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The EPICA deep drilling program

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Abstract: The EPICA deep drill site was at Dome C, 75°S, 123°E, elevation 3250 m. Mean annual temperature was −55°C, and accumulation is 2.7 cm of ice. In a temporary camp located at the permanent Dome C station, the EPICA ice core was drilled in a large tent. The drilling was controlled from a heated cabin, and the core was processed on site in a large scientific facility.

1. Introduction

EPICA is a multinational European plan for deep ice core drilling in Antarctica, to address critical environmental issues of global relevance. It will play a major part in the international effort to understand climate change. EPICA aims to reconstruct high-resolution histories of past changes in climate, atmospheric composition and ice cover in Antarctica spanning several glacial/interglacial cycles. This evidence will improve our understanding of the interplay between atmospheric chemistry and climate and the causes of major climate changes; and promote testing and enhancing of computer models used to predict future climate. EPICA involves two deep drillings in two different regions of Antarctica: Dome C (East Antarctic) and Dronning Maud Land (Atlantic region). The Dome C' is to obtain the longest undisturbed chronicle of environmental change-extending back more than 500000 years at highest resolution.

2. Choice of Dome C location

The Dome C drilling spot location was chosen after a radar echo sounding campaign (Tabaco *et al.*, 1998; Rêmy and Tabaco, 2000). The Dome C drilling site was at 75°06′06″S, 123°23′42″E; elevation 3233 m; ice thickness 3250±25 m.

3. Dome C Camp

The summer camp at Dome C was designed to host supporting personal for the construction of the permanent Italian-French station called Concordia and to host scientists from different programs and organisations. The total capacity was around 40 persons. Since the 96-97-summer season, the EPICA program had the pleasure of being hosted in a camp, which became more and more comfortable each season. Most of the

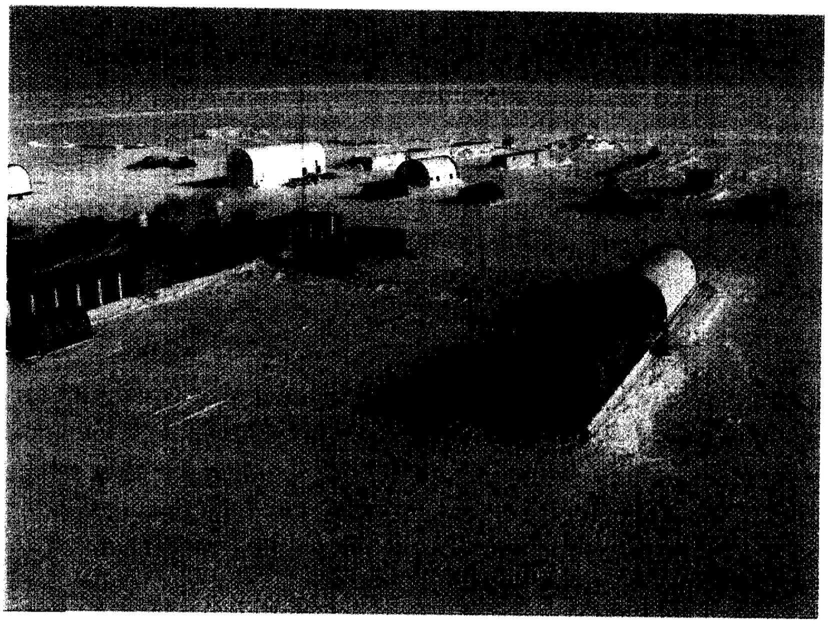

Fig. 1. Concordia summer camp.

buildings and tents were built on sledges in order to allow for easy movement of equipment and to prevent it from being buried (Fig. 1). A first line of containers was equipped with a few bedrooms, an emergency hospital, a kitchen and galley, toilets and a radio room along with the camp manager's office. A second set of containers contained the power plant for the summer camp with two current-generators of 150 kW each. Most of the accommodations, 200 m away from the common facilities, were located in four big tents with six beds each. Two long big tents were used as recreation room and offices, respectively. A big tent was equipped as a garage for vehicle maintenance. The EPICA program had its own drilling and scientific facilities: a workshop, a drilling tent, two buildings for scientific activities and a trench for the ice core storage.

The location of Dome C was perfect for the maintenance of a big camp. Thanks to the very small accumulation and minimal snowdrift, only a little work with a Kässbohrer at the beginning of each season, was necessary to maintain the camp. The snow surface level between the buildings remained the same during five years around most of the buildings and tents.

4. Dome C EPICA facilities

The set up of the drilling equipment was very similar that in GRIP and NGRIP in Greenland (Gundestrup *et al*., 1994). The main difference between Dome C and the two Greenland sites is the annual mean temperature. The annual average temperature at Dome C is about 20°C colder than in Greenland. This temperature difference and the very low snowdrift accumulation guided our choice to work and to install all the equipment at surface level instead of working in a trench. Working at surface level is much more pleasant when it is possible. With five seasons experience at Dome C we can say that the choice was good. The drilling and the workshop tents and science building are still at the same level. There is no need to walk down to reach them. With powerful ventilation evacuating the drilling fluid vapour from inside the drill tent, the tent is in air depression. As the air comes from the outside instead of coming through the snow walls as when the drilling site is buried, we have no frost deposits on the equipment. In fact the opposite is true. When the drill is at surface level overnight, the next morning we find it very clean. The wooden floor, which can be slippery after chip cleaning and treatment, dries off overnight. The ventilation in the tent allows a self-cleaning process to take place, which is very pleasant and gives real comfort.

4.1. Workshop

An insulated tent, 4 m wide and 8 m long, was used as a workshop for EPICA. A gas oil heater provided a nice positive temperature inside. Several working tables provided space for mechanical work on the drill. Another working table was used for electronic activities and repairs. A conventional lathe, a drill press, a press and a grounding machine were good for mechanical repairs and modifications. A mezzanine provided room for computer work and relaxing time.

4.2. Drilling tent

The drilling tent, 21 m long by 6 m wide by 7 m high was built on a plywood floor screwed on a latticework of beams filled with compact snow (Fig. 2). The lining of this tent was made of four layers. Two of them were made from insulated material. The tent was equipped with six large Plexiglas windows, which gave a good natural light for working. One door, on each gable, gave access to the tent. On one gable a big door gave access to vehicles to carrying heavy equipment like the winch. On the opposite side, a second gable had a normal double door.

Tower: The tower was provided by the University of Bern in Switzerland. This tower

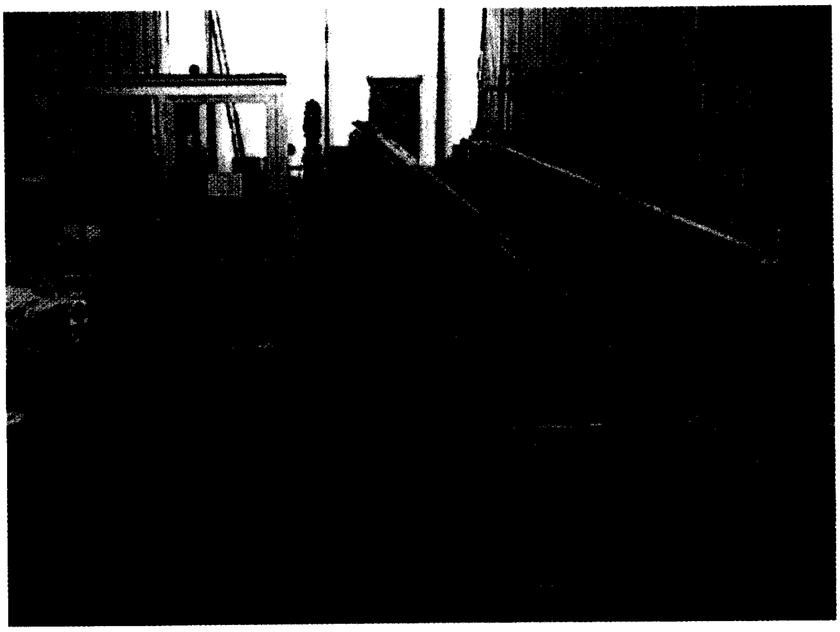

Fig. 2. Inside the drilling tent.

was similar to the ones used for the GRIP and NGRIP projects. Standing 13 m high, the tower rotated using an electric jack. From the vertical position the tower moved to the horizontal position when the drill was at surface level. The horizontal position of the drill, at working table level, gave easy access for maintenance. A load cell transducer on the top sheave axis measured the cable tension from 0 N up to 30000 N. The transducer itself accepted a load of 75000 N. The tower was designed for a load of 80000 N applied on the top sheave.

Winch: The winch was equipped with a 3-phase 15 kW motor giving a 98 Nm torque. The nominal rotation speed of the motor was 1450 rpm and the reducer ratio was 52.26. The speed controller gave a speed under full load from 0 m/s to 1.4 m/s. A Lebus system allowed good spooling of 4000 m of cable. The winch could be rotated manually with a handle directly from the top part of the motor shaft. This manual connection made it possible to put gradual tension on the cable in case of an accident. The total weight of the winch was 2 tons.

Cable: Double stainless steel armour cable with four conductors had an external diameter of 7.16 mm. The breaking strength of the cable was 34700 N. The weight in air was 204 kg/km. The fours conductors were used in parallel. The cross-sectional area was $4\times 0.34\ \mathrm{mm}^2$. In June 2001, a new cable was ordered to replace the original one which had become too short because of an accident in December 1998. In order to make the transfer of data through the cable easier, the choice was fixed on a coaxial cable. The cross-sectional area of the central conductor was $1.3\ \mathrm{mm}^2$, while that of the shielding was $0.049\ \mathrm{mm}^2$. With double external armour the cable was slightly bigger. The diameter was 7.29 mm. The new breaking strength was 35600 N and the weight in air was 230 kg/km. This new cable, produced by the Rochester Company, Virginia was designed to our German and Danish colleagues' specification for the second part of the EPICA program: Dronning Maud Land (Gundestrup and Johnsen, 2002). After changing the winch drum grooves the new cable to fit the drum without changing the front wheel of the spooling system.

Retrieval table: The retrieval table, in line with the tower, received the core barrel full of ice and the hollow shaft after each extraction. A hand winch was used to help with extractions when pulling the core out of the core barrel required too much strength. When the retrieval table become full, it was rolled on one side of the drilling tent in front of the working table, on top of which were fixed the core troughs. From this position the operator pushed the core inside the trough with a stick. Then cleaning of the hollow shaft and its pump, and cleaning of the core barrel and drill head, start. The core barrel and the core are never carried by hand thus avoiding breakage to the core caused by handling. This main reason for a retrieval table is fulfilled.

Chip and drilling fluid treatment system: This system, located at the entrance to the drilling tent, is composed of two pumps to transfer the drilling fluid, one bucket to mix and adjust the density of the fluid and one spinner to dry out the chips. An additional drum heater located close to the camp's power plant is designed to melt the chips after spinning. The treatment line for chips has four steps. From the drill and from around the hollow shaft, the chips fall down into a dripping bucket. The chips are shovelled into the spinning machine and spun for 5 min to extract the drilling fluid. The recovered fluid is reused in the hole after a density check. The dry chips are stored in a 200 litre drum and

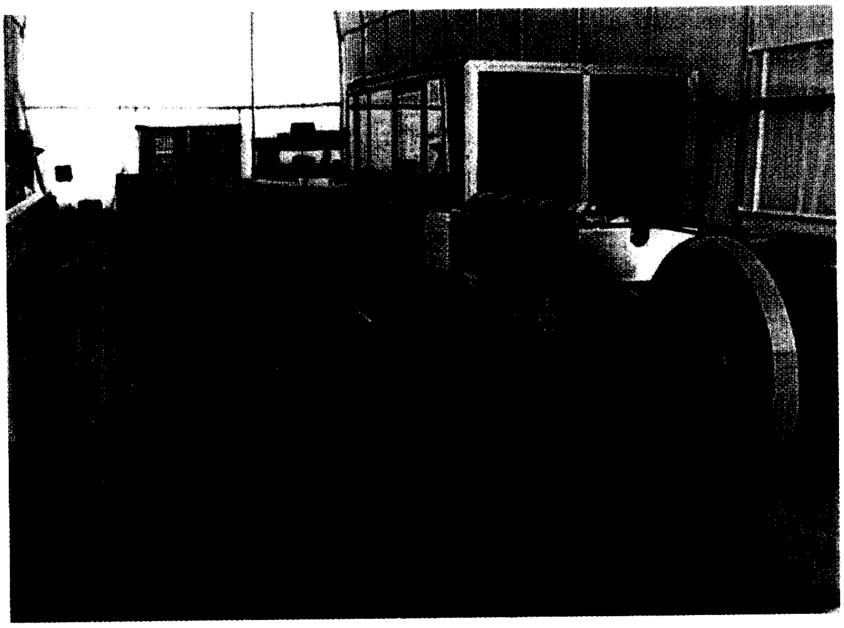

Fig. 3. Inside the drilling tent from the drilling tower top wheel.

melted in a special heater. Fluid and water are separated in this heater. The fluid, after being cooled, decanted and its density adjusted, is used again.

Heated cabin: The cabin, made from insulated walls and glass, provided a comfortable place for the operator piloting the drill (Fig. 3). A control panel to command the winch and a computer to pilot the drill were used. Large windows provided a good all round view from the driller's seat. The driller, while seated, can see from the winch to the bottom part of the tower and over to the retrieval table. This gave the operator excellent visibly and comfort for working. A window in the cabin roof gave the operator a clear view to the top of the tower when the drill arrived at surface level.

Drilling trench: A 6.5 m deep drilling trench was dug in the snow to allow rotation of the tower in its vertical position. Some steps were cut into the wall on each side of the dripping path to provide access to the slush pan. At the bottom, on each side of the slush pan, a cavity was dug to provide a safe place for operators. Two lamps gave good light. A pipe arriving in the casing under the slush pan meant that fluid could be poured in the hole. The temperature at the bottom of the trench was -53°C.

Ventilation: A big ventilator sucked air from the bottom of the incline trench to the outside. Two smaller ventilators were located close to the place where the drilling fluid was prepared and the chips were spun. The total ventilation capacity was 250 m^3/h.

4.3. Science shelters

Made from insulated panels for cold rooms, the science shelters provided excellent facilities with cold and warm laboratories close to each other and conditions for good quality work. The bigger one, in line with the drill tent, hosted a core buffer with two different shelves, each receiving core troughs of 4 m and 2.2 m in length, respectively. In the same building, the logging and cutting into 2.2 m sections, DEP measurements, cutting of all sections for different analysis and physical properties, ECM, light pass recording, helium sampling, CFA and final cutting and packing before storage and shipment were carried out. The second science shelter was equipped for chemical analysis and analysis of physical properties. A total of fifteen people could work simultaneously in these shelters.

4.4. Storage trench

A few standard 20 foot containers were buried 6 m under the snow to provide a cool storage place for the remaining core.

5. Dome C chronology of events

5.1. Season No. 1: 1996-1997, installation and cased pilot hole

1) Installation

This was the first season of EPICA on Dome C. This season, the drillers were transported via Baia Terra Nova on the way in and through Dumond D'Urville on the way back. When the first drillers arrived at Dome C, with the Twin Otter, before the first traverse of the season, there was only one tent on site with a 3 kW generator. A Pisten Bully and a caravan equipped with six beds, kitchen facilities and toilets were stored not too far away, left by a 95–96-season traverse. The first days were spent helping the logistics people set up camp as soon as the first traverse from Dumont d'Urville arrived with cargo for the summer camp and for the EPICA program on 12 December. The total volume brought by the first traverse for EPICA was 40 m^3, totalling 27 tons and included a complete shallow drill set and reamer equipment, all the outfits for installation of the casing, all the wood for the floor, some furniture, a snow blower, the drilling tent and all kinds of tools. Four days were needed to build the drilling tent floor and two days to dig the incline trench.

2) Drilling

For drilling, we used the Grenoble electro-mechanic shallow drill set used many times over the last 15 years. The drilling activities started on 24 December. The pilot hole was drilled, interrupted by a few mechanical problems with the reduction gear of the winch. After six days, we could drill a pilot hole to a depth of 124 m. The porosity test showed a close off around 102 m depth. It was decided to end the casing at 107 m depth. The 17 m difference between the bottom of the hole and the end of the casing provided enough space for the deep drill (11 m in height) to start with the anti torque section placed under good conditions.

3) Reaming

Danish reamer tools, adapted to our shallow drilling equipment, were used to enlarge the hole for the casing. Three different diameters of reamer were needed to ream gradually from 143 mm (diameter of the pilot hole) to 255 mm (diameter of the casing).

The first reamer was blocked, after a few runs, when a depth of 28 m was reached. The reamer tank became full and motor rotation was not stopped in time, causing chips to pack around the cutters. At 28 m deep we were still in soft firn, the density increased rapidly, and the volume of chips increased very fast. Therefore the first 50 m with the reamer tools were always delicate to pass. At that time we had nothing on site to pour into the hole to soften the firn and freed the reamer. Glycol and pipes were ordered in

Baia Terra Nova. We had to wait 10 days for this equipment. In the meantime, an attempt to free the reamer with ethyl alcohol was unsuccessful. We had to pour 50 litres of glycol mixture (90% mixed with water and warmed to 50°C) twice. A spray system was attached at the lower end of the pipe to guide the liquid toward the reamer and the firn wall. Two hours after the second drop we could start to move the reamer up and down with the winch and get it free to the surface. Two weeks later a depth of 107 m was reached with the last reamer. There were no more hitches.

4) Casing

As soon as the fiber glass tube of the casing was checked and cleaned of snow, one day was enough to lower the 18 fibre glass pipes of the casing and connect them to one another with a cable inside a round groove, both in the male and female part of the tubes. The casing was a standard permaglass well casing from Industrial Plastic Services, South Australia (Johnsen *et al*., 1994). It was the same as the one used for GRIP and NGRIP. The casing was in place on 31 January.

5) Other works and departure

As the drilling tent was erected, covered with four liners, all the shallow drilling and reamer equipment was packed, and the drilling tower assembled. The drillers left the camp on 4 February with a Twin Otter flight to Dumont D'Urville then onto Hobart by ship.

5.2. Season No. 2: 1997–1998, start deep drilling, depth reached: 363.50 m

The drilling team arrived at Dome C on 7 December and left on 4 February for Dumont D'Urville. The logistics people erected the workshop tent at the very beginning of the season, providing us with some working comfort.

1) Installation

Until the last day of December, time was needed to continue installaing the equipment: winch with controller, tower with controller and load cell, retrieval table, assembly of the deep drill, test of the electronic equipment, test of the cable anchor and installation of tools, working table and fluid equipment. At the same time the workshop was equipped with a lathe, a drill and grinder machine, working tables and toolboxes.

2) Drill assembly

This very delicate work was successfully completed without any major difficulties. An inner sleeve was mounted inside the outer tube on the upper end of the grooves to prevent the rotation of the new pump designed by our Danish colleagues during the winter of 96–97 in Copenhagen and tested at NGRIP in the summer of 1997. It was possible to connect everything on the first attempt. Everything was perfect and was moving freely. The drill head was prepared with the last cutters machined in Bern. The coupling, electronic and anti-torque sections were prepared as well. The cable anchor was made and a pulling test was successfully completed.

3) Drilling

On 1 January, 1998, the first EPICA core came up. This first run was a good short run, with very good core quality, without any scratches.

Drill pump bearings became stuck before the end of the run, due to an increase of the shaft diameter by ice coating. This had two effects: to stop the run before the drill was full and to break the small ball bearings which support the drill pump wave bearing load.

The electronic equipment broke down. It was repaired and improved. Several times, we lost a short piece of core which was sticking out of the core barrel; each time we found pieces of ice blocking the hole at the same level, 110.93 m deep. These pieces prevented the drill from entering the hole. Each time we were obliged to drill through this small piece with the anti torque section located in the casing section. Three days were needed to make the electronic equipment more stable, and seven to find a good modification for the pump and make it work to the end of each run.

We had three major events this season which stopped drilling activities for several days each. The tower tilting gear breakdown could have had serious consequences for peoples' safety. By luck the tower was not in a dangerous position when the piston rod thread released. The repair made in the field was reliable enough to survive the season. The winch brake failure was due to a shortage with the ground phase in a moulding coil. A modification of the winch brake made it possible to continue drilling with all the safety measures required for lowering and hoisting. Meanwhile we needed one more operator to activate the brake manually. On 20 January, at the end of run 106, it was not possible to pull the drill up. For some reason the drill was stuck. Why was the drill stuck? It is always difficult to answer this question.

We had more chips than usual at the bottom of the hole because, during the previous run, the upper valve was opened and we left all chips in the hole. This happened the day before without any consequences. Looking carefully at the data recording at the end of the run, the graphs were unusual and something had happened that had never happened before; the motor current was 0.6 A while motor rotation was 0 rpm. Why? What was wrong? Further investigation and analysis of graphs and data were necessary to even attempt to determine the cause. First, we were sure that communication between the surface and the drill was not working properly when the drill stuck. Second, we were sure that the electronic equipment was not working any more at the surface. Third, the week before the drill had stuck, the frequency of incidents concerning the electronic equipment had been increasing quite considerably: loss of data, loss of communication, incorrect motor rpm in spite of the configuration, instability of motor rpm and wrong inclination difference. It was not possible to repair the electronic equipment in the field.

4) Differing drill behaviour

We noticed that the behaviour of the drill was different at Dome C from that in NGRIP. With the same clearance between drill cutter edges and shoes, the entrance pitch was smaller than 4 mm, compared to more than 4 mm in NGRIP. The drill pump at Dome C was more efficient than in NGRIP and consequently drilling was much faster; we had to stop runs before 3.5 m and sometimes even earlier, making runs on average shorter than in NGRIP. For core barrel extraction, the pulling-out strength needed was higher at Dome C (up to 15000 N). The main differences between the pump at Dome C and the pump in NGRIP were the flap valve spring strength and the height between the flap valve level and pump body, which was increased by 2 mm. This could explain why chip recovery was better at Dome C than in NGRIP, and why the drill hole was cleaner at Dome C than in NGRIP. We didn't find any solution for reducing pulling out strength. This strength was always too high whatever the core length, however full the chip chamber, whatever the cutting pitch value and whatever the chip size. It was not possible to find any correlation. Drilling activity was interrupted several times and drilling was never stable over a long period, which is why, in spite of a few attempts, it was not possible to work in shifts.

5) Conclusions

By the end of the season the average core length we were able to drill was 2.8 m. At the same time, chip amounts after the spinner step averaged 20 kg. Run time was one hour when everything went smoothly. A four-day period was the longest stable drilling time we had. For these four days, the average drilled distance per day was 25 m, which would be equivalent to 175 m per week, had we been able to extend the stable mode time. This stability was to be tested, repeated and confirmed during the following season.

5.3. Season No. 3: 1998–1999, drill stuck at 783 m depth

The drilling team arrived at Dome C on 22 November and left for Christchurch on 3 February.

1) Modification of drilling equipment

The ground references and the cable shielding were changed in order to improve safety and to reduce noise in transmissions due to the winch motor variator running. The winch motor was changed for a new one with a new brake and a shaft termination for the manual rotations, which had not been installed the previous season. The retrieval table was modified to support a more powerful hand winch.

The biggest trouble we had experienced the previous season was the great strength needed to pull the core barrel out from the outer tube (up to 20000 N). Some plates were mounted on the hollow shaft to divide the length of the chip chamber in to smaller compartments in order to divide the pulling out strength. To improve the efficiency of the pump, we modified the flap valve springs. The brass pump wave bearings were changed for bronze ones. Three sets of electronic equipment were available. A new drill head had been manufactured and designed in Grenoble. The major change on this drill head was to have parallel grooves instead of funnel grooves for transportation of the chips, thus avoiding the chips packing effect when we pulled up fast to break the core.

2) Drilling activities

Seven days after our arrival we were ready to drill the first core.

First run: The drill was in the same configuration as for the last run of the previous season and we drilled a 2.25 m core without any problems. No chips were found on top of the core but pulling out was really difficult and we had to pull more than 10000 N to get the core barrel out.

Electronic problems: After this first run, the electronic equipment ceased to communicate. We found several broken wires. Adjusting the carrier, we improved communications.

Pulling out problem: By adding several plates on the hollow shaft, pulling out strength required decreased to 2500 N, which was an acceptable value and made the pulling out operations much easier. The best configuration we found was to put three plates on the hollow shaft in order to divide the chip chamber into four compartments.

Parallel grooves drill head: Unfortunately, the hole diameter for cutter guidance pins was too large. In spite of the modifications made in the workshop at Baia Terra Nova, the cutter fixing was not good enough to use this drill head in good condition.

Routine mode: Within a few days we found a routine. Core quality was excellent and core length was between 2.5 m and 3 m with good chip recovery (Fig. 4). We could start

Fig. 4. Core extraction from the core barrel to the core trough.

Fig. 5. Pump flap valve with big pieces of ice.

to train drillers at the console on 7 December. We were ready to work in shifts 10 December. Normal maintenance of the drill was the only thing we had to do. Two or three times a core catcher broke. The new springs for pump flap valves were too weak and

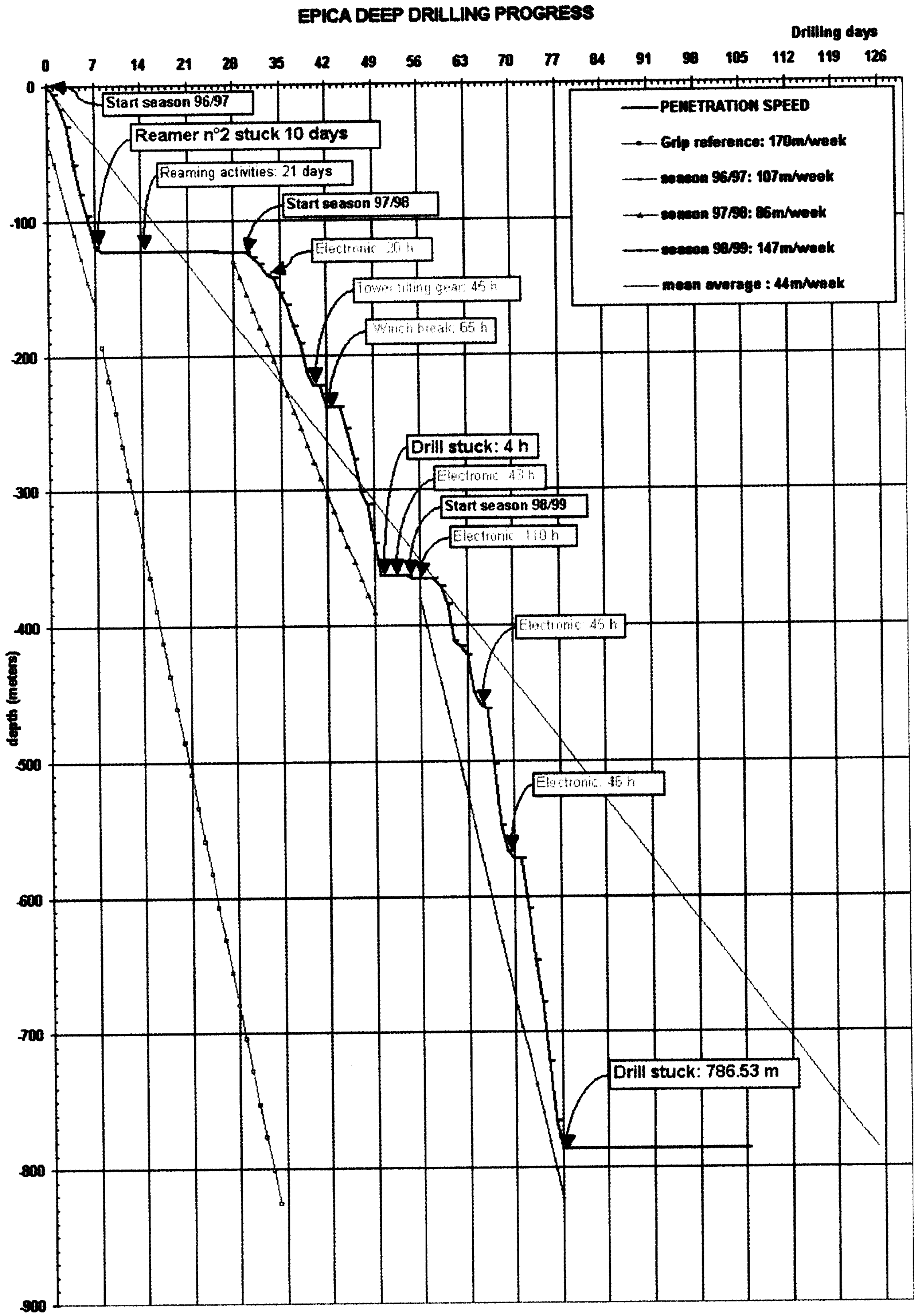

Fig. 6. Drilling progress from 1996 to 1999.

we changed them (Fig. 5). This routine was stopped by several incidents with the electronic equipment. The first week, we drilled 50 m, repairing the electronic equipment and performing tests. The second week progress was 151 m. The third week, progress was almost 220 m. Drilling at that time was finely tuned, with a production of cores of an average length of 2.5 m and a run time of 1 hour at a depth of more than 700 m. The perforation capability of this drill was excellent, with production of more than 30 m of core a day, working in two shifts of 17 hours.

3) Last run and stuck drill

After three working weeks, it was decided to clean the hole in order to check how many chips had been lost in the hole. With two cleaning runs (one down to 660 m, the second one down to 785 m) we collected 6 kg of dry chips, compared to 2500 kg produced. This was less than 0.25% of the chip left in the hole. The impression of working in a very clean hole was confirmed.

Three attempts to start a run: On 20 December, starting 1 m above the bottom, the beginning of the run was normal. As soon as the cutters started to touch the ice, the motor current reached the abnormally high value of 2 A. As soon as penetration stopped, motor current and cutter load went back to normal levels. After 20 s of stabilisation we restarted very slowly. Nothing was happening. Then after 30 s' descent the current increased up to 1.3 A to quickly reach 3 A. Penetration was stopped a second time and cutter load and motor current decreased to normal levels. After stabilisation a third attempt was carried out. The motor current increased suddenly from 2 A to 3.1 A in less than 4 s. At this time, due to overload, all electric communication with the drill stopped and we had to reset the entire program. Once communications with the drill were established again, it was decided to pull up. The drill didn't come it was stuck (Fig. 6).

Rescue attempt: we tried several times to pull few metres of cable slack with the winch up to 22000 N without any success. Then, we pulled by hand up to the cable elastic limit, which was 29000 N, and released to let drill hammers work several times. Nothing significant happened. We tried to rotate the drill motor in forward and reverse without any success. Using the drill hammer, we lost contact with the drill on the third day. We could measure a displacement of the cable at the surface under the same tension as before. This displacement confirmed that the drill moved a few metres. On 24 December, after several contacts and discussions, it was decided to pour 71 litres of glycol mixture (74% glycol, 26% water) into the hole. The estimated time for the glycol to reach the bottom of the hole was one and a half hours. Twenty four hours later, nothing significant had happened. To be sure of recovering the whole drill, we decided to pour a further 172 litres of glycol mixture on 25 December. The tension on the cable was 29000 N. Twelve hours later we noticed a continuous and gradual decrease of cable tension over four hours, before levelling out at around 18300 N. Pulling with the winch, the drill did not free. Several days were spent moving the drill hammer trying to bang the drill up and down without success. On 1 January we decided to pour another 126 litres of the mixture. Nothing significant happened. From 2 January until the end of the season nothing significant happened; we charted the decrease of the cable tension from 29000 N down to 26000 N.

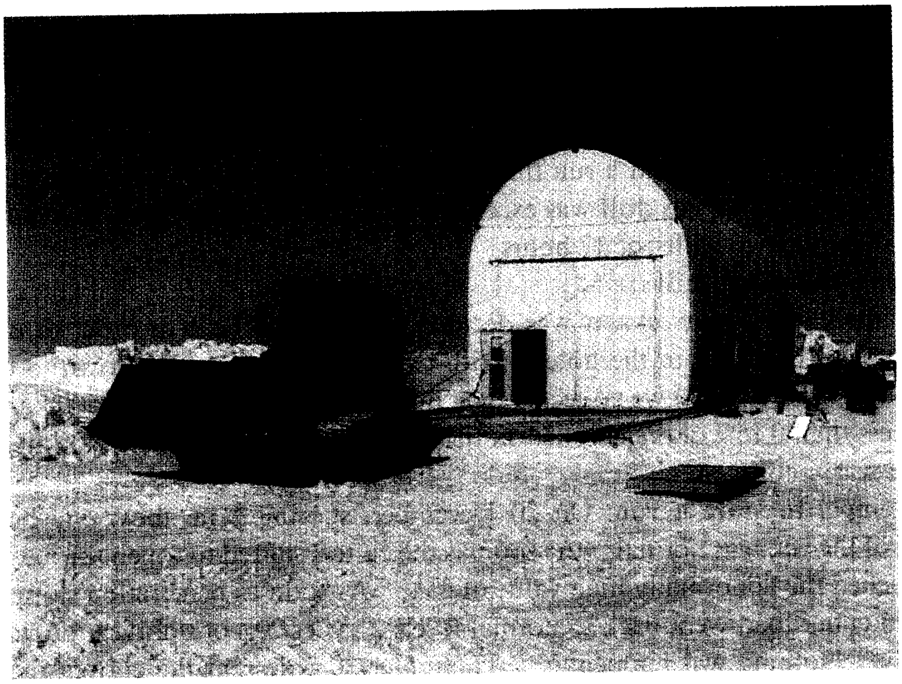

Fig. 7. The move of the tent: one shot.

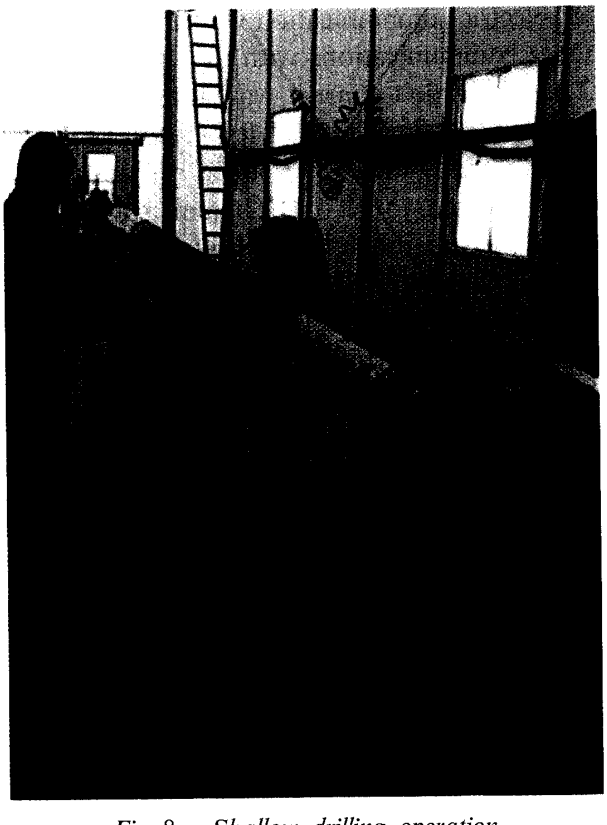

Fig. 8. Shallow drilling operation.

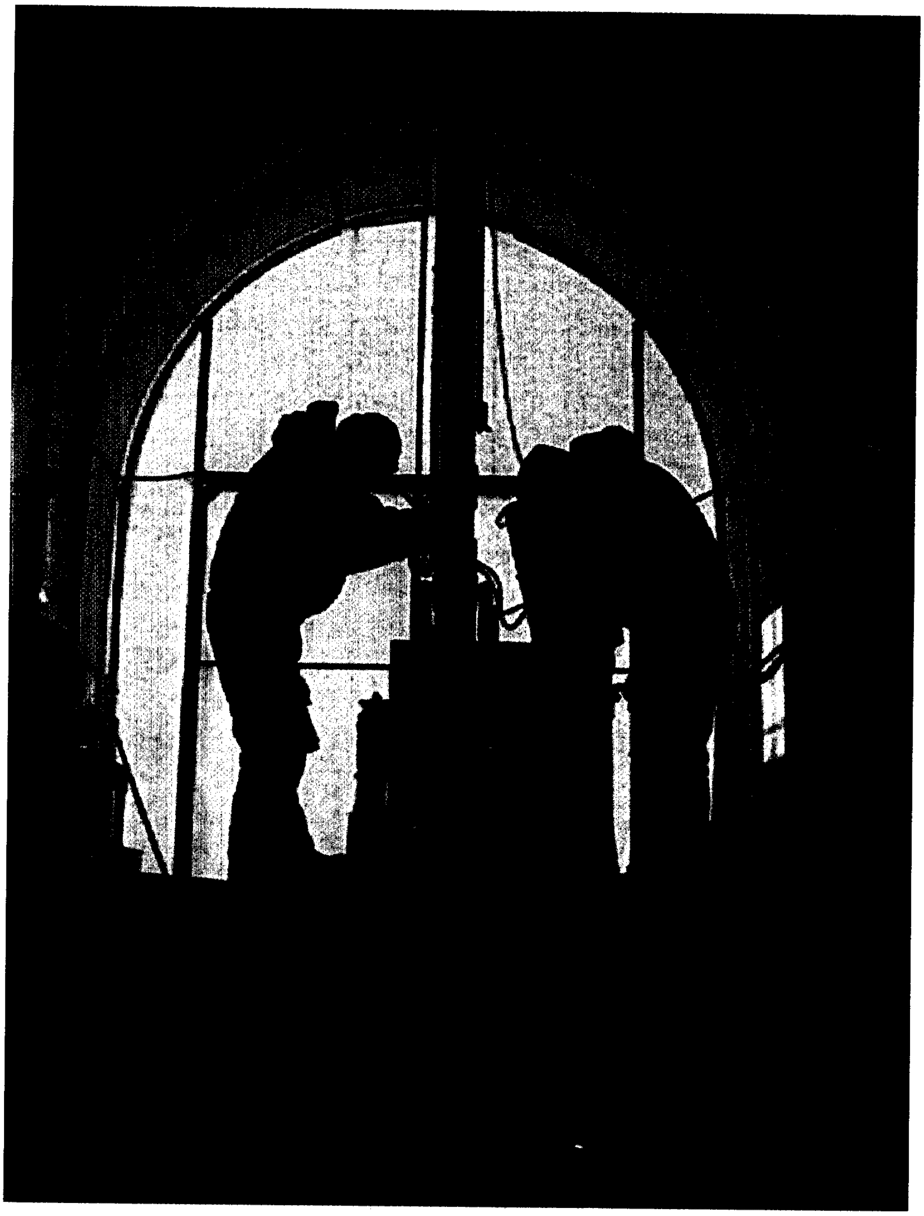

Fig. 9. Reaming activities.

5.4. Season No. 4: 1999–2000, move drilling tent and restart from surface

The drilling team arrived at Dome C on 25 November and left on 22 January for Christchurch.

1) Stuck drill

The tension found was 23640 N compared to 26020 N at the end of the previous season. We decided to pull once more on the cable for the hell of it. Getting the tension up to 29000 N. (NB: All load cell values have to be divided by two due to the wrong load cell indication we discovered later in the season). Twenty four hours later, we couldn't see any noticeable change in cable tension and the decision was made to start a new hole. We decided to cut the cable. All the heavy equipment inside the drilling tent would be moved in order to start the new hole.

2) Drilling tent move

We started to extend the floor area of the drilling site. Secured and emptied of the heavy equipment the tent was pulled 10 m by a vehicle (Fig. 7). As the installation of the shallow drilling equipment to start the new hole got under way, the deep drilling equipment was put back inside the drilling tent at the new location.

3) Pilot hole and winch weakness

We started the pilot hole 16 days after our arrival and 20 days later the new casing was in place (Fig. 8 and Fig. 9). Casing tubes were 20% heavier than the ones ordered in 1995. This did not have any consequences; we were able to put them down the hole using the tower and the winch from the deep drilling equipment. Putting down the twelfth tube we noticed a weakness in the winch motor. The winch was no longer able to hold the load properly (12 tubes=7440 N load). This was the first sign of winch weakness.

4) Assembly of the new deep drill

The shipping of the new tube was very efficient. Thanks to the excellent connection between the ship in Hobart and the traverse at Dumont D'Urville, little more than a month was needed to transport an oversized box (8.5 m long) from Grenoble to Dome C. This gave us the opportunity to start the assembly of the drill before the end of the season. The top part of the core barrel was modified and equipped with a bayonet device to release the core barrel in the hole in case the drill stuck again. This should free the outer tube and allow the operator to pull up the remaining equipment to the surface.

5) Cable shortage

Assembling and connecting the anti torque section, we found a defect in the cable on the winch. Two conductors had an armour shortage. After investigation, the decision was made to cut 1000 m off the cable. After this operation, 2168 m of cable was left on the winch.

6) Electronic equipment

We had several problems with the electronic equipment sent to Dome C. Several sets were not working. We had to run on spare parts and the electronic equipment had to be tuned to the new cable length before starting work. We performed many tests with the electronic equipment under load on a bench developed in Grenoble for this purpose. In spite of the repair, it had not been possible to make the LVDT sensor for the cutter load work and the motor stopped automatically several times before reaching the maximum current limit of the motor.

7) Wrong load cell indications

After calibration of the load cell on top of the tower, we discovered that the value indicated was wrong by a factor of two. That meant we had never pulled more than 15000 N on the cable the previous season instead of 29000 N, which is the elastic limit of the cable. The previous year we noticed that the core breaks were much more than in NGRIP, sometimes double. We checked that two wires of the external armour of the cable started to break just before the elastic limit. At that time the indication of the load cell was in phase with two parameters: the winch power and the elastic limit of the cable. We never pulled enough on the cable the previous season when the drill was stuck. We made one last attempt at the end of this season. This was unsuccessful. The conditions for pulling on the cable were not perfect because we did not have the right equipment available in camp. The attempt was ended by cable failure under 20000 N tension.

8) First EPICA core

On 19 January we were able to drill a core with the new version of the EPICA drill. Working without cutter load, we could drill a 2.8 m core in a smooth run with normal motor current. All recorded parameters were satisfactory. This unique run drilled with the new long version of the EPICA drill showed that the mechanical part of the drill was ready and operational for the following season.

5.5. *Season No. 5: 2000-2001, depth reached: 1458 m*

The drilling team arrived at Dome C on 23 November and left on 7 February for Christchurch. Due to severe problems with the C130 and bad weather conditions, the transportation of cargo and personnel for the EPICA program was delayed. All this affected the start of the season and we were ready to drill the first core on 7 December.

1) Confused drilling

The drilling was confused for several reasons until Christmas. We couldn't repeat good runs and only had occasional good runs. Sometimes there were motor current spikes without clear explanation in middle of the runs. Sometimes it was possible to restart and sometimes it was not. At the same time we noticed a reduction of the core diameter by 1 or 2 mm were we observed the current spikes. All parts of the drill were checked and tuned one after the other in order to find the source of the problems. This was done very carefully without any improvement in the behaviour of the drill. We decided to ream the bottom part of the hole to be sure of having a geometrically regular hole. During this reaming operation, the drill motor ran for more than an hour, leading to a mechanical breakdown in the motor section.

2) Motor section repair

We discovered a broken ball bearing. The steel cage was found in several pieces inside the second level of dynamic sealing of the motor driven shaft. The surface of the motor driven shaft was wounded and the bottom pressure tube plug, which guides this shaft, was damaged. In spite of careful repair, the trouble happened again a short while later. A piece of the damaged steel cage was inserted inside the wall of the bottom pressure tube plug. We had to machine a new drill motor shaft in camp. The consequence of the repair and modification was loss of control for a leakage of the dynamic sealing system of the motor driven shaft.

3) 50 RPM

After tuning the drill and repairing the motor section, the motor rotation speed was lowered from 70 rpm to 50 rpm. 70 rpm was the speed used in 97/98 and 98/99 the Dome C seasons without trouble. 50 rpm was closer to the speed used in NGRIP. Runs started to be repeatable and regular with a smooth low current until the chips chamber was full. Later when we went back to 70 rpm we had some trouble again with current spikes. It was difficult to find out why the speed, which had been used without significant trouble two seasons previously was no longer good.

Two years before, we had used some plates to divide the chips chamber in order to reduce the pulling out force. These plates acted as guides for the 4 m long hollow shaft inside the chips chamber. It was probable that without those plates, the shaft would reach a kind of resonance and disturb the drilling. Without being sure, this is, at the moment, the only logical explanation we can find.

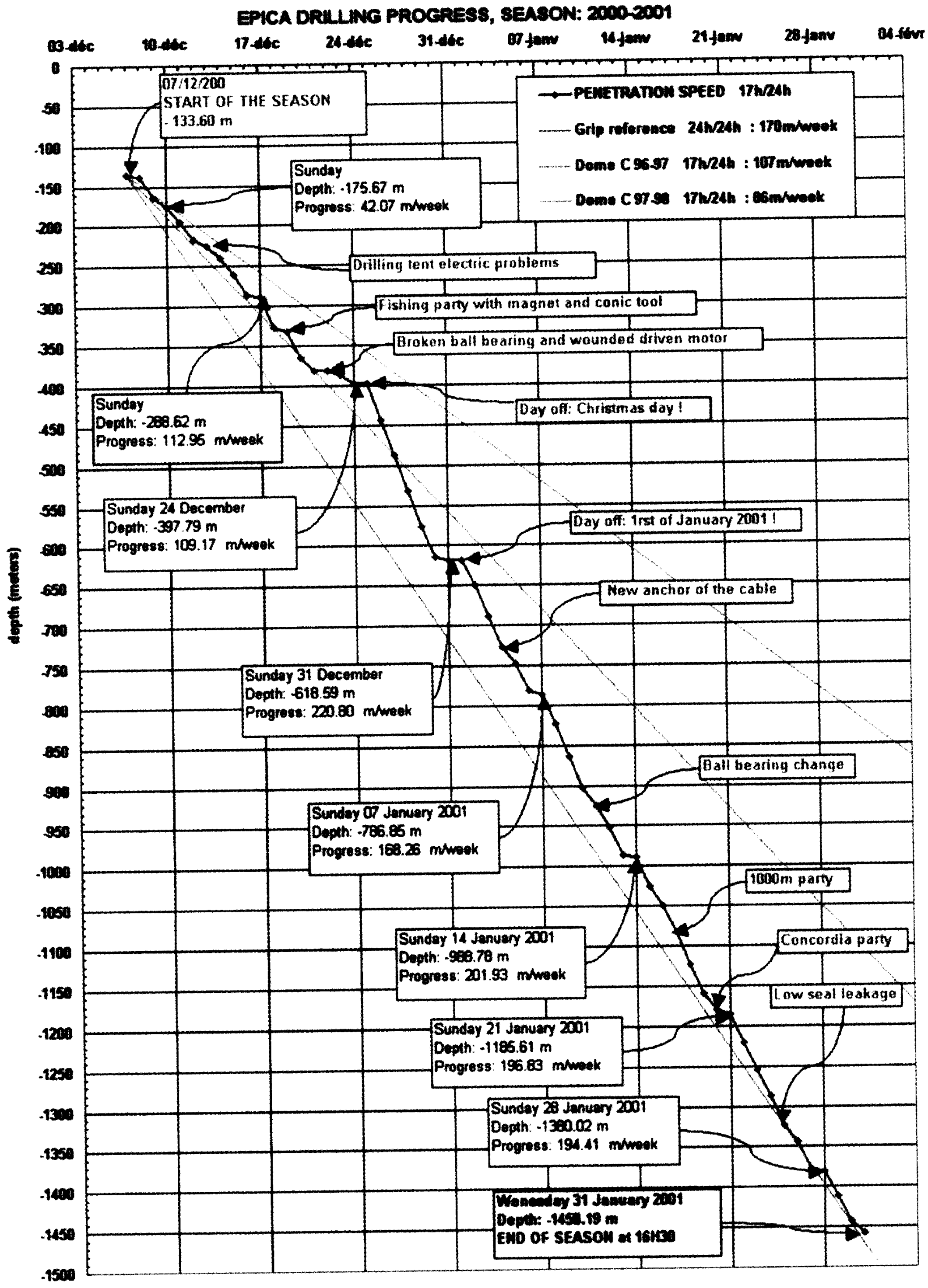

Fig. 10. Drilling progress season 2000–2001.

4) Tuning of the drill for good core production

The average production for the last five weeks of the season was 196 m of cores drilled per week. After Christmas the drill motor rotation was reduced to 50 rpm (Fig. 10). We had good regular runs in spite of mechanical problems in the motor section. Communication with the drill was not possible when the motor current was over 1.6 A. The drill had to be tuned to finish the runs in safety and to prevent accidents as much as possible.

We had to work within the drill capacity, which limited the tests we could perform. The loss of communication always happened at the worse moment of the run: just before the end. This is the worse time because, at the end of the run, there are many chips around the drill head and everywhere inside the drill and the pump. The drill is full of chips. When we lose communication, instantaneously we are blind. The only possible thing to do is to stop the penetration and wait for communication to resume. The communication came back after several seconds with decrease of the motor current. Sometimes, when the current spikes were not too high, the motor continued to rotate and chip transportation continued. Drill performance was limited by communications.

5) Season 2000–2001 statistics:

-Final depth: 1458.19 m.
-Number of runs: 528.
-Total distance covered by the drill: 796 km.
-Core length drilled: 1330 m.
-Core length average: 2.52 m.
-Total core weight: 9230 kg.
-Total dry chips weight: 8490 kg.
-Fluid consumption: 16 litres per metre (theoretical volume: 13.19 l/m).
-Total D30 drums: 85.
-Total 141B drums: 32.
-Hoisting and lowering speed: 1 m/s.
-Penetration speed: 3.5 mm/s.

6. Dome C drilling plans

There are still 1792 m to drill before reaching bedrock. The intent is to finish in two seasons from now. The best would be to drill as deep as possible in 2001–2002 in order to have to drill as little as possible in the last season. Close to bedrock the ice will be much warmer and we expect considerable difficulty and a reduced average core length. We will probably need manytimes to go through the last hundred metres. Next season the cable will be changed as soon as the depth of 2000 m is reached. In the same time the electronics should be improved in order to provide full power without disturbance of the data transmission. A few things will change from a mechanical point of view to increase the reliability of the pump. The interchangeable hollow-shafts with three pumps were, this year, a great improvement allowing good maintenance without disturbing productivity. Some modifications to the retrieval table guiding system and change of the plates on the hollow shaft simplify core extraction. All this should improve the reliability which was already very good last season from Christmas to the end of the season.

7. Conclusions

The fifth year of the EPICA program at Dome C was at the end a more routine year, with very high productivity. The season started with difficulties and mechanical breakdown. It was not possible to find a routine mode. The errors were confusing. When we reduced the cutting speed to 50 rpm, drilling became remarkable steady with production close to 200 m per week in 17 working hours per day. The pump is now very reliable and maintenance has been reduced to a minimum. The run time was 1 hour 15 min at 1400 m depth. Even though it is always possible to optimise, the drill is now approaching a mature state. In the last several years the same drill has been used in NGRIP and at Dome C. At both sites the drill has been stuck once, at 1371 m depth for NGRIP and at 786 m depth for Dome C. At each site a second hole has been started. A different team is working on each site. For this new equipment, this prototype, more than 2 km of drilling has been necessary to understand the full behaviour of the drill and confirm that we now understand better what can happen. These events show once more that ice core drilling is very complex and difficult.

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