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

snow corn firn glacier
snow = neve ice

0.05-0.2 0.2-0.3 0.4-0.8 0.8-0.9
\( \text{g/cm}^3 \) \( \text{g/cm}^3 \) \( \text{g/cm}^3 \) \( \text{g/cm}^3 \)

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.  

\[ \begin{array}{c|c|c|c}
\text{Depth} & \text{Summer} & \text{Winter} \\
\hline
-20^\circ & -15^\circ & -10^\circ & -5^\circ & 0^\circ \\
\hline
\end{array} \]

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

Subpolar Glaciers

Pressure-melting point = -1°C at 140 bars

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

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>

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
Greenland Ice Sheet: Radar Image

Antarctic Radar Map

2 Antarctic Ice Sheets

http://pubs.usgs.gov/factsheet/fs50-98/
### 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</td>
<td>180,000</td>
<td>0.55</td>
<td>0.45</td>
</tr>
<tr>
<td>fields, valley glaciers, etc.</td>
<td>2,600,000</td>
<td>7.90</td>
<td>6.50</td>
</tr>
<tr>
<td>Greenland Ice Sheet</td>
<td>30,109,800</td>
<td>91.49</td>
<td>73.44</td>
</tr>
<tr>
<td>Antarctic</td>
<td>26,039,200</td>
<td>8.06</td>
<td>64.80</td>
</tr>
<tr>
<td>East Antarctica</td>
<td>3,262,000</td>
<td>64.80</td>
<td>73.44</td>
</tr>
<tr>
<td>Ross Ice Shelf</td>
<td>229,600</td>
<td>8.06</td>
<td>64.80</td>
</tr>
<tr>
<td>Totals</td>
<td>32,909,800</td>
<td>100.00</td>
<td>80.44</td>
</tr>
</tbody>
</table>
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

Icebergs at Terminus of Gilkey Glacier

Bear Glacier Calving Icebergs, Alaska
Floating Glaciers

Ice Shelf
(floating Ice Sheet or Ice Cap)

Ice Tongue
(floating Valley Glacier)
Filchner Ice Shelf

http://terraweb.wr.usgs.gov/webcgi/webvista.cgi
Image no longer available

Filchner Ice Shelf Calving

1973 1986

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

Iceberg A-38

Shrinking Antarctica
A 2,750-square-mile chunk of ice has recently broken off the Ronne Ice Shelf.

This satellite photo shows Iceberg A-38 to scale with the state of Delaware.

SOURCE: National Ice Service
Clay Trout / NSIDC
Ronne Ice Shelf
Before A-38 Calving

Schedule Update
Forthcoming

http://www.geo.wvu.edu/~kite/LectureSchedule321.html

Geology Colloquium
Thursday, April 12th,
Dr. Mark Abbot, Univ. of Pitt

The Holocene Environmental History of the Central Andes from Lakes and Glaciers

4:00 pm in Room 105, White Hall.
Refreshments will be available at 3:45 PM.

Everybody is welcome!
Final Field Camp Meeting
18 April 2007
4:20 pm
301 White

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**
Mass Balance

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?

Geothermal Heat
All Glaciers Creep Like Silly-Putty

Strain Rate vs. Shear

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

Plotted “Backward”:
Dependent Variable on X axis

Graph = fig. 16.10 Bloom, 1998

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

$\tau_b \leq 1.5 \text{ bars}$, 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,</td>
<td>Geothermal gradient or frictional heat is</td>
</tr>
<tr>
<td>temperate glaciers</td>
<td>inadequate for bed to reach 0°C, thin polar</td>
</tr>
<tr>
<td>geothermal hot spots</td>
<td>glaciers in Canadian Arctic, Greenland,</td>
</tr>
<tr>
<td></td>
<td>Antarctica</td>
</tr>
</tbody>
</table>

Regelation:
- Refreezing after Melting
How Do Basal Conditions Determine Landforms?

- Sliding Bed
- Melting bed
- Freezing bed
- Regelation Ice
- Bedrock Substrate

- Thin Layer of Water

Glacier Ice
How Do Basal Conditions Determine Landforms?

Glacier Ice

Abrasion

Regelation & Plucking

Bedrock Substrate

Striations & Grooves

& Grooves

Plucked Faces

Stose & Lee Form =

Roches Moutonée

Bedrock Substrate
How Do Basal Conditions Determine Landforms?

- Frozen Bed
- Glacier Ice
- No Erosion at Bed!!
- Bedrock Substrate
Frozen-Bed Margins (e.g. MN, WI, RI)

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)

No luck in 2006-2007

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

Transverse crevasses on Persgletscher, Grisons, Switzerland. Photo J. Alean.

http://www.swiseduc.ch/glaciers/glossary/icons/transverse-crevasse.jpg
Marginal Crevasses

valley wall

Ice Flow

valley wall

Marginal Crevasses

Shear Couple

Marginal & Transverse Crevasses

under Extending Flow = Tension

valley wall

velocity plan view

Ice Flow

valley wall
**Velocity Profile: Subpolar Glacier**

- Viscoplastic Flow + Sliding

  Crevasse Fill (dust filling)
  down-ice deformation - foliation, thrusting

- Wet Bed
- Frozen Bed

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**Surging**

*Figure 2. Basal hydrologic system during surge: linked cavity configuration.*

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**Moraines, Alaska**

- Looped Moraines
- Surging Glaciers