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# Kohnen Station – the Drilling Camp for the EPICA Deep Ice Core in Dronning Maud Land

by Hans Oerter[1], Cord Drücker[1], Sepp Kipfstuhl[1] and Frank Wilhelms[1]

The authors dedicate this paper in admiration to Dr. h.c. Oskar Reinwarth on occasion of his 80th anniversary in April 2009

**Abstract:** The European Project for Ice Coring in Antarctica (EPICA) was a joint European Science Foundation and European Commission scientific programme, funded by the European Union and by national contributions. It aimed in drilling two deep ice cores in Antarctica. Kohnen Station at 75°00'06"S, 0°04'04"E served as the logistic base for drilling the deep EPICA ice core, EDML, in Dronning Maud Land (DML). AWI has been in charge of providing the logistics for the EPICA drilling operations in DML. Kohnen Station was put into operation on January 11, 2001. It is a summer-only base. An extensive pre-site survey had been carried out between 1995 and 1999 to find the site with the best glaciological conditions for deep ice core drilling. Access to Kohnen Station is possible by means of sledge traverses starting from Neumayer Station at the coast or by aircraft support in the frame of the Dronning Maud Land Air Network (DROMLAN). A Comprehensive Environmental Impact Evaluation (CEE) was worked out for the drilling activity. Two austral summer seasons were needed to construct the base as well as the drill and science trench. Kohnen Station itself consists of eleven containers on a steel platform, which serve for power supply, snow melting, kitchen and accommodation. To host up to 27 people movable containers adjacent to the main base are used additionally. The drill and science trench is a 6 m deep trench in the firn covered by a wooden roof. It is fit out with the needed drilling equipment. The drilling operation lasted for four summer seasons. It started in 2001/2002 and was finished on January 16, 2006 at the final drilling depth of 2774.15 m. The technical equipment is described in the paper. Core processing took place at the cold lab of AWI at Bremerhaven as an international effort. In addition to the drilling activities several associated programmes for glaciology, meteorology and air chemistry have been carried out in the vicinity of Kohnen Station. A short summary with scientific results of the investigations at the EDML ice core is presented.

**Zusammenfasung:** Das European Project for Ice Coring in Antarctica (EPICA) war ein gemeinsames wissenschaftliches Programm der European Science Foundation und der Europäischen Kommission, finanziert aus Mitteln der Europäischen Union und der nationalen Projektpartner. EPICA hatte zum Ziel, zwei tiefe Eiskernbohrungen in der Antarktis abzuteufen, eine davon in Dronning Maud Land (DML; EDML). Die Kohnen-Station (75°00'06"S, 0°04'04"E) war dabei die logistische Basis für die Tiefbohrung in DML, für deren gesamte Logistik das AWI verantwortlich zeichnete. Die nur im Südsommer geöffnete Kohnen-Station wurde am 11. Januar 2001 in Betrieb genommen. Mit einem umfangreichen Vorerkundungsprogramm wurde der aus glaziologischer Sicht am besten geeignete Bohransatzpunkt ausgewählt. Die Kohnen-Station kann mit Schlittenzügen über das Eis von der Neumayer-Station an der Küste aus versorgt oder im Rahmen des Dronning Maud Land Air Network (DROMLAN) mit Flugzeugen erreicht werden. Für die Durchführung des Bohrprojekts wurde eine umfangreiche Umweltverträglichkeitsstudie (CEE) erarbeitet. Der Bau der Station und des dazugehörigen Bohr- und Wissenschaftsgrabens nahm zwei Sommer in Anspruch. Die Station selbst besteht aus elf Containern auf einer Stahlplattform, in denen Energieversorgung, Schneeschmelze, Küche und Wohneinheiten untergebracht sind. Um bis zu 27 Personen beherbergen zu können, wurden zusätzliche, mobile Wohneinheiten neben der Station aufgestellt. Der Bohr- und Wissenschaftsgraben (drill and sciencetrench) ist ein 6 m tiefer Graben im Firn, abgedeckt mit einem Holzdach, der mit aller notwendigen Ausrüstung zum Bohren ausgestattet ist. Die Bearbeitung des Eiskerns, das so genannte *coreprocessing,* fand im Kühlraum des AWI in Bremerhaven, als gemeinsame Aktion der internationalen EPICA-Partner statt. Zusätzlich zu den Bohrarbeiten, wurden in der Umgebung der Kohnen-Station noch weitere glaziologische, meteorologische und luftchemische Programme durchgeführt. Die wissenschaftlichen Ergebnisse, die bisher aus den Untersuchungen am EDML-Eiskern hervorgingen, werden kurz zusammengefasst.

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## THE EUROPEAN PROJECT FOR ICE CORING IN ANTARCTICA – EPICA

The Antarctic ice sheet is an unique archive to study the climate of the past. The ice provides a multitude of information on the paleoclimate and the paleoatmosphere, like temperature, precipitation, atmospheric circulation, aerosol concentration, and trace gases. To retrieve this information, deep ice-core drilling is required on top of the Antarctic inland ice. The European Project for Ice Coring in Antarctica (EPICA) took up this challenge. EPICA was organized twofold, as a programme of the European Science Foundation (ESF) and as projects of the European Commission (EC). Ten European nations were working together within the frame of EPICA: Belgium, Denmark, France, Germany, Italy, The Netherlands, Norway, Sweden, Switzerland, and the United Kingdom. EPICA aimed to drill through the Antarctic ice sheet at two different locations, at first on Dome C (EPICA COMMUNITY MEMBERS 2004; JOUZEL et al. 2007) and a second time in Dronning Maud Land (DML) adjacent to Kohnen Station (EPICA COMMUNITY MEMBERS 2006) (Fig. 1). The scientific motivation to choose the DML drill site (later named Kohnen station, 75°00'06''S, 0°04'04"E) was the fact that DML is facing to the Atlantic Ocean and should therefore reveal the best data for a comparison with the Greenland ice cores. Second, the accumulation rate at Kohnen Station with 64 kg $m^{-2}$ $a^{-1}$ is more than twice the accumulation rate than at Dome C, which amounts only to 25 kg $m^{-2}$ $a^{-1}$. The higher accumulation rate promised a higher time resolution of the DML ice-core record compared to the Dome C record, at least for the last 80,000 years (depth approx. 70 % ice thickness at Kohnen and 30 % at Dome C). For deeper and older ice the thinning due to ice dynamics makes the annual layers at Kohnen Station thinner than at Dome C. On the other hand Dome C has the advantage of providing much older ice than the DML site. Italy and France provided the logistics for the Dome C drilling, whereas Germany was in charge of logistics for the DML ice-core drilling at Kohnen Station.

EPICA started as a programme of the ESF in January 1996 and was extended after five years in 2001 for another five years and finally in 2005, without additional funding, until the end of December 2006. ESF contributed 490,000 € to this

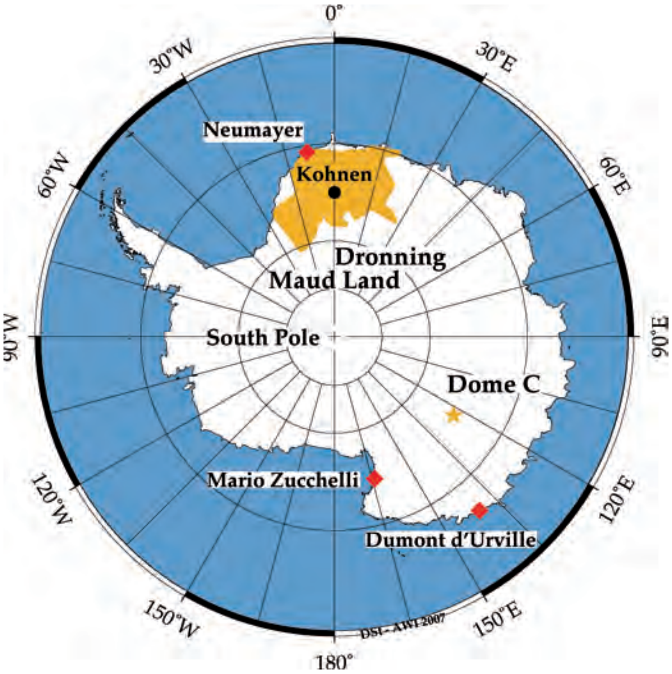



**Fig. 1:** Map of Antarctica showing the area (yellow) investigated during the EPICA pre-site survey in DML and the two EPICA deep drilling sites, in DML (Kohnen Station) and on Dome C (yellow star). The German, Italian, and French wintering bases Neumayer, Mario Zuchelli, and Dumont d'Urville, respectively, were the starting points at the coast for accessing the drilling locations. (Map drawn by D. STEINHAGE)

**Abb. 1:** Übersichtskarte der Antarktis mit dem Untersuchungsgebiet des EPICA-Vorerkundungsprogramms in Dronning-Maud-Land (DML, gelb) so wie die beiden Bohrlokationen der EPICA-Eiskernbohrungen in DML bei der Kohnen-Station und auf Dome C (gelber Stern). Die Überwinterungsstationen Neumayer (Deutschland) beziehungsweise Mario-Zuchelli (Italien) und Dumont d'Urville (Frankreich) waren Ausgangspunkte an der Küste für den Zugang zu den Bohrlokalitäten (Karte gezeichnet von D. STEINHAGE).

programme, predominantly for funding of coordination meetings, science workshops, and publications. The EPICA Steering Committee was chaired by Jean Jouzel, LSCE Saclay, France (1996-2001) and Heinz Miller, AWI Bremerhaven, Germany (2001-2006). Bernhard Stauffer, University of Bern, Switzerland, and Eric Wolff, BAS Cambridge, UK, served as EPICA Chief Scientists from 1996-2002 and 2002-2006, respectively.

The EC-projects EPICA1 (Contract ENV4-CT95-0074, 01.02.1996-31.01.1999, Budget 11.68 Mill. €, EC funding 5.00 Mill. €), EPICA2 (Contract ENV4-CT98-00702, 01.02.1999-30.04.2001, Budget 6.31 Mill. €, EC funding 2.90 Mill. €), and EPICA3 (EVK2-CT -2000-00077, 01.05.2001-30.04.2004, Budget 7.06 Mill. €, EC funding 2.42 Mill. €) were carried out within Frameworks 3, 4, and 5, respectively, from February 1996 to April 2004. EPICA1 was co-ordinated by Jean Jouzel, France, EPICA2 by Dominique Raynaud, France, and EPICA3 by Heinz Miller, Germany. Under Framework 6 the EC was funding this ice-core research as the Specific Targeted Research Project EPICA-MIS (**E**nhanced **P**alaeo-reconstruction and **I**ntegrated **C**limate **A**nalysis through **M**arine and **I**ce-core **S**tudies). The project EPICA-MIS started in December 2004 and was finished in May 2008. It was co-ordinated by Dominique Raynaud from LGGE in Grenoble. EPICA-MIS had a budget of 5.42 Mill € of which 2.50 Mill € were funded by the EC.

On March 12, 2008, EPICA was awarded the Descartes Prize for Research 2007 of the European Commission. For excellent communication of scientific results, especially those of EPICA, to the public within Germany the Stifterverband für die Deutsche Wissenschaft together with Deutsche Forschungsgemeinschaft awarded on June 14, 2007 the Communicator-Preis 2007 to the Working Group of Glaciology under the leadership of Prof. Heinz Miller, AWI.

## EPICA PRE-SITE SURVEY IN THE AUSTRAL SUMMER SEASONS 1995/96 – 1998/99 AND ENVIRONMENTAL EVALUATION

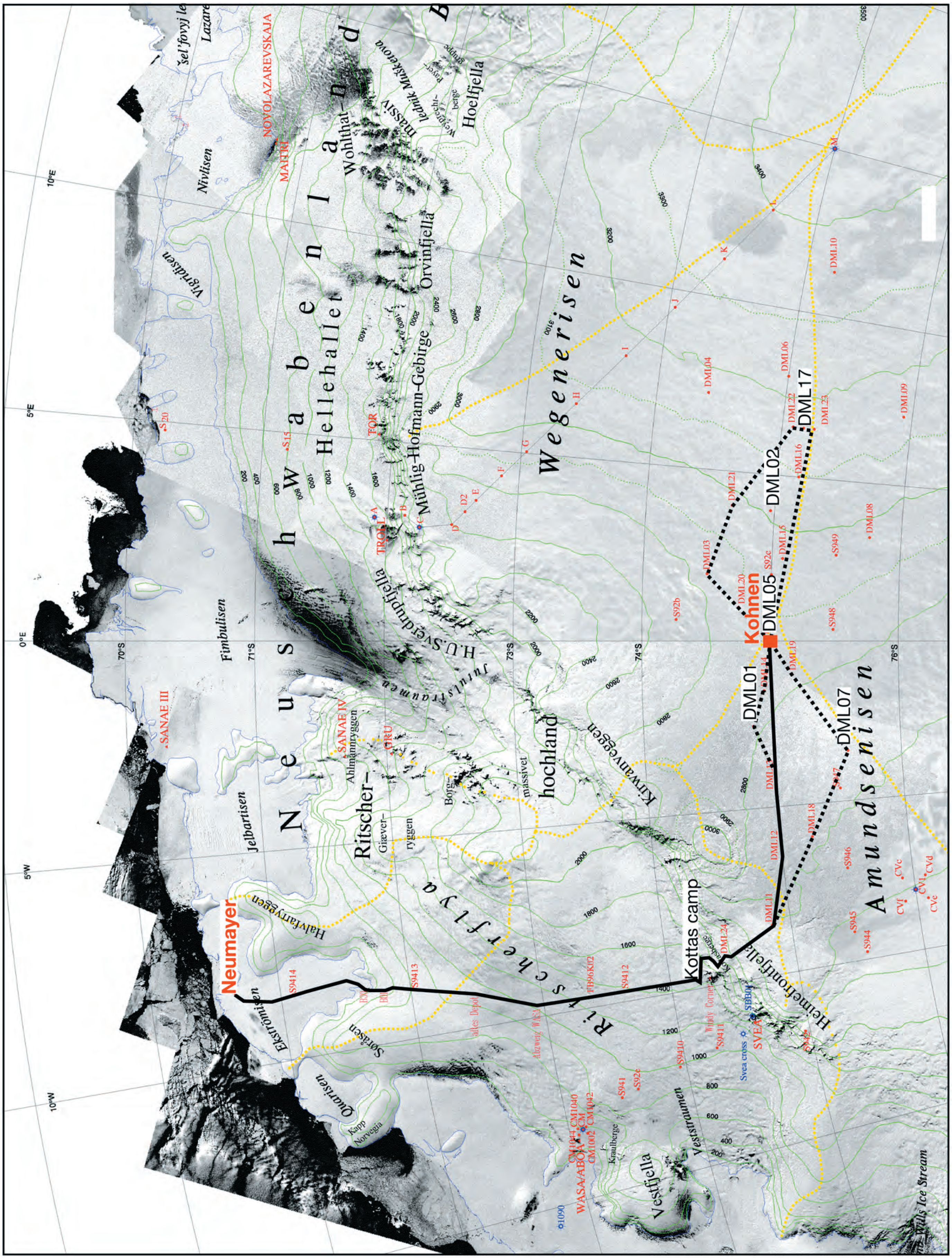
### *Site selection*

The interior of the inland ice in DML, which is named Amundsenisen and Wegenerisen (Fig. 2), was rather unexplored prior to the EPICA investigations. To define a suitable location for deep ice-core drilling one has to know surface topography, bottom topography, ice thickness, ice velocity, and ice deformation as well as the rate of snow accumulation at the drilling site and upstream of it. None of these parameters were known in detail and early modelling could only use values from rough interpolations of sparse data. The situation at the EPICA drilling site on Dome C was different. There the needed glaciological parameters had already been investigated before EPICA started. Therefore, in DML the first four years of EPICA were dedicated to an intensive pre-site survey in central DML comprising airborne radio-echo sounding measurements for ice thickness and bottom topography and ground-based measurements for accumulation and ice movement as well as a mapping project.

For surface topography the data set compiled from ERS-1 data by Huybrechts et al. (2000) was mainly used and sometimes the slightly modified version of BAMBER & BINDSCHADLER (1997). The bottom topography in central DML has been determined since 1994 by airborne radio-echo sounding measurements carried out by AWI by means of the AWI aircraft Polar 2. The measurements between 1994 and 1999 (STEINHAGE et al. 1999, 2001, STEINHAGE, 2001) were already used for the BEDMAP compilation (LYTHE et al. 2001). The measurements continued, especially in the vicinity of the drilling location as soon as it was fixed.

**Fig. 2:** Map of Dronning Maud Land (DML). The solid black line shows the traverse route from Neumayer Station via Kottas Camp to Kohnen Station. The black dashed line shows the route of the 1997/98 traverse, where it deviated from or extended the main traverse line. The pale yellow lines show the ice divides in DML. Intervals of contour lines (green) are 100 m. The map is based on the Satellite Image Map 1:2 000 000, Draft version 4.2, Bundesamt für Kartographie and Geodäsie (BKG), Frankfurt a.M., Nov. 1998 (http://141.74.33.52/stagn/antarktis/Uebersichten.htm).

**Abb. 2:** Übersichtskarte Dronning-Maud-Land (DML). Die durchgezogene schwarze Linie markiert die Traversenroute von der Neumayer-Station via Kottas-Camp zur Kohnen-Station. Die gestrichelte schwarze Linie zeigt die Route der Traverse von 1997/98, dort wo sie von der Hauptroute abwich oder diese erweiterte. Die blass-gelben Linien zeigen die Eisscheiden (ice divides) in DML. Die Äquidistanz der Höhenlinien (grün) beträgt 100 m. Die Karte basiert auf der Satellitenbildkarte 1:2 000 000, Entwurf 4.2, Bundesamt für Kartographie and Geodäsie (BKG), Frankfurt a.M., Nov. 1998 (http://141.74.33.52/stagn/ antarktis /Uebersichten.htm).


Neumayer
Kottas camp
Kohnen
DML01
DML02
DML05
DML07
DML17
Neuschwabenland
Hellehallet
Wegenerisen
Amundsenisen
Ritscherflya
Ritscher-hochland
Mühlig-Hofmann-Gebirge
H.U. Sverdrupfjella
Heimefrontfjella
Kirwanveggen
Jutulstraumen
Wohlthat-massiv
Orvinfjella
Hoelfjella
Fimbulisen
Jelbartisen
Ekströmisen
Quarisen
Vestfjella
Veststraumen
Halvfarryggen
Nivlisen
Vigridisen
SANAE III
SANAE IV
NOVOLAZAREVSKAJA
TROLL
SVEA
WASA/ABOA
Kapp Norvegia
0°E
5°E
10°E
5°W
10°W
70°S
71°S
73°S
74°S
76°S

Snow accumulation and ice velocities have been measured since the summer season 1995/96 in central DML (Jokat & Oerter 1998). The standard set-up for a site of measurements was to dig a 1-2 m deep snow pit for snow sampling, to drill a 10-15 m deep firn core for later analysis in the home lab, to measure the temperature in the 10 m depth, and to carry out static GPS measurements at a pole fixed in the snow (Fig. 3). In the 1995/96 and 1996/97 seasons Kottas Camp in front of Kottasberge, Heimefrontfjella, was the base for flights with the aircraft Polar 4 to the ten sites DML01 to DML10 on the Amundsenisen (Fig. 2). DML01 and DML02 were visited in both seasons.

During the 1997/98 season an over-snow traverse drove up to Amundsenisen (Fig. 2), revisited four of the old sites and set up 13 new sites (Oerter 2001). At the new sites approximately 30 m deep firn cores were drilled instead of 10-15 m deep cores, each reaching the well dated horizons of 1816 AD and 1810 AD, marked by the aerosols from the volcano Tambora (eruption 1815 AD) and an unknown one (eruption 1809 AD), respectively. At three sites the cores were drilled even deeper to a depth of 115 m (DML07), 150 m (DML05, 1.6 km westwards of the later Kohnen/EDML site) and 130 m (DML17). The results of those three seasons of intensive pre-site survey were used to describe the glacio-chemical conditions on the inland ice plateau (Göktas et al. 2002) as well as to compile a new map of accumulation rates to which also the other EPICA partners contributed (Rotschky et al. 2007).


**Fig. 3:** Field work at Site DML01 (see Fig. 2 for location), the first site investigated during the pre-site survey on the inland ice plateau of DML in 1996. During the season 1995/96 the base for both aircraft Polar 2 and Polar 4 was Kottas Camp. Polar 4 (in the back) had only two landings (at one day) at two sites on the inland-ice plateau, at DML01 and DML02, due to technical problems. At both sites a 1.5 metre deep snow pit (not visible) was dug, a 10 m long firn core drilled, and GPS measurements carried out. (Photo H. Oerter, 05 02 1996).

**Abb. 3:** Arbeiten am Punkt DML01 (vgl. Abb. 2 für Orientierung), dem ersten Punkt, der 1996 im Rahmen des EPICA-Vorerkundungsprogramms auf dem Plateau des Inlandeises in DML beprobt wurde. Während der Saison 1995/96 waren die beiden Polarflugzeuge Polar 2 und Polar 4 am Kottas-Camp stationiert. Wegen technischer Schwierigkeiten absolvierte Polar 4 (im Hintergrund) in dieser Saison nur zwei Landungen (an einem Tag) auf dem Plateau, bei DML01 und DML02. An beiden Stellen wurde ein 1,5 Meter tiefer Schneeschacht (im Bild nicht sichtbar) beprobt. Ein 10 m langer Firnkern gebohrt und die Positionen mit GPS bestimmt. (Foto H. Oerter, 05.02.1996).

During the 1998/99 summer season the traverse route of 1997/98 was redone once more carrying out radio-echo sounding measurements by means of an ice-penetrating radar and doing repeated GPS measurements at the marked points (Fahrbach & El Naggar 2001, Eisen et al. 2004, Rotschky et al. 2004).

During the 2000/2001 season, before the construction work of the drill and science trench started, a detailed survey with ice-penetrating radar was carried out across the drilling site to get a better insight in the layering of the snow and ice as well as the spatial variation of accumulation rates (Fahrbach et al. 2003, Eisen et al. 2005).

Finally, the decision was made by the EPICA Steering Committee to choose a location 1.6 km east of DML05 as the drilling site for the EDML ice core and to establish Kohnen Station there. On January 10, 2001, before the drilling operation started, the borehole was located at 75°00'09''S, 00°04'06"E at an elevation of 2,892 m (WGS84) (Wesche et al. 2007). The ice thickness is 2,782 ±10 m (Eisen & Steinhage pers. comm.), which is in very good agreement with the final logging depth of 2774.15 m. According to the ice-core B32, the mean accumulation rate is 64 ±0.5 kg m$^{-2}$a$^{-1}$ for the last 1000 and the last 4000 years (Sommer et al. 2000). Eisen et al. (2005) determined a value of 65 kg m$^{-2}$a$^{-1}$ by analysing radio-echo sounding measurements. The surface flow velocity of the ice at the drill site is 0.756 m a$^{-1}$ with a direction of 273.4° (Wesche et al. 2007). The mean annual temperature, as measured 1997/98 in 10 m depth, is -44.6 °C (Oerter et al. 2000). Reijmer (2001) reports values of -45.0 °C, -45.1 °C, and -45.2 °C for 1998, 1999, and 2000, respectively. The recent temperature regime since Kohnen Station was built in 2000 is illustrated by data from an Automatic Weather Station (Fig. 4). During winter temperature falls to -70 °C and in summer it will not be warmer than -17 °C. The midnight sun is shining from von October 31 through February 12. Sunset in February determines the length of the working season, as temperature then goes down far below -40 °C during the night hours.

*Access route to the inland ice*

Another important task of the pre-site survey was to find a safe route for travelling from the German wintering-over base Neumayer Station (70°39'S, 08°15'W) on Ekströmisen, adjacent to Atka Bay (Kohlberg & Janneck 2006), to the drillling site on Amundsenisen. There are two critical parts, firstly the ascend from the floating Ekströmisen to the grounded ice of Ritscherflya and secondly, the ascend from Ritscherflya to Amundsenisen, crossing the mountain range of Heimefrontfjella east of Kottasberge (Fig. 2).

SPOT images were used to find areas, which are free of crevasses, to ascend from Ekströmisen to Ritscherflya (Fig. 5) and for the passage through Heimefrontfjella south of Strømebakken. Haushold (1997) produced the Satellite Image Map (scale 1:100 000) Kottasberge, using SPOT images and a digital elevation model of Institut für Angewandte Geodäsie. The map shows the recommended route (Abb. 6).

The route to the inland ice starts at Neumayer Station and

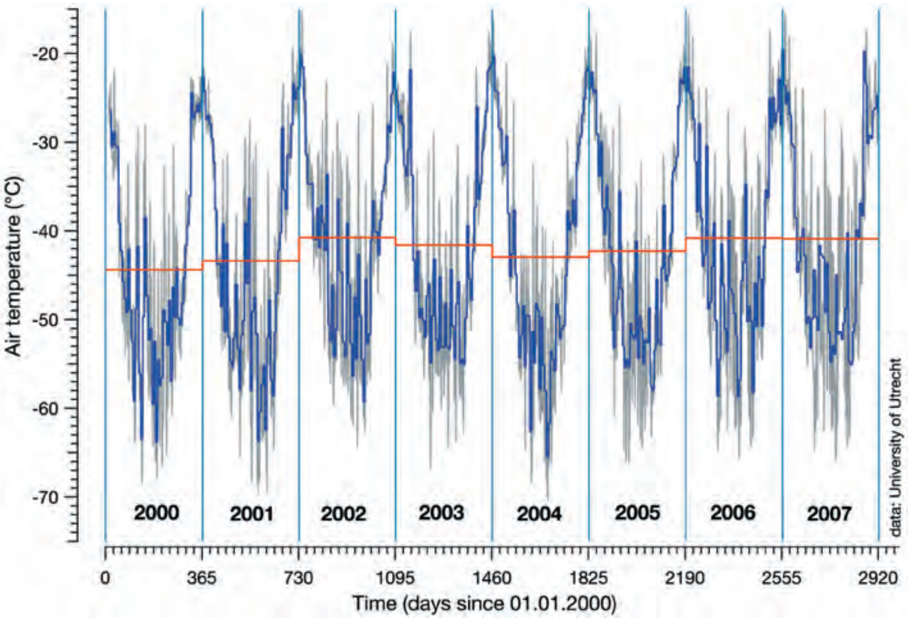



**Fig. 4:** Air temperature as measured at AWS9, 1.6 km westwards of Kohnen Station, from 2000-2007. Daily means are shown in grey, seven-days means in blue, and annual means in red. Data provided by C.H. Tjim-Rejimer & MR. Van den Broeke, University of Utrecht.

**Abb. 4:** Jahresgänge der Lufttemperatur, wie sie am Punkt AWS9, 1,6 km westlich der Kohnen-Station, im Zeitraum 2000-2007 gemessen wurden. Die Tagesmittelwerte sind grau, siebentägige Mittel blau und Jahresmittel rot dargestellt. Daten von C.H. Tjim-Rejimer und MR. Van den Broeke, Univ. Utrecht.

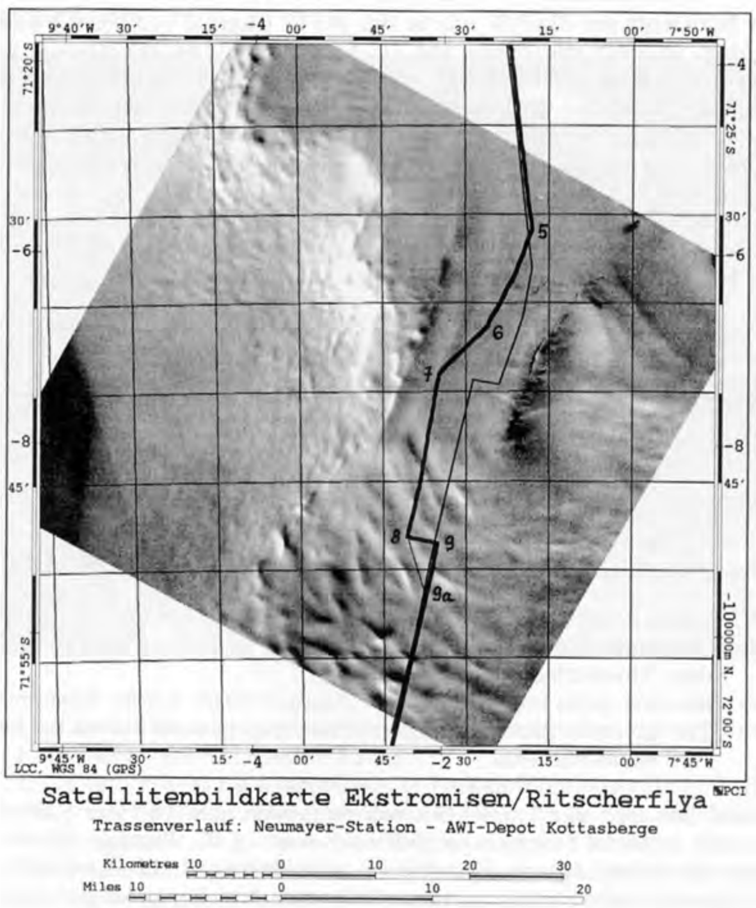



**Fig. 5:** Grounding line area of Ekströmisen (SPOT image). The thick line shows the traverse route used in 1996 and 1997; the thin line marks the former route, which is not recommended any longer. The thin line between waypoints 8 and 9a indicates the changed route of the following seasons (JOKAT & OERTER 1998).

**Abb. 5:** Gebiet der Aufsetzzone des Ekströmisen (nach SPOT-Szene). Die dicke Linie markiert die Traversenroute in den Jahren 1996 und 1997; die dünne Linie markiert den früheren Trassenverlauf, der nicht mehr zur Benützung empfohlen wird. Die dünne Linie zwischen Wegpunkten 8 und 9a markiert die Routenänderung in den nachfolgenden Jahren (JOKAT & OERTER 1998).

leads for about 120 km south across Ekströmisen to the hinge zone of the ice shelf. Further the route leads across Ritscherflya to Heimefrontfjella about 450 km south of the coast. This part of the route was established and marked with bamboo poles every 500 m for the first time in 1986. This stake line was re-established in 1995/96 and has been annually maintained since then until the season 2005/06 (Fig. 7). It has also been used for accumulation studies (ROTSCHKY et al. 2006, RICHARDSON-NÄSLUND 2004, EISEN et al. 2008). The so-called Kottas Camp, located 10 km north of Kottasberge at an altitude of 1440 m a.s.l., served as a depot for fuel and was used in the seasons 1995/96 and 1996/97 as a base for air-borne investigations further south on the inland ice. There are several nunatakker located close to the camp site with easy access, which have been used for GPS and gravity measurements. For the next 100 km south of Kottas Camp, the route climbs more

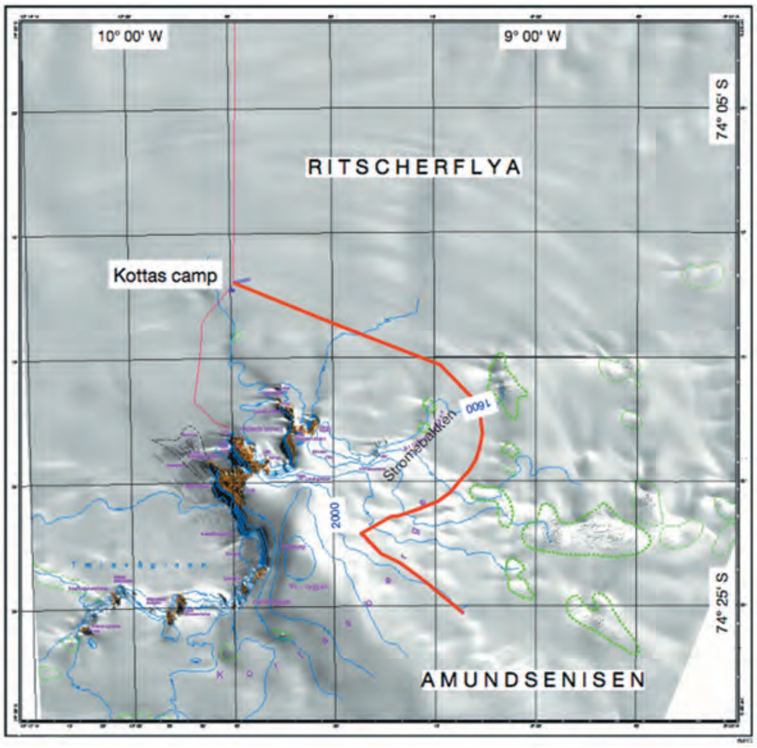



**Fig. 6:** Satellite image (SPOT) map for the area of Kottasberge, Heimefrontfjella, with the recommended traverse route (thick red line) from Kottas Camp along Strømebakken to Amundsenisen. The green lines mark heavily crevassed areas being off limits for travelling. Interval of contour lines (blue) 100 m. The 2000 m and 1600 m contours are especially labeled. After HAUSOLD (1997).

**Abb. 6:** Satellitenbildkarte (SPOT) für die Umgebung der Kottasberge, Heimefrontfjella. Die dicke rote Linie zeigt die empfohlene Traversenroute vom Kottas-Camp entlang des Strømebakken auf den Amundsenisen. Grüne Punkt-Linien kennzeichnen stark mit Gletscherspalten durchzogene Gebiete, die nicht befahren werden dürfen. Die Äquidistanz der Höhenlinien (blau) beträgt 100 m. 2000-m- und 1600-m-Höhenlinie sind gesondert beschriftet. Nach HAUSOLD (1997).

**Fig. 7:** Stop of the sledge traverse en route to Kottas Camp. In the front the Skidoo with Nansen sledges, which was used for reading the bamboo stake line between Neumayer Station and Kottasberge. (Photo G. Patzelt, 12 12 1997).

**Abb. 7:** Halt der Schlittentraverse auf der Fahrt zum Kottas-Camp. Im Vordergrund ein Skidoo mit zwei Nansenschlitten, der benützt wurde, um Akkumulationspegel (Bambusstangen) zwischen der Neumayer-Station und den Kottasbergen nachzumessen. (Foto G. Patzelt, 12.12.1997).

than 1000 m to an altitude of 2500 m a.s.l. On Amundsenisen the ice sheet surface increases only by another 400 m along the remaining 250 km to the site of Kohnen station. The overall travel distance between Neumayer and Kohnen stations is 760 km.

*Environmental evaluation*

In 1999-2000 the "Comprehensive Environmental Impact Evaluation (CEE) for Recovering a Deep Ice Core in Dronning Maud Land, Antarctica" was carried out by AWI in co-operation with the Institute for Polar Ecology, University of Kiel. The study comprises the whole activity of "Drilling a deep ice core", including the construction of a permanent camp on the inland ice, later called Kohnen Station, the drilling operation itself as well as all activities along the complete access route to the drill site. According to the Protocol on Environmental Protection to the Antarctic Treaty (Madrid Protocol) the draft CEE was made available to the public, circulated to the parties of the Antarctic Treaty and submitted to the Committee for Environmental Protection (CEP) at its meeting in The Hague September 11-15, 2000 and the following Antarctic Treaty Consultative Meeting. The final version was published on October 4, 2000. The German environmental authority "Umweltbundesamt" (UBA) approved the activity on October 6, 2000 for the period until April 2005. On March 10, 2004 the approval was extended until April 30, 2007. AWI plans to operate Kohnen Station for further 10 to 15 years. The negotiations with UBA are ongoing.

AWI TRANSPORT LOGISTICS

*Sledge traverses to Kohnen Station*

AWI has been in charge of providing the logistics for the EPICA drilling operations in DML. The gate to access the Antarctic ice sheet on ground has been the German wintering-over base Neumayer Station. RV "Polarstern" or other supply vessels have been calling at Atka Bay usually twice a year at the beginning of the austral summer season in December, and at the end in mid February to beginning of March. During the rest of the year the ice-shelf front at Atka Bay is not accessible by ship due to heavy sea-ice conditions. Fuel and heavy cargo has been shipped to Neumayer Station and transported from there by means of sledge traverses to Kohnen Station.

AWI has used track vehicles of the type Kässbohrer PistenBully to transport personnel and cargo. The PistenBully was originally designed to prepare skiing grounds in Alpine areas. For the use in Antarctica they were slightly modified and strengthened. The cargo sledges are made of steel with four skids, which can move independently from each other. The sledges are designed to load all kind of 20-feet container units (2.45 m x 6.05 m) as well as conventional cargo, e.g. boxes, drums, and other equipment. The 20-feet units accord with the ISO Norm. They are used for standard cargo, fuel and drilling liquid (tank container), food and ice cores (reefer container, heated or cooled), lab container specially prepared for scientific programmes, and units for accommodation.

Traverses have to be autonomous in terms of mobility, navigation, communication, energy, food, and medical supply. Traverses are extensive in terms of manpower, costs, and time. Therefore efforts have to be made to increase the efficiency as much as possible. Efficiency of traverses means transporting large amount of cargo (mass and volume) over long distances in short time with few personnel and low fuel consumption. AWI traverses operate with one driver per vehicle and whenever possible a cook as well as a physician. Almost all drivers are also mechanics. One of the drivers is an especially skilled person, hired from the producer of the PistenBully, the company Kaessbohrer. This way of staffing ensures that all faults that may arise will be found and can be repaired. Therefore, also a large stock of spare parts goes along with the sledge traverses. Drivers have to be able to use all capabilities of the vehicles utterly, including the GPS for navigation, and to treat the machine fairly.

With respect to the duration of the traverses, one has to avoid exhaustion of the personnel. AWI traverses normally refuel three times per day after four hours of driving each time. Refuelling five to six vehicles from one of the tank containers takes approximately 30 minutes. Tank containers have a capacity of 14.5 m³ and are equipped with filter, pump, volume gauge, and a 20-metre hose on a drum with a safety valve at the end. The pump is either working with 24 V DC from one of the PistenBullies or with 220 V AC from a generator. Another 30 minutes are taken for rest and small meals and hot drinks prepared by the cook. The fuel consumption for the transport on the route between Neumayer and Kohnen Stations is about 400 litres per one ton of payload over a distance of 1000 kilometres. This means that for each kilogram of cargo transported from Neumayer to Kohnen 0.3 litres of Arctic Diesel are needed. To travel from Neumayer to Kohnen Station takes eleven days on an average. For a typical arrangement of sledge trains see THIEDE & OERTER (2002) and FAHRBACH et al. (2003). On an average about 180 tons of supply goods had to be transferred to Kohnen Station per season to run the base. It came out that supplying Kohnen Station by surface traverses is a big effort compared with construction works and running the base.

*Aircraft support*

Since the Dronning Maud Land Air Network (DROMLAN) was established in 2002 (GERNANDT et al. 2006), another gate to Antarctica was opened with the airfield adjacent to the Russian base Novolazarevskaja. The runway is in operation during the austral summer season except for January, when melting occurs and the runway cannot be used for heavy aircraft like the Iljushin 76TD. Since 2005/06 also the runway of the Norwegian base Troll has been used for intercontinental flights, especially in January. DROMLAN offers feeder flights within DML from the Novolazarevskaja and Troll airfields. The air link is used mainly for the transport of personnel and light weighted cargo.

The snow runway is 1200 m long and orientated 065°/245°. The extends from 74°0.037'S, 0°1.995'E to 74°59.742'S, 0°4.272'E. AWI's aircrafts of the type Dornier 228-110 and Basler BT67 transfer personnel and small amount of cargo between Kohnen and Neumayer and other stations. An advantage of this aircraft access is that it became possible to start early in the season before the sledge traverse from Neumayer Station had arrived or to carry out a short season with maintenance of the base without traverse support, as it was done in January-February 2008 (Fig. 8). All ice cores of the EDMLcore were flown to Neumayer Station, because aircraft transport is a much more careful treatment of the valuable ice cores than sledge transport across the snow surface, which is some times very rough, especially along the lower parts of the traverse route.


**Fig. 8:** DROMLAN aircraft Basler BT67 in front of Kohnen Station. The base was not in operation prior to the arrival of the AWI team on board the aircraft. In the background on the left, the blue container with the automatic aerosol-sampling device is visible. (Photo H. Oerter, 08 01 2008).

**Abb. 8:** Ein DROMLAN-Flugzeug vom Typ Basler BT67 vor der Kohnen-Station. Die Station war zwei Jahre still gelegen und wurde vom AWI-Team an Bord des Flugzeuges wieder in Betrieb genommen. Im Hintergrund links ist der blaue Container der automatischen Aerosolsammelstation zu erkennen. (Foto H. Oerter, 08.01.2008).

## CONSTRUCTION AND OPERATION OF KOHNEN STATION

### *Construction of the base*

First considerations about the design oft the drill camp were made in 1999 (DRÜCKER et al. 2002). The main aspects to be considered for this new summer camp, which has to operate as a base for the deep drilling activity, were:

- The camp has to give full support to the ice-core drilling operation.
- The construction of the camp and the following yearly

supply will primarily be done by traverses with additional aircraft support.

- The camp has to accommodate 20 persons permanently during the drilling season with additional short-term accommodation for up to 5 to 7 persons.
- Energy has to be provided for the camp including drilling and scientific activities.
- Mass and volume of all building material has to be as low as possible for transportation.
- The impact to the environment due to transport, construction and operation of the camp has to be as low as possible.
- Only a short time window is available for the construction work.
- The construction has to be simple and reliable so that it withstands the given climatic conditions at the construction site.
- Deep drilling should start in the austral summer season 2001/2002 and will take three to four summer seasons.

The central building was designed as a steel platform on 16 pillars with eleven 20-feet ISO-Norm containers on top of it (Fig. 9).

Kohnen Station was constructed in the two austral summer seasons 1999/2000 (THIEDE & OERTER 2002) and 2000/2001 (FAHRBACH et al. 2003). For this, in the first season two traverses transferred 220 tons of material from Neumayer Station to the construction site. However, 30 % of this mass was fuel for the track vehicles and for the energy supply of the camp. In the first season the complete steel platform with the first seven containers (radio room, mess room, kitchen, bathroom, and sleeping rooms) were erected (Fig. 9). Ground pressure under the footplates was designed to be about 0.4 kg cm$^{-2}$, which is roughly only double the pressure of a person with 85 kilograms and German shoe size of 44. The snow underneath the foot plates was blown with a snow blower into a 15 cm high wooden formwork levelled horizontally. All 16 foundations were levelled within ±0.5 cm. After one night the snow got hard enough to put the plates on it (Fig. 10). These first seven containers had been part of the former Filchner Station, which was salvaged in February 1999 from a floating iceberg (FAHRBACH & EL NAGGAR 2001).

In the second season again two traverses supplied Kohnen camp with 187 tons of material to complete the platform and

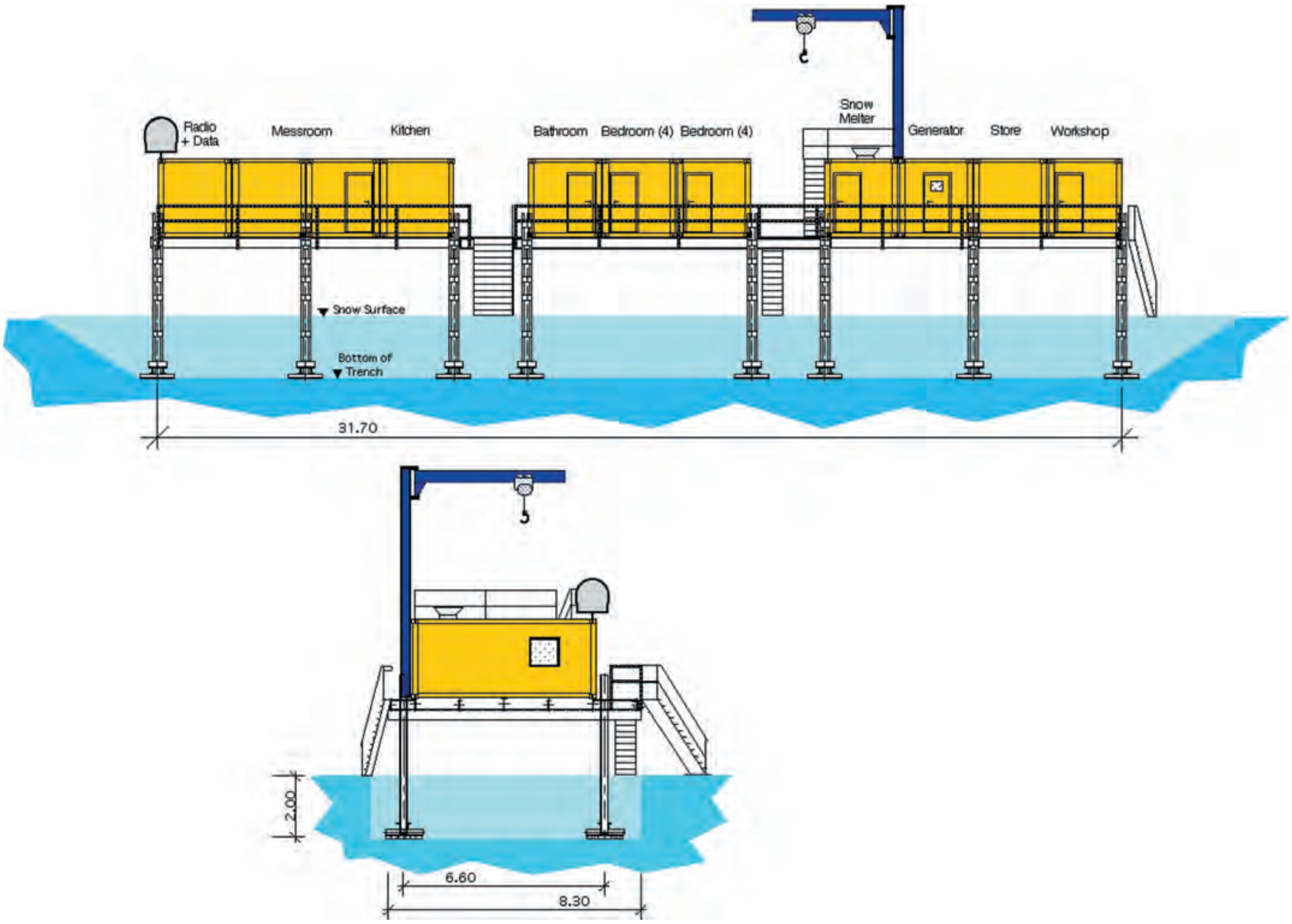



**Fig. 9:** Kohnen Station in longitudinal view (top) and gable view (bottom) of the container platform. The sketch shows also the foundation of the platform pillars. Using of the different containers is indicated: Radio & data transfer, mess room, kitchen, bathroom, two bedrooms, snow melter, generator, store, and workshop. The snow melter can be filled via an opening in the roof. For this purpose big bags with snow are lifted by the crane above the opening, where they get emptied.

**Abb. 9:** Schema der Kohnen-Station in Frontansicht (oben) und Giebelansicht (unten). Die Zeichnung zeigt auch die Gründung der Stützen, auf denen die Plattform ruht. Über den Containern ist der jeweilige Verwendungszweck angegeben: Funk und Datenübertragung, Messe, Küche, Waschraum, zwei Schlafräume, Schneeschmelze, Generator, Ersatzteillager, Werkstatt. Die Schneeschmelze wird über einen Trichter auf dem Dach befüllt. Dazu wird mit dem Kran ein mit Schnee gefüllter Sack über die Station gehievt und entleert.

**Fig. 10:** Kohnen Station under construction. The excavation for the 16 pillars and the steel platform was 2 m deep (cf. Fig. 9). Some of the footplates under the pillars are already covered with snow by means of a small snow blower. Later the whole excavation was filled completely with snow. (Photo H. Oerter, 06 01 2000).

**Abb. 10:** Kohnen-Station im Bau. Die Baugrube für die 16 Stützen und die Stahlplattform war 2 m tief (vgl. Abb. 9). Die Fußplatten unter den Stützen im hinteren Teil sind bereits mit Schnee abgedeckt. Später wurde die ganze Baugrube mit einer Schneefräse komplett mit Schnee verfüllt. (Foto H. Oerter, 06.01.2000).

to build the trench. In this season the missing four containers (snow melter, power supply, store, and workshop) were added on the platform.

**Fig. 11:** Jacking up of the platform of Kohnen Station by winches mounted on top of the extended pillars. Each synchronous turn of the winches lifts the platform by three millimetres. (Photo H. Oerter, 18 01 2008).

**Abb. 11:** Anheben der Plattform der Kohnen-Station mit handbetriebenen Schleusenwinden. Die Winden wurden auf die Verlängerungselemente der Stützen aufgesetzt. Eine synchrone Umdrehung aller Winden hebt die Plattform um drei Millimeter. (Foto H. Oerter, 18.01.2008).

Inauguration of Kohnen Station was celebrated on January 11, 2001. The base was named Kohnen Station to commemorate the late Heinz Kohnen (* 05 Feb. 1938 in Oberhausen, † 25 July 1997 in Nienberge nearby Münster), who was the first head of the logistics department of AWI. Heinz Kohnen strongly promoted EPICA from the very beginning.

AWI is experienced in building, running, maintenance, and

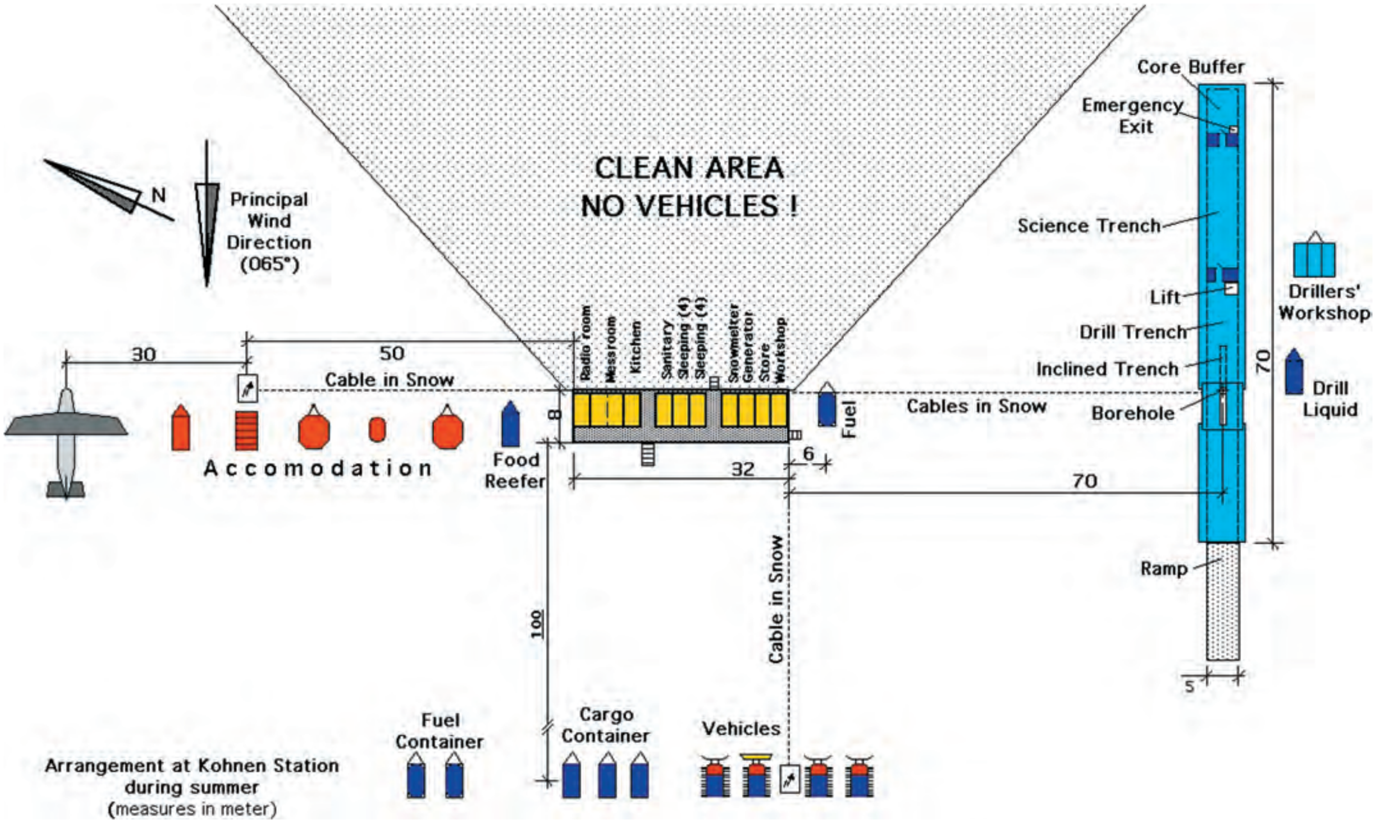



**Fig. 12:** Layout of the EPICA drill camp with Kohnen Station during drilling operations.

**Abb. 12:** Lageplan des EPICA-Bohrcamps mit der Kohnen-Station während der Zeit von Bohraktivitäten. Maßangaben in Metern.

removal of this kind of construction that had been used as a summer camp on the Filchner-Ronne Ice Shelf before (FAHRBACH & EL NAGGAR 2001). The platform with the container modules on top has to be jacked up according to the snow accumulation at the campsite. The mass that has to be lifted by manpower with mechanical jacks is about 69 tons (Fig. 11). Due to the lower accumulation and lower wind speeds on the Amundsenisen compared to the Filchner-Ronne Ice Shelf the maintenance interval at the drilling site was expected to be much lower than for the Filchner Station. In 1999/2000 the platform was approximately 2 m above the undisturbed snow surface. The pillars were extended by 1.2-metre pieces in January 2005 and 2008. The platform was jacked up in January 2003 by 0.5 m, in January 2006 by 0.23 m and in January 2008 by 0.76 m. This sums up to 1.79 m, in total.

Settling of the platform is not uniform. It is larger in the middle of the platform than on the peripheral ends. In January 2008 the pillars deviated by 7.0 ±4.6 cm from a common zero level. These small deviations could be almost completely levelled when the platform was jacked up. The remaining deviations were only 2.8 ±1.6 cm.

As the central building on the platform offers only eight beds for accommodation, additional housing was designed as mobile units according to the needs during the drilling operation. For the complete camp layout including the trench see Figure 12.

### *Construction of drill and science trench*

After the base was finished, construction of the drill and science trench started immediately (FAHRBACH et al. 2003). The building for drilling and *in situ* measurements on the ice core was designed as an excavated trench in the natural snow (Fig. 13) with a wooden floor and a wooden roof on top. For drilling and investigations on the ice core it was important to have low and constant temperatures in this building. Therefore it was decided to build the trench deeper than it was done by similar constructions on the Greenland Ice Sheet.

A trench 66 m long, 4.8 m wide, and 6 m deep (1900 $m^3$ of snow) was excavated with a Yanmar snow blower and covered with a wooden roof (Fig. 14). The topping-out ceremony was celebrated on January 24, 2001 (Fig. 15). In the 2004/05 summer season the trench was elongated by another 12.5 m. The trench was divided by 2.5 m thick plywood walls filled with snow into three sections for drilling (Fig. 16), for science (Fig. 17), and for temporary core storage (core buffer, Fig. 18). Wooden beams were mounted into the floor as foundation for the drill tower and the winch together with the frame and cover for the so-called inclined trench. This trench is needed to give

**Fig. 14:** Drill and science trench under construction: After the trench was excavated, it was covered with a wooden roof. The roof rests on wooden beams on top of compacted snow (see Fig. 13). On the ground of the six metres deep trench one recognizes the wooden foundation for the winch and the drill tower. (Photo H. Oerter, January 2001).

**Abb. 14:** Bohr- und Wissenschafts-Graben im Bau: Nachdem der Graben ausgefräst worden war, wurde er mit einer hölzernen Dachkonstruktion eingedeckt. Das Auflager des Daches besteht aus künstlich verdichtetem Schnee und darauf liegenden Holzbalken (vgl. Abb. 13). (Foto H. Oerter, Januar 2001).

**Fig. 15:** Construction of drill and science trench: Topping-out ceremony on January 24, 2001. Sitting (from left): Jan Igel, Claudia Piel, Olaf Eisen, Holger Wohltmann, Michael Pelz. Standing: Günter Stoof, Guido Kleffel, Adi Ackermann, Eberhard Kohlberg, Lutz Reise, Sverrir Æ Hilmarsson, Cord Drücker, Hans Oerter. (Photo C. Drücker/H. Oerter).

**Abb. 15:** Bau des Bohr- und Wissenschaftsgrabens: Richtfest am 24. Januar 2001. Sitzend (von links): Jan Igel, Claudia Piel, Olaf Eisen, Holger Wohltmann, Michael Pelz. Stehend: Günter Stoof, Guido Kleffel, Adi Ackermann, Eberhard Kohlberg, Lutz Reise, Sverrir Æ Hilmarsson, Cord Drücker, Hans Oerter. (Foto: C. Drücker/H. Oerter).

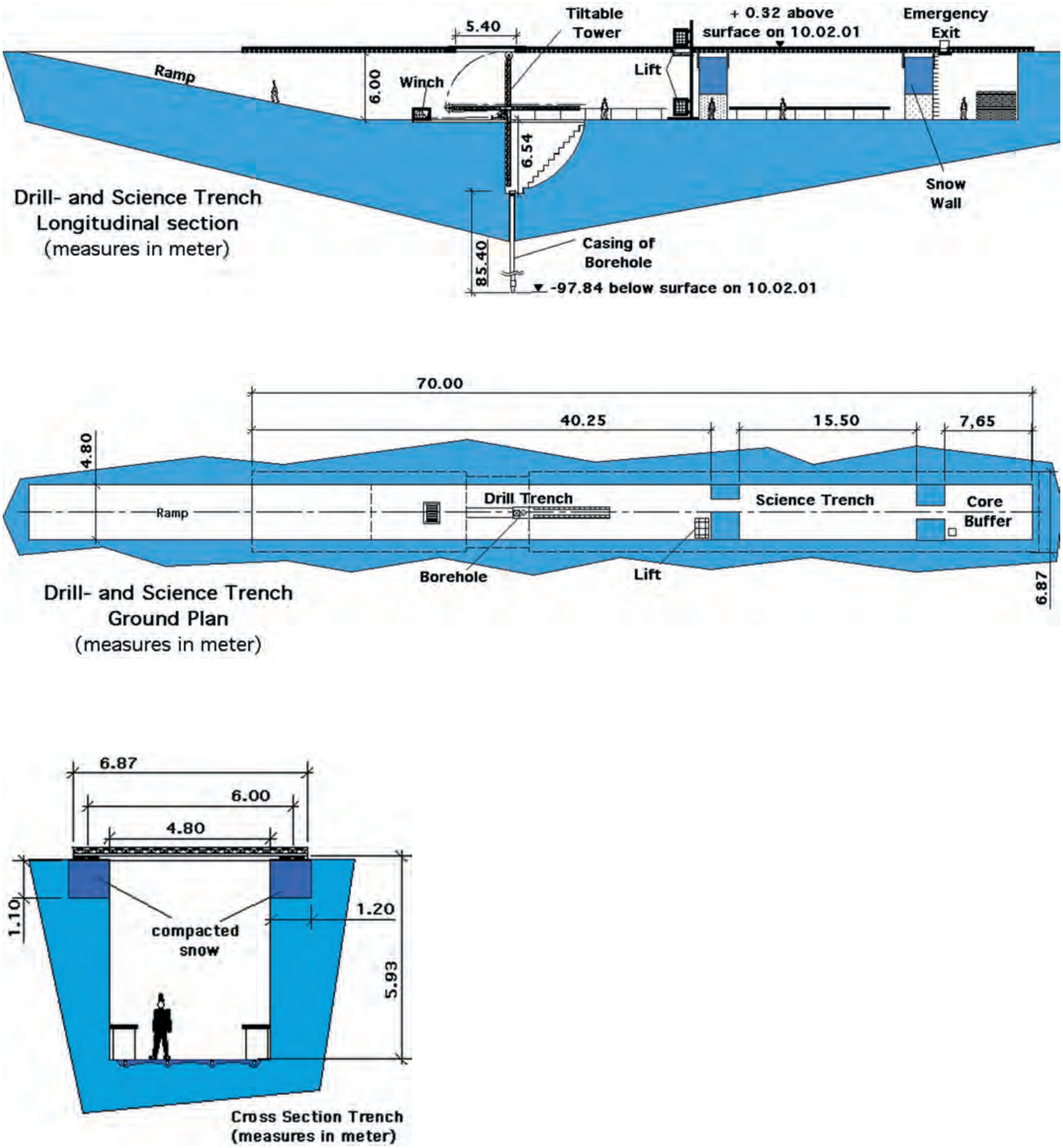



**Fig. 13:** EPICA drill and science trench at Kohnen Station: Top = longitudinal section. Middle = ground plan. Bottom = cross section.

**Abb. 13:** Bohr- und Wissenschafts-Graben *(drill und science trench)* der EPICA-Bohrung an der Kohnen-Station. Oben = Längsschnitt. Mitte = Grundriss. Unten = Querschnitt (alle Maße in m).

**Fig. 16:** View of the drill trench at Kohnen Station during drilling operation. The twelve metres long swivelling drill tower (the lower six metres are not visible) in the middle is standing upright and a new drill run just started. The last cover of the six metres deep inclined trench is getting closed. After the run it will be opened again to allow the tower to be tilted horizontally for taking out the core barrel. On the left, one can see the heated driller's hut with the control and steering device inside. At the beginning of a run the drill is steered via a remote control outside the hut. The winch with 3500 m of coaxial cable is visible behind the tower. The floor of the trench is covered by wood. Along the wall there are wooden tables on which the core barrel is placed for taking out the ice core. A special device (partly visible in the foreground center) with a small winch was constructed to pull out the core barrel from the outer tube, which some times got stuck very heavily. Air temperature inside the trench was around -30 °C. (Photo H. Oerter, 12 12 2005).

**Abb. 16:** Blick in den Bohr-Graben an der Kohnen-Station während der Bohrarbeiten. Der zwölf Meter lange, schwenkbare Bohrturm (die unteren sechs Meter sind nicht sichtbar) in der Mitte steht momentan senkrecht, da der Bohrer ins Bohrloch gefiert wird. Die letzte Abdeckung des noch unter dem Boden liegenden sechs Meter tiefen, schrägen Grabens (inclined trench) wird gerade geschlossen. Wenn der Bohrer gehievt wird, wird die Abdeckung wieder geöffnet, um den Bohrturm umlegen und das Kernrohr entnehmen zu können. Links sieht man die geheizte Hütte für das Bohr team, in der auch die Kontroll- und Bedieneinheit des Bohrers untergebracht ist. Am Beginn des Fierens und am Ende des Hievens kann der Bohrer – wie im Bild zu sehen – auch über eine tragbare Fernbedienung gesteuert werden. Die Winde mit 3500 m Koaxialkabel ist hinter dem Bohrturm erkennbar. Der Bohr-Graben hat einen Holzfußboden. Entlang der Wände stehen hölzerne Arbeitstische, auf die das Kernrohr zum Entleeren abgelegt wird. Um das Kernrohr leichter aus dem Hüllrohr ziehen zu können, wurde eine spezielle Vorrichtung mit einer kleinen Handwinde gebaut (im Vordergrund in der Mitte gerade noch erkennbar), da das Kernrohr manchmal extrem fest im Hüllrohr sitzt. Die Raumtemperatur im Bohr-Graben lag bei etwa -30 °C. (Foto H. Oerter, 12.12.2005).

room for the drill tower when it is tilted from the horizontal to its vertical position. Access to the trench for persons and material was given by a ramp at one end of the trench and by a lift in the middle. At the other end an emergency exit via a ladder was installed. Building the trench consumed about 25 tons of construction material for roof, floor, and the basic installations. The trench and the generator on the platform were linked by three power cables separately for drill trench, winch, and science trench. In addition, a fibre-optic cable for data transfer linked the trench with the radio room on the platform. In the first drilling season 2001/02, an additional cave was excavated at the end of the core buffer with a small heated hut. This hut had been used as Continuous Flow Analysis (CFA) lab at the NorthGRIP drilling site in Greenland before. The cave was used for the field investigation of physical properties on thick and thin sections. The ice samples and the microscope were standing in the cold environment whereas the computer was standing in the heated cell.

After the trench was finished, the dry access hole was drilled down to a depth of 98 m below the bottom of the inclined trench (113 m below the original snow surface) and the hole was cased (Fig. 19). A casing is necessary to prevent the drilling liquid from penetrating into the porous firn in the upper part of the ice body.

## THE SCIENTIFIC PROGRAMME

### *Drilling the ice core*

#### Drilling equipment

The drilling equipment inside the drill trench (Fig. 16) consisted of the 12 m long drill tower, the winch including motor and brake and the heated driller's hut, as well as electrical installations, tables and pullout table for the core barrel. The drill trench was also equipped with an air ventilation system. A railway system connected the drill trench and the core buffer to guarantee a safe transport of the ice cores inside the trench.

**Fig. 17:** View into the science trench. The band saw on the left side was used to cut the core in 1-m-pieces, which thereafter were measured by DEP. The person in the red clothing is wrapping the core piece for DEP, while the other is observing the measurement. The white PP-foam boxes are used for storage and transportation of the 1-m-pieces, six of them are fitting in one box. (Photo H. Oerter, 23 12 2005).

**Abb. 17:** Blick in den Wissenschafts-Graben. Mit der Bandsäge auf der linken Seite werden die gebohrten Eiskerne jeweils auf einen Meter abgelängt. An diesen 1-m-Stücken wird dann die elektrische Leitfähigkeit des Eises mit DEP gemessen. Die Person mit rotem Parka wickelt die Kernstücke zur Vorbereitung der nächsten Messung in dünne Haushaltsfolie ein, während die andere die laufende Messung kontrolliert. In den weißen Kisten aus Polypropylen werden die Eiskerne gelagert und transportiert. Jeweils sechs 1-m-Stücke passen in eine Kiste. (Foto H. Oerter, 23.12.2005).

**Fig. 18:** View into the core buffer after drilling operation was finished. The shelf with the core troughs was used for temporary core storage, especially when drilling the so-called brittle zone to allow the cores to get adjusted to the temperature and air pressure in the science trench. On the left, the entrance to the ice cave for the investigation of physical properties is visible. (Photo H. Oerter, 29 01 2008).

**Abb. 18:** Blick in das Zwischenlager für die Eiskerne nach Abschluss der Bohrarbeiten. In dem Regal wurden die Eiskerne nach dem Bohren in Kerntrögen gelagert, bevor sie zersägt wurden. Eine Ruhephase zur Adaption an Raumtemperatur und Atmosphärendruck war besonders für die Kerne aus der so genannten brittle zone wichtig, da sie sonst beim Sägen zu leicht zersprungen wären. Links führen einige Stufen in die Eiskaverne, in der physikalische Eigenschaften des Eises, möglichst ungestört, untersucht wurden. (Foto H. Oerter, 29.01.2008).

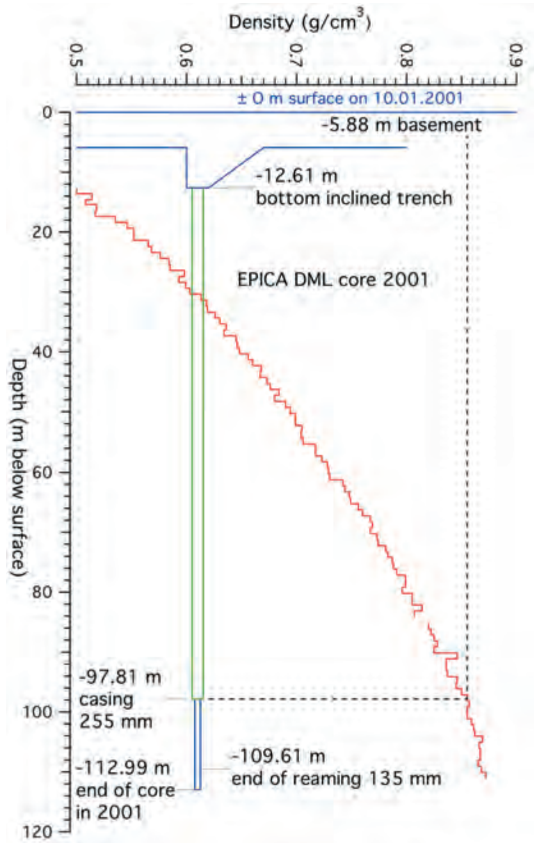



**Fig. 19:** Cross section through drill trench and cased borehole of the EDML core with density profile. All measures are given in reference to the snow surface on 10 January 2001.

**Abb. 19:** Querschnitt durch den Bohr-Graben und den verrohrten Teil des Bohrlochs des EDML-Bohrkerns. Alle Höhen- bzw. Tiefenangaben beziehen sich auf die Schneeoberfläche am 10. Januar 2001.

Specially designed metal core troughs were used for temporary core storage. Outside the trench, the driller's workshop was established in a container. It had facilities for various kinds of mechanical work on the drill, including a lathe and milling machine.

The drill is a common design that was used for the NorthGRIP and EPICA drilling operations (AUGUSTIN et al. 2007a). The down-hole unit is lowered and hoisted with a 3500 m long 7.29 mm armoured steel cable (Rochester Culpeper, VA, USA 2-H-287D) on a winch (Lebus International Engineers Ltd., Sittingbourne, England). Besides the mechanical connection, the coaxial cable provides the electrical connection for powering the down-hole unit at 380 V DC with a modulated 600 baud modem signal for communication between the surface control and the down-hole pressure section. The pressure section is a 1.4 m long and 114 mm wide stainless steel tube in non-magnetic grade with an inner diameter of 100 mm. The electronics is modularly mounted into the tube, consisting of the following modules (from the lower end): a motor (Parvalux) and gear reducer (Harmonic Drive) section with a drive shaft, a power supply with AC-DC converters (VICOR 380 V to 48 V), a microcontroller section (TERN AE machine), a modem section, and a top plug. The top plug is the mechanical and electrical connection to the so-called anti-torque section by standard marine connectors (Seacon). The cable's end is fixed in the anti-torque section with a commercial cable termination (Evergrip). The conductors of the cable are connected to the electronics section with standard marine connectors (Seacon).

During operation, the microcontroller receives commands through the cable from the surface modem and transmits approximately four times per second the most important status parameters, e.g. temperatures at different locations inside the drill electronics, pressures in expansion volumes to check for leakage of the high pressure seals, motor status and inclination of the drill. Besides the connection of the electronics to the cable, the anti-torque section transfers the torque of the rotating drill head for provision of the cutting force into the wall through three blades made from spring steel that hold onto the borehole wall.

The above-described electronics section powers the mechanical section of the drill that is in total 8 m long. Together with the electronics section and the anti-torque section, the 12 m long drill rests on a tipping tower (Kaba-Gilgen) while it is on the surface for core retrieval, cleaning, and maintenance. To lower the drill into the hole, the tower is erected, so that the drill is hanging free over the hole on the cable and can be lowered into the hole by paying out cable from the winch. Depending on the drilling depth, the travel for down to the bottom of the almost 3000 m deep hole or up to the surface takes up to 45 minutes. Together with drilling for up to more than 30 minutes a run at the bottom of the hole can easily exceed two hours.

The mechanical section consists of a drill string that is pulled out of the 8 m long outer tube for surface handling of the drill. The lower part of the drill string is the 4 m long core barrel with the drill head. For retrieving the core, the core barrel is detached from the chip chamber shaft on top, where the cuttings are filtered from the circulating borehole liquid and stored for retrieval.

During drilling, the motor shaft of the electronics section rotates the chip-chamber shaft that moves a piston pump by the rotary action so that the drill liquid is circulated. The chip chamber shaft also rotates the core barrel below. The drill head at the lower end of the core barrel is equipped with cutters that cut a ring with 129.6 mm outer and 98 mm inner diameter The generated cuttings are removed from the drill head area with the chip-laden liquid between the core barrel and the outer tube, to press it into the chip chamber, where the cuttings are retained by meshed filters. While cutting proceeds, the central core cylinder of the ring moves into the core barrel. After an ideally approximately 3 m-depth increment, the core will be broken by pulling up the drill with the winch. Simultaneously, little core catchers get engaged in the drill head that wedge into the ice and break the core. The average force for breaking the core increased with rising temperatures at greater depth (Wilhelms et al. 2007).

## Drill fluid

The drill fluid was a mixture of petroleum oil D40 and Forane F141b (Alemany & Mityar 2007). D40 was transported in tank containers (15 $m^3$ each) to the drill site whereas the F141b was transported and stored in drums. Tank container and drums were standing at the snow surface beside the trench. They were connected by hoses to a big barrel in the trench, in which the drilling fluid was mixed to the right density. The barrel itself was connected directly to the borehole. After each run the recovered drill chips soaked with drilling fluid, were dried in a spin-drier to recover as much fluid as possible. In total 32 $m^3$ of D40 and 13.9 $m^3$ of F141b were used for the whole drilling operation. After the drilling was finished the liquid level in the borehole was at 67 m below the head of the casing to prevent the borehole from closing due to the hydrostatic pressure of the ice. Thus, further access to the borehole is ensured.

## Drilling operations

According to the proposed time schedule wet drilling started in the season 2001/2002 and continued through four austral summer seasons (no drilling in 2004/05) until January 16, 2006, when the borehole had reached the final depth of 2774.15 m (total core length) below snow surface.

However, in the season 2001/2002 the EPICA operation had experienced a considerable delay caused by very difficult sea-ice conditions that did not allow RV "Polarstern" to reach the ice shelf edge near Neumayer Station as planned. The last 30 miles were extremely problematic so that offloading operations were started with ten days delay on December 21, 2001. At December 26 the first traverse left Neumayer Station with seven sledge trains and ten persons. It reached Kohnen Station at noon of January 4, 2002. Camp was opened without problems and on January 6 twelve more persons were flown from Neumayer to Kohnen Station. The period January 7-24, 2002 had to be used to install the drilling equipment inside the trench (Fig. 16). Parallel to the installations in the drill trench also the science trench and core buffer as well as the cave for physical properties were equipped with a shelf system, tables, saws, the DEP device, microscopes, and microtomes.

Deep drilling started on January 25, 2002. On top of the first core, there were 5.5 cm with a diameter of 3 inches, which had already been drilled with the access hole (Fig. 19) but not removed in the year before. Thus the main EDML core is the direct continuation of the core from the dry access hole. The progress of drilling the EDML core is shown in Figure 20. Drilling stopped on February 12, 2002. Total core production in this season was 337.3 m, the logging depth reached 450.9 m (Fig. 20).

In the 2002/03 summer season, drilling went quite smoothly. At the end of the season, on February 9, a logging depth of 1564.5 m was reached. Total core production in this season was 1114 m (Fig. 20).

In the 2003/04 season the drilling and science personnel came with DROMLAN from Cape Town to Novolazarevskaja by IL76-TD aircraft and from there directly to Kohnen Station by the AWI Dornier-228 aircraft (December 2-4). Cargo was transferred from Novolazarevskaya to Kohnen by BAS Twin-Otter. The camp had already been opened by the logistics team one week in advance before the drilling team arrived on December 3, 2003. Thus, the camp was already in full operation and core recovery started as early as December 9. Drilling continued until February 8, 2004 when the logged depth of

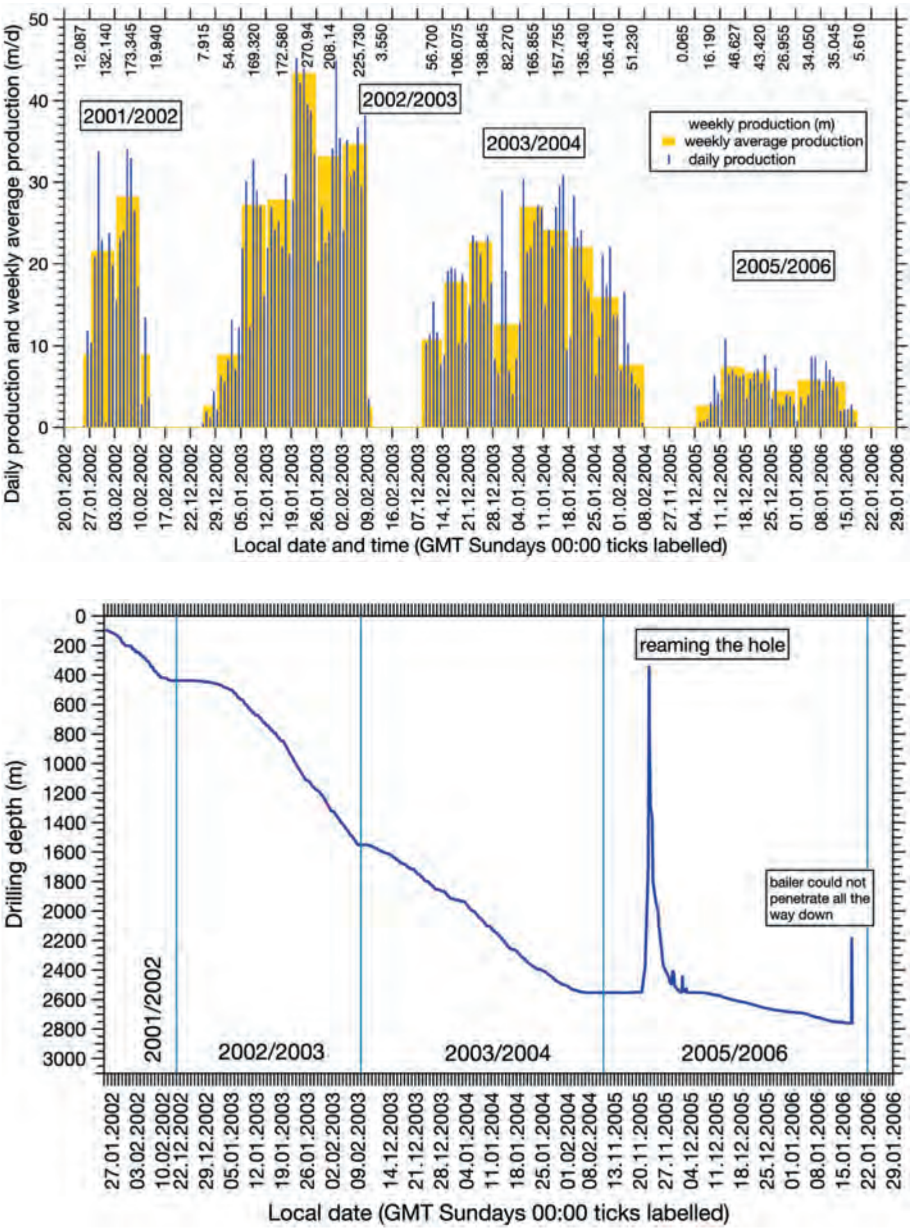



**Fig. 20:** Progress of drilling the EDML ice core. Top = Daily and weekly production rates for the four drilling seasons. The sticks (blue) give the daily production, while the bars (yellow) give the daily production averaged over one week. The total core production of the week is provided as a figure on top of the graph. Bottom = The penetration of the drill. Given is the final depth of the respective runs.

**Abb. 20:** Fortschritt beim Bohren des EDML-Eiskerns. Oben = Die täglichen und wöchentlichen Eiskernproduktionsraten in den vier Bohrsaisons. Die Linien (blau) geben die täglichen Raten, die Balken (gelb) die über eine Woche gemittelten täglichen Produktionsraten wider. Die Zahlenwerte des Gesamtkerngewinns pro Woche sind oben im Diagramm angegeben. Unten = Der Bohrfortschritt während der Bohrzeit. Angegeben ist die jeweilige Endtiefe eines Kernhols.

2565 m was reached. Total core production in this season was 1001 m (Fig. 20).

In the 2004/05 season, no drilling activities took place. The work done in this season was maintenance of trench and base.

In the last drilling season 2005/06 drilling and science personnel again came with DROMLAN from Cape Town to Novolazarevskaja by IL76-TD aircraft and from there directly to Kohnen Station by Basler BT67 aircraft (November 10-12). The camp had been opened by the logistics team on November 6 and thus, was already in full operation on arrival. Drilling activity started with logging of the borehole, re-spooling of the drilling cable, reaming the borehole, and carrying out filter runs. Successful core recovery started on December 6 (Fig. 20). Coming closer to bedrock drilling became more difficult due to warm ice under high pressure (AUGUSTIN et al. 2007b). The final depth of 2774.15 m was reached on January 16, 2006. The end of the drilling was caused by subglacial water entering into the borehole. The drilling team of the last season, who was very happy with the successful finish of this operation, is shown in Figure 21.

*Ice-core processing*

The principal idea of how to deal with the scientific measurements at the EDML ice core was to do as little as needed in the field and retrograde the complete core to Bremerhaven. The 1-m-core pieces were packed in insulated PP-foam boxes, 6 m in each box summing up to a weight of the boxes of 48 kg in the deeper parts of the core, below the firn – ice transition. The filled boxes were flown to Neumayer Station. There, they were stored into reefers. The reefers were shipped to Cape Town by RV "POLARSTERN" or another supply vessel and from Cape Town by a commercial cargo vessel to Bremerhaven. The AWI cold lab at Bremerhaven (Fig. 22) should then be the place for core processing and a commercial cold storage the place to archive the core samples. In the science trench of Kohnen Station the core was logged and cut into 1-m pieces. After-

**Fig. 21:** Group potrait of the international drilling team on the occasion of the end of the EDML deep ice-core drilling. The drill is completely iced-up when it was in contact with the subglacial water in the lowermost part of the borehole. The Team: Karin Weiler (Switzerland), Tobjörn Karlin (Sweden), Sepp Kipfstuhl, Jens Köhler, Birthe Twarloh, Fernando Valero, Sergio Faria, Gunter Lawer, Dorothee Dick, Anja Lambrecht, Diedrich Fritzsche, Frank Wilhelms, Klaus Trimborn, Heinz Miller, Hans Beiersdorf, Johannes Freitag, Patrik Kaufmann (Switzerland), Jochen Krischat, Marc Blattner, Andreas Frenzel, Adi Ackermann, Cord Drücker, Hans Oerter, Gerit Birnbaum, Andreas Brehme, Günter Stoof. (Photo S. Kipfstuhl, 17 01 2006).

**Abb. 21:** Gruppenbild des internationalen Bohrteams nach Abschluss der tiefen EPICA-Eiskernbohrung. Der Bohrer ist komplett vereist, nachdem er Kontakt mit dem subglazialen Wasser im untersten Bereich des Bohrlochs hatte. Das Bohrteam, zu sehen sind: Karin Weiler (Schweiz), Tobjörn Karlin (Schweden), Sepp Kipfstuhl, Jens Köhler, Birthe Twarloh, Fernando Valero, Sergio Faria, Gunter Lawer, Dorothee Dick, Anja Lambrecht, Diedrich Fritzsche, Frank Wilhelms, Klaus Trimborn, Heinz Miller, Hans Beiersdorf, Johannes Freitag, Patrik Kaufmann (Schweiz), Jochen Krischat, Marc Blattner, Andreas Frenzel, Adi Ackermann, Cord Drücker, Hans Oerter, Gerit Birnbaum, Andreas Brehme, Günter Stoof. (Foto S. Kipfstuhl, 17.01.2006).

**Fig. 22:** View into the cold lab of AWI at Bremerhaven, where ice-core processing of the EDML core took place. Processing – at an average temperature of -20 °C – starts on the left side, where the cores are cut by the horizontal saw. For the cuts perpendicular to the core axis several other saws, e.g. on the right side, are available in the cold lab. In the middle of the room the cores are scanned on a bench with a moving line-scan camera. (Photo H. Oerter).

**Abb. 22:** Blick in das große Eislabor des AWI in Bremerhaven, in dem der EDML-Eiskern – bei einer Raumtemperatur von etwa -20 °C – prozessiert wurde. Der Arbeitszyklus beginnt auf der linken Seite, wo die Kerne zuerst mit einer Horizontalsäge der Länge nach geteilt werden. Für die weiteren Schnitte, senkrecht zur Kernachse, stehen weitere Sägen zur Verfügung, die z.B. auf der rechten Seite zu sehen sind. In der Mitte des Raumes werden die Kerne mit einer Line-Scan-Kamera, die auf einem Schlitten über den Kern fährt, abgelichtet. (Foto H. Oerter).

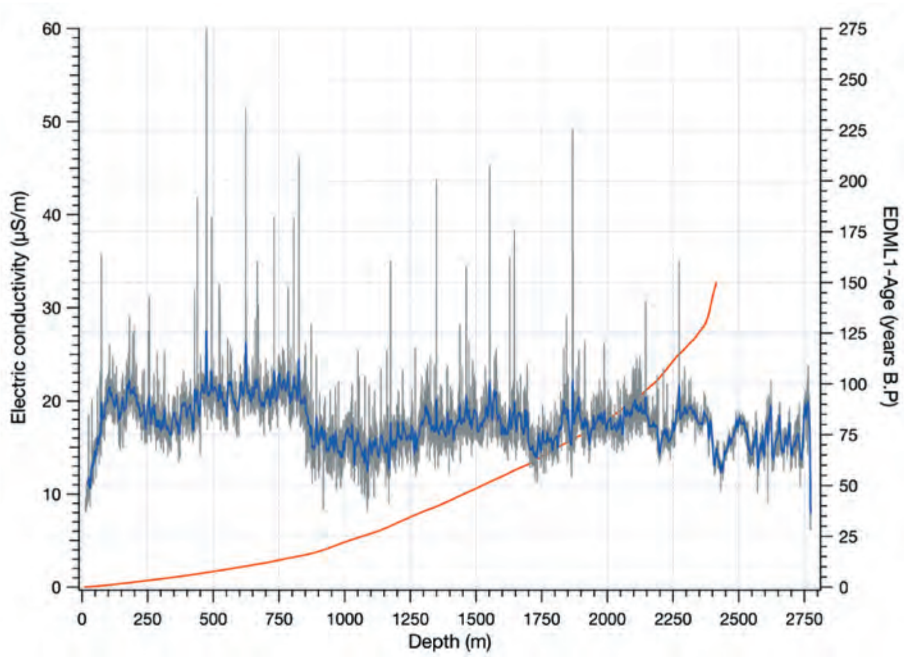



**Fig. 23:** Profile of the electric conductivity of the EDML ice core as measured by DEP in the science trench at Kohnen Station. Shown are temperature corrected (-20°C) values. Breaks were not removed. The data are sampled to 0.5-m intervals (grey). The smoothed curve (blue) shows moving averages over 10 m.

**Abb. 23:** Tiefenprofil der elektrischen Leitfähigkeit des EDML-Eiskerns, wie es mit der DEP-Methode im Wissenschafts-Graben an der Kohnen-Station gemessen wurde. Dargestellt sind die auf eine Temperatur von -20°C korrigierten Messwerte, ohne Korrektur der Brüche. Die Werte wurden auf 0,5-m Intervalle interpoliert (grau). Die geglättete Kurve (blau) ist ein gleitendes Mittel über 10 m. Die rote Kurve zeigt die Alters-Tiefen-Beziehung (EDML1 Altersmodell, Ruth et al. 2007).

wards dielectric profiling (DEP) was done along the entire core. DEP is a non-destructive measurement (WILHELMS et al. 1998). The DEP measurements gave the first data set to identify varying chemical composition and were thus a first tool for a rough dating of the ice core (Fig. 23).

Every 10 m a 1 cm thick slice was cut parallel to the core axis for investigation of the physical properties by means of thick and thin sections (KIPFSTUHL et al. 2006). This was done in order to have the core samples as fresh as possible. Later re-measurements at home might show any changes of the ice structure due to aging of the ice.

Representatives of each lab of the EPICA partners met at Bremerhaven for the ice-core processing to cut the core according to an agreed cutting scheme (Fig. 24). Ice-core processing took place four times, in June 2002 (113-449 m), July and September 2003 (449-1563 m), June 2004 (1563-2564 m) and April 2006 (2564-2774 m). As the cutting scheme shows, there are four main groups of investigations: (i) stable isotope measurements ($^{18}O$, $^{2}H$), (ii) chemical analyses including dust, (iv) gas measurements, and (v) physical properties.

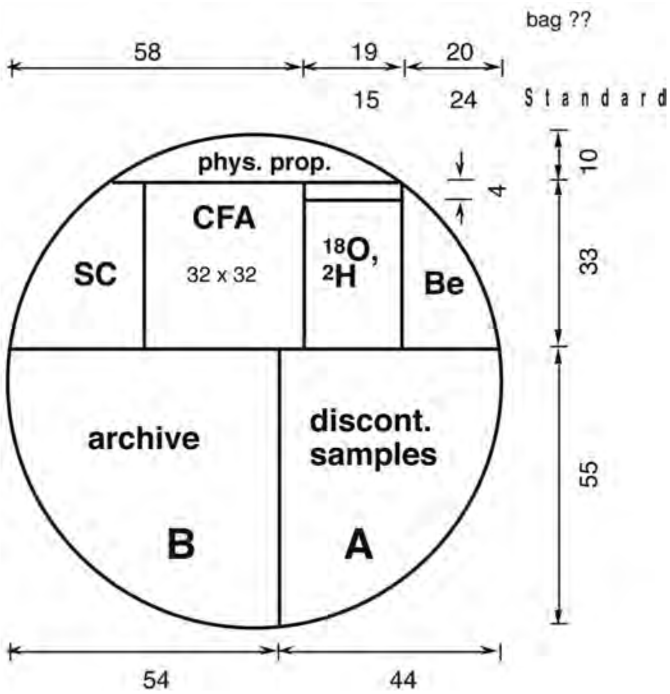



**Fig. 24:** Cutting scheme for the EDML ice core. The standard width for $^{18}O$, $^{2}H$ and $^{10}Be$ samples was 15 and 24 mm. Only some selected bags (bag??), which were used to measure $^{18}O$, $^{2}H$ on a 2.5 cm depth resolution, were cut differently. The core diameter is 98 mm; all measures are given in mm.
SC = EPICA Steering Committee can make special arrangements for this piece. CFA = Continuous Flow Analysis. Phys.prop. = physical properties. Discont. samples = samples used for measurements of gas content and isotope ratios in gases as well as dust, which were done not continuously along the whole core.

**Abb. 24:** Schnittplan für den EDML-Eiskern. Die Standardbreite für die $^{18}O$, $^{2}H$ und $^{10}Be$ Proben war 15 und 24 mm. Nur einige ausgewählte Kernstücke (bag??), an denen $^{18}O$ und $^{2}H$ mit 2,5 cm Tiefenauflösung gemessen wurden, hatten eine davon unterschiedliche Breite. Der Kerndurchmesser ist 98 mm; alle Maße angegeben in mm. SC = Stück, über das das EPICA-Steering-Committee gesondert verfügen konnte. CFA = Kontinuierliche Durchflussmessung (Continuous Flow Analysis). Phys. prop = physikalische Eigenschaften. Discont. samples = An diesen Proben wurden Gasgehalte und isotopische Zusammensetzung der Gase sowie Staub gemessen, jedoch nicht kontinuierlich über den gesamten Eiskern.

*Associated programmes for glaciology, meteorology, and air chemistry*

Not only during the EPICA pre-site survey but also during the years when the EDML ice core was drilled and thereafter glaciological work has been carried out in the surroundings of Kohnen Station.

## Topography and ice velocity

Geodetic measurements with GPS were used to derive a digital model of the topography as well as strain and velocity fields in the surroundings of Kohnen Station (WESCHE et al. 2007).

## Radio-echo sounding

A detailed ground based radio-echo sounding (RES) study was carried out in 2000/01 before the drill and science trench was excavated. The survey was centred on the proposed drill site and showed in detail the variability of snow accumulation around the drill site (EISEN et al. 2005). Another RES study in 2002/03 gave direct evidence for a continuous radar reflector at the depth of 2035 m originating from changes in crystal-orientation fabric measured in the EDML core in a depth between 2024-2045 m (EISEN at al. 2007).

## Snow pits and shallow firn cores around and upstream of Kohnen Station

In January 2006 a 280 km long traverse run upstream of the drill site along the ice divide to sample 15 snow pits (2.1 m deep) every 20 km and to drill 15 m deep firn cores at two different sites. The samples with a depth resolution of 1.5 cm and 10 cm have been analysed with respect to major ions and stable isotopes at AWI. In addition, samples were taken for $^{10}Be$ studies at University of Heidelberg. The results that were not published yet, will be used to improve the upstream corrections needed for the data measured along the ice core. According to calculation by HUYBRECHTS et al. (2007) all ice above 2477 m depth (89 % of total depth) was deposited within 190 km of the drilling site. Ice with an age of 150,000 years (2449 m) was deposited approximately at a distance of 160 km.

## Meteorology

In the 1997/98 season of the pre-site survey the automatic weather station (AWS) number 9 of the University of Utrecht was installed at site DML05 (75°00'09''S, 00°00'26"W, 2892 m a.s.l.) adjacent to the borehole of the B32 drilling. The AWS consisted of sensors for temperature, humidity, wind speed and direction, incoming and outgoing radiation, ultrasonic snow-hight sensor, and snow temperature (Fig. 25). A 100 m thermistor string in the borehole of B32 was connected to the AWS as well (REJIMER 2001, VAN DEN BROEKE et al. 2004). The AWS was in operation from December 31, 1997 until January 21, 2008. Data transmission was via the ARGOS system. In addition the data were stored in a data logger, which was downloaded once a year by the summer staff at Kohnen

**Fig. 25:** The automatic weather station, AWS9, at site DML05 after construction on December 31, 1997. AWS9 was operated at this location until January 2001 and then shifted approximately 150 m to the NNE (Fig. 26). AWS9 belongs to University of Utrecht. (Photo H. Oerter).

**Abb. 25:** Die automatische Wetterstation AWS9 an der Lokation DML05 nach Fertigstellung am 31. Dezember 1997. AWS9 war an dieser Stelle bis Januar 2001 in Betrieb und wurde dann um ca. 150 m nach NNE verlegt (Abb. 26). AWS9 gehört zur Universität Utrecht. (Foto H. Oerter).

**Fig. 26:** The automatic weather station, AWS9, (left) at site DML05 on December 26, 2005. In 2001/02 the first station had been excavated and reconstructed approximately 150 m to the NNE of the old location (Fig. 25). In addition a wind generator (right) was installed to produce heat for the ARGOS transmitter. In the background, at a distance of 1.6 km to the east, Kohnen Station is visible. AWS9 was in operation at this site until January 2008. AWS9 belongs to University of Utrecht. (Photo H. Oerter).

**Abb. 26:** Die automatische Wetterstation AWS9 (links) an der Lokation DML05 am 26. Dezember 2005. In der Saison 2001/02 wurde die erste AWS9 (Abb. 25) ausgegraben und etwa 150 Meter NNO wieder aufgestellt. Zusätzlich wurde ein Windgenerator zur Stromversorgung des ARGOS-Senders aufgebaut. Im Hintergrund ist die etwa 1,6 Kilometer weiter östlich liegende Kohnen-Station erkennbar. AWS9 war an dieser Stelle bis Januar 2008 in Betrieb. AWS9 gehört zur Universität Utrecht. (Foto H. Oerter).

**Fig. 27:** The new automatic weather station, AWS9, adjacent to Kohnen Station on February 1, 2008. The station was placed approximately 300 m to the NE of the base (at the site of B36). It is in operation since January 21, 2008. AWS9 belongs to University of Utrecht. (Photo H. Oerter).

**Abb. 27:** Die neue automatische Wetterstation AWS9 in der Nähe der Kohnen-Station am 1. Februar 2008. Die Wetterstation steht etwa 300 Meter nordöstlich der Kohnen-Station an der Stelle der Firnbohrung B36. Sie ist seit 21. Januar 2008 in Betrieb. Auch die neue AWS9 gehört zur Universität Utrecht. (Foto H. Oerter).

Station. In the 2001/02 season, after four years of operation and about 1 m of accumulation, the highest beam of the AWS protruded only 1.5 m above the surface, and it was decided to excavate the station and move it approximately 150 m to the NNE. This was necessary to keep the AWS away from the artificial accumulation effects of two radar reflectors at the old AWS site. New sensors were fitted and the logger programme updated. In addition to the regular maintenance, a wind generator was installed to produce heat for the ARGOS transmitter, which stops working when the temperature in the logger box drops below -55 °C (Fig. 26). On January 21, 2008 the AWS was replaced by a new AWS (75°00'41"S, 00°00'44" E, 2892 m a.s.l.) located adjacent to Kohnen Station. The new AWS (Fig. 27) again is operated by University of Utrecht and will be maintained by the summer staff of Kohnen Station.

In addition, in the 1999/2000 season three snow height rangers with ultra-sonic distance meters were installed around AWS9 in a distance of 1 km each (HM1, HM2, HM3), which were operated by University of Utrecht. These snow-height rangers were also dismantled in the January 2008. A 2-m snow pit was dug underneath the sensor of each station. Snow samples were taken at 2 cm depth resolution for later measurements of stable isotopes (Fig. 28).

In 2001/02 Helsen at al. (2005) conducted a study on stable isotopes with samples taken close to AWS 9 and two other locations in the vicinity of Kohnen Station. They used the AWS9 data of 1998-2001 for accurate dating of snow-fall events. The aim of the study was to analyse the $\partial^{18}O$ records as well as the prevailing temperatures during accumulation in detail, to infer to what extent isotopic composition in this area can be interpreted as temperature information. The results showed that the strongly intermittent nature of the accumulation in this area can result in the exclusion of entire seasons from the isotope records. The temperature records also reveal that the oxygen isotope records in these snow pits are biased towards higher temperatures, since snowfall conditions are associated with higher temperatures. More results were published by Helsen et al. (2006, 2007).

Precipitation events, which contribute considerably to the total annual snow accumulation, occur at Kohnen only a few times a year. For ice core interpretation, it is important to understand synoptic processes leading to these relatively high precipitation rates. Birnbaum et al. (2006) used visually observed

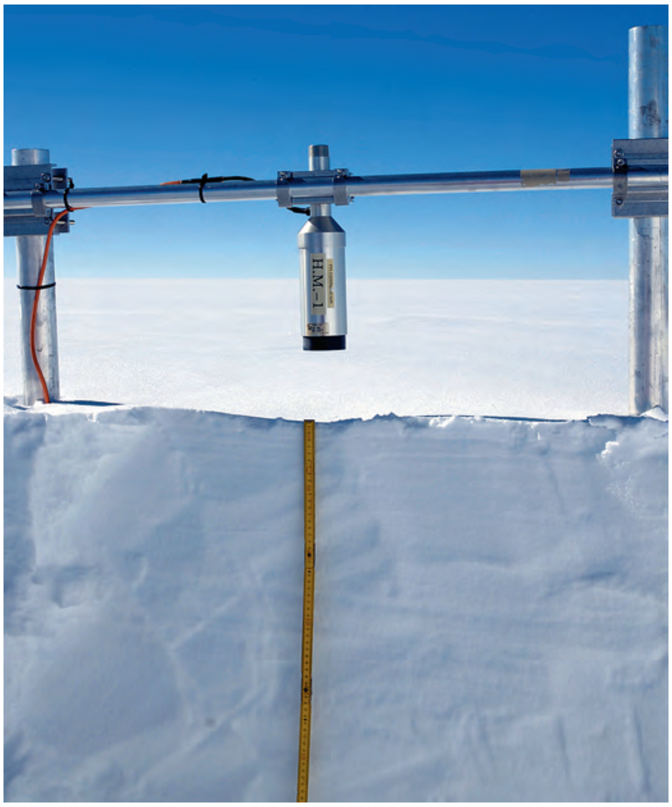


**Fig. 28:** Snow height ranger (ultra sonic) HM1 on the day of dismantling (23 Jan 2008). HM1 was operated by University of Utrecht. (Photo H. Oerter).

**Abb. 28:** Schneehöhensensor (Ultraschall) HM1 der Universität Utrecht am Tag seines Abbaus (23. Januar 2008). (Foto H. Oerter).

periods of heavy snowfall at Kohnen during summer campaigns since 2001/2002 and the corresponding synoptic situations. They found that the synoptic situations can be grouped into three categories. Category I is where occluding fronts of eastward-moving low pressure systems reach the plateau, a fairly frequent occurrence. Category II is where lows or secondary lows formed east of the Greenwich Meridian move to the west (retrograde movement) and frontal clouds influence the plateau. In Category III, large-scale lifting processes (due to an upper air low west of Kohnen Station) lead to cloud formation over the plateau of Dronning Maud Land.

From January 3 through February 13, 2002 University of Utrecht carried out the EPICA-Netherlands Atmospheric Boundary Layer Experiment (ENABLE) at Kohnen Station. It comprised general meteorological observations as well as a 10-m profile tower for measurements of wind speed, temperature and relative humidity. Also the radiation balance was measured. In addition, a system consisting of a zeppelin balloon filled with Helium carrying a maximum of five tethersondes was used to gauge the atmosphere between the surface and 400-600 m. The tethersondes measured air pressure, temperature, relative humidity, wind speed and direction. During the period January 26 to February 9, every three hours a vertical profile was measured with one tethersonde. In between five tethersondes measured simultaneously at vertical spacing of 20-40 m, depending on weather conditions and time of day. Radiosondes were released twice a day to monitor the vertical structure of the lowest 10-20 km of the atmosphere. In total, 68 balloons with radiosondes were released in the period January 8 to February 11.

Also snow-drift sensors were in operation and sub-surface temperatures were recorded at five levels between 5 and 80 cm. The resulting calculations of the surface-energy balance, which used data from these experiments, were published by VAN AS et al. (2005a,b, 2006a,b).

## Aerosol sampling at Kohnen Station

Since 2000, aerosol sampling with high- and low-volume devices were performed during summer at Kohnen station by University of Heidelberg and AWI. During January/February 2000 (THIEDE & OERTER 2002), 2001 (FAHRBACH et al. 2003) and 2002 (PIEL et al. 2006) measured the ionic composition of the aerosol at the EPICA deep-drilling site at Kohnen Station with daily resolution.

From 2000 trough 2002 PIEL et al. (2006) observed mean non-sea salt sulfate (nss-$SO_4^{2-}$) concentrations of 353 ±100 ng m$^{-3}$ and 320 ±250 ng m$^{-3}$, as well as methane sulfonate (MS) concentrations of 59 ±36 ng m$^{-3}$ and 74 ±80 ng m$^{-3}$, respectively. For the summer campaign in 2001, significantly lower nss-$SO_4^{2-}$ and MS levels were observed. The mean MS/nss-$SO_4^{2-}$ ratio ranged from about 0.1 to 0.2 ng m$^{-3}$. MS and nss-$SO_4^{2-}$ concentrations and their variability were roughly comparable to coastal stations at summer. Supported by air mass back trajectory analyses, this finding documented an efficient long-range transport to Kohnen Station via the free troposphere.

In February 2003 an unattended operating aerosol sampler was successfully deployed in the vicinity of Kohnen Station (WELLER & WAGENBACH 2007), aimed at year-round recording of the chemical aerosol composition in central Antarctica (Fig. 29). Analyses of teflon/nylon filter packs consecutively collected over bi-weekly intervals during the February 2003 to December 2005 period, allowed to evaluate seasonal concentration variations of MS, $Cl^-$, $NO_3^-$, nss-$SO_4^{2-}$, and $Na^+$. For MS and nss-$SO_4^{2-}$ distinct late summer maxima were found, while (total) $NO_3^-$ showed a broad November maximum. In contrast, the highest concentrations of $Na^+$ were observed during the winter period. The seasonality of these species broadly coincided with long-term observations at the coastal Neumayer station, including surprisingly comparable $NO_3^-$ levels. However, the biogenic sulfur and sea-salt concentrations were lower at Kohnen Station by typically a factor of 2-3 and 10, respectively. The arrival of sea-ice derived sea-salt particles at Kohnen Station could not clearly be detected, since even during mid-winter the nss-$SO_4^{2-}$ to $Na^+$ ratio was generally too high to unambiguously identify a sulfur depleted sea-salt $SO_4^{2-}$ fraction.

## Sampling of firn air

During the season 2005/06 the division of Climate and Environmental Physics of the University of Berne, Switzerland, carried out a firn-air project in co-operation with AWI. The main purpose of this study was to obtain a more precise esti-

**Fig. 29:** Container with the automatic aerosol sampler inside at Kohnen Station (background right). The air intake is on the roof. Solar panels on the outer walls and the wind generator provide the needed electrical power for year-round charging of the batteries. The container had not been moved during the past two years. (Photo H. Oerter 11 01 2008).

**Abb. 29:** Container an der Kohnen-Station (am Horizont rechts), in den ein automatischer Aerosolsammler eingebaut ist. Der Luftansaugstutzen befindet sich auf dem Dach. Solarzellen und ein Windgenerator liefern die nötige Energie, um die Batterien im Innern während des ganzen Jahres zu laden. Der Container war in den letzten beiden Jahren nicht bewegt worden. (Foto H. Oerter 11.01.2008).

mate of the age difference between gas and ice regarding the interpretation of the deep EDML ice core. Further emphasize was put on the firn-ice transition and a possible fractionation of the ratio of $O_2/N_2$. In order to investigate this fractionation a detailed field study was carried out, where the gas composition of the firn air as well as of the already enclosed air will be considered. Also the physical structure of the ice and its chemical composition has been investigated. Three shallow cores were drilled in the vicinity of Kohnen Station: B35 (30 m), B36 (78 m), and B37 (124 m). After recovering the cores firn-air sampling took place in various depths.

*Scientific results from the EDML ice core*

Stable isotopes

The measurements of the $^{18}$O content gave the basic climatic information about changing temperature over the recovered time interval. Figure 30 shows the $\partial^{18}$O profile for the EDML ice core (EPICA community members 2006) on the EDML1 age scale (RUTH et al. 2007). One specific result of the EDML core was the correlation of the $\partial^{18}$O record with the $\partial^{18}$O record of the NGRIP core from Greenland, showing that in the past Glacial Antarctica warms slowly during cold phases in the North. Greenland warms up rapidly (Dansgaard-Oeschger events) as soon as the temperature decreases in Antarctica again. This mechanism can be explained by the ocean circulation of the Atlantic, with the so-called bipolar seesaw (STOCKER & JOHNSEN 2003). The counterparts to Dansgaard-Oeschger events in the North were called Antarctic Isotope Maxima (AIM) in the South.

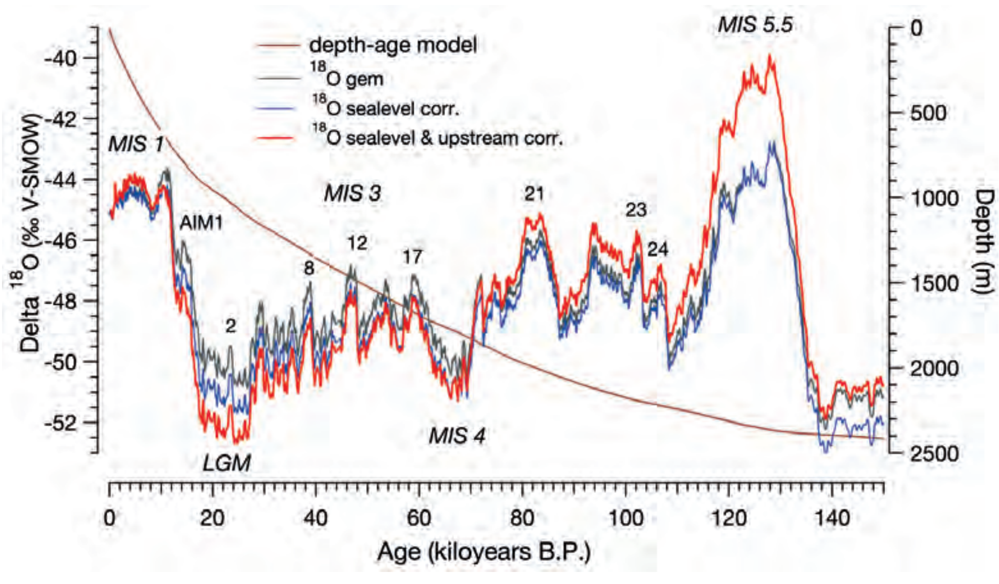



**Fig. 30:** $\partial^{18}$O record from the EDML ice core (EPICA COMMUNITY MEMBERS 2006) on the EDML1 age scale (RUTH et al. 2007). The grey curve shows the measured $\partial^{18}$O data, re-sampled (AnalySeries2.0 software, PAILLARD et al. 1996) to 50-years time steps and smoothed by 5-point running averages. The blue curve shows the same data corrected for changes of the original isotope content of sea water due to changing ice volume in the past (sea level change). The red curve contains in addition the necessary upstream corrections including temporal changes of the elevation of the ice surface. The brown curve represents the correlation between EDML1 age and depth. Some selected Antarctic Isotope Maxima (AIM), the Antarctic counterpart to the Dansgaard-Oeschger-Events in the North, are indicated by figures. MIS = Marine Isotope Stage. LGM = Last Glacial Maximum.

**Abb. 30:** $\partial^{18}$O-Gehalt des EDML-Eiskerns (EPICA COMMUNITY MEMBERS 2006) aufgetragen gegen das EDML1-Alter (RUTH et al. 2007). Die graue Kurve zeigt die ursprünglichen $\partial^{18}$O Messwerte, umgerechnet auf 50-Jahre Zeitschritte (AnalySeries2.0 software, PAILLARD et al. 1996) und geglättet mit einem gleitenden Mittelwert über jeweils fünf Werte. Die blaue Kurve enthält dieselben Daten einschließlich einer Korrektur für die Änderungen des $\partial^{18}$O-Ausgangsgehalt im Meerwasser infolge des sich ändernden globalen Eisvolumens. In den Daten der roten Kurve sind außerdem die Korrekturen enthalten, die die räumlichen und zeitlichen Änderungen der Höhe der Eisoberfläche entlang des Fließweges des Eises zum Bohransatzpunkt berücksichtigen. Die braune Kurve stellt, die Beziehung zwischen der Tiefe und dem EDML1-Alter dar. Einige ausgewählte Antarktische Isotopenmaxima (AIM), die den Dansgaard-Oeschger-Ereignissen im Norden entsprechen, sind als Zahlen über den Isotopenkurven eingetragen. MIS = Marine Isotopenstadien; LGM = Letztes glaziales Maximum.

## Chemical analyses

The chemical analyses comprise continuous flow measurements (CFA), fast IC measurements, dust measurements (Fischer et al. 2007) as well as IC measurements at discrete samples, which were also collected by continuously melting the ice core.

Fundel et al. (2006) investigated the influence of large-scale teleconnection patterns on methane-sulfonate (MS) records from ice cores in DML during the past 2000 years. They wanted to check the potential of MS records as an environmental and climate archive for the Atlantic sector of the Southern Ocean. Despite post-depositional changes, years of extraordinary MS concentrations were clearly detected in the ice core records. Fundel et al. (2006) used composite anomaly maps of atmospheric parameters from the NCEP/NCAR reanalysis fields for years of extreme MS concentration to detect atmospheric patterns causing MS variability. Changing atmospheric transport appeared to be an important, but not exclusive parameter being conserved in the MS record in DML. The often hypothesized direct link between high MS concentrations and El-Niño events was not supported whereas the Antarctic dipole (ADP), which is modulated by ENSO conditions, exerts significant influence. A clear 13.9-year cycle was found throughout a 2000 year MS record, which can be related to variations in the ADP. Over the last 300 years also a 4.6-year cycle was revealed in the MS (and sea-salt record), which vanishes in the deeper part of the ice core as a consequence of diffusion processes. In the long-term perspective periods of high MS concentrations are connected to on average higher sea salt aerosol as well, reflecting a seasonally independent influence of transport on both species.

Beside the question of sea-salt transport to the interior of the Antarctic inland-ice also the transport of dust is investigated by means of ice cores. These investigations are still in progress and first results were published by Ruth et al. (2008).

## Gas studies

Ice is the only climate archive, which keeps direct information on the gas composition of the past. Direct atmospheric $CO_2$ measurements started only as late as 1958. When firn is transforming to ice, air is occluded in air bubbles. This happens at the EDML drilling site at a depth of approximately 90 m (cf. density profile in Fig. 19). However, this process causes a complication, as the age of the surrounding ice is different from the age in the freshly formed air bubbles. This age difference is called Δage. Siegenthaler et al. (2005) give a value for the Δage in the EDML core of 825 years and an age distribution in the air bubbles of 59 ±5 years. The focus of the gas measurements is on the concentration of the greenhouse gases carbon dioxide ($CO_2$), methane (CH4), and nitrogen oxide ($N_2O$) and the stable isotopes $^{13}C$ and $^{2}H$ in the gas molecules. $^{13}C$ in $CO_2$ as well as $^{13}C$ and $^{2}H$ in $CH_4$ can give a hint on the source of these gases. Using $^{13}C$ in methane Fischer et al. (2008) showed for the period 10,000-22,000 years BP, the period that include the transition from the past Glacial to the Holocene period, that boreal wetlands emitted less methane during cold periods than during warm periods. In contrast, the emission of methane by forest fires was fairly constant under cold and warm climatic conditions. Further, the ratio of the concentrations of the gases nitrogen ($N_2$) and oxygen ($O_2$) is obviously dependent on solar insulation and has therefore been measured in the ice core as well.

Siegenthaler et al. (2005) measured $CO_2$ concentrations in the EDML core for the time since 1000 AD and compared it with the results of Law Dome (Etheridge et al. 1996), which serve so far as a reference for pre-industrial $CO_2$ values. The new EDML record is the first very strong support of the Law Dome record from an ice core of the Antarctic plateau.

While a direct synchronization of ice core records from the two hemispheres is pending, matching of gas records is currently the best tool to interpret the link of climate events in the two hemispheres (Blunier et al. 2007). The quality of the synchronization depends on the quality of the gas records and their resolution but to a main portion on the ability to calculate correctly the Δage by means of densification models (e.g. Blunier & Schwander 2000). The EDML core was matched by means of the variations in the $CH_4$ record to a composite $CH_4$ record of the Greenland ice cores (GRIP, GISP2, NGRIP) (EPICA community members 2006, Blunier et al. 2007). It was estimated that the total synchronization error adds to 250 years for the Younger Dryas, 500 years for the Dansgaard-Oeschger events 2 and 3, and about 400 years for other Dansgaard-Oeschger events. In between the rapid $CH_4$ changes the synchronization error may be larger, up to about 800 years where small $CH_4$ variations were found.

## Physical properties

The metamorphism of snow to firn and finally ice and changes in the microstructure of the ice due ice dynamics and various kind of inclusions is a complicated process. But especially for an in-depth understanding of the process how gases get occluded into the ice matrix the study of physical properties of the ice is needed. Freitag et al. (2004) used X-ray micro-computer tomography ($\mu$CT) to show how the densification of polar firn is depended on its microstructure. The $\mu$CT method analyses 3D-samples and offers to calculate a large set of parameters including different ice and pore size measures, neck radius, coordination numbers, and anisotropy factors (Freitag et al. 2008). The visual stratigraphy of the EDML core was recorded with a line scanner, aside from a first visual inspection of the freshly drilled ice cores in the field and later during ice-core processing in the lab (Lambrecht et al. 2004). Kipfstuhl et al. (2006) developed microstructure mapping as a new method for imaging deformation-induced micro-structural features of ice on the grain scale. The output data of the complete set of thick-section images of the EDML ice core has been archived in the PANGAEA InformationSystem (Kipfstuhl 2007).

## Dating the ice core

Dating of the ice core and deriving the age scale EDML1 (Figs. 23, 30) was a combination of several methods (Ruth et al. 2007). It is based on ice sheet modelling, comparison with the EDC core, on the EDC3 age scale (Parrenin et al. 2007), by means of dust and chemical compounds (Severi et al.

2007) and a synchronisation with the Greenland ice cores by means of methane concentrations (BLUNIER et al. al. 2007, EPICA COMMUNITY MEMBERS 2006). The age at the depth of 2416 m is 150,104 years BP according to the EDML1 age scale. Below that depth, for the remaining 358 m (13 % of the core length) the core is not dated well so far. There should approximately another 100,000 years of ice history be stored in the core. But it is not unambiguously clear whether or not some faulting had happened close to the glacial bed. The correlation between EDML and EDC becomes poor below 2600 m depth.

## Other records

Other measurements on smaller subsets of ice samples comprised radiocarbon analyses (VAN DE WAL et al. 2007) and cosmic dust deposited on the ice during the past 30,000 years (WINCKLER & FISCHER 2006).

EPICA decided to use the PANGAEA InformationSystem (www.pangaea.de) as one of the main repositories for the data measured at the EDML and EDC ice cores.

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