- Ice core drilling
- Recrystallization in ice

The central ice divide is an ideal location for deep core drilling. No horizontal movement, layers deposited at drilling site.

Outside the ice divide, layers at depth originate upstream! Layers near the bed often folded and distorted by ice flow over hilly bedrock.
The Greenland ice cores provide the best available data on climate variations in the Northern Hemisphere during the last 125,000 years!

Extensive data on aerosol deposition, volcanic history and physical properties of polar ice!
Antarctic deep ice core drilling 1960-2004:

<table>
<thead>
<tr>
<th>Location</th>
<th>Start-End</th>
<th>Depth</th>
</tr>
</thead>
<tbody>
<tr>
<td>Byrd</td>
<td>1968-1969</td>
<td>2164 m</td>
</tr>
<tr>
<td>Vostok</td>
<td>1975-1997</td>
<td>3623 m</td>
</tr>
<tr>
<td>Dome F</td>
<td>1992-1995</td>
<td>2500 m</td>
</tr>
<tr>
<td>Dome C</td>
<td>1996-2004</td>
<td>3270 m</td>
</tr>
<tr>
<td>Kohnen</td>
<td>1999-2005</td>
<td>2700 m</td>
</tr>
</tbody>
</table>

The Vostok core has provided an unparalleled record of Earth’s climate and atmospheric history over the past 420,000 years.

This record is being prolonged by the new record from Dome C, where the oldest ice known on Earth has now been retrieved!

Completion of drilling at Dome C! Age of ice estimated to 900,000 years!
Ice core drilling sites around the world:

Shallow (50-300 m) or intermediate length (300-800 m) ice cores from ice caps around the world:

- South America
- Tibet
- European Alps
- Svalbard (Spitzbergen)
- Severnaya Zemlya
- Rocky Mountains
- Iceland
- Patagonia
- Kamtchatka
Ice core drilling: Site selection

Start with general reconnaissance of potential drill site.

The aim is to retrieve an undisturbed record going as far back in time as possible.

Important criteria:

- High ice thickness
- Low annual accumulation
- Flat bedrock
- No melting at surface (distorts some parameters)
  - For Greenland, this means altitude >2800 m
- Ice below melting point at the bed (old ice removed if melting occurs)
Reconnaissance: Radar measurements of ice thickness

Example from Central Greenland, GRIP and GISP2 sites

Summit - airborne radar survey of ice thickness and bedrock topography

From Hodge et al. (1990)
Reconnaissance: Determination of annual accumulation ($\lambda$)

Expressed in *water equivalent thickness* *(w.eq.)* of snow layer (or gcm$^{-2}$yr$^{-1}$).

10 cm/yr < $\lambda$ < 50 cm/yr on most of ice sheet.

Low accumulation area in the NE-part.

GRIP: 23 cm/year  
NGRIP: 19 cm/year

Shallow core drilling (100-150 m) during the North Greenland Traverse 1993-1995
Reconnaissance: GPS measurements of ice velocities

Typical ice flow velocities in the NGRIP area: 1-2 m/yr

Ice movement along ridge in a NNW direction

Away from ridge: Ice movement to W and NE
An ice core drilling station: NGRIP

Housing for 30 people over 5 summers

A runway that can receive Herkules transport planes

Ice cores on a logging table

Celebrating a milestone in the drilling at NGRIP

A trench beneath the surface where drilling and part of the scientific analysis of the ice cores takes place
**Ice core drills:**

Shallow ice core drill built at the Alfred Wegener Institute in Germany

---

**Dry hole:** Chips transported upward on spiral, fall through hatches and are collected in upper part of barrel. Core length in each run: ~ 1 m.
Deep drills:

- Similar basic design as in shallow drills, but more sophisticated.
- Must operate in borehole liquid.
- Built-in pump aids chips transport.
- Motor and electronics in sealed pressure chamber.
- Drill length 10 m. Core length in each run: ~ 3-4 m.
Deep holes must be liquid-filled:

- Ice sheet surface
- Bedrock
- Top firn layer (70-100 m) is permeable!
- Impermeable glacial ice
- Drill hole filled with liquid with density 0.92 g/cm³ to prevent closure!
- Hole liquids:
  - D60 diesel mixed with F141
  - n-butyl acetate
- Hole inclination:
  - < 2° above 2 km
  - 2-4° below 2 km

GRIP drilling progress:
- 1989: Startup
- 1990: 770 m
- 1991: 2320 m
- 1992: 3028 m (bedrock)

100-1500 m: Air bubbles present in the ice

700-1500 m: Air bubbles disappear and clathrates form
Air bubbles in glacial ice: Examples from Siple Dome, Antarctica.
Vostok ice core:

Air bubbles at 250 m depth

2500 m depth:

Clathrates
Possible scenario for the transformation of an air bubble to a clathrate
Textures and fabrics in ice cores:

Textures: Sizes and shapes of ice crystals
Fabrics: Orientations of symmetry axes (c-axes)
Ice crystals with different c-axis orientations display different interference colours when viewed between crossed polarizers.

Mean crystal size determined by:

- counting the number of crystals in a transect across the thin section
- image analysis techniques
What causes the difference in crystal size?

Let’s look at recrystallization processes operating in polar ice.

500 years old ice at 130 m depth.

Average diameter: 2 mm

100,000 years old ice at 2850 m depth.

Average diameter: > 2 cm
Crystal size variations in the GRIP ice core, Central Greenland
See explanations on following slides
Normal grain growth in the uppermost 700 m:

Simple analogy to a single grain (crystal) of ice embedded within the averaged environment of other grains:

A bubble of material 1 is blown into a medium of material 2, with \( \rho_1 \sim \rho_2 \). To increase the volume of the bubble by \( dV \) we must apply the work

\[
W = PdV
\]

The only resistance to the expansion of the bubble is the increased surface area being formed and the associated surface energy \( \gamma dA \). At equilibrium:

\[
PdV = \gamma dA
\]

\[
\Rightarrow P(4\pi r^2 dr) = \gamma 8\pi rdr
\]

\[
\Rightarrow P = \gamma dA/dV = \gamma (8\pi rdr)/(4\pi r^2 dr)
\]

\[
\Rightarrow P = 2\gamma/r
\]

Thus, at equilibrium, a pressure difference is set up across the boundary between the bubble and the liquid enclosing it:

\[
\Delta P = 2\gamma/r
\]

\( (\gamma = \text{surface tension [J/m}^2])\)

This pressure difference causes the liquid to rise in the capillary.
Normal grain growth in the uppermost 700 m (cont’d):

In a similar way, a pressure difference is set up across a curved boundary between two grains in a polycrystalline material like ice.

Pressure will normally be directed from the smaller grain to the larger grain (from the concave side of the boundary), causing molecules to jump across the boundary to the larger grain.

The boundary thus moves towards the center of the smaller grain, as indicated by the small, black arrows.

Ideally, grains with fewer than 6 edges will shrink, those with more than 6 edges will grow. Grains with 6 edges and straight boundaries will be in equilibrium.

Note: Only grains with <6 edges and concave boundaries are analogous to the bubble in the liquid (previous slide).

This leads to an increase in the average grain size (normal grain growth)!

Driving force: Minimization of surface energy.
A simple formula describing the increase in mean grain area with age:

\[ A(t) = A_0 + k \cdot t \]

- \( A = \) mean grain area at time \( t \)
- \( A_0 = \) mean grain area at time \( t = 0 \)
- \( t = \) time since deposition at surface

\(* \quad k = k_o \exp(-Q/RT) = \) growth rate = \( (A-A_0)/t \) - highly temperature dependent!

- \( k_o = \) constant
- \( Q = \) activation energy for grain boundary self-diffusion (42.5 kJmol\(^{-1}\))
- \( R = \) gas constant = 8.314 JK\(^{-1}\)mol\(^{-1}\)
- \( T = \) ice temperature (K)

GRIP ice core: \( k = 5.6 \times 10^{-3} \text{ mm}^2/\text{åri} \)

Log-normal distribution of crystal sizes characteristic for normal grain growth.

Using \(*\) we may write:

\[ \ln(k) = \ln(k_o) - (Q/R)^* (1/T) \]

Data on growth rates, \( \ln(k) \), from different ice core drilling sites plotted versus \( 1/T \): Allows estimation of \( k_o \) og \( Q \)!
Polygonization (rotation recrystallization) below 700 m depth:

Ideal structure of the ice crystal lattice, viewed along c-axis, perpendicular to the basal planes: Oxygen atoms form hexagonal arrangement in basal plane; two hydrogen atoms form a bond with each O-atom.

Dislocation: An extra atomic plane has been inserted along the dislocation line CD.

Dislocations in an ice crystal

The dislocations slide to lower energy positions within the crystal, on top of each other.

The ice crystal becomes bent and when the misorientation angle between the c-axes of the two parts reaches a critical value (~15°) we speak of two crystals instead of one.

This process is induced by increasing strain and is probably the main explanation for the stop in grain growth below 700 m.
Lowest ~200 m of the ice sheet: Migration recrystallization

Nucleation and growth of large crystals at temperatures close to the melting point. Grain boundaries migrate rapidly, large interlocking crystals with irregular shapes are formed.

This recrystallization process is not well understood. The main driving force is believed to be the difference in stored strain energy between adjacent grains, in highly strained ice near the bed.

Migration recrystallization on a small scale in NaCl:

The large grain boundary is moving to the left and a heavily strained (polygonized) grain structure is being consumed by a new, strain free grain. This grain, in turn, is becoming polygonized on the right. (From Guillopé and Poirer, 1979).
Crystallographic structure of ice Ih

Deformation of ice crystals

C-axis rotation

Fabric evolution and rheology of polar ice sheets
Each oxygen atom is surrounded by four neighbouring oxygen atoms in a tetrahedral arrangement.

Hexagonal unit cell

c-axis = symmetry axis

a-axes - in basal plane
Crystallographic planes and basal glide:

Basal plane – plane of closest packing of atoms, perpendicular to c-axis

Prismatic planes – vertical planes of the hexagonal cell

Pyramidal planes – at angle $\phi$ to c-axis

Basal glide – a dislocation moves through the lattice and positions of basal planes are shifted. Main deformation mechanism in ice!

a) Undisturbed

b) Dislocation shifts A to join B’

c) Top basal plane in a) has been sheared to the right relative to the lower basal plane

Ice crystal lattice viewed from the side
Deforming single crystals of ice:

Illustrating basal glide (basal slip)

No preferred slip direction within basal plane, crystal will deform in the direction of the applied stress.

If stress $\tau$ is applied to an ice crystal, the deformation rate is strongly dependent on the direction of stress relative to the basal planes. Deforms $\sim$60 times) faster in “easy” glide position.

A creep curve for a single crystal of ice.

The rate of deformation in a specified direction (strain rate) increases up to $\sim$20% strain, then reaches a steady value.

Explanation: Dislocation multiplication. Dislocation density in balance with applied stress once stationary strain rate is reached.
Deforming polycrystalline ice:

Explaining the creep curve for polycrystalline ice:

1. **Initial elastic deformation**

2. **Primary creep**: Favorably oriented grains deform but load is gradually transferred to grains in “hard glide” positions, whereby the strain rate decreases.

3. **Secondary creep**: A temporary minimum in the creep rate, resulting from a balance between hardening in parts of the sample and recrystallization softening elsewhere.

4. **Tertiary creep**: A stage of accelerating creep, attributed to recrystallization in the sample, which produces grains more favourably oriented for deformation (c-axis at ~45° to axis of compression).
In a polycrystalline ice sample, the c-axis of a crystal confined by its neighbours will rotate \textit{towards} the axis of vertical compression!

In a samples subjected to tension, c-axes will rotate \textit{away} from the axis of tension!

The rotation of c-axes on long timescales in ice sheets is observed in deep ice cores!
Stress systems in ice sheets:

Uniaxial extension: At ice divide!

Uniaxial compression: At ice sheet summit!

Pure shear: Upper part of ice sheet outside ice divide

Simple shear: Lowest 10-15% of ice sheet, outside ice divide
1. Prepare 0.5 mm thin section

2. Measure c-axis orientations

3. Plot c-axis orientations in horizontal plane, using a Schmidt net.

4. Interpret fabric diagrams
Fabric evolution in ice sheets:

Random fabric:
Near ice-sheet surface

Single maximum fabric:
Develops at GRIP and Dome C

Vertical girdle fabric:
Develops at NGRIP and Vostok

Strong single maximum fabric:
In lowest 10-15% of ice sheet in locations where simple shear is active

Observed in deformation tests, where strain rates are much higher than in natural ice masses!
Fabric evolution in the GRIP and NGRIP ice cores, Greenland:

- **250 m**: Single maximum develops at ice sheet dome! Fabric evolution dominated by vertical compression!
- **1050 m**: Vertical girdle develops at ice divide! Tension across divide dominates fabric development!
- **1750 m**:
- **2250 m**:
- **2800 m**:

GRIP  |  NGRIP
---    |  ---

148 m  |  148 m
806 m  |  806 m
1434 m |  1434 m
1860 m |  1860 m
2232 m |  2232 m
2840 m |  2840 m