What is a Glacier?

♦ Mass of Ice
♣ Derived from Snow
♥ Lasts from Year to Year
♠ Moves Due to Its Own Weight

GLACIOLOGY vs.
GLACIAL GEOLOGY

Transformation of Snow to Glacial Ice

<table>
<thead>
<tr>
<th>Snow</th>
<th>Corn</th>
<th>Firn</th>
<th>Glacier</th>
</tr>
</thead>
<tbody>
<tr>
<td>Snow</td>
<td>= neve ice</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.05-0.2</td>
<td>0.2-0.3</td>
<td>0.4-0.8</td>
<td>0.8-0.9</td>
</tr>
<tr>
<td>g/cm³</td>
<td>g/cm³</td>
<td>g/cm³</td>
<td>g/cm³</td>
</tr>
</tbody>
</table>

Pure Ice = 0.917 g/cm³
Air Bubbles trapped in glacial ice "pop" when melting.

Snow to Glacier Ice Transition

Rate Varies,
Faster Nearer Melting Point (0°C).

<table>
<thead>
<tr>
<th>Location</th>
<th>Depth to Ice</th>
<th>Time Required</th>
</tr>
</thead>
<tbody>
<tr>
<td>So. Alaska</td>
<td>13 m</td>
<td>3-5 y</td>
</tr>
<tr>
<td>Byrd Station, AA</td>
<td>65 m</td>
<td>200 y</td>
</tr>
<tr>
<td>Plateau Sta., AA</td>
<td>160 m</td>
<td>3500 y</td>
</tr>
</tbody>
</table>
Snow Pit on Greenland Ice Sheet Summit:
Dark Bands = Winter
Light Bands = Summer

Figure from
Taylor, Kendrick, 1999,
Rapid Climate Change
American Scientist,
Volume 87, July-August,
No. 4

http://www.maxey.dri.edu/WRC/waiscores/Amsci/Taylor.html

---

GLACIER "BUDGETS"

Radiation Budget
VS.
Mass Budget

---

Radiation Sources:

Surface Sources

Radiation
Albedo (= Reflectivity)
Sensible heat conduction
Heat in precipitation
Most Important Sources of Heat

- Heat of Vaporization
  - Condensation: + 540 cal/g H₂O
  - Evaporation: - 540 cal/g H₂O

- Heat of Fusion
  - Freezing: + 80 cal/g H₂O
  - Melting: - 80 cal/g H₂O

- Heat of Sublimation
  - Frost: + 620 cal/g H₂O
  - Sublimation: - 620 cal/g H₂O

Basal Radiation Sources

- Geothermal Heat
- Frictional Heat
- Freezing & Melting

Glacier Thermal Profile: High Polar Glacier

Mean Temp.: Summer Winter

Depth

Frozen Bed

Rock
Polar Glaciers: Too Cold to Slide (They Creep Very Slowly)

Subpolar Glaciers

Mean Temp. Summer Winter

Pressure-melting point = \(-1^\circ\text{C}\) at 140 bars

East AA Ice Sheet pressure-melting point = \(-2^\circ\) or \(-3^\circ\)
Lake Vostok, East Antarctica, beneath almost 4000 m of ice, roughly the size of Lake Ontario. Image courtesy of K.C. Jezek.

http://www.nationalacademies.org/ssb/comp-europach4.htm

Temperate Glaciers:

<table>
<thead>
<tr>
<th>Mean Temp.</th>
<th>Summer</th>
<th>Winter</th>
</tr>
</thead>
<tbody>
<tr>
<td>-20°</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-15°</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-10°</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-5°</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0°</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Depth
Pressure-Melting Point Throughout

Wet Bed

Rock

Temperate Glacier, College Fiord Alaska

S. Kite Photo, 2002
Morphological Types of Glaciers

Grounded Glaciers

Floating Glaciers

Grounded Glaciers

*Continental*
Ice Sheet > 50,000 km²
Ice Cap < 50,000 km²

*Transitional*
Piedmont Glacier
Tongue Glacier
Outlet Glacier

*Alpine*
Valley Glacier
Cirque Glacier
### Present-Day Volume of Glaciers and Maximum Sea Level Rise Potential

From:

Satellite Image Atlas of Glaciers of the World
U.S.G.S. Professional Paper 1386-A
Chapter A: Introduction

Editors: Richard S. Williams, Jr., & Jane G. Ferrigno, 1999

<table>
<thead>
<tr>
<th>Geographic Region</th>
<th>Volume (km³)</th>
<th>%</th>
<th>Sea Level Rise (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ice caps, ice fields, valley glaciers, etc.</td>
<td>180,000</td>
<td>0.55</td>
<td>0.45</td>
</tr>
<tr>
<td>Greenland Ice Sheet</td>
<td>2,600,000</td>
<td>7.90</td>
<td>6.50</td>
</tr>
<tr>
<td>Antarctic</td>
<td>30,109,800</td>
<td>91.49</td>
<td>73.44</td>
</tr>
<tr>
<td>East Antarctica</td>
<td>26,039,200</td>
<td>84.80</td>
<td>66.80</td>
</tr>
<tr>
<td>West Antarctica</td>
<td>3,262,000</td>
<td>8.06</td>
<td></td>
</tr>
<tr>
<td>Ross Ice Shelf</td>
<td>229,600</td>
<td>0.01</td>
<td></td>
</tr>
<tr>
<td><strong>Totals</strong></td>
<td><strong>32,909,800</strong></td>
<td><strong>100.00</strong></td>
<td><strong>80.44</strong></td>
</tr>
</tbody>
</table>
Byrd Glacier Antarctica = Outlet Glacier

http://pubs.usgs.gov/fs/2005/3056/

Jakobshavns Isbrae (Sermeq Kujatdelq in Greenlandic) Landsat Image

Moves 7 km/y


West Greenland Fiords Outlet Glaciers

Franz Joseph Glacier, New Zealand

Athabaska Glacier, Banff NP, Alberta

Cirque Glaciers Feeding Valley Glacier
Vaughn Lewis Icefall, Juneau Ice Field

Seracs, Vaughn Lewis Icefall

Ice falls: series of rotational slumps or slides (normal faults)
Ogives
(Kinematic Waves)
On Gilkey Glacier
Below Vaughn Lewis Icefall,
Juneau Ice Field

Detail of Ogive below Vaughn Lewis Icefall

Gilkey Glacier, Juneau Ice Field
Floating Glaciers

Ice Shelf
(floating Ice Sheet or Ice Cap)

Ice Tongue
(floating Valley Glacier)

Two Ice Tongues; Ross Sea

http://terraweb.wr.usgs.gov/web-cgi/webvista.cgi
Image no longer available
Filchner Ice Shelf Calving

LANDSAT MSS Imagery from USGS:
http://pubs.usgs.gov/factsheet/fs50-98/

Iceberg A-38

Shrinking Antarctica

A 2,781-square-mile chunk of ice has recently broken off the Ronne Ice Shelf.

http://terraweb.wr.usgs.gov/web-cgi/webvista.cgi

Ronne Ice Shelf
Before A-38 Calving
GLACIER "BUDGETS"

Radiation Budget

VS.

Mass Budget

Ablation = Melting + Sublimation + Calving

Zone of Accumulation
(+ Mass Balance)

Equilibrium Line (ELA) vs. firn limit, vs. snow line

Zone of Ablation
(- Mass Balance)
Glaciers flow from zone of accumulation to zone of ablation.

Where is ice "discharge" greatest?

Equilibrium Line
Dynamic Classification of Glaciers

Active Ice
Passive Ice
Dead (Stagnant) Ice

"Flow" =
Viscoplastic Flow
& Sliding

Glaciers Move By Sliding and By Creep
Sliding Requires Film of Water at Bottom of Glacier

How Can a Film of Water Form at the Bottom of a Glacier?

All Glaciers Creep Like Silly-Putty

Geothermal Heat

AC = Total movement
AB + AV = Sliding on bed
BC = Internal flow
Strain Rate vs. Shear

- strain rate ($\varepsilon$) vs. shear stress ($\tau$) for plastic behavior
- viscous behavior
- glacier ice behavior (visco-plastic)

"Always" Plotted Backward

Graph = fig. 9.7 Ritter et al., 2002

Glen’s Flow Law

$$\varepsilon = A \tau^n$$

$\varepsilon$ = strain rate
$A$ = coefficient varies with temperature & xlinity of ice
$\tau$ = shear stress
$n$ = exponent varies with temperature & xlinity of ice

Basal shear stress ($\tau_b$)

$$\tau_b = \rho g h \sin \alpha$$

$\rho$ = density of ice
$g$ = gravity
$h$ = thickness (height) of ice
$\alpha$ = slope of upper glacier surface
\[ \tau_b = \rho \ g \ h \ sin \ \alpha \]

\[ \tau_b \leq 1.5 \text{ bars, basis for ice sheet profiles} \]

Velocity Profile: Polar Glacier
- **Laminar Flow** dominates Glaciers
- Viscoplastic Flow = “Creep” Only

Velocity Profile: Subpolar Glacier
- Viscoplastic Flow + Sliding
Basal Sliding

Amount is function of
- type of material
deformable bed
- amount of water at the bed
decreases basal friction

Wet bed vs. Frozen Bed

<table>
<thead>
<tr>
<th>Wet bed</th>
<th>Frozen Bed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thick ice, temperate glaciers</td>
<td>Geothermal gradient or frictional heat is inadequate for bed to reach 0°C, thin polar glaciers in Canadian Arctic, Greenland, Antarctica</td>
</tr>
<tr>
<td>geothermal hot spots</td>
<td></td>
</tr>
</tbody>
</table>

Regelation:
- Refreezing after Melting

How Do Basal Conditions Determine Landforms?

- Sliding Bed
- Glacier Ice
- Melting bed
- Freezing bed
- Bedrock Substrate
How Do Basal Conditions Determine Landforms?

Glacier Ice

Thin Layer of Water

Regelation Ice

Melting bed

Freezing bed

Bedrock Substrate

How Do Basal Conditions Determine Landforms?

Glacier Ice

Bedrock Substrate

How Do Basal Conditions Determine Landforms?

Glacier Ice

Bedrock Substrate

Abrasión

Regelation & Plucking

Bedrock Substrate
How Do Basal Conditions Determine Landforms?

Glacier Ice

Bedrock Substrate

Strose & Lee Form =
Roches Moutonee

Bedrock Substrate

Striated Outcrop, Maine

Striations & Grooves
Plucked Faces

Striations & Grooves
Plucked Faces

www.state.me.us/doc/nrme/photogal/surfical/surfphot.htm
How Do Basal Conditions Determine Landforms?

Frozen Bed

Glacier Ice

No Erosion at Bed!!

Bedrock Substrate

Frozen-Bed Margins (e.g. MN, WI, RI)

Wet Bed

Freezing Bed

Frozen Bed

Wet-Melting Wet-Freezing Frozen
**Map Basal Conditions for Ice Sheets & X-section of half of Ice Sheet**

*Look For Web-based Figure*

*Detail of Cross Section - margin (during + after)*

---

**Flow Lines**

- Zone of Accumulation
- ELA
- Zone of Ablation
- Basal Melting

---

**Crevasses**

- Extending flow (tension)
- Transverse Crevasses
- Compressive flow
  - Longitudinal Crevasses
  - Splaying Crevasses
Valley Glacier Ice Flow

Brittle ice over Visco-plastic ice

Marginal Crevasses

Ice Flow

Valley wall

Marginal Crevasses

Shear Couple
Marginal & Transverse Crevasses under Extending Flow = Tension

![Image of Marginal & Transverse Crevasses]

Longitudinal & Splaying Crevasses

![Image of Longitudinal & Splaying Crevasses]

Snow Bridge over Crevasse

![Image of Snow Bridge over Crevasse]
Down-Ice Deformation of Crevasses

Velocity Profile: Subpolar Glacier

- Viscoplastic Flow + Sliding
- Crevasse Fill (dust filling)
- down-ice deformation - foliation, thrusting

Surging
Moraines, Alaska

Looped Moraines

Surging Glaciers

Alpine Glacial System

After Davis, 1909

Alpine Glacial Landscape

After Davis, 1909
Parabolic (~U-Shaped) Valleys

Pater-Noster Lakes

Hanging Valley, Glacier NP
<table>
<thead>
<tr>
<th>Deposits Related to Glaciers</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Outwash - Glaciofluvial</td>
</tr>
<tr>
<td>• Glaciolacustrine</td>
</tr>
<tr>
<td>• Glaciomarine</td>
</tr>
<tr>
<td>• (Glacio) Aeolian</td>
</tr>
<tr>
<td>• (Glacio) Colluvial</td>
</tr>
</tbody>
</table>