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Sticking deep ice core drills: Why and how to recover

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Abstract: The GISP deep drill became stuck in 1981, but was free the following year. The NGRIP/EPICA deep drill has suffered from two big setbacks: The drill is stuck both at NGRIP in Greenland and at Dome C in Antarctica. Both events occurred in a period with routine drilling and high productivity. The reasons for the two events are believed to be different, but the chosen bore-hole liquid seems to be problematic. The densifier can adhere to the surface of the ice cuttings, making fine ice cuttings to sink in the liquid, in spite of a liquid density of 935 kg/m^3.

In spite of changed procedures and modified constructions, the drill became stuck again at NGRIP. It was freed using glycol, making use of both the temperature and temperature gradient in the hole.

1. Why sticking drills ?

Sticking a drill is fairly common for shallow drillings operating in an non-liquid filled (dry) and uncased hole. The most likely reasons are problems in moving cuttings away from the drill head, and snow falling from the surface down on top of the drill, filling the narrow space between the drill and the hole wall.

A deep drilling working in a liquid filled hole is inherently more safe. First, the cutting process itself is lubricated by the hole liquid, thereby to some degree preventing that the ice cuttings are sticking to the drill head. Also, the liquid will help guide the ice cuttings away from the drill head. Some cuttings will not be picked up by the drill right away, but because the drilling liquid in general has a slightly higher density than the ice, any ice chips not collected by the drill will slowly rise in the hole, and can be filtered out closer to surface. Next, a casing with lid will protect the upper part of the hole, preventing any snow to drop down. The more complicated drill construction for a deep drill, however, also means that more can go wrong. And as shown below, the modern and more high tech drilling liquids also possesses problems of their own.

The ISTUK drill used at Dye-3 (Gundestrup *et al*., 1984; Johnsen *et al*., 1994) became stuck in 1981 after drilling down in the silty ice. The core breaks became difficult, and finally the core did not break, trapping the drill. It was attempted to free the drill, using the hammer in the antitorque section, however without success. The drill was left for the winter under tension in the hole. Also, the density of the hole liquid was increased to ensure a positive pressure difference between the hole liquid and the ice. The following year, the drill was free, and inspection revealed that the problem indeed was caused by a core that did not break, there were no mechanical problems. The core was so ductile, that the core catchers had produced 10 cm long grooves in the ice core from the hammering, without causing the core to break. A later logging of the hole indicated, that the core broke within 3 months (Gundestrup and Hansen, 1984).

The first problem with the EPICA drill (Gundestrup *et al.*, 1996) happened at NGRIP in 1997 at a depth of 1371 m. The drilling was completely routine, with very high productivity. The only anomaly was a little high loss of cuttings, but the lowering speed of the drill in the hole did not show any accumulation of cuttings. Most likely, the drill became stuck, simply because the core did not break, thereby trapping the drill at the bottom of the hole. Unfortunately, the depth of the stuck drill was at the temperature minimum in the hole (−32°C). Using different techniques, it was attempted to place glycol at top of the drill, but in lack of a clear indication of the success of this technique, a barrel of technical glycol was pumped into the hole, hoping that it would drop down to the bottom, freeing the drill during the next months. This did not work, and the drill is still stuck. On reason for the failure of freeing the drill could be, that there actually was a higher amount of ice cuttings in the hole than anticipated. Experiments showed, that the chosen densifier (HCFC141b) adheres to the ice cuttings in the hole, making them dense. The theory then is, that these heavy ice cuttings "rained" down on top of the drill in the days following the sticking event, packing between the drill and the hole wall, thereby effectively moulding the drill to the ice cap. Figure 1 shows a mixture of ice cuttings in drilling liquid. In the left sample, the liquid is a mixture of D60 and HCFC141b to a density of 935 kg/m^3. In the right sample, the HCFC141b is replaced with HCFC123. Both samples have been stored about a week at −15°C, and shaken shortly before the picture was taken. In the sample with 141b, the ice cuttings separates in 3 fractions: At the top, we have the larger ice crystals, floating on the liquid. Smaller ice crystals are floating almost weightless in the liquid, and some have already sedimented to the bottom. In the sample with HCFC123 as densifier, all ice floats in the liquid. A test performed at −23°C show the same pattern, although not quite so pronounced.

Based on this experience, the drilling procedures were changed for the Dome C drilling in the Austral summer 97/98. First, the hole was filtered frequently down to the bottom of the hole, to ensure that the hole was clean. Next, the drill rotation, and thereby the drill pump was started above the bottom of the hole, and the drill slowly lowered the last meter or so, thereby pumping away the cuttings that may have accumulated at the bottom. This seemed to work fine, and in addition the pump that pumped the chips from the drill head to the storage inside the drill worked perfectly, with a negligible loss of ice cuttings. Everything worked fine until a depth of 780 m, where it was difficult to start the drilling. The drill did not penetrate. Three attempts were made to start the drilling, and it is assumed that the drill in total penetrated say 20 cm. Then it was stuck. The event is well documented from the logging of the information from the drill and surface electronics. The most likely reason for the event is, that the cuttings were not pumped away from the drill head due to a mechanical error. The result was a heavy slush at the

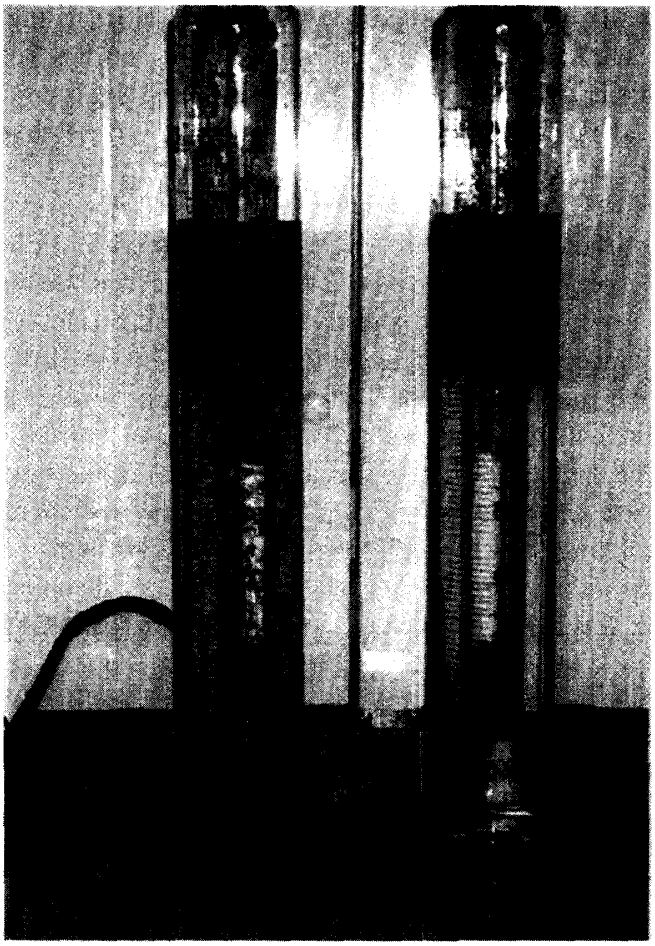

Fig. 1. The left sample contains HCFC141b as densifier, the right HCFC123. Both samples have been shaken shortly before the picture was taken. Ice cuttings in the left sample have absorbed 141b, increasing their density to or above the density of the hole liquid.

bottom of the hole was not pumped away before the actual drilling started, the cuttings then got squeezed between the drill head and the ice, resulting in a stuck drill.

The conclusion is, that the two events are uncorrelated, except for the densifier used to correct the density of the bore hole liquid. And at both events, the heavy ice cuttings created by the densifier was a major contributor to the problems. As usual, several things need to go wrong before an accident happens!

When the drilling resumed at NGRIP in 1999, a new densifier was used: HCFC123. This densifier did in a cold room test over several weeks not show any sign of adhering to ice cuttings, thus making them dense. This also worked fine in the beginning, however at depths more than 300 m, ice cuttings tended to accumulate at an increasing rate at the bottom of the hole. And at the same time, the mixture of hole liquid and cuttings was difficult to pump. The result was, that HCFC123 under pressure made the ice cuttings even more dense than the HCFC141b, and we had to replace the liquid in order to maintain a stable drilling.

We now knew, that the finer ice cuttings lost in the hole would drop to the bottom. This was controlled by having a night shift filtering the hole all the way to the bottom every night. Also, before the drill was started, it was lowered close to the bottom, and raised fast. The idea was, that the turbulence should remove the cuttings from the bottom of the hole, making them easier to collect in the drill before the drilling resumed. This technique worked well until a depth of 2500 m, where the cable had to be changed.

The new cable—a standard oceanographic cable as usual—was ordered tar free. Having 2500 m of new cable in the hole naturally produced some heavy residue in the hole, and the productivity suffered somewhat. However, in spite of diminishing problems in the first days after the cable was changed because the cable was cleaned in the hole, the problems seemed soon to increase, and already at a depth of 2600 m, we had problems with a heavy black substance that tended to clog the holes in the drill filter screen. This required extended cleaning operations between each run, and a shorter core length. Although the productivity suffered, the weekly production still exceeded 140 m/week. The problems with heavy ice cuttings falling to the bottom of the hole increased fast with increasing pressure and temperature. The longer run time also increased the sedimentation between runs, making the runs more and more irregular. On a good run, the motor current is stable until the end of the run, where the filter in the chip chamber start to be blocked. If the filter was partly blocked by contaminants or ice cuttings, the motor current rises. By holding back on the drill cable, the penetration stopped, and the pump in the filter would clean the drill, making it ready for the next cycle (Fig. 2). As time went on, more and more cleaning stops were required, and we also added filter runs during the day, in addition to the night filtering. At 2900 m, ice started to form on the cutters, which made it difficult to drill with a low pitch. Finally, at a depth of 2931 m, and a hole temperature of −6°C, the drill became stuck Sunday morning after a run with many lost cuttings, and a run with 8 drilling restarts. It was clear, that the cause was packing of cuttings in the spirals, rendering the pump ineffective and finally sticking the drill at the

Fig. 2. Motor current for two runs. The right run is good, with only one cleaning, the left needed 4 times cleaning. Time goes from right to left.

drill head.

2. Drill recovery

Having the drill stuck at this time, 2 days before a planned flight, required fast action. Within hours, the range of the cable load transducer was adjusted, giving a calibrated cable load range for the full strength of the cable. Also the stand of the hole liquid was raised to ensure over pressure at the bottom of the hole. The pull in the cable was increased manually to a cable tension of 17000 N. The tension then slowly decreased to 14000 N. Even while the cable was tensioned manually, the force in the cable tended to return to 14000 N, although with an increasing tendency. After 4 m of cable was wound manually, it was decided to stop. The ice higher up is colder, and it could be more difficult to get the drill free further away from the bottom. If the drill was raised too much, it would also not be possible to keep it immersed in glycol.

The next day, the drill was still stuck. Then, after several unsuccessful attempts of releasing the inner core barrel from the drill, a safety pin in the transmission broke, making further attempts of releasing it impossible. At the same time, more hoses were requested from Copenhagen. These extra hoses would make it possible to dump glycol below a possible high density hole liquid layer just below the casing. No change in cable tension could be observed. It was then decided to release 160 *l* of technical glycol (antifreeze) in the hole. Glycol is relative heavy (Industrial Solvents Handbook) (Fig. 3), and experiments showed that we could assume the glycol to fall in the hole with a velocity not less than 20 cm/s. In 4 hours after dropping the glycol, it should be active at the drill, and we

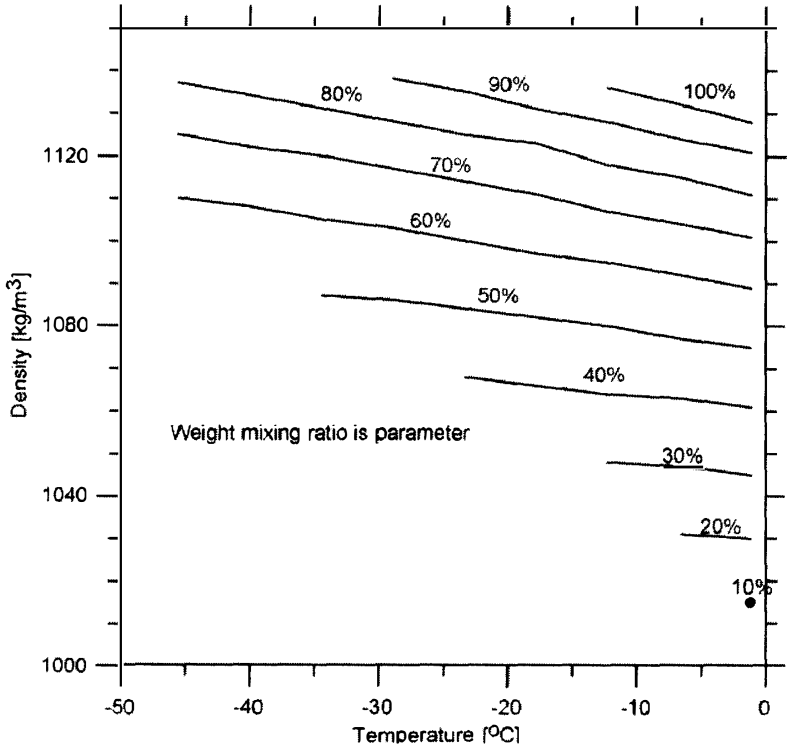

Fig. 3. Density of a glycol / water mixture versus temperature.

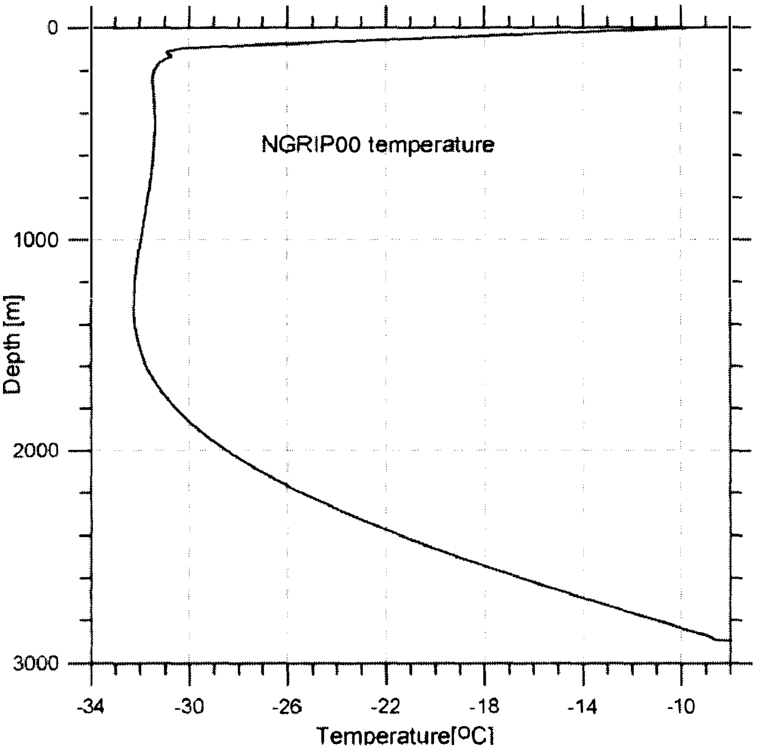

Fig. 4. *Temperature of the NGRIP bore hole.*

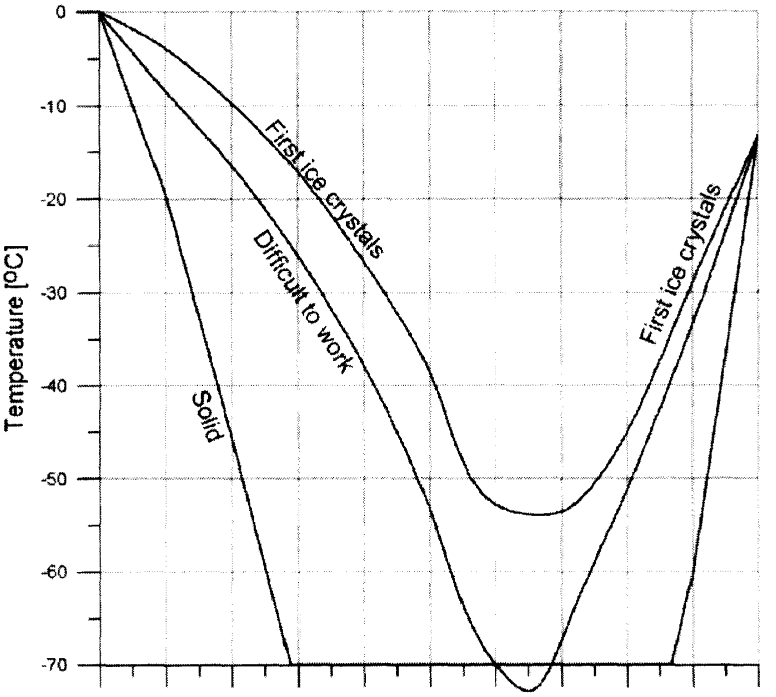

Fig. 5. *Freezing properties of a ethylene glycol/water mixture.*

should be able to see a temperature decrease in the drill temperature sensors.

At the same time, it was clear, that we had no indication about how much the glycol would be diluted when it arrived at the drill, 2900 m down in the hole. From the temperature sensors in the drill, the bottom temperature was known to be about −6°C (Fig. 4), *i.e.* below the glycol melting point of −13°C. It was then clear, by combining the calculated hole temperature *versus* depth with the glycol freezing properties (Fig. 5), Polderman (1969), that the optimal solution would be to drop frozen glycol in the hole. This glycol would stay frozen until a depth of 2750 m, and arrive essentially undiluted at the drill. Monday afternoon, experiments were performed to freeze the glycol, using a CO_2 fire extinguisher as cooling medium. The experiments revealed, that at a temperature of −32°C, the technical glycol was only half frozen. A Cryocool CC100 freezer and pure glycol was then requested and arrived Wednesday evening, 3 days after the event together with pure monoethylene glycol—a non colored substance. It was not trivial to locate the correct glycol as one company alone offered 600 different types and grades, all called something with glycol!

Before midnight, the CC100 freezer was set up, and some bags with technical glycol placed in a foam box to freeze. Later, the pure glycol was also placed in the freezer. It turned out, that the technical glycol did not freeze at −28°C. Thursday, experiments on how to freeze the pure glycol continued (Fig. 6). We decided to use plastic hoses, sealed in one end, and keep the other end above the cooling liquid. Also, we decided to cut the frozen glycol in pieces not larger than 5 cm, in order to avoid that it could be trapped between the hole wall, and the cable. Finally, at 2100, 3.5 kg of frozen glycol pills were dumped, followed by 2.5 kg at 0030. At 0200, a cooling of the electronic section of the drill was observed indicating that the frozen glycol had reached the drill, and was active

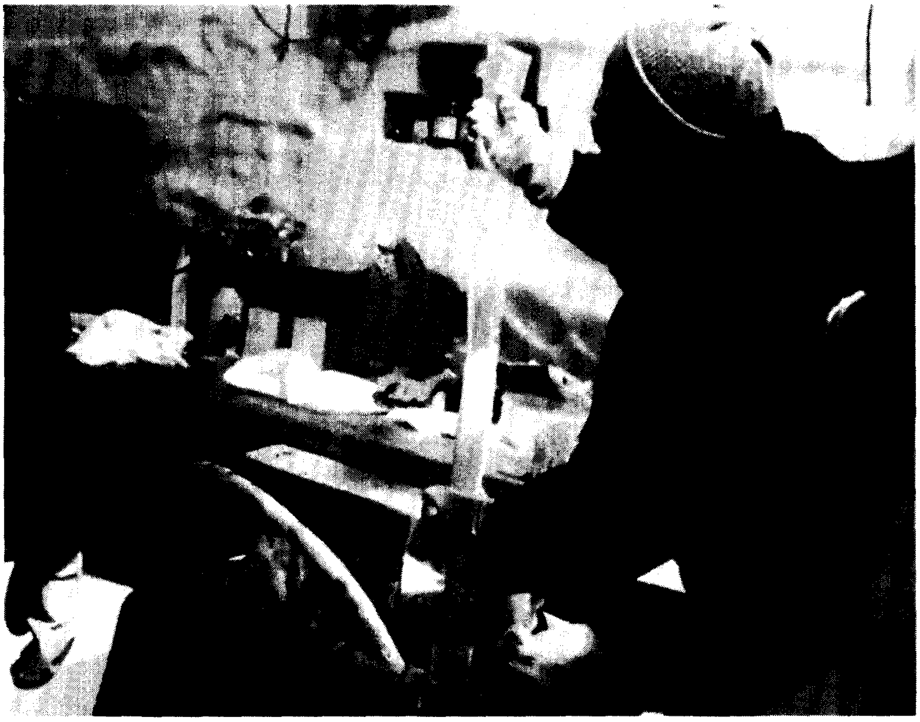

Fig. 6. Checking the condition of the frozen glycol.

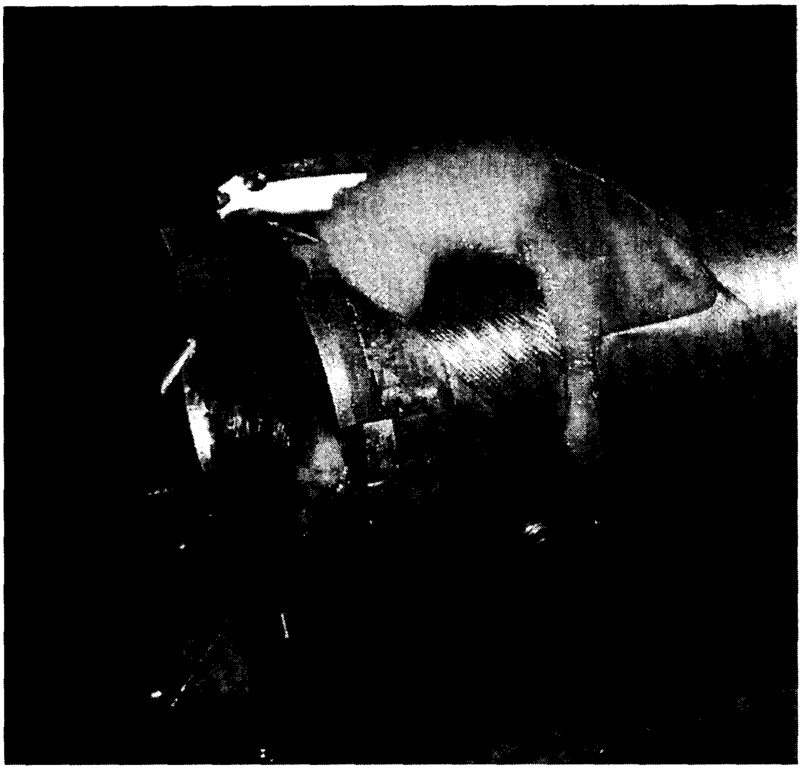

Fig. 7. The drill head after the drill was back on surface. One-third of the area was blocked by hard ice.

there. At 0509, the cable tension decreased from 10590 N to 5690 N. The temperatures indicated by the drill was then −9°C at the coolest sensor. The drill was slowly pulled to surface. At 0707, the drill was back on surface.

After a short celebration, the inner core barrel was removed. There was heavy packing around the core catchers, and it was clear, that the drill had been trapped here (Fig. 7). Also, one of the spirals was packed with ice at the bottom. The space between the inner and outer core barrels was filled with cuttings, but the coupling between the drill and the rotating inner core barrel was clean. It was easy to remove the core barrel, and there were no indications why it had not been possible to separate it from the drill. The pump did not show any anomalies. The 68 cm long core was extracted using alcohol, it was in two pieces, with the upper 3 cm piece showing sign of wear. On top was a hard packed 25 cm long slush cake. The core showed 7 increments of shorter and shorter penetration. The chip chamber was nearly empty.

3. Bailing

Having dropped 160 *l* of glycol in the hole with no apparent reaction on the drill meant, that we could assume about 1 tons of glycol slush at the bottom of the hole, with a consequent damage of the hole wall. This slush needed to be removed for the drilling to continue. In order to get an impression of the slush properties, several test samples with mixtures of hole liquid, ice and glycol were stored at −6°C, the same temperature as the glycol in the hole. During the test, the temperature in the sample was monitored, and it stayed close to $-6°C$. These test samples showed the slush to be a thick homogenous substance, that should be relatively easy to collect with a bailer. Also, we performed experiments to see how fast a 5 cm piece of frozen glycol would be dissolved in the mixture. After 4 days, the piece was still only partly dissolved. This indicated, that the glycol melting/dissolvent rate is heavily dependent on pressure, *i.e.* in the bore hole at a pressure of about 280 Bars, the melting/dissolvement rate is approximately 20 times faster than at normal pressure. This was later confirmed, when the bailer got stuck. Friday afternoon, the first slush run was made using a short bailer. Fifty-two m above the bottom of the hole, the electronics showed errors, and excess current was drawn from the surface power supply: The electronics was partly shorted. Pulling up, the short disappeared. Going down, the short reappeared. For operating the bailer, it is essential that the electronics works. If not, the bottom valve can not be closed. Thus, the bailer was finally operated by lowering it fast into the slush, and immediately closing the valve, before the electronics shorted. This procedure was used for the first two slush runs. Then it was decided to change to a longer (8 m) bailer. Using the long bailer Saturday July 29, it only shorted on the first run. The electronics survived the abuse, although the brass centre conductor in the antitorque showed clear sign of electrolytic corrosion.

It was difficult to remove the glycol from the tank, because it froze on the way up. It needed to be heated by the Herman Nelson heater and covered with an air duct for one hour, before the glycol could be removed. The glycol was then moved to a slush factory. First, the more solid slush was removed. Next, the hole liquid/slush was moved to a cooling drum. When cool, the boundary layer between glycol and hole liquid was determined by a conductivity measurement, and the hole liquid recycled. The glycol mixture was deposited. Using this procedure, we minimized the environmental impact of the operation to dumping snow containing glycol.

The bailing operation was never routine. In contrary to the experiments, the glycol in the hole build solid bridges at the top of the glycol layer. We speculate, that the temperature gradient in the hole make the glycol mixture unstable, creating one or more convection cells (Fig. 8). This convection effectively remove ice from the lower part of the hole, and deposit it at the top of the slush layer, where the temperature is lower, and less ice can be dissolved by the glycol. In order to pass the bridges, and fill the barrel, it was required to go into the glycol with a speed of about 30 cm/s. And even with this speed, the penetration almost stopped at bailing run 15, Monday July 31 at 88 m above the bottom of the hole. Then a scraper was mounted vertically on the bottom valve of the bailer (Fig. 9). The idea was to use this valve with scraper as a sort of drill by rotating the drill motor backwards. The valve is not intended for continuos operation, so we expected some problems. Also, the surface drill control program was modified in order to make this form of reverse drilling easier. Finally, 0.5 kg of frozen glycol was used to soften the glycol bridges.

It worked, and until run 23, at a slush height of 75 m we had reasonable penetration. Then the glycol slush bridges got too strong. The scraper was then modified on August 1 to extend 5 mm below the bailer, and 1 mm further out. Lowering this device with 15 cm/s while rotating the scraper, broke the bridge. We were aware, that the bailing operation now was highly risky. The glycol freezing factory was reestablished, and 3 kg

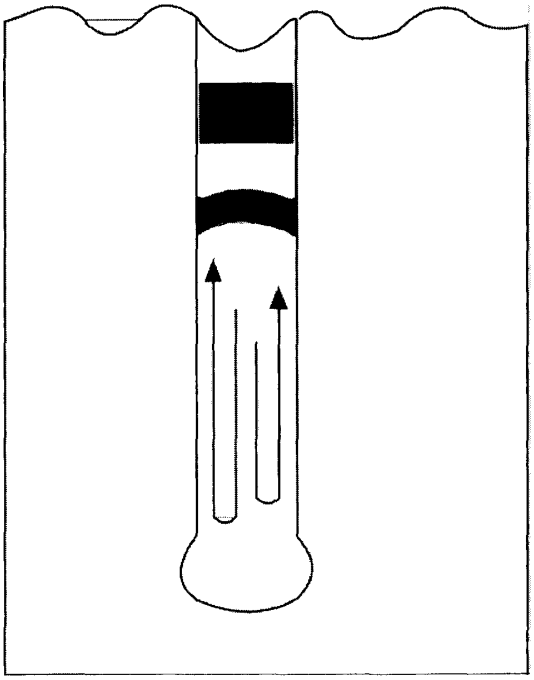

Fig. 8. Estimated flow of glycol in the hole. The flow is maintained by the temperature gradient.

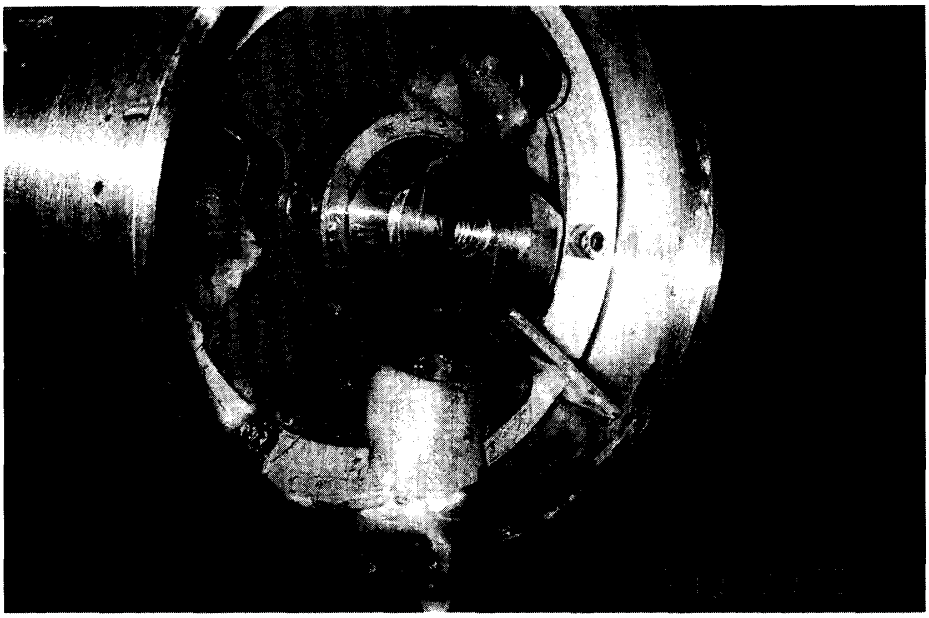

Fig. 9. Bailer mounted with scraper, first version.

of frozen glycol was ready at any time, should the bailer get stuck.

The bailing then continued in relative routine until August 3, where one of the 4 wires in the cable shorted to the steel armour. The faulty wire was disconnected. With the risk of losing the wires in the cable, it was decided to log the bore hole before continuing the

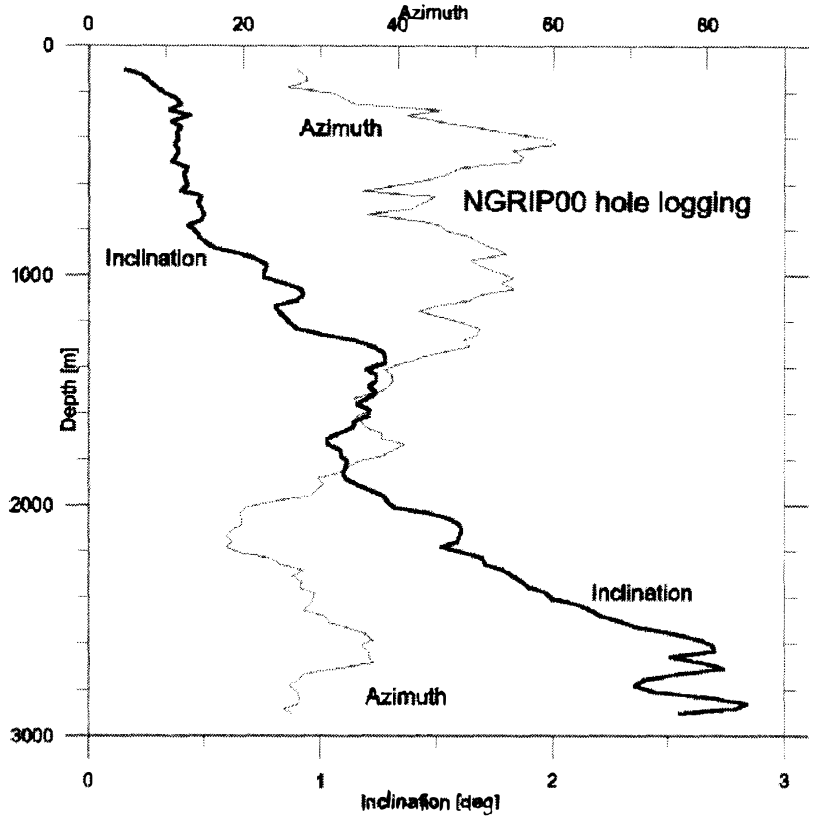

Fig. 10. Inclination and azimuth of the bore hole. The inclination clearly shows the unstable drilling deeper than 2600 m.

bailing. The logging showed the first sign of the hole wall being dissolved by the glycol at 2820 m, 110 m above the bottom of the hole (Fig. 11). At 2880 m, 50 m above bottom, the diameter frequently exceeded the range of the calipers of 174 mm, compared to the undisturbed diameter of 129.5 mm. Note, that the logging did not go all the way to the bottom, at 34 m above the bottom, the tool shorted due to the conductive substance in the hole. The diameter curve can—a bit speculative—be explained by the technical glycol starting to dissolve the hole at 2820 m, being exhausted before reaching the drill 110 m futher down. The frozen glycol started to be active at 2880 m, and remained active due to its frozen condition until reaching the drill.

Following the logging, the 24 hour bailing shift continued. Again, it got more and more difficult to continue due to bridges. Friday, August 4, at run 42, a more aggressive scraper was mounted. It sticks 1 cm out of the barrel, and 1 mm to the side. The angle is 80 deg, and it has a sharp edge with relief angle. This tool was used for the last part of the season. In spite of this aggressive tool, we still had to go down with up to 30 cm/s in order to penetrate the bridges, that seem to build up, almost as fast as we bailed. Bailing continued in 24 hr shift. It was still required to lower the bailer with 30 cm/s in order to break the bridges, but Sunday morning August 6, it seemed that we finally got down to the glycol liquid: After the bridge was broken, the bailer was hanging free in the hole at a depth of 10 m above bottom of hole. The same happened for the next run #53, the bridge was penetrated, and the bailer lowered 3 m free hanging. Pulling up, the bailer

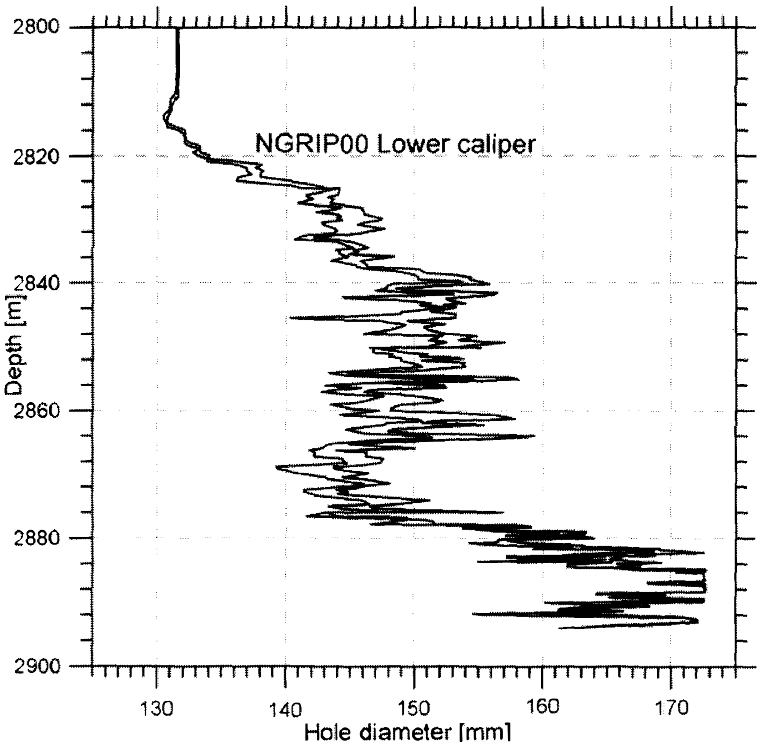

Fig. 11. Diameter of the lower bore hole.

was stuck! Immediately, 0.6 kg frozen glycol was released in the hole. It is worth noting, that the bottom of the bailer was situated where the drill was stuck previously, and the diameter of the hole may be less than for the region above, where we would expect that the glycol had increased the diameter significantly. Maximum cable tension used was 15000 N. The bailer was left with a cable tension at the bailer of 5500 N. Based on temperatures from the electronics, the glycol was active around the drill latest 6 hours after the glycol was released.

Monday August 7, the temperature at the electronic section went down to -12°C, and the temperature distribution indicated the lower part of the electronic section to be colder than the top, suggesting that the active glycol was moving down. Also, the liquid in the hole was raised to 67 m, ensuring a positive pressure difference at the bottom of the hole.

Tuesday, the bailer was not free. At the same time, the electronics showed the inclination to increase with time. We had assumed, that if the bailer was stuck at the bottom, the inclination should decrease with time, as the glycol created more clearance around the upper part of the bailer and antitorque. That the inclination now increased, could be interpreted as the bailer being stuck at the top, and not at the bottom. It became clear, that a different treatment was required. During the night, we continued dropping 1 kg of frozen glycol each hour, at the same time as 60 kg frozen glycol was prepared in 3 cm plastic tubes. The tubes were placed in holes in a cave below -13°C. At 1800, Wednesday, the 60 kg was dropped within 15 min. The 1 kg/hr treatment continued. At 2203, a step on the cable, and the tension dropped from approximately 1.5 tons to 5600 N. At 2209, the bailer was slowly raised, and at 2335 it was on the surface, greeted by our last

Fig. 12. Bottom of bailer when it arrived at surface. Bottom is filled with frozen glycol. The scraper can be seen. The valve is in closed position, although it is difficult to see.

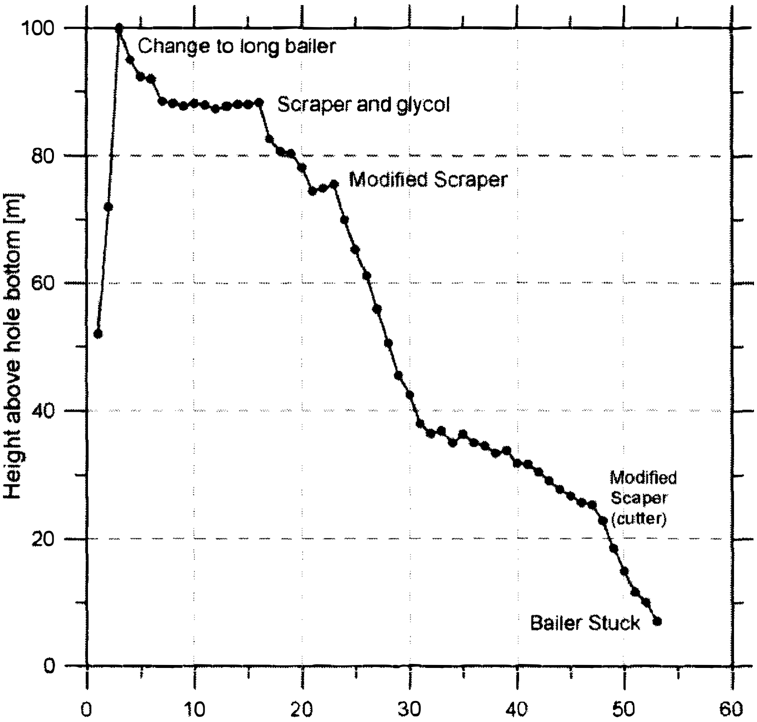

Fig. 13. Progress of bailing operation.

champagne. There were several pieces of frozen concentrated glycol in the antitorque section, at about half of their original size. These pieces must originate from the glycol dropped down 3 hour earlier. Compared to our tests, this is a much higher dissolvent rate.

It seems, that the reaction rate of glycol is highly dependent of pressure. Inspection of the bailer and damage to the leaf springs in the antitorque revealed, that the unit had been stuck at the antitorque section, and not at the bailer end (Fig. 12). Our 70 kg of glycol dropped slowly the last days had then melted at the antitorque, and slowly seeped to the bottom, making the hole larger below the antitorque. First when it got the massive amount of glycol, the glycol concentration at the antitorque was large enough to free it. Checking the logbook, we could identify the incriminating layer as a hard layer 20 m above bottom. Next the short (4 m) bailer was mounted. The purpose was to get an idea about the stand of the glycol, and if possible remove some of it. The bailer went smoothly down to 30 m above the bottom, at what depth it was closed and hoisted to surface. Here the tower tilting motor broke, stopping further cleaning attempts for the season. The bailer contained little glycol, and we expect the glycol to be in the lower 20 m of the hole.

4. Summary

The authors have had the mixed pleasure of being involved in 6 deep drilling operations, Dye-3, GISP, GRIP, NGRIPI, Dome C and NGRIPII. In 4 of these drillings, the drill became stuck, and two drills were lost. Two cases (3 if we include Dome C) were due to difficulties in breaking the core. Two (3 if we include Dome C) were caused by the densifier used. The more advanced HCFC liquids used to adjust the density of the bore hole liquid can adhere to the ice cuttings, causing them to sediment in the hole. This property is highly depending on pressure and temperature, and that a liquid does not show any anomaly at atmospheric pressure does not in any way make it unproblematic as densifier in a drilling operation. The old CFC's did not show this anomaly, and the properties of the newest type, the HFC's are not known.

The dissolvement rate of frozen glycol is highly dependent on pressure. At a test, a piece was not completely dissolved in 4 days at the surface, where as the same amount of dissolvement took only 4 hours at 280 Bar. Also, the glycol solution, at least at temperatures close to the pressure melting point, can not be regarded as a stagnant solution. Due to the temperature gradient in the hole, circulation cells are formed, moving ice from the deeper parts higher up in the hole.

One drill was free, simply by keeping a large force in the cable, and ensuring a positive pressure difference in the hole. Using the technique of dropping frozen glycol, one drill was recovered from a depth of almost 3 km. Using this technique, it should be possible to free a drill stuck in a deep hole, provided it is stuck at a depth with increasing temperature with depth. By adjusting the glycol/water mixture of the frozen pills, the technique should be useful at temperatures down to approximately −30°C. At lower temperatures, the effectiveness of the glycol may be too low, and the correct water/glycol mixture too critical.

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