Ice core drilling and subglacial lake studies on the temperate ice caps in Iceland

Iceland astride the Mid-Atlantic ridge

Astrobiology Winter School
University of Hawaii, Jan. 2005

Lecture # 36
Ice drilling projects in Iceland
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Ice cover during the late glacial period.
Combination of hot spot volcanism, spreading on the Mid-Atlantic ridge and glaciation leads to unusual geology.
Subglacial volcanism beneath an ice sheet creates unusual landforms:

Tuyas (tablemountains) and ridges.

From Thordarson and Höskuldsson (2003).
Submarine eruptions create similar formations.


Biological colonization monitored from the beginning
Recent subglacial eruption in Grímsvötn, Vatnajökull ice cap.
Jökulsárgljúfur canyons, N. Iceland: Formed in a catastrophic flood from Vatnajökull 2500 years ago.
Icelandic analogs to hillside gullies on Mars

Fig. 9. (a) Martian gullies show advanced erosion, dissecting the talus into triangular facets. MGS M15-001616, 41.7°S, 163°W. (b) Aerial view of similar Icelandic examples at the western edge of Ólfócull, showing triangular remnants of the original talus face. (c) Ground view of similar Icelandic formations on south face of Esja Pláttar.
- Dynamic ice caps in a maritime climate.
- High accumulation rates (2-4 m w.eq. yr\(^{-1}\))
- Extensive melting during summer, except at highest elevations (> 1800 m)
- Mass balance of ice caps negative since 1995

1972: A 415 m ice core was drilled on the NW-part of Vatnajökull
Activities not continued at that time, drill was discarded.
Mass balance of Hofsjökull Ice Cap

![Diagram showing the mass balance of Hofsjökull Ice Cap with data points for winter balance, summer balance, net balance, and cumulative mass balance from 1987 to 2002.]
Climate, Water, Energy: A research project investigating the effect of climate change on energy production in the Nordic countries

CWE uses IPCC data to create scenarios for temperature and precipitation change in the Nordic region in the future.

Modelled glacial meltwater discharge (run-off) 2000-2200.
100 m ice core drilled at Hofsjökull summit, 1790 m above sea level, using a German-built shallow drill.

- What kind of drill design is suitable for coring in temperate ice?
- Can annual layers be identified in the cores?
- Can climate records be retrieved from the temperate ice caps?
**Polar ice:**

Temperature below melting point, borehole dry (Deep coring: Liquid dumped in hole, to prevent closure)

**Temperate ice:**

At melting point throughout! Meltwater (and rain) seeps down into snow and firn, and is present in small veins on crystal boundaries below the firn-ice boundary! Water table in ice cap!

![Drill hole water-filled below firn-ice boundary!](image.png)

Hofsjökull – density profile
Shallow ice core drill built at the Alfred Wegener Institute in Germany

Dry hole: Chips fall through hatches and are collected in upper part of barrel. Core length ~ 1 m.

This system does not work well in a water-filled hole, where:

- Motor must be water-protected
- Travel time up & down in water column must be > 0.5 m/s
- Chips chamber must be designed in a different way
A different design was tested with success on the ice shelf covering the Grímsvötn subglacial lake in 2002.

Core length in each drilling run increases with new system!
\[ \delta^{18}\text{O} = \frac{^{18}\text{O} / ^{16}\text{O}_{\text{sample}} - ^{18}\text{O} / ^{16}\text{O}_{\text{SMOW}}}{^{18}\text{O} / ^{16}\text{O}_{\text{SMOW}}} \times 1000 \% \]

<table>
<thead>
<tr>
<th>LOCATION</th>
<th>ALT</th>
<th>T(_m)</th>
<th>(\delta^{18}\text{O})</th>
</tr>
</thead>
<tbody>
<tr>
<td>SMOW</td>
<td></td>
<td></td>
<td>0.0‰</td>
</tr>
<tr>
<td>Reykjavík, Iceland</td>
<td>14 m</td>
<td>4.4 °C</td>
<td>- 8.0‰</td>
</tr>
<tr>
<td>Hofsjökull, Iceland</td>
<td>1800 m</td>
<td>~ - 6 °C</td>
<td>- 12.9‰</td>
</tr>
<tr>
<td>Greenland summit</td>
<td>3200 m</td>
<td>- 32 °C</td>
<td>- 35.0‰</td>
</tr>
</tbody>
</table>
Hofsjökull δ¹⁸O profile (0-20 m)

Summer surfaces determined from:
- annual mass balance measurements
- dust measurements on core

Identification of annual layers from δ¹⁸O data not straightforward!
Marine aerosol dominates.

Washout occurs during first melting season!
Lava fields and sandy deserts in the interior are snow covered in winter, but snowfree 2-3 months during summer:

Windblown dust covers ice caps in late summer!

(Ó. Arnalds et al. 1997)
Temperature, stratigraphy and dust concentration in a 15 m snow core at drill site May 2003

2002 summer surface

2001 summer surface
Dustpeaks allow identification of annual layers.

Volcanic ash layers provide reference horizons.

Dust concentration (ppmv)

Grímsvötn eruption
November 2 2004
Comparison with the precipitation record from Hveravellir weather station (650 m a.s.l.), 35 km west of drilling site.

Measured annual layer thicknesses.

Correction for density differences and plastic thinning of layers with depth yields net mass balance at drilling site 1970-2000.
Mean annual values of $\delta^{18}O$ in ice core correlate with mean annual temperature at Hveravellir.
How many annual layers are preserved in the Icelandic ice caps?

Sandwich model – simple model that describes the thinning of annual layers with depth. Assumes vertical strain rate constant throughout ice sheet.

\[ t(y) = \frac{H}{\dot{c}_H} \ln \frac{H}{y} \]

Change in annual layer thickness (λ) with depth

\[ \dot{c}_y = y \frac{\dot{c}_H}{H} \]
Sandwich model:
Vertical strain rate constant from surface to bedrock (unrealistic in lower part)

Dansgaard-Johnsen model:
Vertical strain rate constant down to distance $h$ above bed, but decreases linearly with depth to 0 below $h$.

More sophisticated model that does not assume constant vertical strain rate.
Melting at the bed can be assumed in model.
Results for Hofsjökull summit (H = 300 m, $\lambda_H = 3.6$ m ice)

500 year record could be retrieved, and annual layers still detectable at 270 m!
Model results at 700 m depth:

- 1100 years old ice
- Annual layers 17 cm thick
- New drill being built in Iceland, operational in 2005. The drill could be made available for coring efforts on temperate or polythermal ice caps elsewhere (Svalbard, Scandinavia, Patagonia)

- Ice cores from temperate ice caps in Iceland can be accurately dated

- Proxy records for precipitation and temperature can be obtained

- A 500 year record could be retrieved with a 300 m drilling at the summit of Hofsjökull

- A record covering historical time in Iceland (870 AD – present) could be retrieved with a deep drilling (>700 m) in the ice-filled caldera at Bárðarbunga, Vatnajökull ice cap
The Grímsvötn volcanic caldera beneath the Vatnajökull ice cap:

Powerful geothermal system, frequent eruptions. Steady melting of ice from below, up to 300 m thick ice shelf covers a subglacial lake that empties out in jökulhlaups every few years.
Lake Vostok: The largest of ~70 subglacial lakes beneath the Antarctic ice cap

Plans to sample the lake under development.

Lake Vostok possibly hosts microbial life, isolated from other life on Earth over millions of years.

Webpage: “Subglacial Antarctic Lake Exploration:”  http://salegos-scar.montana.edu/
Vostok core reaches 420,000 years back in time.

Drilling was stopped 150 m above the subglacial lake, after drilling 70 m into ice accreted to the base of the ice sheet. Microbes were found in the accreted ice.

Kerosene was used as a drilling fluid, and hence biological contamination cannot be ruled out.
Recent hypothesis (P.B. Price):

Microscopic liquid veins on the boundary between three crystals in deep Antarctic ice are microbial habitats!

Psychrophilic bacteria can move in the veins and obtain energy and carbon from ions in solution.

Fig. 1. Microbial habitat consisting of solid ice grains (approximated by truncated semiregular octahedra) bounded by liquid veins (not to scale). Two microbes are depicted as living in the vein of diameter $d_{\text{vein}}$ surrounding a single grain of diameter $D$. 
Grímsvötn 2002:

Core drilling to 115 m and hot water drilling through 280 m thick ice shelf to sample the subglacial lake for a biological study.
Hofsjökull ice core

Dýpi (m)

- 2000
- 1999
- 1998
- 1997
- 1996
- 1995
- 1994
- 1993
- 1992
- 1991
- 1990
- 1989
- 1988
- 1987
- 1986
- 1985
- 1984
- 1983
- 1982
- 1981
- 1979
- 1978
- 1977
- 1976
- 1975
- 1974
- 1973
- 1972
- 1971
- 1970
- 1969

Dust concentration (ppmv)

- 100 m
- 81 m
- 65 m
- 43 m

Hekla 2000

- No dust peak

Hekla 1991

- No dust peak

Hekla 1980

33 annual layers identified with dust measurements

Rapid crystal growth!

30 year old crystals at 100 m equal in diameter to 100,000 year old crystals at 2850 m depth in the Greenland ice sheet.
Growth rates in top 100 m: Comparison of Hofsjökull / Vatnajökull data with polar locations.

East Antarctica (T = -55 °C): \( \sim 10^{-5} \text{ mm}^2/\text{yr} \)

Greenland summit (T = -32 °C): \( \sim 10^{-3} \text{ mm}^2/\text{yr} \)

Hofsjökull/Vatnajökull (T = 0 °C): \( \sim 10^2 \text{ mm}^2/\text{yr} \)

The effect of high concentrations of dust on crystal growth appears similar in both polar and temperate ice!
2002: Hot water drilling into the Grímsvötn subglacial lake

Investigators:  
Eric Gaidos (U. of Hawaii)  
Brian Lanoil (UC Riverside)  
Th. Thorsteinsson (NEA / U. of Iceland)
Grímsvötn Caldera Lake

- Altitude = 1400 m
- Volume of ~1-5 km$^3$
- Depth of 150 m
- Ice cover of 250 m
- Glacial drainage basin of 300 km$^2$
- 4250 MW over 100 km$^2$
- Episodic drainage (1 km$^3$ @ 10$^4$ m$^3$ sec$^{-1}$)
Project Goals

1) Determine if there is an active microbial community in the lake
2) Identify dominant lineages/species using molecular techniques
3) Assay community potential to fix carbon and nitrogen
DAPI CELL COUNTS
source: Whitman et al. (1998)
Main results of 2002 pilot study on Grímsvötn subglacial lake:

- Microorganisms in lake water and bottom sediment
- DNA analysis indicates that the lake community is distinct from communities in the snow and ice
- Gene sequences highly similar to known psychrophilic organisms

Paper on results can be downloaded at: www.liebertpub.com/ast
Future work:

We hope to carry out a 4 year program sampling the Grímsvötn lake and the nearby Skaftá cauldrons (beneath 500 m thick ice cover).

A new hot water drill has been built in Iceland for this purpose.