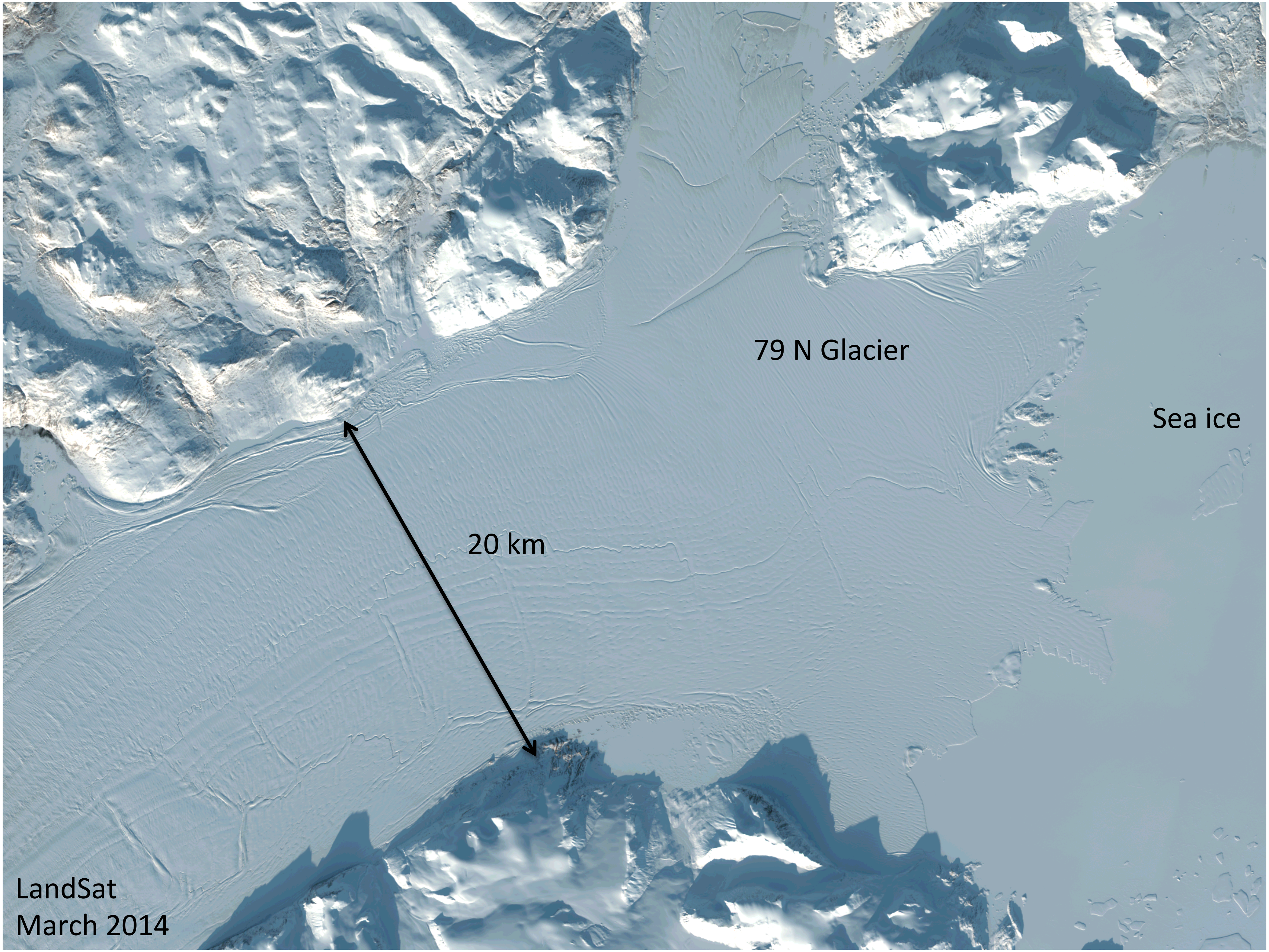
79 N Glacier
Sea ice
20 km
LandSat
March 2014

Glaciers

Kevin Mullins, Flagstaff

Glaciers

- Definition: a perennial body of ice that moves over land/water and forms from the accumulation and compaction of snow
  - Flows down-slope from their own weight and gravity
  - Flows due to the processes of gravity, sublimation and pressure melting
    - Sublimation – directly from solid to gas
    - Pressure melting – pressure forces water to open areas to refreeze

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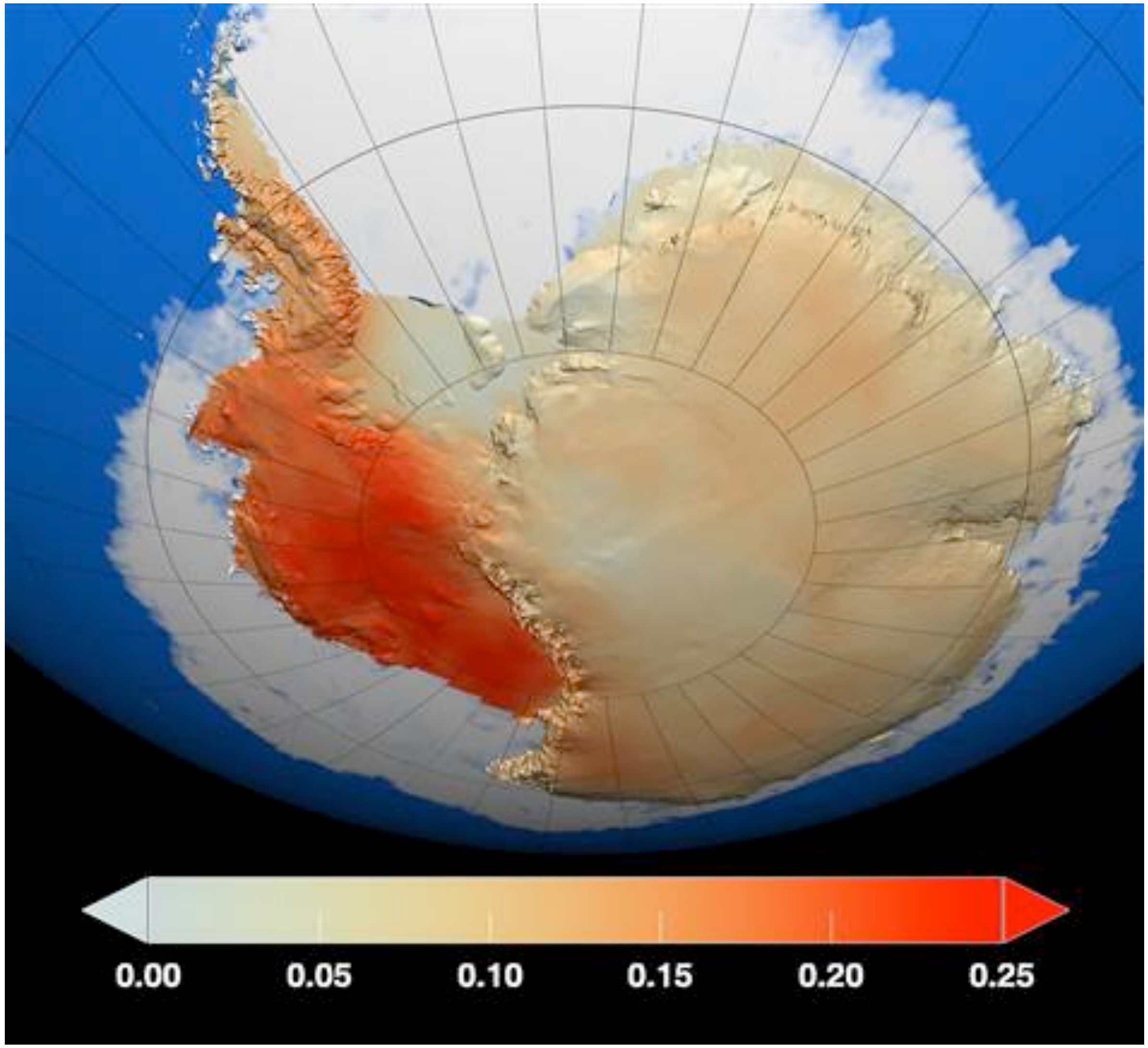
Global Glacier Volume

Region	Volume (10^6 km^3)	Sea level Equivialent (m)
East Antarctic Ice Sheet	22	52
West Antarctic Ice Sheet	2	5
Ice Shelves	1	-
Peripheral Ice Caps	0.5	0.4
Greenland Ice Sheet	3	7
Rest of World	0.5	0.3

Marshall (2012)

Temperature Change over 50 years

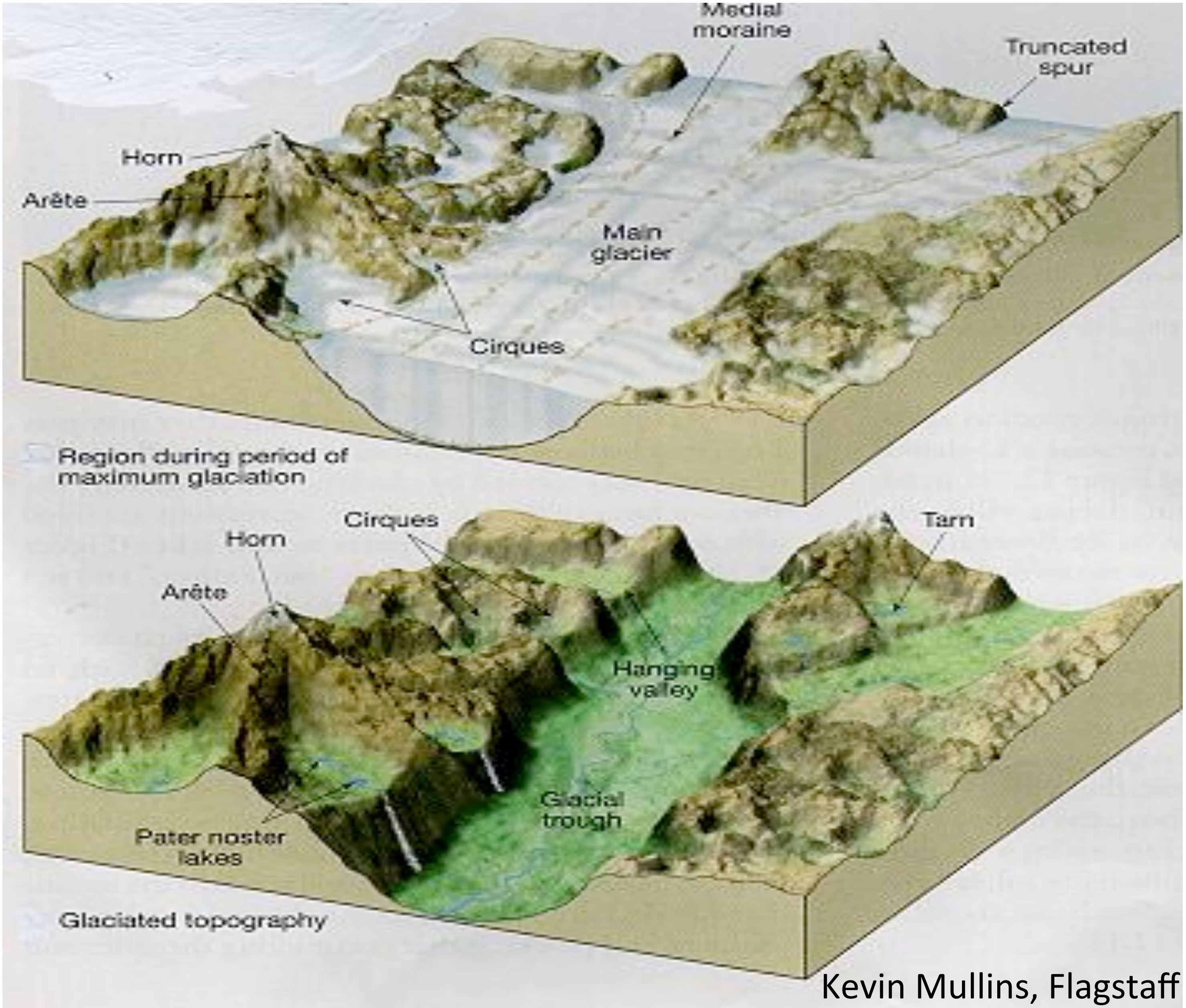


West Antarctic
Ice Sheet Unstable

East Antarctic
Ice Sheet Stable

NASA/GSFC Scientific
Visualization Studio

Glacier Terminology



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Types of Glaciers

- Alpine – confined by surrounding bedrock; relatively small (Alps, Alaska)
  - Cirque – semicircular basins on mountainsides or heads of valleys
  - Valley – conform to pre-existing valleys (U-shaped)
  - Ice caps – tops of mountains (Himalayas)

- Piedmont – Alpine glacier that reaches lowlands and spreads outs

- Tidewater – piedmonts or valleys that reach sea water

- Continental ice-sheet – Greenland/Antarctica

- Rock – surfaced by rock, fragments and unconsolidated material

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Types of Glaciers
Alpine
Muddy River Glacier, Frederick Sound, Alaska (1948)

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Alpine Glacier

ExtremIceSurvey.org

Types of Glaciers
Piedmont
Bylot Island glacier

Types of Glaciers
Piedmont
Elephant Foot Glacier, NE-Greenland

GEUS

Types of Glaciers
Tidewater
Outlet glaciers, Royal Society Fiord, Nunavut Bay, Canada

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Types of Glaciers
Ice sheets/Caps
Ice cap complex, Iceland

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Glacier Budget

- Definition : difference between annual gain and loss of snow and ice
  - When accumulation exceeds ablation the net budget is positive and glacier grows

- Zones :
  - Accumulation – area where precipitation is adding snow & ice to glacier
  - Ablation – area where ice is removed by melting, sublimation, wind-erosion (ablation), and sometimes calving
  - Equilibrium line – separated the two areas (where process is balanced)

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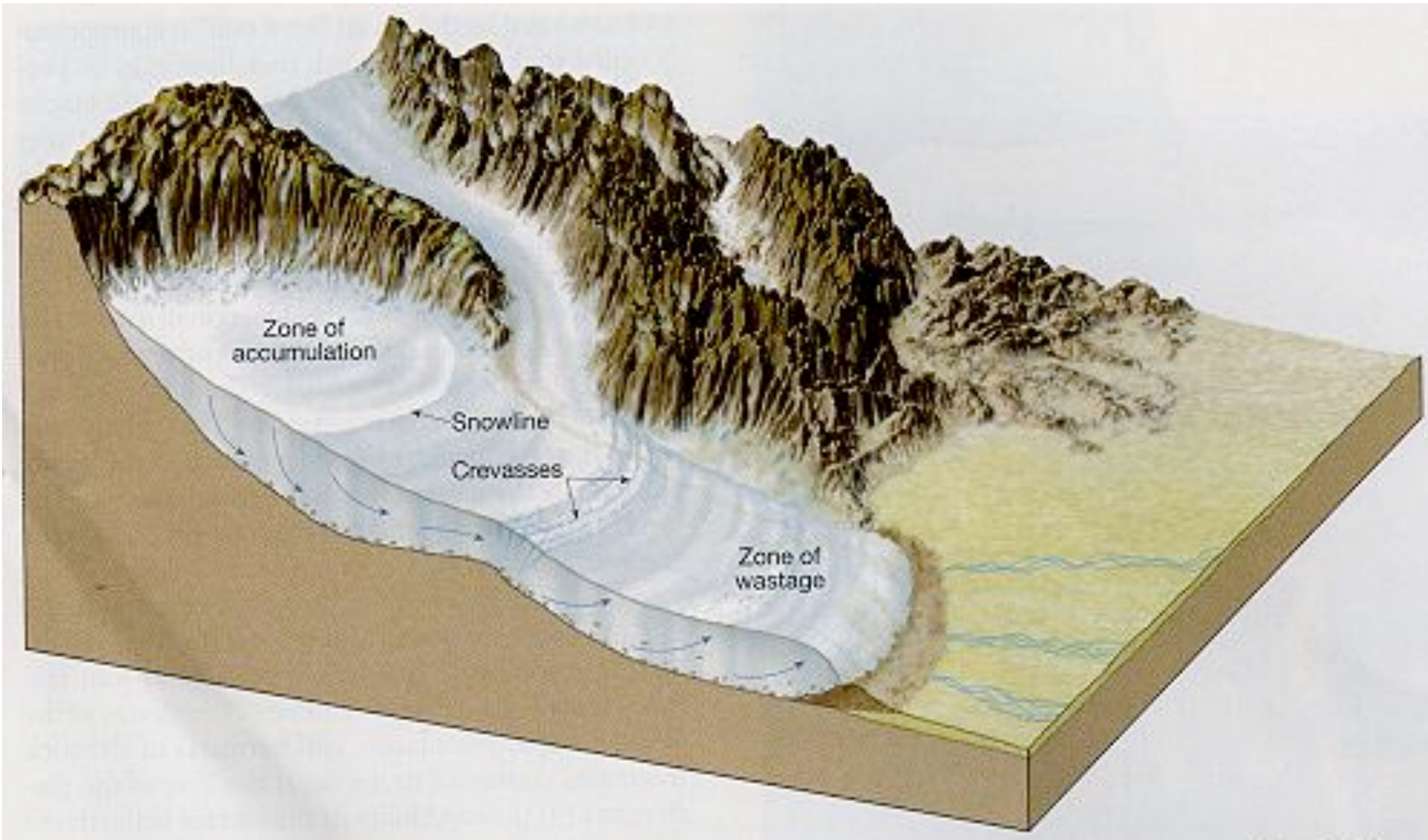
Glacial Zones



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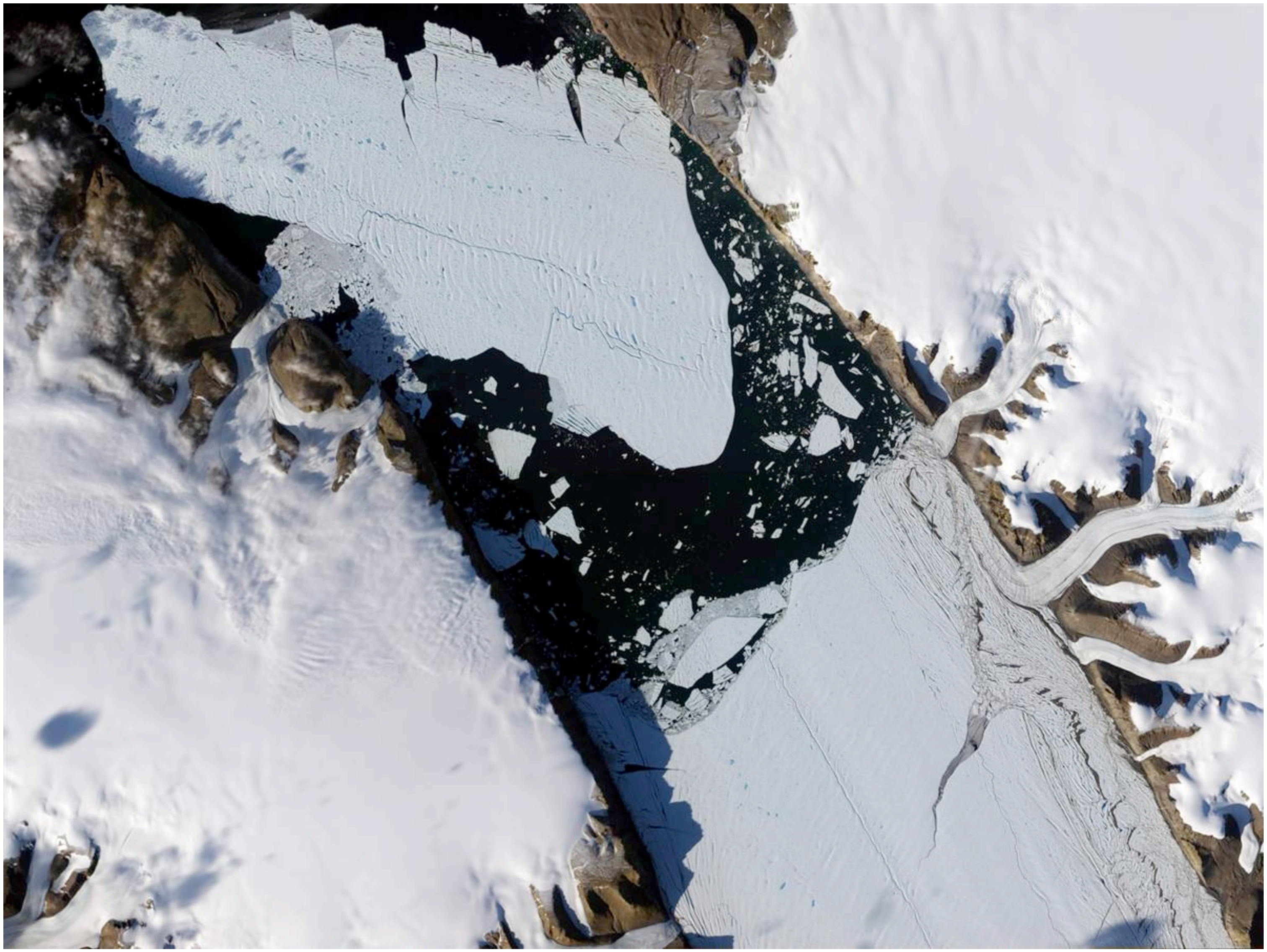
Ice tongue calving 2010

Petermann Glacier, Greenland



NASA

Petermann
Gletscher

Central melt
Channel

2009

Greenpeace

Glacial Flow

- Glaciers always move from zone of accumulation to zone of ablation
  - Accumulation zone – glacier and ice move downward relative to glacier bed
  - Ablation zone – glacier and ice move outward and up

- Internal deformation – movement within ice due to fractures, gravity and ice crystals deforming

- Basal sliding – pressure and temperature cause melting at ice/ground interface creating less friction

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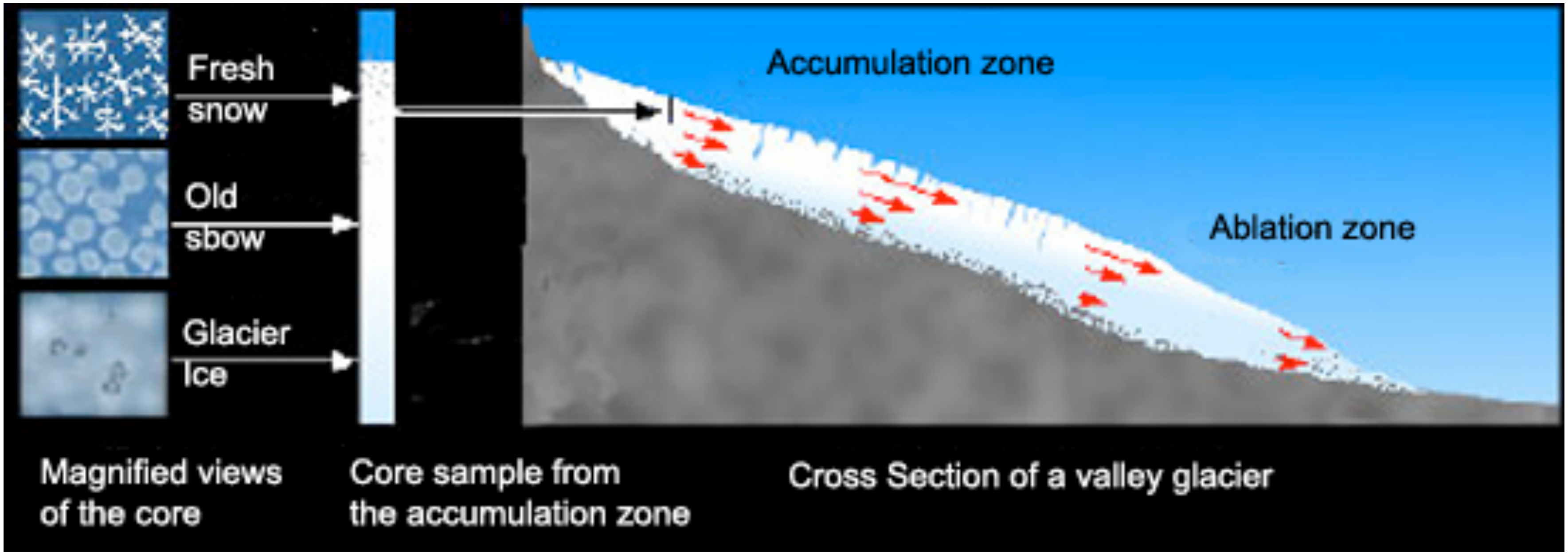
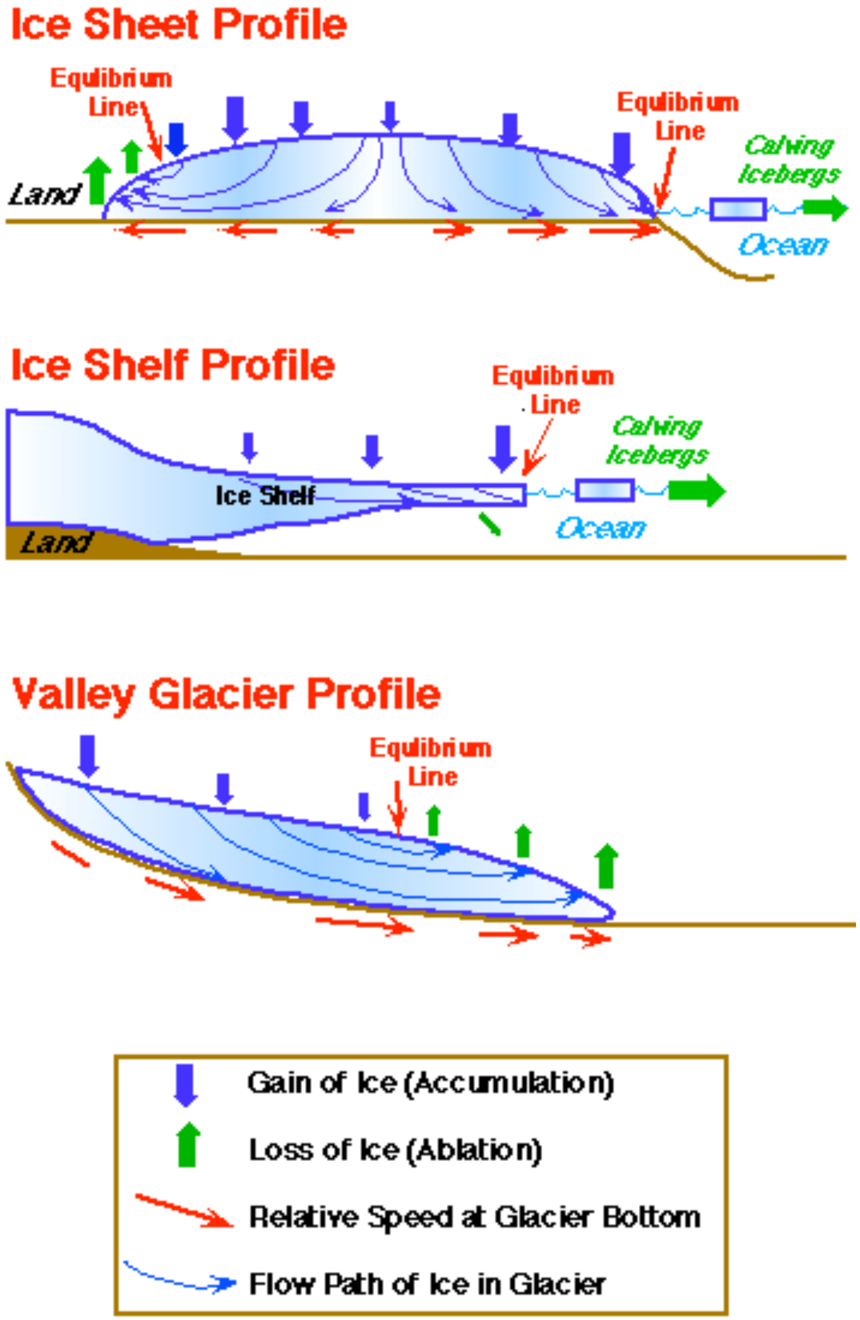


National Park Service

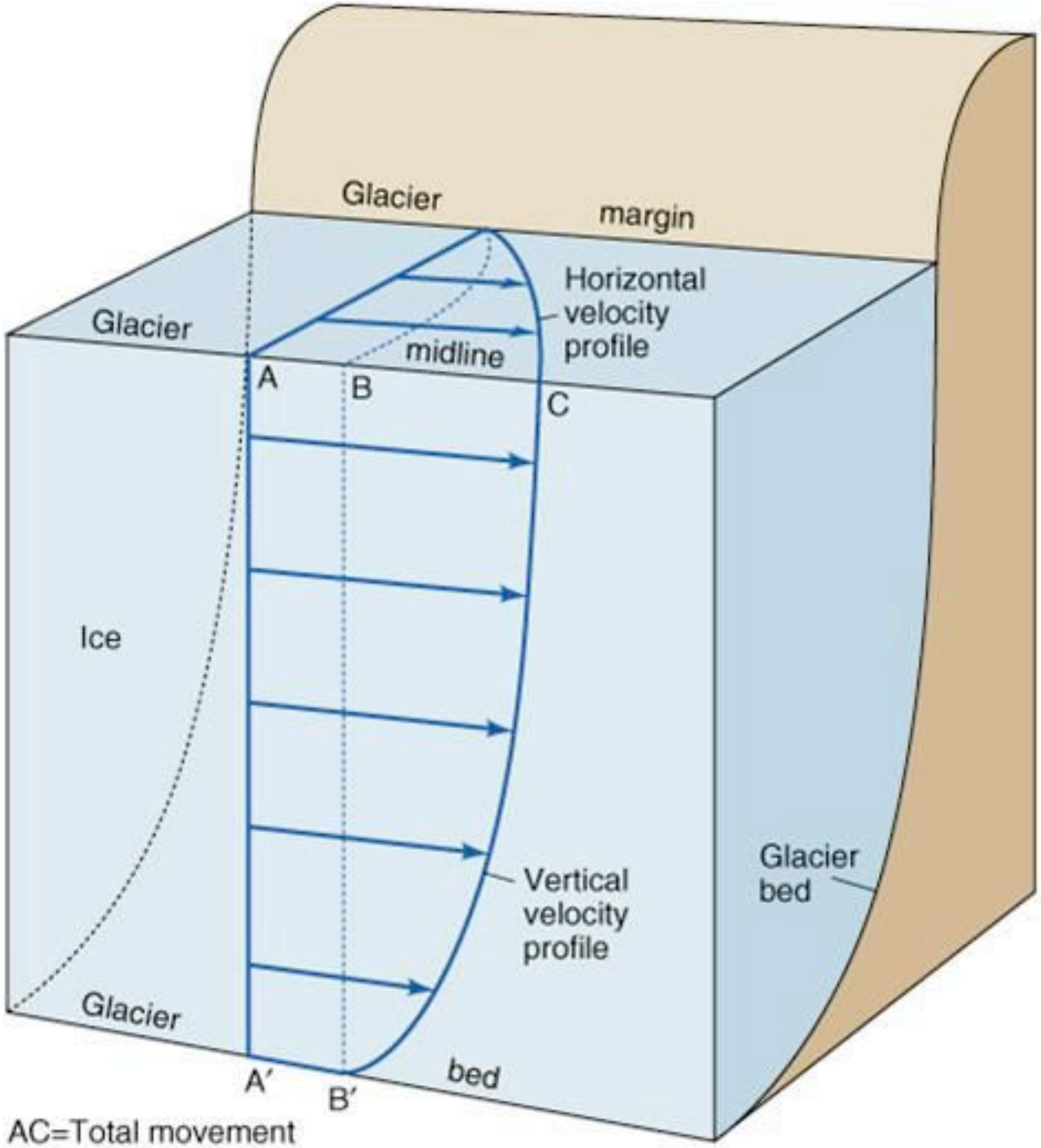


Greenland
Antarctica

Petermann
Glacier

Himalaya
Alaska

Rice University



AC=Total movement
AB=A′B′=Sliding on bed
BC=Internal flow

Glacial Flow (velocity)

- Temperature impacts velocity
  - Generally – closer ice is to melting point the faster it flows
  - Angle of slope impacts velocity
  - Terminus "floating" impacts velocity

- Surge – periods of increased velocity
  - Weather patterns
  - Calving
  - Accumulation of water near terminus

http://extremeicesurvey.org/

Glacier Dynamics

Conservation of Mass

$$\partial H/\partial t + \nabla(\vec{u}H) = \dot{a} - \dot{m}, \quad (3)$$

where H is the ice thickness, $\vec{u} = (u, v)$ is the vertically averaged velocity vector with across- and along-stream

Conservation of Momentum

$$\nabla \cdot \tilde{\boldsymbol{\sigma}} + \rho\tilde{\mathbf{g}} = 0,$$

Stress tensor generally NOT proportional to strain tensor (Non-Newtonian Fluid)

Conservation of Energy

Strain rate tensor relates to stress tensor:

The most widely used flow relation for glacier ice is (*Glen*, 1955; *Steinemann*, 1954)

$$\dot{\varepsilon}_{ij} = A\tau^{n-1}\sigma_{ij}^{(d)}. \tag{1}$$

with $n \sim 3$, and where $\dot{\varepsilon}_{ij}$ and $\sigma_{ij}^{(d)}$ are the strain rate tensor and the deviatoric stress tensor, respectively. The rate factor $A = A(T)$ depends on temperature and other

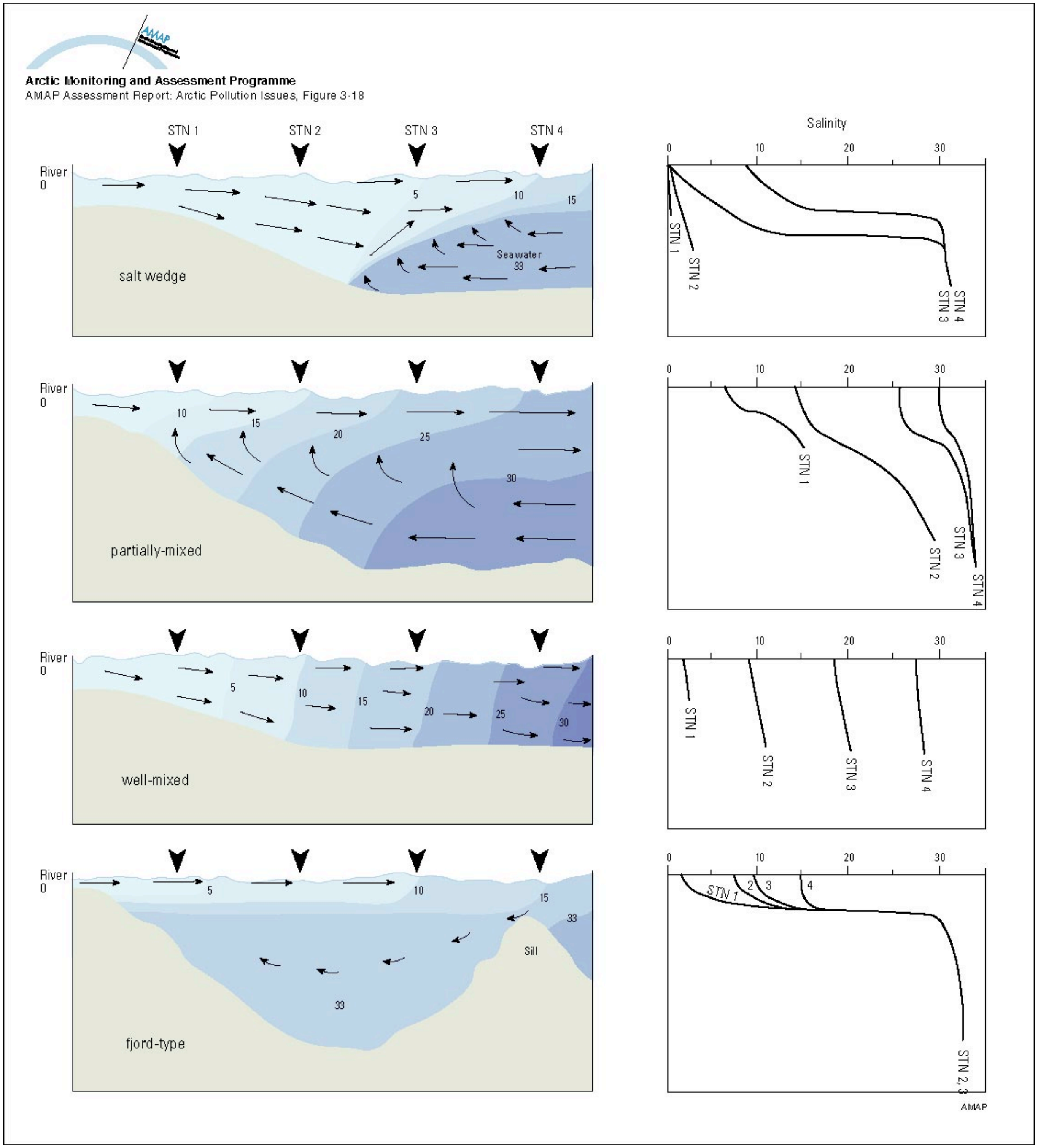
"Viscosity" depends on "effective stress" <---> Yikes

A *Newtonian viscous fluid*, like water, is characterized by the *viscosity* η

$$\dot{\varepsilon}_{ij} = \frac{1}{2\eta}\sigma_{ij}^{(d)}. \tag{2}$$

By comparison with Equation (1) we find that viscosity of glacier ice is

$$\eta = \frac{1}{2A\tau^{n-1}}.$$



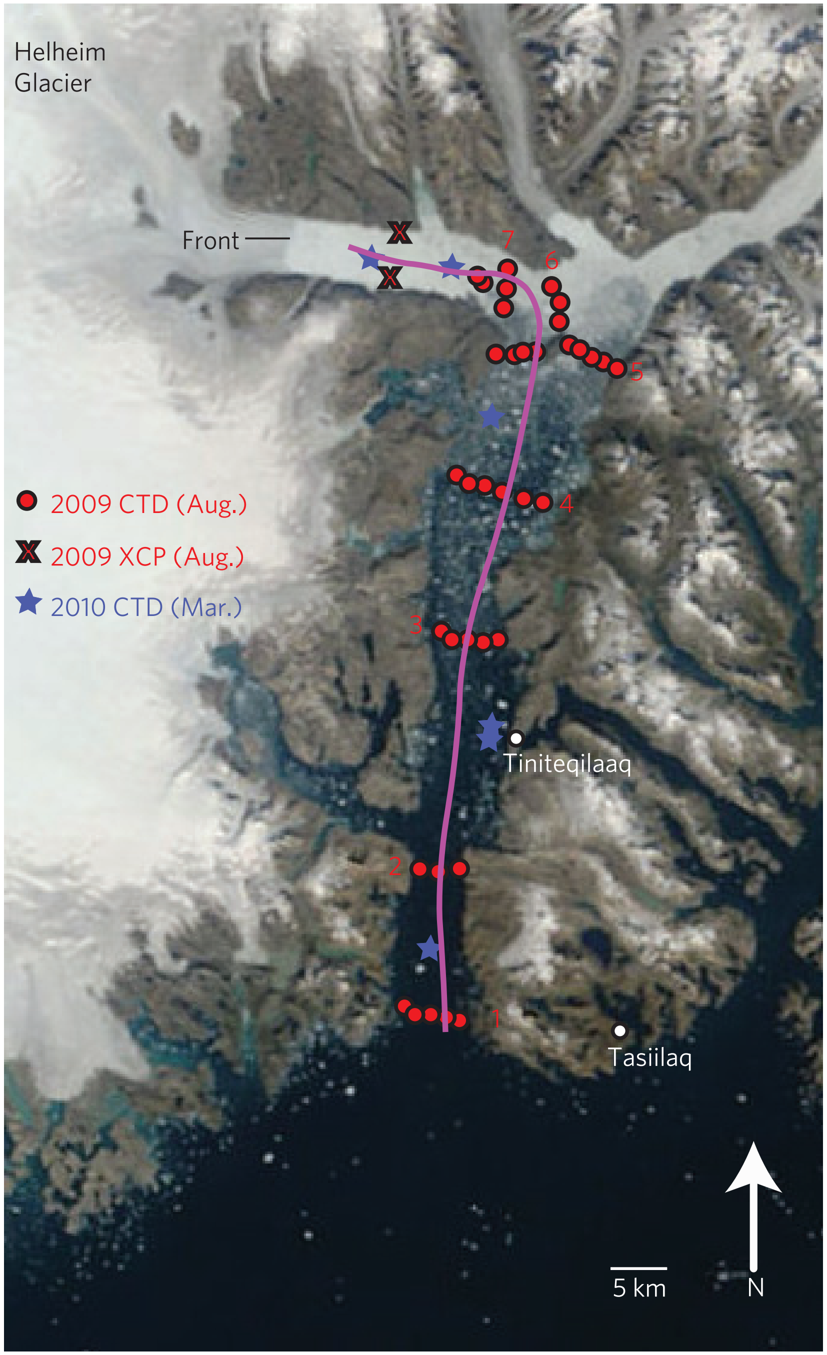
Estuarine Circulations:

Salt-wedge, Hudson River

Patially-mixed, Delaware Estuary (neap tide)

Well-mixed, Delaware Estuary (spring tide)

Fjord-type, Pudget Sound



Helheim Glacier Greenland

Straneo et al. (2011)