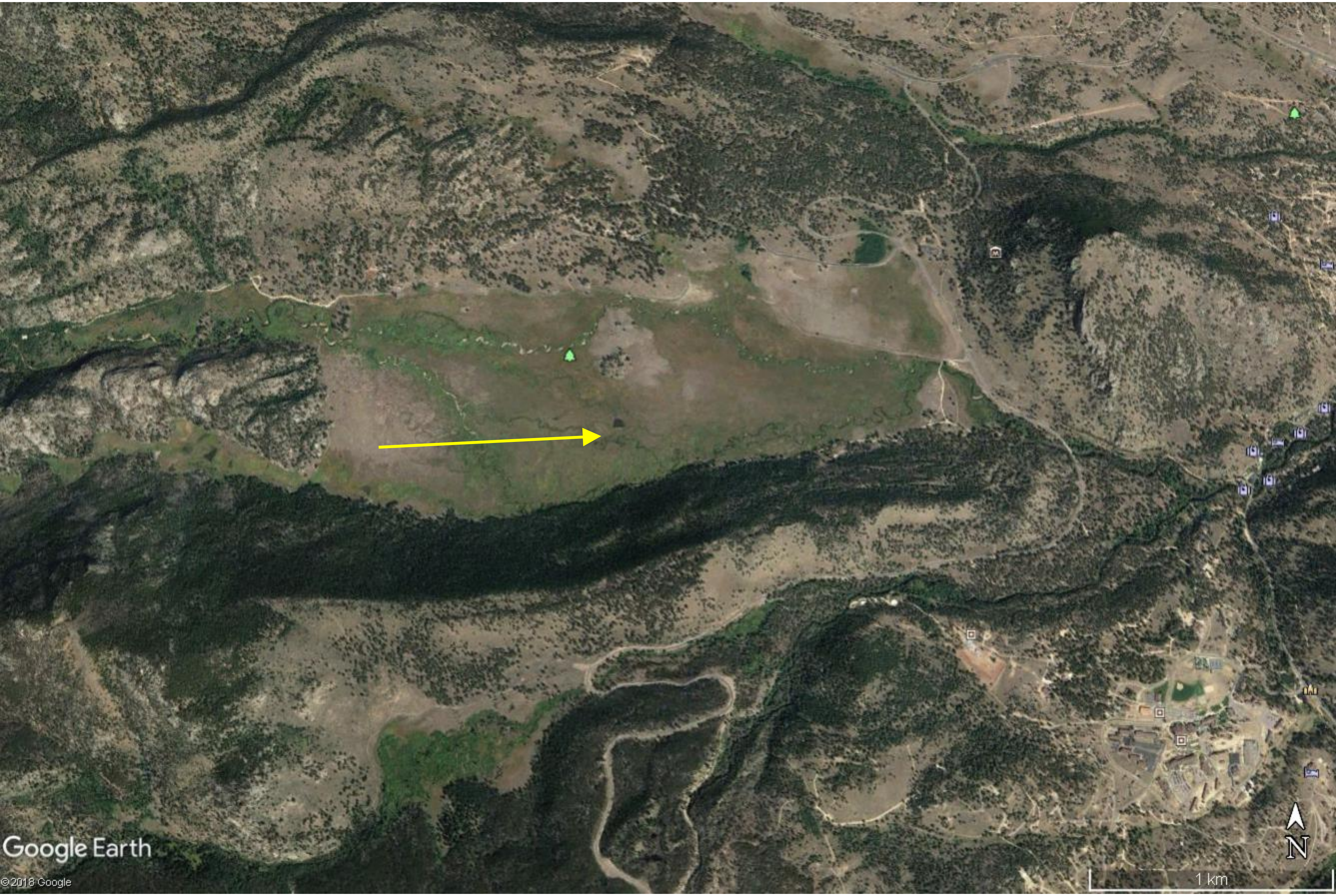

lateral moraine, Jasper
National Park, Canada

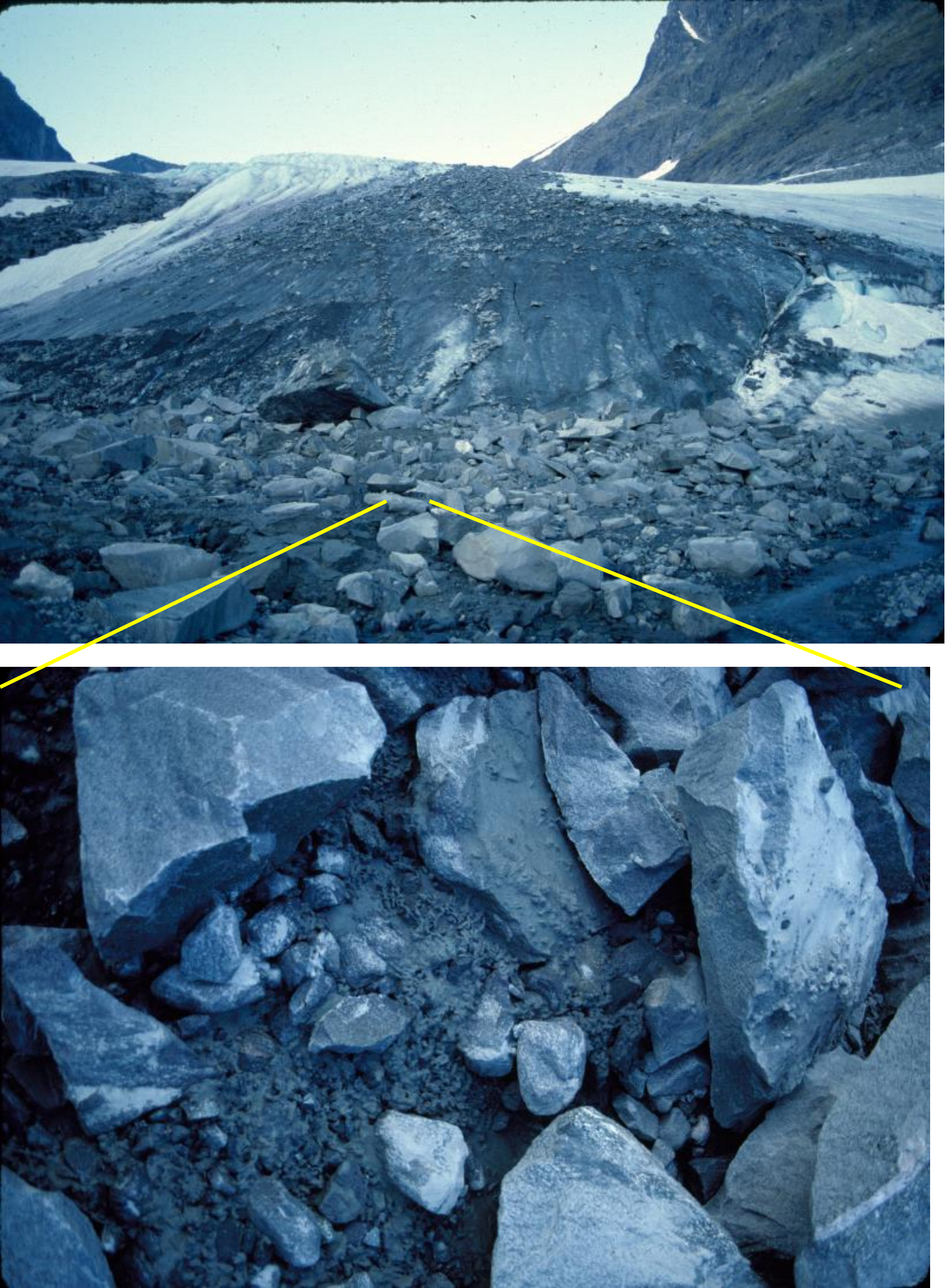

Nepal

moraine-dammed lake & lateral moraines, Wind River Range, Wyoming

Holocene moraines, Longs Peak, CO

recent moraine, Great Basin N.P., Nevada

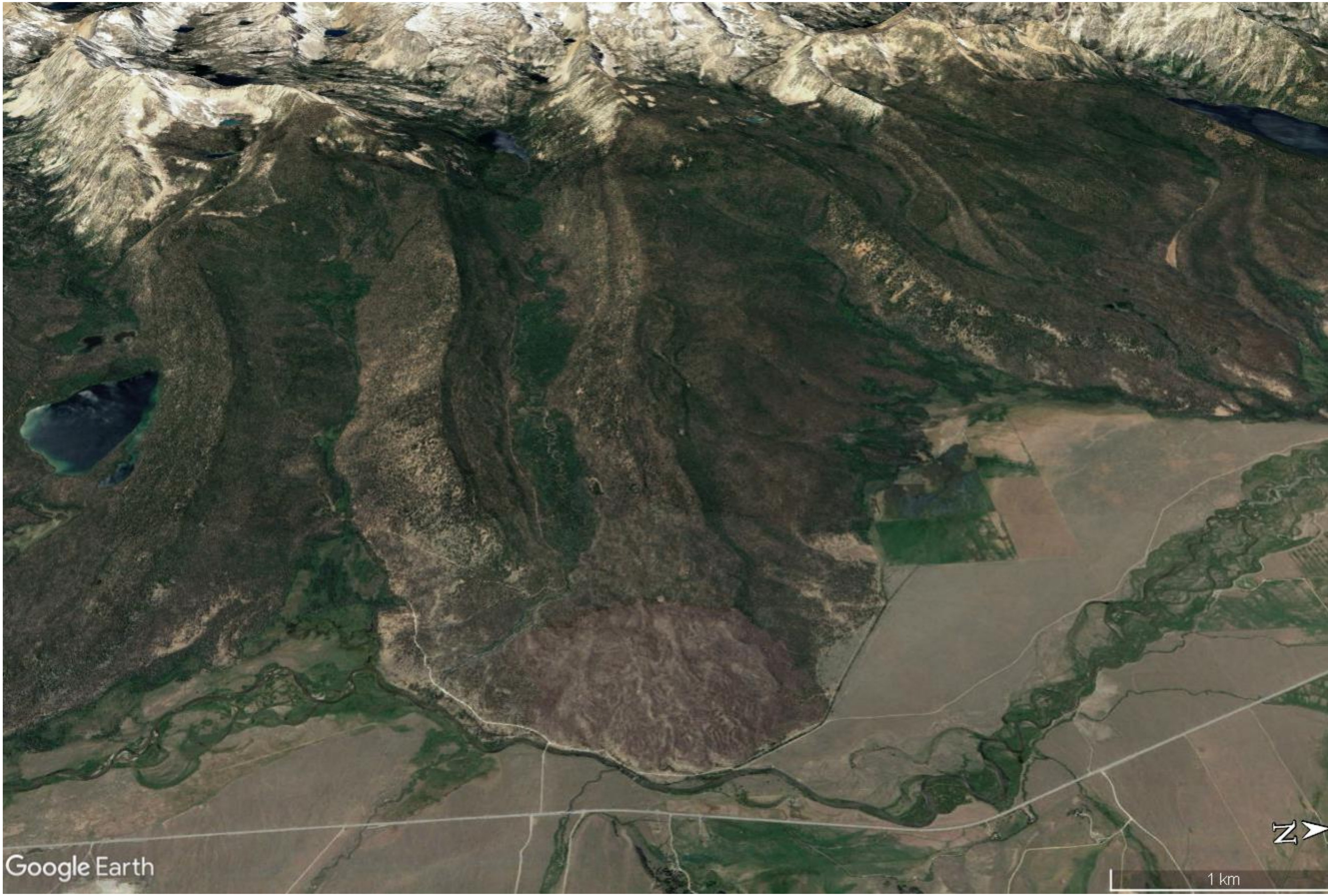

Google Earth
©2018 Google
1 km
N



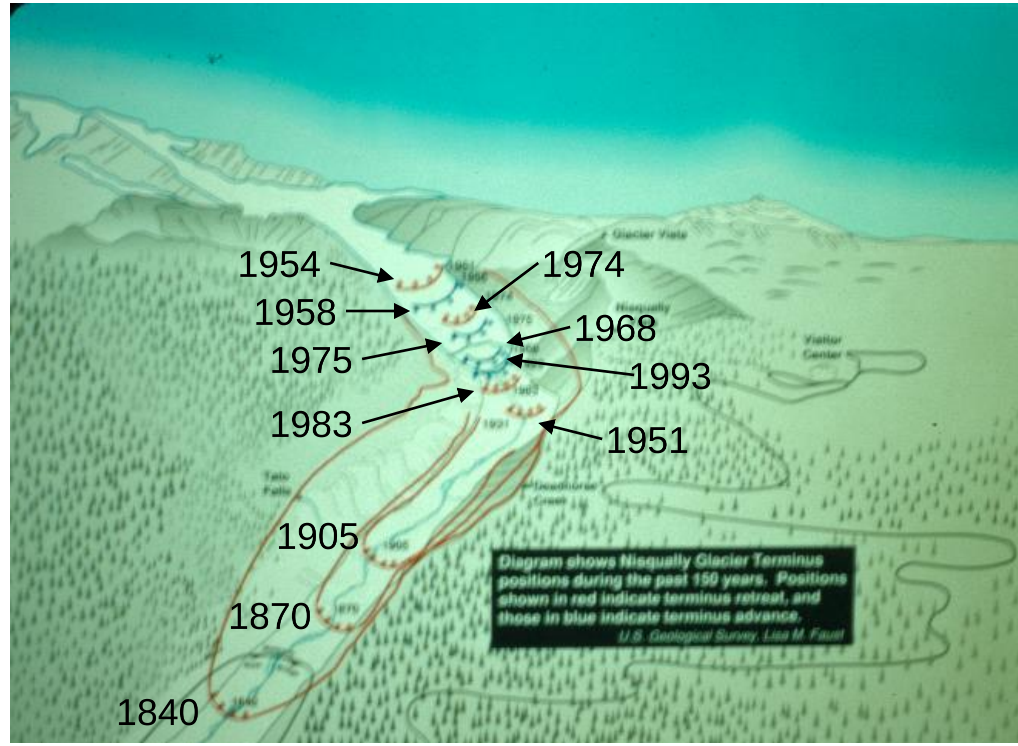
medial & recessional moraines,
Storjuvbreein Glacier, Norway

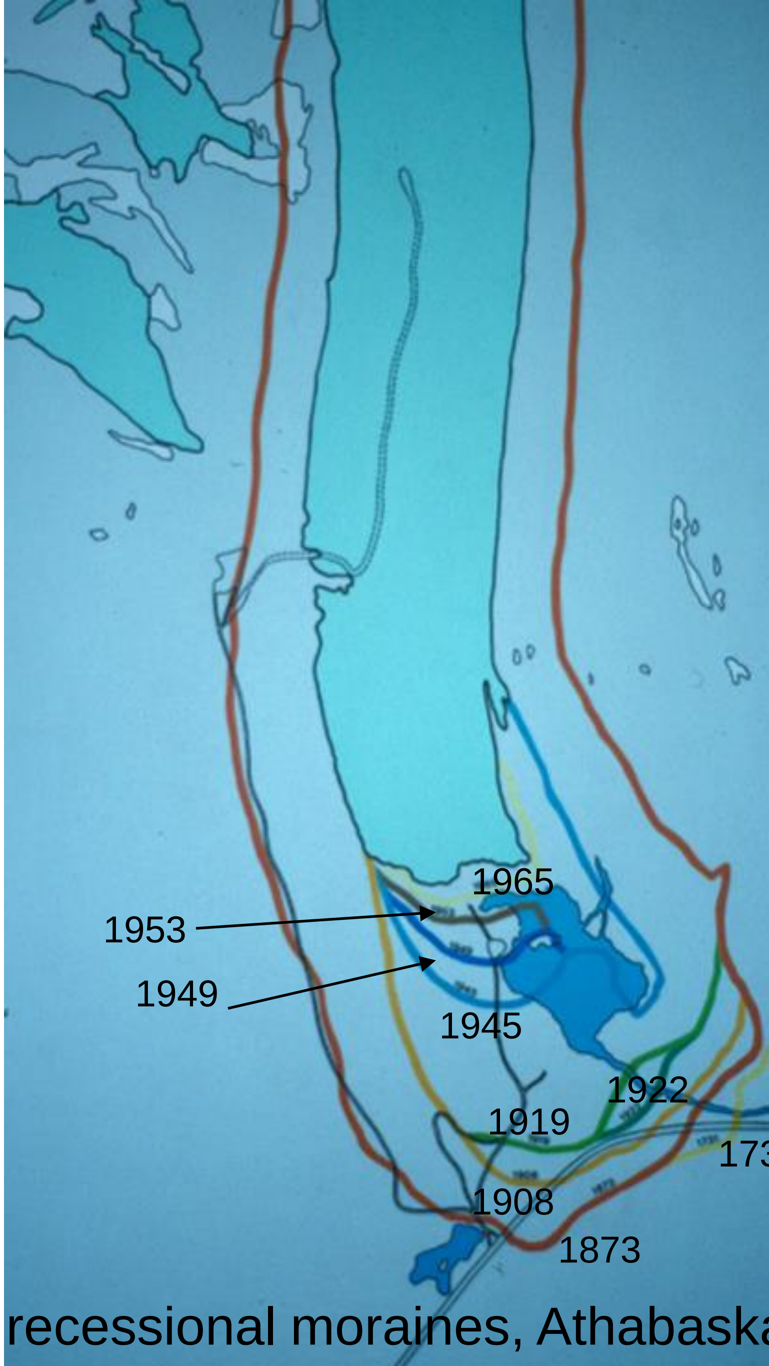
Greenland

Sawtooth Mountains, Idaho


Google Earth
1 km
N

recessional moraines, Mt. Rainier, WA





recessional moraines, Athabaska Glacier, Canada

Proglacial

sandur (plural sandar): large plain of outwash; similar to alluvial fans

valley sandur: created by one main river & anabranches (called valley trains in US)

plain sandur: coalescence of many braided rivers (called outwash plain in US)

sandar are composed of sand & gravel (fines deflated)

Three zones of sandar are

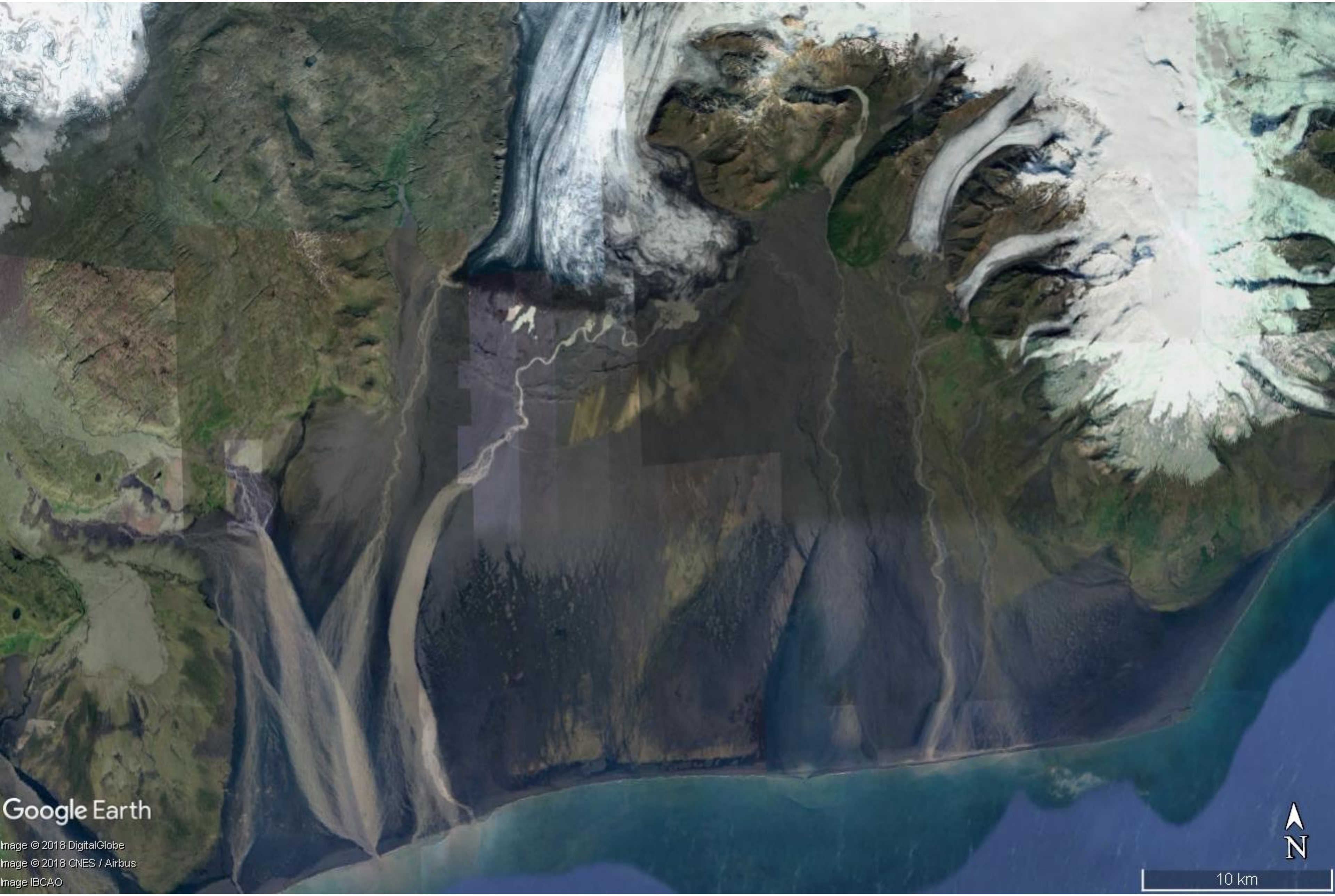
proximal: close to ice, rivers entrenched, pitted surface (kettled sandar) due to kettleholes

intermediate: channels wide, shallow, braided & rapidly laterally shifting

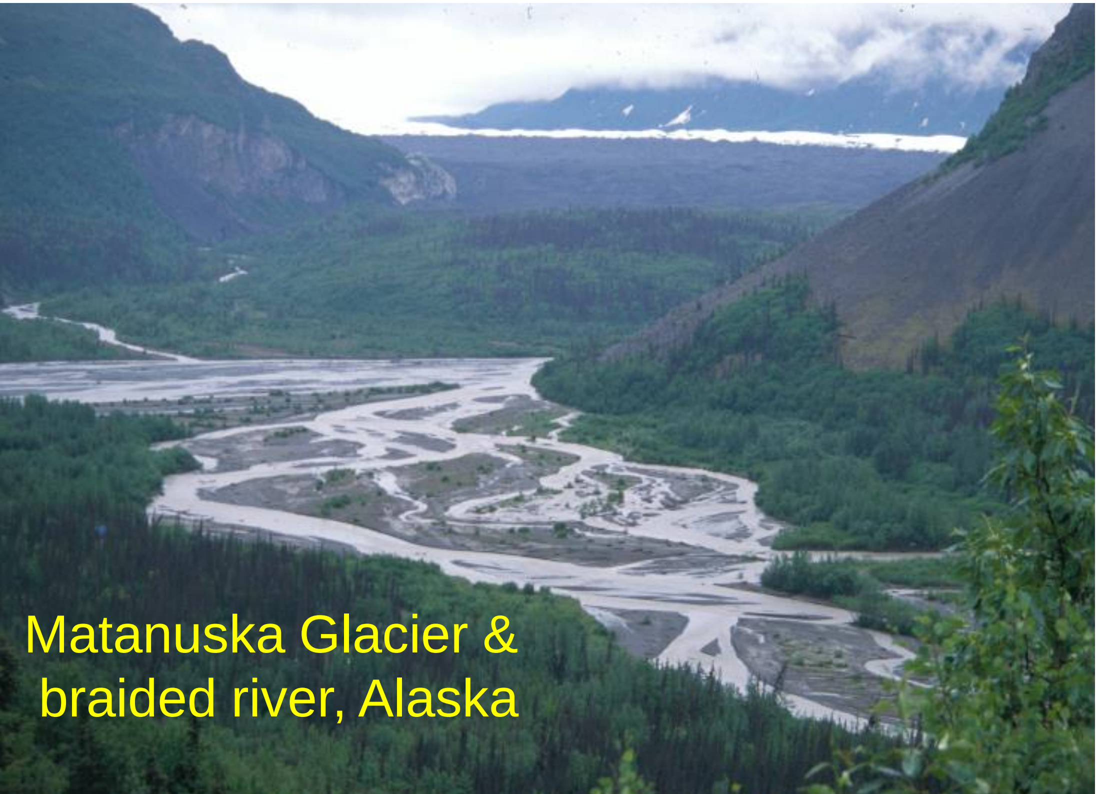
distal: channels so shallow that rivers merge to a single sheet of water at high flow

Sandar form via a large sediment supply & high floods such as jokulhlaups – sudden release of lake water dammed within ice


Vatnajokul
Google Earth
Image Landsat / Copernicus
Image IBCAO
N
50 km

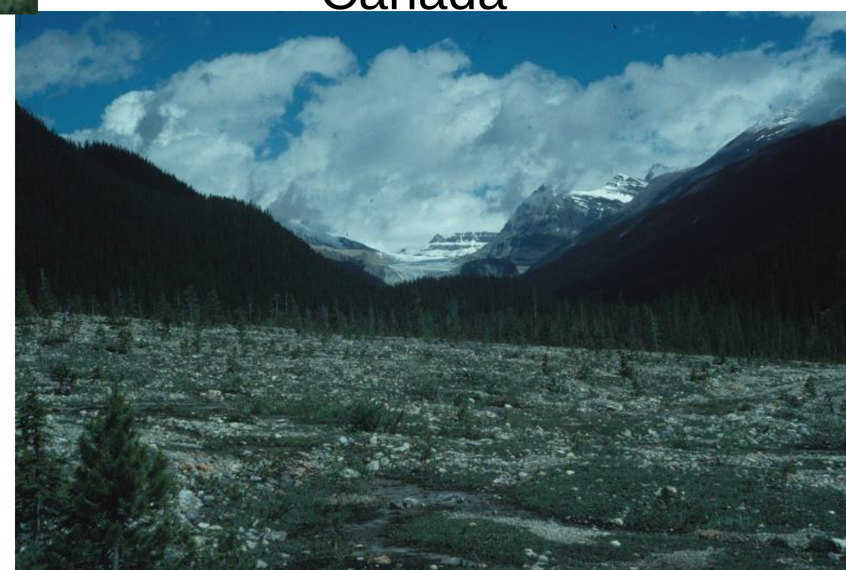

Google Earth
Image © 2018 DigitalGlobe
Image © 2018 CNES / Airbus
Image IBCAO
N
10 km

sandur, s. Iceland



Matanuska Glacier & braided river, Alaska

glacial outwash fan, Yoho National Park, Canada



outwash fan, Glacier Bay, Alaska

Fairweather Range, Alaska

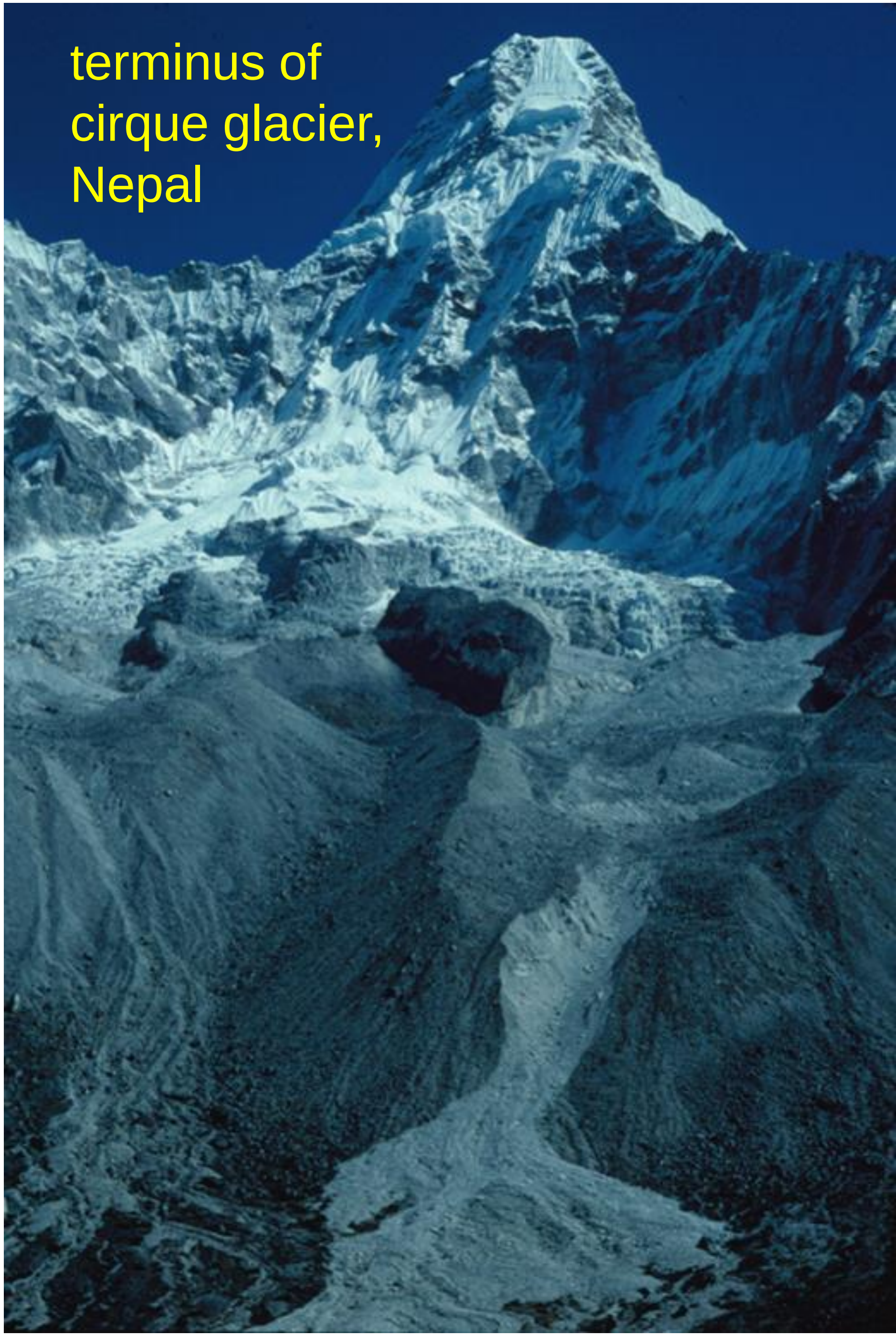
glacial lacustrine sediments, Nepal

river with glacial flour,
Yoho National Park, Canada

Glacial Depositional Environments

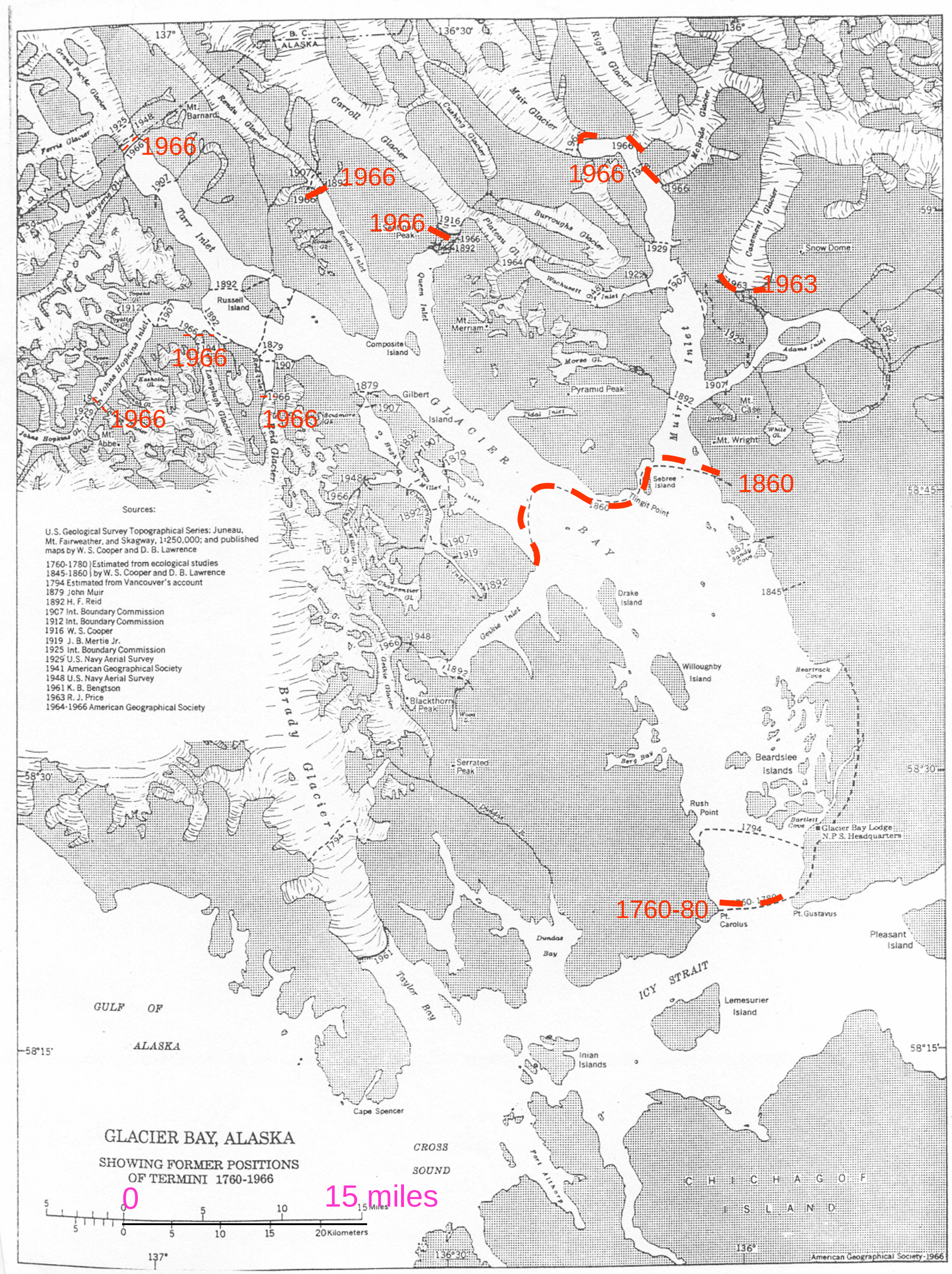
Setting	*Features*	*Type of drift*
Ice contact		
marginal	end moraines	till, fluvioglacial
	kames	fluvioglacial
	kame terraces	“
	kettle holes	“
	eskers	“
interior	medial moraines	till
	interlobate moraines	till
	ground moraines	lodgement till
	fluted surfaces	“
	drumlins	“
proglacial	sandar	fluvioglacial (outwash)
	kettled sandar	“


terminus, Cavell Glacier, Canada


terminus of
cirque glacier,
Nepal

terminus of glacier, Denali National Park, Alaska

ice & rock glacier, Great Basin N.P., Nevada



Map of Glacier Bay, Alaska showing historical changes in terminus of glaciers

Broecker's Great Ocean Conveyor Belt

Great Ocean Conveyor Belt: warm water moves northward at the surface in the North Atlantic; transfer of heat from sea to air where current meets air cooled during passage over frigid Canada

heat transferred is 30% of that received by the surface of the North Atlantic from the sun

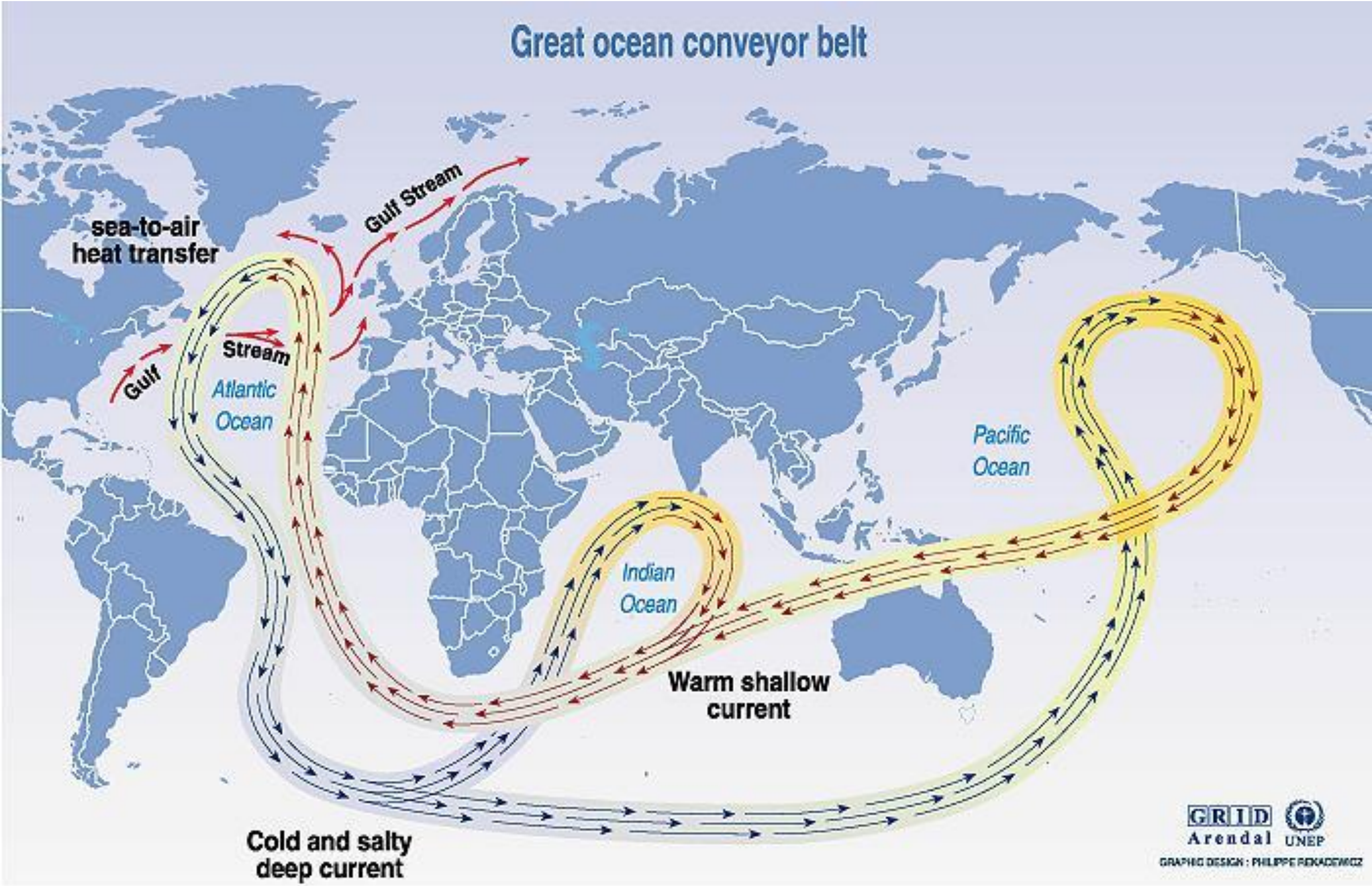
this transfer keeps northern Europe warmer, & the waters cool and sink because they are now more dense

so the ocean current acts as a pump, extracting heat from low-latitude air & transferring it to high-latitude air the pattern of this circulation is governed by the sea’s salt: the Atlantic loses more water through evaporation than it gains through precipitation & continental runoff – the situation is reversed in the Pacific

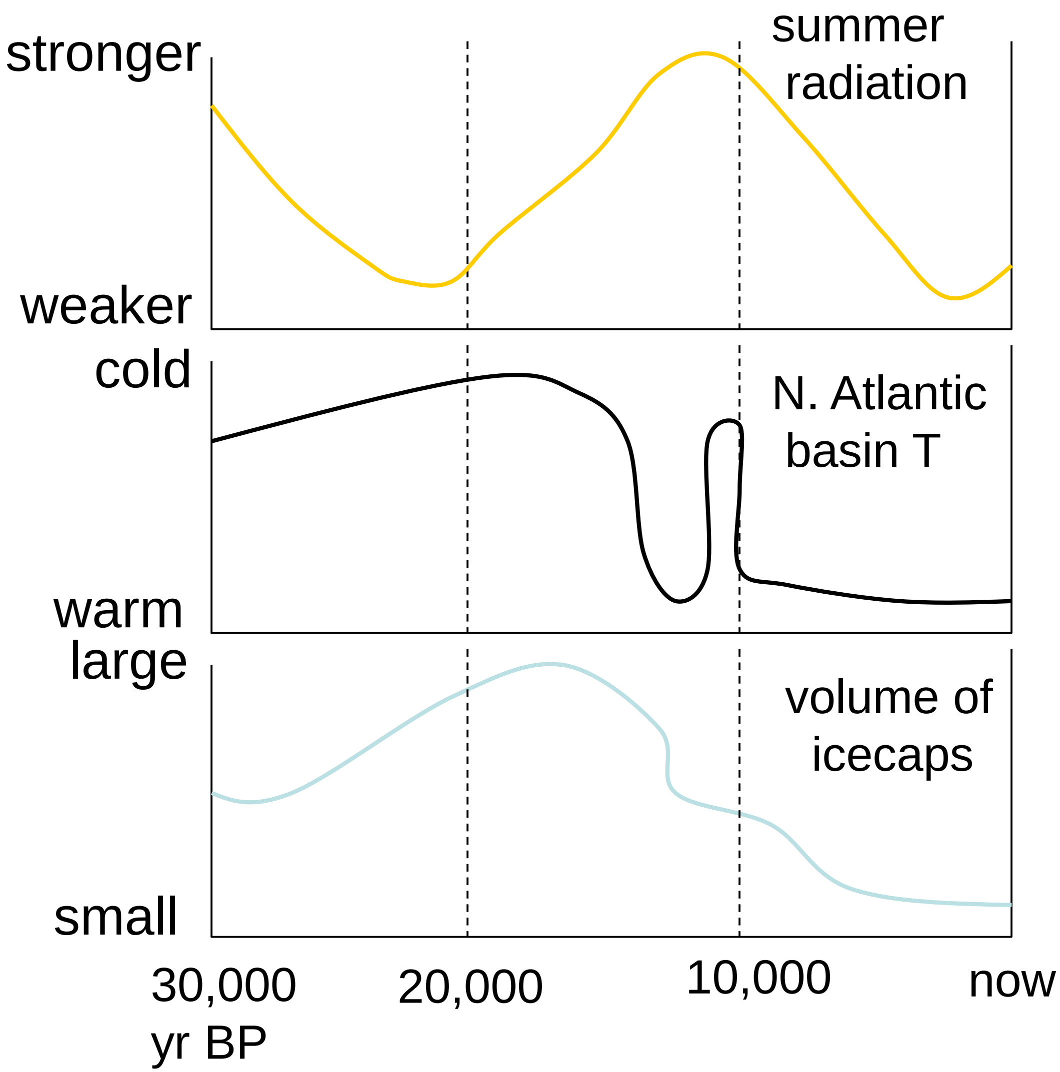
net flow of seawater from the Pacific to the Atlantic, but the Atlantic is still enriched in salt content – flow of more salty water from Atlantic to Pacific (hence, great conveyor belt)

conveyor did not function during glacial time; when the belt operates, its warmth prevents ice accumulation on lands surrounding the northern Atlantic (conveyor shut off for about 700 years during the Younger Dryas)

so there must be some link between the conveyor & seasonality



Source: Broecker, 1991, in Climate change 1995, Impacts, adaptations and mitigation of climate change: scientific-technical analyses, contribution of working group 2 to the second assessment report of the intergovernmental panel on climate change, UNEP and WMO, Cambridge press university, 1996.



1) Fluctuations in Earth's orbit affect how much summer sunlight Earth receives
2) This expands & contracts polar icecap, driving Northern Hemisphere in & out of glacial episodes
3) Volume of ice changes sluggishly & gradually (bottom)
4) Abrupt global warming has marked end of each glacial period, indicating that ocean-atmosphere operation can change suddenly (middle)
5) Younger Dryas, 700-year return to glacial conditions, thought to have been caused by sudden diversion of melting Canadian ice sheet waters from the Mississippi to the St. Lawrence River