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Instruments and Methods

A hot-water ice-coring drill

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ABSTRACT. A new method of ice-core drilling uses an annulus of hot-water jets to melt out a cylindrical ice core. This lightweight device used in combination with a fast hot-water drill can quickly obtain ice cores from any depth.

INTRODUCTION

Ice cores are retrieved from glaciers and ice sheets for the purpose of studying the physical properties and chemical composition of the ice, and particularly for obtaining climatic records contained in the ice. Mechanical and electrothermal ice-coring techniques have been greatly developed and have been employed in major drilling projects in Greenland and Antarctica and on smaller ice caps and glaciers (Shreve and Kamb, 1964; Ueda and Garfield, 1968, 1969; Hansen, 1976; Korotkevitch and Kudryashov, 1976; Rand 1976; Rufli and others, 1976; Browning and others, 1979; Zotikov, 1979; Johnsen and others, 1980; Gundestrup and others, 1984; Holdsworth, 1984; Stauffer, 1993; Mayewski and others, 1994; Thompson and others, 1995). Hot-water drilling has been used extensively to provide deep access holes for borehole geophysical measurements within the ice and at the base of the ice (Engelhardt and others, 1990). Hot-water drilling is efficient and fast. With the Caltech hot-water drill, a borehole 100 mm in diameter and 1000 m deep can routinely be drilled in cold ice of −26°C in <24 h. This drilling technique is based on designs by Iken and others (1977, 1989), Taylor (1984) and Iken (1988).

CONCEPT AND DEMONSTRATION

Even with modern designs, ice-coring by means of a mechanical drill is time-consuming and expensive, but it is still the preferred way to recover a complete ice core. Where a complete ice core is not required, however, a combination of hot-water drilling with an ice-coring capability is desirable.

The new concept of drilling ice cores with hot water was developed and tested for the first time in the 1992/93 Antarctic drilling season. In the 1993/94 season, the hot-water ice-coring drill was fully developed and successfully used to retrieve 18 ice cores up to 2 m long and 70 mm in diameter. The ice cores were drilled at depths of 300 and 950 m in the heavily crevassed chaotic shear zone between Ice Stream B and the Unicorn (83°37′ S, 138°3′ W) (Jackson and Kamb, 1997). On Siple Dome, a series of hot-water drilled ice cores, spaced 100 m apart vertically, were drilled from the top to the bottom of the ice sheet during the 1997/98 drilling season (Gow and Engelhardt, unpublished). The Siple Dome cores were 94 mm in diameter and 4 m long. The bottom core contained some rock fragments. In principle, a continuous hot-water drilled ice core could be obtained, but this has not been attempted, because of the novelty of this tool which is in its rigorous demonstration phase. The many setbacks in mechanical ice-coring, however, show that this time-proven method has many problems of its own. The Siple Dome cores will enable us to compare the two drilling technologies from the point of view of core quality in the first place, but also regarding logistics, cost, efficiency and speed.

DESIGN

Two hot-water ice-corers were built, for 70 and 94 mm diameter ice cores. The core-barrels were 2 and 4 m long. A sketch of the complete 70 mm ice-corer is shown in Figure 1. In Figure 2 more details of the scaled-up 94 mm version are shown. The essential part is the lower ice-core-cutting device that consists of 40 holes, each 1 mm in diameter, on an annulus with a diameter of 108 mm. The axes of the small holes are tilted outward at an angle of 12° to the vertical axis of the corer. As the corer is lowered and the jetlets spray hot water, an ice cylinder is cut and pushed up into the plastic tubing behind the cutting head. The large number of hot-water jets and the slightly conical shape of the cutting head through which the ice enters the core barrel guarantees a cylindrical ice core, 94 mm in diameter, from a borehole that has been drilled and reamed to a diameter of 150 mm. Built into the cutting head is a core-catching device consisting of two sharpened spring-loaded wedges that are pushed back into the wall by the upward-moving ice cylinder. Raising the corer causes the wedges to grab the ice, break the core free and prevent it from sliding out. A picture of the coring head is shown in Figure 3.

The hot water is supplied by the same hydraulic hose that is used for the hot-water drilling of the borehole. At the upper end of the corer, the hydraulic hose is connected to a backdrill as shown in Figure 4. The hot water passes through the backdrill before it enters a manifold (Fig. 5) from where it is conducted through four thermally insulated 6 mm stainless-steel tubes along the outside of the Lexan core barrel to the cutting head.

The backdrill comprises a mechanism that can redirect the flow of hot water from downward to upward in case the borehole is blocked by refreezing and backdrilling becomes necessary. Figure 4 shows the construction of this mechani-

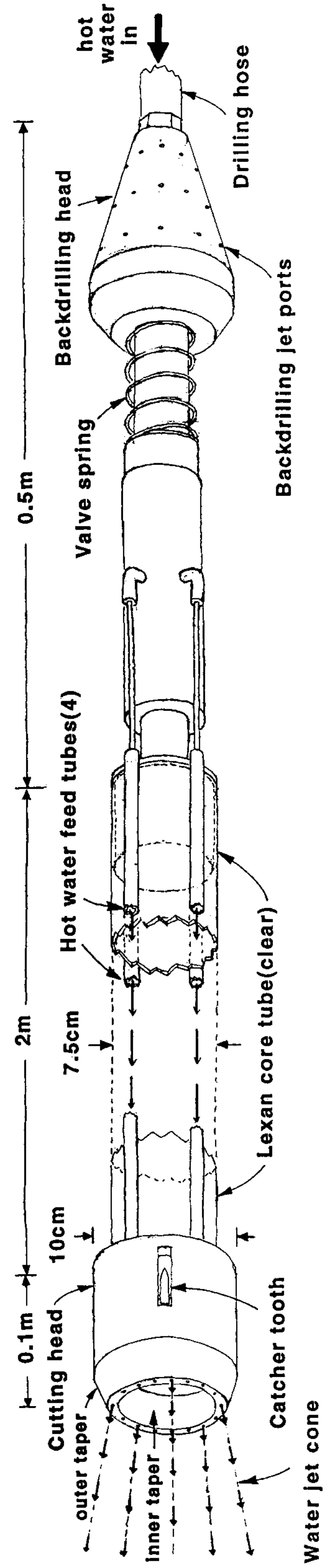

Fig. 1. Complete assembly of hot-water ice-corer for 70 mm diameter ice cores.

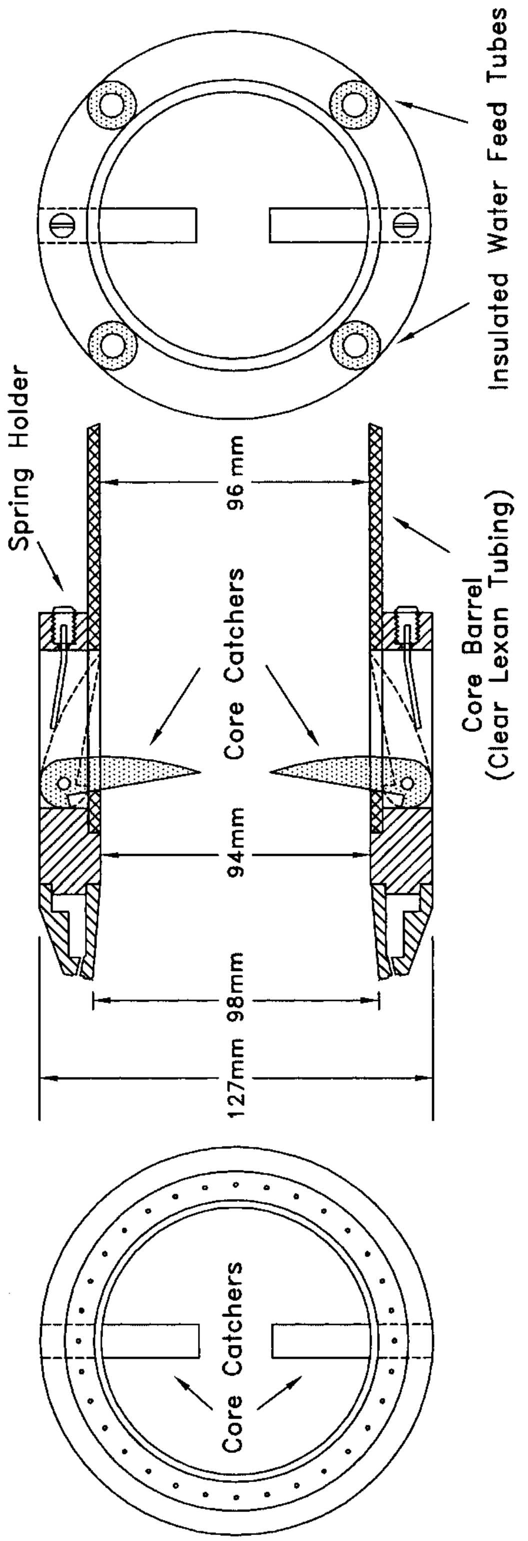

Fig. 2. Design of drilling head of the 94 mm corer.

cal flow valve in two plane views that are perpendicular to each other. One view is in drilling, the other one in backdrilling position. The backdrill assembly consists of two parts that can slide against each other. In normal drilling operation the outer part is held in the upward position by a spring (right view). If, however, on pull-up the outer part is held by an obstruction in the borehole, the inner part that is attached to the high-pressure hose is pulled up against the spring until it comes to a definite stop (left view). In this position, the water passage to the drilling head is blocked, but it is redirected through a pattern of 36 jets against the obstructing ice above the corer. This simple device guarantees the safe retrieval of valuable borehole instruments, like

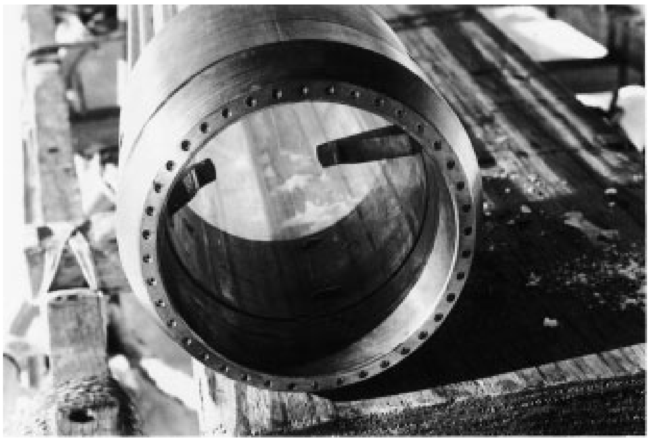

Fig. 3. Oblique view of drilling head with nozzles and spring-loaded core catchers.

the ice-corer, and eliminates the need for oversize boreholes, thus saving time and fuel. Of course, the aim is to drill a borehole of just the right size using optimizing drilling programs that control the drilling speed for any given drilling parameters, such as hot-water flow rate, hole diameter, ice temperature, depth and heat loss. However, the many uncertainties of the actual borehole-drilling operation do not lead to such an ideal borehole. The backdrill serves as a built-in self-rescuing device that we learned to appreciate whenever emergencies occurred over the years of drilling.

OPERATION

The hot water for coring is generated at the surface and supplied through the 19 mm inner-diameter high-pressure drilling hose to the ice-corer at depth. Although our heaters and pumps can supply up to 65 L min^{-1} at 95°C at the surface, the coring works better at a lower flow rate of 40 L min^{-1}. Since the water temperature is 95°C at the surface and decreases to about 30°C at 1000 m depth, because of heat loss through the hose walls, the drilling procedures depend on the depth. For 300 m depth the procedures are as follows. In order to avoid melting of the ice core during transit to the surface, the water in the borehole has to be kept at the pressure-melting temperature at all depths. Therefore, the

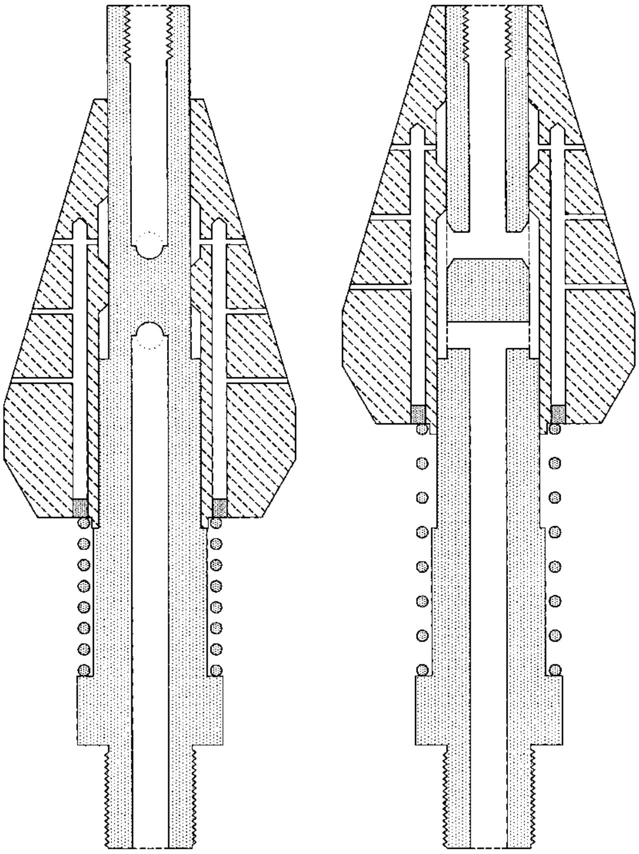

Fig. 4. Backdrill in two plane views perpendicular to each other. The right side shows the coring position with spring fully extended. At the left is the backdrilling position with spring fully compressed. Backdrilling is activated by pushing the conical outer part down against the spring. The water is diverted from flowing downward to flowing sideways through small spraying holes in the conical backdrilling head. The plane view also shows 2 out of 12 holes drilled vertically into the outer part connecting the small spraying holes with the inner chamber. They are plucked off at the entrance where the spring is seated.

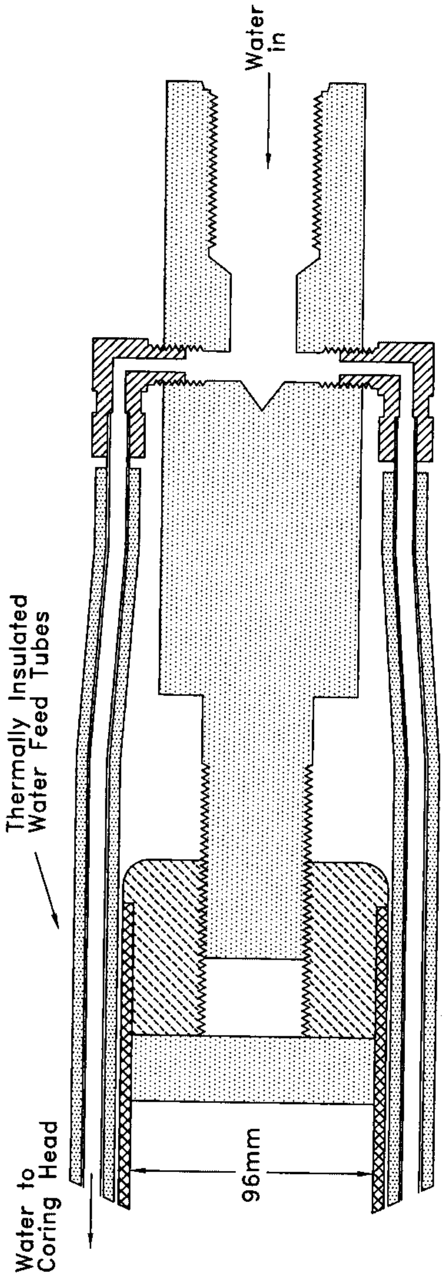

Fig. 5. Manifold to divert hot water into four small, insulated tubings for piping along the plastic core barrels down to the coring head.

core drill is lowered while cold water is pumped through the hose to the coring head. The exact bottom of the borehole is sensed using a load cell that measures the weight of the submerged hose and corer. The corer is raised from the bottom of the drilled borehole by at least 5 m, and then the hot-water flow is switched on suddenly. The water temperature of 95°C at the surface will drop to 67°C at the corer in 300 m depth. A previous experiment determined the time the water needs to reach the tip of the corer, in our case about 4 min for 300 m depth. That time period is available for the corer to be lowered again to the ice bottom to start the coring action. At that moment the corer has to reach a coring speed of 80 m h^{-1}. It takes 5 min to drill a 4 m ice core in 300 m depth. If we drilled for a longer time the corer would bottom out, which can be sensed by the load cell. In this case no more ice can enter the core barrel, and the ice core would start to melt off from below. When coring is complete, the hot-water flow has to be switched off immediately. As the corer is being pulled up, the core catchers grab and some extra pull is required to break the core loose at its lower end. High initial lifting speed assists the rapid progress of the core through the lower warm zone. Since there is still warm water in the hose, no water should flow for the first 20 min. Later a trickle flow is necessary to avoid freeze-in in the upper part of the borehole above the water level at the firn–ice transition where the ice is very cold. Too low a coring speed leads to smaller-diameter cores with a wavy surface. Too high a speed produces cores that are too large in diameter to fit into the core barrel. The cores will eventually fit but will have necks and segregate into several pieces. With adherence to established procedures, ice cores of consistently good quality can be drilled.

Thermal shock of the ice during hot-water drilling does not pose problems, because the cutting is done at the in situ overburden pressure. However, removal of the ice to the surface has to be carried out slowly enough to allow relaxation of the pressure within the ice. This is especially important for the so-called brittle-ice zone at about 300–1100 m, where air bubbles in the ice are highly compressed. Ice under so much internal pressure, when removed from the borehole, easily fractures either spontaneously or upon slight mechanical stresses or exposure to sunlight. Below the transition from bubbly ice to clear ice the air is incorporated into the ice lattice, forming a clathrate structure. This ice is ductile and quite easy to handle. About 1 hour may be required to raise the core from 1000 m to the surface to prevent the ice from fracturing. Hot-water ice-coring is conducive to the retrieval of complete ice cores from a zone where mechanical drilling encounters brittle ice. Most of the hot-water drilled ice cores reached the surface intact. Only handling at the surface produced some fractures, but not nearly as many as in cores drilled with the mechanical coring drill. We found that ice from the brittle zone has to anneal for several hours at the surface before it can be touched by mechanical means, such as a saw, without fracturing into many pieces. Sunlight is also detrimental to the integrity of the freshly drilled ice cores.

Since hot water can be conducted over considerable distances, we set up the water production at a suitable site near the edge of Ice Stream B. From there we pumped the hot water through a hose on the surface to the remote sites in the chaotic shear zone between Ice Stream B and the Unicorn to use it for drilling and ice coring. One of our remote sites was 1.7 km from the main production site where all the high-pressure pumps, heaters and reservoirs were installed. A small lightweight booster heater at the remote site increased our drilling speed. It would have been extremely difficult if not impossible to do this kind of work using a conventional mechanical corer.

Figure 6 shows an ice core drilled with our new technique on Ice Stream B. It shows the sharp transition from

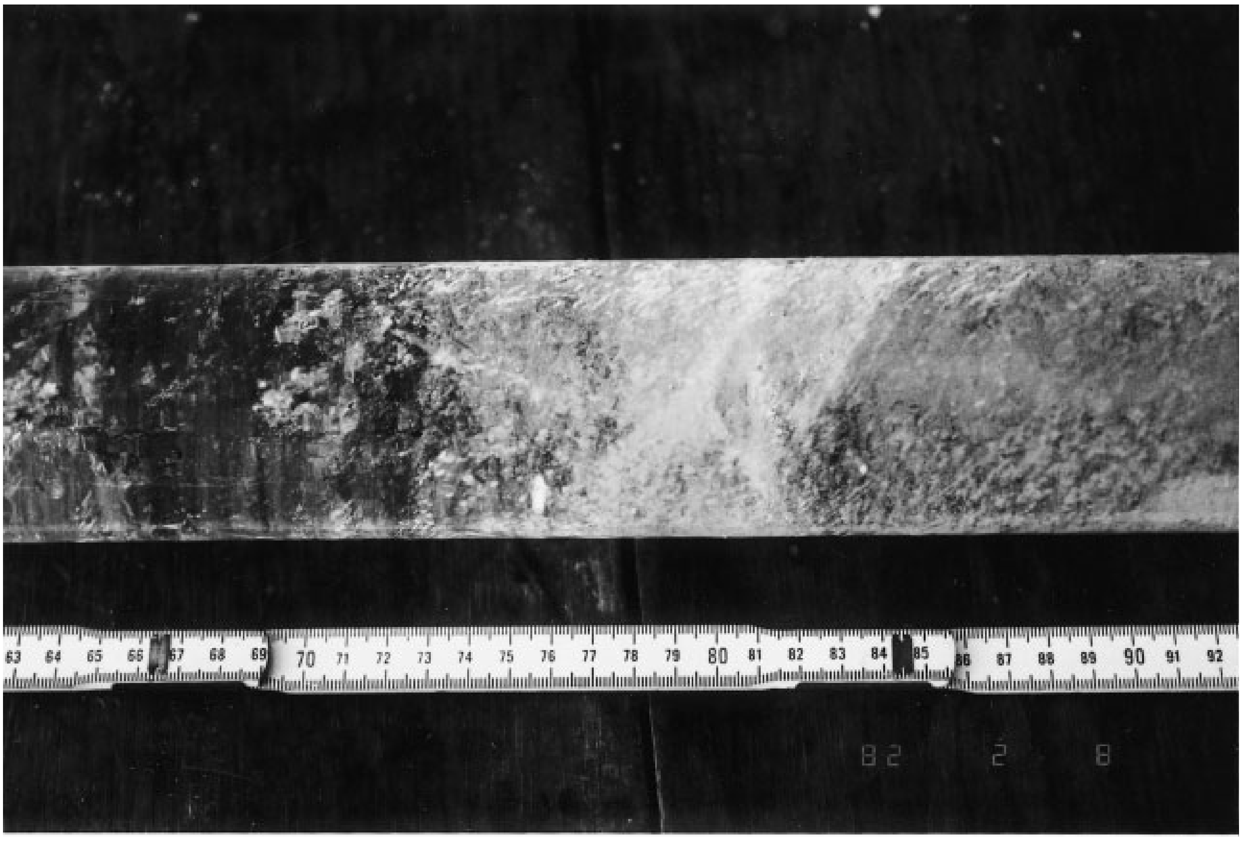

Fig. 6. Hot-water drilled ice core from 1100 m depth showing the transition from bubbly ice at right to clear ice at left.

bubbly ice to clear ice at 1100 m depth. Thin sections of the Siple Dome ice cores have been prepared by A. Gow (Gow and Engelhardt, unpublished). These thin sections, from ten discrete depths spaced about 100 m apart down to the bottom at 1004 m, were cut a few hours after drilling, whereas thin sections from the main Siple Dome ice core, drilled mechanically, could not be cut below 700 m in order to avoid further disintegration of the badly fractured ice core. These thin sections also revealed that the ice fabric and composition is not altered by the hot-water drilling process. At most, the outer 2 mm of the core might be affected, where some freeze-on may have occurred. The ice core is exposed to warmer conditions in the water-filled borehole for no more than 1 hour, depending on depth, before it is stored at temperatures of −22°C.

CONCLUSION

The hot-water ice-corer is a possible alternative to, but certainly is a tool that complements, mechanical core drilling. Some of its advantages over its mechanical counterpart are obvious. It is light, weighing only 30 kg when empty, is sufficiently portable to be used in remote locations and on traverses, and is fast. In conjunction with a hot-water drill that can provide deep access holes quickly, it can deliver a series of ice cores for site-selection studies and for determination of all ice properties where a complete core is not essential. It could be targeted for specific depths, like the Holocene–Wisconsin transition, or some other recognizable horizon to be followed laterally to demonstrate the continuity or discontinuity of structural and compositional features in the ice. Since borehole-drilling and ice-coring is done with hot water only, contamination with other fluids used in mechanical drilling like *n*-butylacetate or diesel fuel cannot occur, and ice-cutting chips are not produced, thus simplifying the core-handling procedures. A small, lightweight (60 kg), 5 m high derrick is sufficient to lift the corer out of the borehole. A team of nine people can operate the hot-water drilling and ice-coring in three shifts per day continuously. Setting up the whole hot-water drilling operation out of the shipping crates and establishing a fully operational system takes 3 days. Every component of the drilling system comes with its own sled, and resetting the drill rig to a new location requires about 1 day or more depending on distance. The farthest distance we have moved was 22 km in 4 days. High-quality ice cores with few fractures can be assured by using core liners for confinement during the relaxation process after drilling. Morgan and others (1998) have shown that a small confinement pressure can improve core quality considerably. This is why the ice cores from hot-water drilling, reaching the surface in the plastic core barrel, are mostly intact. The design of the corer can easily be changed to produce ice cores of other diameters and lengths. An ice-corer 150 mm in diameter and 6 m long would be a very efficient, robust and productive tool.

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