Drilling a deep ice core at the NEEM site in Greenland

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We summarize the different approaches and logistical requirements for completing an ice core drilling. We also present the recent North Greenland Eemian Ice Drilling (NEEM) international project.

Ice cores are drilled in glaciers and on ice sheets on all of Earth's continents. Whilst mountain glacier "shallow" ice core drilling reaches depths of ~300 m, "deep" drilling of several kilometers can be achieved on the Greenland and Antarctic ice sheets.

Drilling an ice core

Specialized drills are used to drill ice cores. They range in length from 3.5 m to 15 m. The devices hang on a steel cable with electrical wires inside allowing remote control from the surface. The cable runs from a winch over a top wheel on a vertical tower during drilling. Ice core drills can be either electromechanical or thermal.

An electromechanical drill is simply a rotating pipe (core tube) with cutters at the head (Fig. 1A). During rotation, the cutters incise a circle around the ice to be cored until the core tube is filled with ice. The cuttings (also referred to as ice chips) are transported to a chip chamber in the drill. Rotation of the drill head is achieved by anchoring the motor section to the wall of the borehole with knife springs that allow sliding up and down but prevent any rotation. When the drill tube is full, the ice core is broken by a pull in the cable. Several barbs inside the core tube grab the core and break it. The drill is subsequently hoisted to the surface and in the case of most intermediate and deep-sized drills the drill and tower are tilted horizontally for easy removal of the core.

In the thermal drill, a ring-shaped heating element melts a circle around the ice to be cored and the melt water is stored in a tank in the drill.

Ice cores have typical diameters of 75 mm, 98 mm or 123 mm. They are usually retrieved in sections that are 1 m to as much as 4 m in length (Fig. 1B). As glacier ice deforms under pressure, it is necessary to fill the borehole with a drilling fluid for depths below ~400 m to compensate for the increasing hydrostatic pressure of the surrounding ice with depth. This drilling fluid has a density slightly above the density of the glacier ice (920 kg m^3) and thus prevents plastic deformation of the borehole and constriction of its width.

The logistics of ice core field camps

A "shallow" drilling for a ~100-m-deep ice core can be performed on open snow as the drilling only takes a day or so. However, "intermediate" drilling to several hundred meters in depth may take weeks, and this is normally done in the shelter of a tent or in a covered snow trench (Fig. 2A). "Deep" drilling to more than one kilometer depth take many months and span several summer field seasons. In this case substantial infrastructure, such as a drill shelter, drill fluid supply and handling, electrical installations, campsite facilities, and organized transportation are needed.

The logistics involved in setting up and running a deep ice coring camp are considerable and costly (e.g. the total cost of the NEEM field activities was ~7.4 million euros) and so far only 11 cores deeper than 1.5 km have been drilled worldwide. A substantial part of the costs occur from transportation, either over land by tractor train or, in the case of the NEEM project, by ski-equipped LC-130 Hercules air planes. In the past two logistical philosophies have been used:

- One can limit the scientific analyses in the field to an absolute minimum, which in principle reduces the expensive manpower required for this task. The ice cores are then cut and analyzed in cold rooms back home;
- One can do as many analyses in the field as possible, taking advantage of nature's own clean "cold room" in an excavated science trench (Fig. 2B). This approach requires more manpower in the field; the advantages, though, are that scientists can work on the fresh core and that data are available at the end of the field campaign.

The key to a successful ice core drilling is the retrieval and documentation of an unbroken ice core, i.e. the top and bottom of an ice core section have to match up with the previous and subsequent cored sections. The core length (depth) must also be assigned with millimeter precision.

Drilling an ice core

The NEEM project (2007-2012) is the result of collaboration between 14 international partners and was initiated as an International Polar Year project.

*Figure 1: Drilling an ice core. **A)** The drill head of the NEEM drill (photo: J.P. Steffensen). **B)** A freshly drilled 3.5-m ice core section at NEEM (photo: T. Burton).*

Figure 2: The NEEM ice coring project field camp. ***A)*** *360° view of the NEEM drill trench, 7 m below the surface (photo: M. Leonhardt and J.P. Steffensen).* ***B)*** *A 360° view of the NEEM science trench, 7 m below the surface (photo: M. Leonhardt and J.P. Steffensen).* ***C)*** *Panoramic view of the NEEM camp in the 2010 field season (photo: J.P. Steffensen).*

The strategy chosen was to perform as many analyses as possible on site.

Typical NEEM field season began May 1st and ended August 15th. A brief synopsis outlines the highlights from each field season during the project:

• 2007: The project team reached the NEEM ice core drilling site (77°N, 51°W, 2480 m above sea level) by tractor train from the former NGRIP ice core site some 365 km away.

• 2008: The team constructed the camp consisting of a four-level geodesic dome, two garage tents, a roofed drill trench and roofed science trench, a powerhouse and six tent buildings (Fig. 2C). The first 110 m of ice were drilled using a mobile "shallow" drill and the "deep" drill was installed in the drill trench.

• 2009 and 2010: The team completed the ice core drilling and ice core scientific processing. The first ice core with material from the bedrock was drilled in July 2010 at 2535 m depth. During these two seasons the camp population was around 35.

• 2011 and 2012: Special rock drill extensions were mounted on the drill and several meters of debris-laden ice from the base of the ice sheet were drilled. The NEEM camp was deconstructed in July and August 2012. Most of the camp infrastructure, including the geodesic dome, was designed to be stored on heavy sleds, ready to be towed to a future drilling site.

The drilling of the NEEM ice core was carried out by two shifts of two drillers and one mechanic with ~30 m of ice drilled per day. An average of 15 scientists were in the science trench to process the drilled ice with the work organized as an assembly line (Fig. 2B). Typical activities in the science trench consisted of documenting and cutting the cores into sections of 55 cm and performing a large range of measurements such as the Di-Electric Properties (DEP) and electrical conductivity of the ice (solid ice Electrical Conductivity Method, ECM). Thin sections of ice were also prepared to define the physical properties of the ice, and volcanic tephra layers were sampled. In addition, we also conducted on-line Continuous Flow Analysis of the ice for dust, Na^+, Cl^-, SO_4^{2-}, NO^{3-}, NH_4^+, liquid conductivity, black carbon, formaldehyde, peroxide, and Ca^{2+}. For the first time, water isotope measurements by laser spectrometry and on-line measurements of gas concentrations by laser spectroscopy (CH_4; see Blunier et al. this issue) were coupled with the main on-line system. The remaining ice core sections (such as those set aside for discrete gas concentration and water isotopes measurements) were then packed in insulated boxes and shipped to cold rooms in Copenhagen for storage.

More than 270 individuals spent a total of 12,520 man-days at NEEM. These persons consisted of 51% young scientists, 21% senior scientists, 20% logistics and 8% related to associated projects. In this way NEEM has not only been a project fulfilling a scientific objective to retrieve last interglacial ice (NEEM community members 2013; Dahl-Jensen this issue) but it has also been a unique opportunity for young scientists to gain fieldwork experience in the high Arctic. For many of them, a stay at NEEM has laid the foundation for future successful international collaborations in ice core science.

Reference

NEEM community members (2013) *Nature* 493: 489-494