Rapid Microstructure Analysis of Polar Ice Cores

Analyzing past climates using the Large Area Scan Macroscope

Anja Krischke, Ulrich Oechsner and Sepp Kipfstuhl

With climate change and its implications for society and the Earth being a frequent topic in both politics and science, measureable data on the influence of mankind on current and past climate has become essential information for making predictions and decisions about future climate. The polar ice sheet provides information about temperature, precipitation as well as gas and aerosol concentration as a unique depiction of climate throughout hundreds of thousands of years. The information obtained from ice cores enables future climatic events as well as general material properties of ice to be better understood. The longest ice core drilled in Antarctica has a length of 3270 m and contains climate information dating back more than 800,000 years. The rapid analysis (minimum scan time 3 s) provided by the large area scan macroscope (LASM; Fig. 1) with a resolution of 5 µm has proven to be an essential tool for analyzing the microstructures of ice cores, both in the field and in the laboratory. A stratigraphic image that supports dating the ice cores can be obtained using Intermediate Layer Core Scanner.

Fig. 1 Large area scan macroscope for the analysis for microstructure of polar ice cores. (Source: Lars Berg Larsen, NEEM ice core project)

The densification of snow to ice at the glacier surface is a complex process influenced by temperature, the amount of precipitation, wind and the presence of impurities on trace levels. Snow is compressed throughout the years to firn, which is still permeable to air, and finally to ice. At the transition of firn to ice, 50 to 100 m below the surface, atmospheric air is enclosed in air bubbles, which at greater depths transform into air clathrates and make the ice transparent like plexiglas.

By analyzing the microstructure of the ice core for example, glaciologists learn about deformation and recrystallization of ice and the entrapped gases in order to reconstruct climatic events in the past.

Ice coring projects EPICA and NEEM

The challenge of retrieving the ice cores necessary for these evaluations was taken on by several ice drilling projects, such as the EPICA (European Project for Ice Coring in Antarctica) that managed to drill two cores trough the Antarctic ice sheet, one on Dome C (3270 m) in the Pacific sector and a second one at Kohnen Station (2774 m) in the Atlantic sector.

One drilling camp was Kohnen Station, about 760 km inbound from the Neumayer Station, the German overwintering base in Antarctica. All equipment, including the measuring equipment to analyze the ice cores, was either flown into the camp or transported by overland traverses using cargo sledges, that take an average of eleven days to get there [1].

Drilling operations took place during the austral summer (December – beginning of February) from 2001 throughout 2006. The temperature in the drill trench during the austral summer season was about −30 °C. The annual average air temperature at Kohnen Station is −45 °C (at Dome C: −55 °C).

Another ice coring project is NEEM (North Greenland Eemian Ice Drilling Project) from 2007 to 2011. The 2.5 km long ice core retrieved in Greenland provides data characteristic for the Northern hemisphere dating back to the last interglacial period, also called Eem warm period (115,000 – 130,000 years ago) when the Earth was about 3 – 5 °C warmer than today, and thus comparable with the climate we might be facing soon.

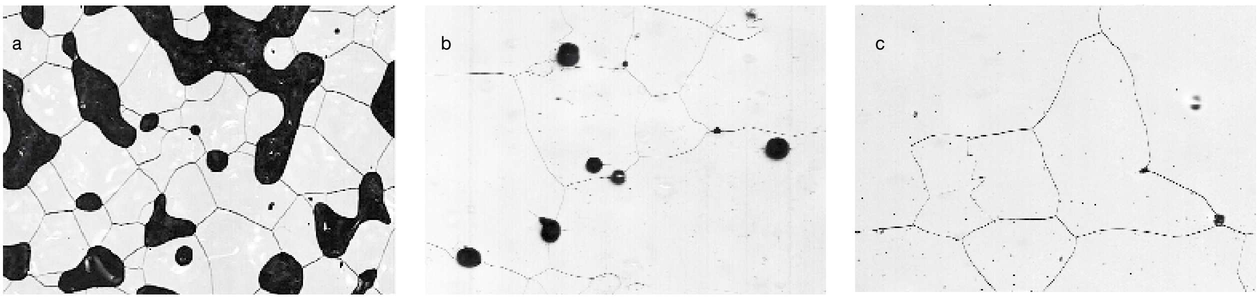

Fig. 3 Ice core sample images from different depths. All scans are obtained using the large area scan macroscope. The ice core image from 60 m depth (a) shows grain boundaries and pores. These inclusions become rarer and smaller with depth (b; 615 m depth). Finally, at a depth of 1035 m, almost all gas inclusions have transformed into air hydrates.

Standard analysis using a microscope

One method used to analyze the ice cores is microstructure mapping. It maps the microstructure of firn and ice at microscopic resolution, visualizing air inclusions, grain and subgrain boundaries, thus also grain size and shape.

The ice cores are first cut into 1 m pieces, and then the single cores are cut according to a predetermined scheme for individual analyses. Defined sections of about 45 × 90 mm² and 6 mm thickness are cut and microtomed. The polished surface is exposed to the free atmosphere for sublimation: The scratches produced by the microtome blade disappear and grooves, lines and pits start to develop at the sites where grain or subgrain boundaries or inclusions meet the surface.

The most common analysis method for ice cores uses an optical microscope, a CCD area scan camera, a frame grabber as well as an *xy*-stage [2]. Images are taken in transmission.

An overall area of 45 × 90 mm² is mapped by acquiring single microscopic images about 2.5 by 1.8 mm in size. After image capture, the ice core sample is moved using the translation stage so that an image is taken about every 2 mm. The overlap of about 0.5 mm between the images is helpful for the later reconstruction. A series of 1500 images with an acquisition time of about an hour to 90 minutes is necessary to reconstruct a sample section with a resolution of 3 – 4 µm.

Fig. 2 shows a single (b) and a fully reconstructed picture (a) of a 20 × 45 mm² wide ice core section. The dark lines are grain boundaries, the dark spots air hydrates. The few gas inclusions indicate that this sample was taken from a greater depth (1291 m).

Rapid ice core analysis – the large area scan macroscope

The time-consuming ice core analysis using a microscope was replaced in 2007 by using the specially developed LASM with a line scan camera, as shown in Fig. 1.

Line scan cameras are a popular choice whenever a high resolution image of a large area is necessary. In order to achieve a 2D image, the object is moved with defined velocity against the sensor and the individual line signals are put together to form the complete image.

Fig. 3 shows the scans of three ice core samples obtained from different depths. The ice core image from 60 m depth (3a) shows well defined grain boundaries (dark lines) and pores. The air inclusions become rarer and smaller with depth (3a; 615 m depth). Finally, at 1035 m almost all gas inclusions have transformed into air hydrates.

The LASM is depicted schematically in Fig. 4a and consists of a line scan camera with 8192 pixels and Gigabit Ethernet interface, a high resolution lens as well as an illumination unit. The ice is imaged in reflection with a resolution of 5 µm. The measuring width is 41 mm with an unlimited measuring length and a scan speed of up to 36 mm/s. Total scan time for a sample with 40 × 90 mm² is less than 1 minute (minimum actual scan time 3 s).

In order to capture the relevant microstructures, bright-field illumination is used. The principal scheme of this illumination technique is depicted in Fig. 4b.

The light that is directed at the sample is reflected by surfaces parallel to the sensor. Light reflected from structured areas and edges is reflected away from the sensor and appears dark. Thus, also in the images obtained with this method, the grain boundaries appear as dark lines and gas inclusions appear as dark bubbles or spots.

Undisturbed, high quality images in much less time

While for the image acquisition technique using a conventional microscope, thousands of images have to be stitched to form a complete picture, only two or three scans are necessary using the LASM depending on sample dimensions. This reduces the imaging time considerably and obviates the alignment and matching of the many individual images of these sections, which requires significant computing time. Since the microscope method takes a long time, all images are additionally taken with slightly different contrast

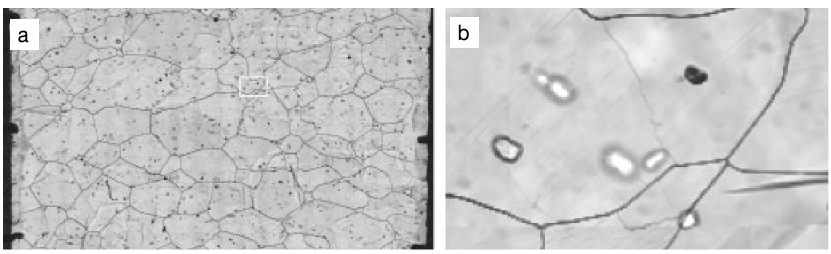

Fig. 2 Image of a 20 × 45 mm² wide ice core section mapped by an optical microscope. A series of 300 images is necessary for the fully reconstructed picture (a). A single picture, 2.5 × 1.8 mm² in size, is marked with a white rectangle and shown in (b). The dark lines show grain boundaries, the inclusions are air hydrates. [2]

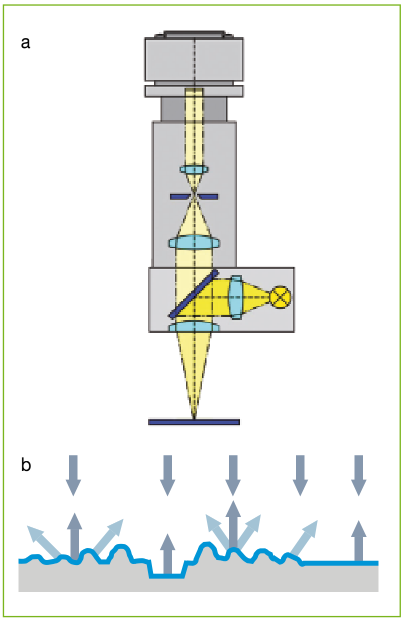

Fig. 4 Scheme of the LASM (a) and optical scheme of bright-field illumination (b): The light directed at the sample is reflected by surfaces parallel to the sensor. Light reflected from structures areas and edges is reflected away from the sensor and appear dark.

due to the ongoing sublimation process, which also needs to be corrected for. In order to stitch the complete picture, the images also have to be corrected for both vignetting as well as for distortion.

Using the LASM, a shading correction done prior to scanning allows for evenly illuminated images that also do not show significant signs of distortion due to an excellent correction of the field of curvature. Since only two or three images are necessary to cover the whole sample the time required for stitching is severely reduced.

The short time necessary to acquire a complete picture (from > 1 h to about 1 – 2 minutes) of an ice core allows for many more samples to be taken during the limited time available in the field, providing a much more detailed picture of the microstructure within the whole ice cores. While with the microstructure mapping approach a 10 cm sample can only be mapped every 10 m, using the LASM ten images can be obtained over 1 m in the same time. Since the image acquisition is so fast, the ice core samples can even be scanned several times to document the sublimation process (for example right after microtoming, and some later time) which is not possible using the microscope technique.

Dating the ice cores – the stratigraphy scanner

The annual variations in the amount of precipitation and the deposition of mineral dust and other particles leads to a layered structure of the ice. Visual stratigraphy visualizes these climate induced annual variations [3] and helps date the ice cores by counting the layers. Global climatic events, such as the eruptions of volcanoes, are sometimes visible when the layers contain ash particles.

The specially developed Intermediate Layer Core Scanner (ILCS, Fig. 5a) is used to examine samples up to 1.7 m in length. After microtoming the sample on both sides, the layered structure is captured using a line scan camera based scanner. The camera (SK2048GPD-4L with 2048 pixels and Gigabit Ethernet interface) located above the sample is moved synchronously to an indirect light source, that is mounted below the sample. As can be seen in the scheme in Fig. 5b which is depicting this dark-field illumination technique, the light from two sources is focused into the sample from two sides. Only light scattered from the sample is directed back into the camera, direct light from the illumination unit does not reach the sensor.

With a resolution of 51 µm and an imaging width of 105 mm, ice core samples up to 1200 mm (1700 mm with two overlapping scans) can be scanned with a speed of up to 22.7 mm/s. Total scanning time is ~10 s for a core of 1100 mm in length.

Fig. 6 shows a stratigraphic image. Transparent ice appears dark while bubbles or dust particles form bright visible layers. The number density of layers in a core section characterizes the climate, colder periods show more and brighter layers, whereas transparent thus dark ice indicates that the ice was formed during a milder climate period. Colored layers indicate volcanic ash layers.

Company

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Schäfter+Kirchhoff has accumulated a lot of experience in the development of optomechanical and optoelectronic systems for use in research, aviation and in space, as well as for demanding medical and industrial applications. Schäfter+Kirchhoff designs and manufactures their own CCD line scan camera systems, laser sources, beam-shaping optics and fiber-optic components, including laser beam couplers, fiber collimators and fiber port clusters for customers worldwide.

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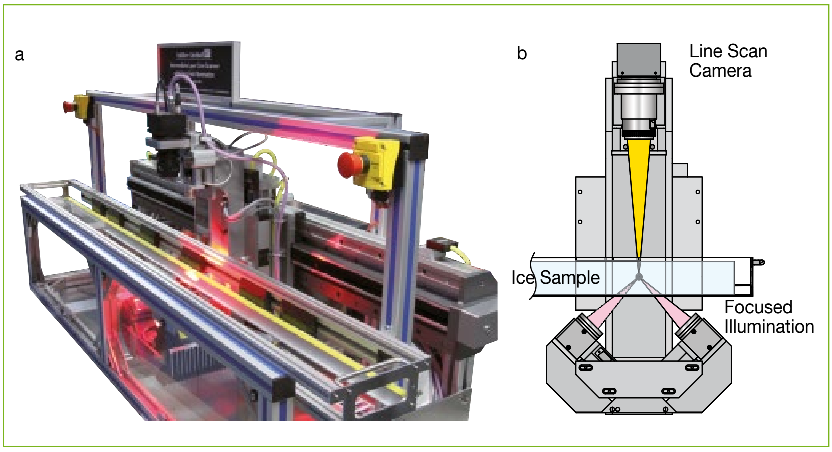

Fig. 5 Intermediate Layer Core Scanner (ILCS, a) and optical scheme (b). The camera located above the ice sample is moved synchronously to an indirect light source that is mounted below the sample. Relevant structures are visualized using the dark-field illumination technique. The light from the two sources is focused into the sample from two sides. Only light scattered in the sample is directed back to the camera, direct light from the illumination unit does not reach the sensor.

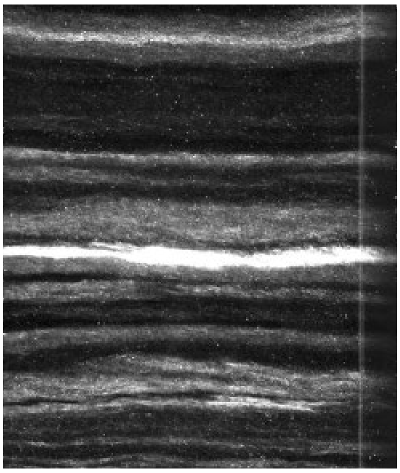

Fig. 6 Stratigraphic scan showing the layered structure of the ice core. Transparent ice appears dark while micro-inclusions like mineral dust or salt particles form brighter visible layers. Colored layers indicate volcanic ash horizons, grey layers mineral dust and salts inclusions.

Acquiring high resolution images in harsh environments

As the analysis of both the microstructure as well as the visual stratigraphic need to be done in the field during drilling as well as in the lab in Bremerhaven or elsewhere, both line scanners need to be robust and insensitive to the harsh environment.

The components used in both setups (mechanical, optical as well as electrical) are designed to work properly at temperatures down to –45 °C and are stable and robust enough to endure the long and bumpy ride to and from the drilling site (eleven days each way for Kohnen Station).

Both scanners described here have been used in the field in Antarctica as well as in Greenland multiple times. Whenever drilling is not ongoing they are used in the lab at AWI in Bremerhaven.

Conclusion

The polar ice sheet (in itself one of the purest natural materials on Earth) provides unique information about temperature, precipitation as well as gas and aerosol concentration depicting the climate throughout hundreds of thousands of years.

The microstructure of the ice cores can be imaged rapidly and with high contrast and resolution by using the LASM with integrated bright-field illumination. While the standard microscopic method takes hours for image capture (about 1500 images are necessary for a sample size of 45 × 90 mm^2) and requires extensive computing time, only two or three scans taking a total of 1 minute (min. scan time 3 s) are necessary to acquire high resolution images of much larger sections with the LASM. Accordingly, more scans can be taken during the limited time available in the field, thus depicting a much more detailed picture of the microstructure within the moving ice sheets.

The Intermediate Layer Core Scanner that uses dark field-illumination to visualize the layers in the ice helps date ice cores. The robustness of both scanner systems allows their transport as well as their use in the field at temperatures down to –45 °C.

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More information on glaciology is available from Alfred Wegener Institute at www.awi.de.

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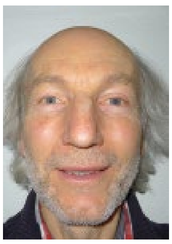

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