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THERMAL ICE CORE DRILLING TO 700 M DEPTH AT MIZUHO STATION, EAST ANTARCTICA

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Abstract: As part of the Glaciological Research Program in East Queen Maud Land, Antarctica in the Japanese Antarctic Research Expedition (JARE), thermal ice core drilling to the depth of 700.63 m was conducted at Mizuho Station, East Antarctica (70°41'53"S, 44°19'54") in 1983-1984.

For the operation, an improved version of the drill was designed and manufactured by Geo-Tecs Co. Ltd. in Japan. With the aid of a micro-processor, the drill could send to the surface analog data (converted to 8 bites) on the temperature of the main-heater, water tank, etc. during drilling. Drilling of the first borehole started on April 22, 1983 and terminated on July 22 at 411.5 m depth.

Drilling was stopped because closure of the borehole became so rapid that the drill might be come stuck. This drilling was conducted by a five-man team during 499 working hours. On March 11, 1984 reaming of the drill-hole was conducted. The core drilling of the second borehole was started from the depth of 133.5 m on June 11, and finished on August 1, 1984. At that time the drilling was conducted with larger clearance between the drill and the hole. A drill 168 mm in diameter was used for drilling to 633m and another drill 142.6 mm in diameter was used up to 700.63 m depth. A six-man team spent 1014 working hours to reach that depth.

1. Introduction

In 1969–1975, the Glaciological Research Program of JARE was conducted in the area of Enderby Land, East Antarctica. The ice core drilling operations at Mizuho Station (Fig. 1) were included in this program. Thermal drilling operations began from JARE-12 in 1971 at Mizuho Station (70°41'53", 44°19'54") with a 400 m winch and a 2.4 kW thermal drill. The total weight of drilling equipment was about 1000 kg. Beginning in 1975, thermal drilling of four boreholes was conducted at Mizuho Station. Some holes reached down to 147.5 m. About of 300 m ice cores were recovered, contributing somewhat to the success of the drilling project on the whole. Nevertheless, the drilling operations themselves failed to achieve their targets: the 400 m drilling in 1971 and 1972 (JARE-13) and the 800 m drilling 1974–75 (JARE-15) (SUZUKI, 1976; SUZUKI and TAKIZAWA, 1978). These drilling operations were conducted by JARE in Mizuho Plateau, Enderby Land, East Antarctica.

A target depth of 400 m was assigned to JARE-12 and -13. The JARE-12 drill was lost at 75 m because the cable slipped off the connector. The JARE-13 drill was stuck and recovered at 110.1 m and stuck again at 147.5 m. The cause in the latter case was

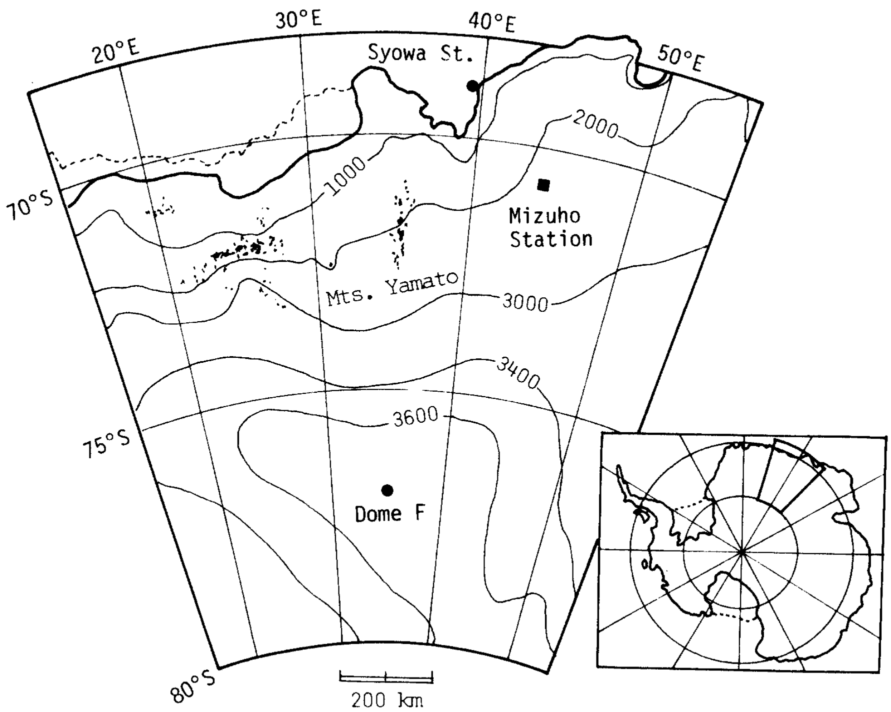

Fig. 1. Location of Mizuho Station (70°41'53"S, 44°19'54"; 2230 m.a.s.l.; ice thickness 2095 m).

attributed to leak age of water from the drill. In 1974–75 (JARE-15), drilling was carried out again but the drill was lost at 142 m. These drilling operations could hardly be regarded as successful.

In 1980, the Glaciological Research Program in East Queen Maud Land, East Antarctica (EQGP), started and Mizuho Station was chosen as a drilling site. A working group for development of a 500 m-depth core drill was established. The concept for a new drill adopted. The reasons for past failures were freezing of melt water in the drill and melt water leak age from the drill during the drilling. Improvements emphasized these points. The drills were modified to promote monitoring and control of drills' functions during operation. In addition, mechanical strength was reinforced and heaters were added to major parts in the drill. After these improvements, the drill was tested on an ice block in Japan. Practical test-drilling was carried out on the ice cap on Southern Ellesmere Inland, Canada, by members of the drilling project of JARE-24 and -25.

In this paper, the design and specifications of drill system are introduced, and logistics and operation of core drilling at Mizuho Station, East Antarctica are described.

2. The New Thermal Drill

The target depth of drilling in JARE-24–25 was 500 m. The working group designed the new version of the thermal drill. A few new drills were manufactured by Geo-Tecs Co. Ltd. in Japan. The drilling system components have the following parameters:

(a) Power sources: 16 and 12-kVA, 200 V three-phase AC generators provided power for the winch and the drill.

(b) Cable: Steel armored CRREL-type cable has seven control and one power conductors. Specifications of the cable are the same as for the JARE-15 cable (SUZUKI and TAKIZAWA, 1978).

(c) Winch: The plans of winch and mast are shown in Fig. 2. The winch with the 730 m cable was also improved. With the aid of a frequency inverter, a 3.7 kW electrical motor provided a hoisting speed ranging from 0.1 to 1 m/s. Average speed of drill lowering and raising was 1800 m/hr. The winch also had an auxiliary motor for slow lowering at about 0.001 m/s during drilling. In order to keep an optimal penetration rate and to provide an average lowering speed matched to the output heat of the drill bit, this motor and the powered brake were alternatively activated automatically in response to the cable tension (provided as two-bit information).

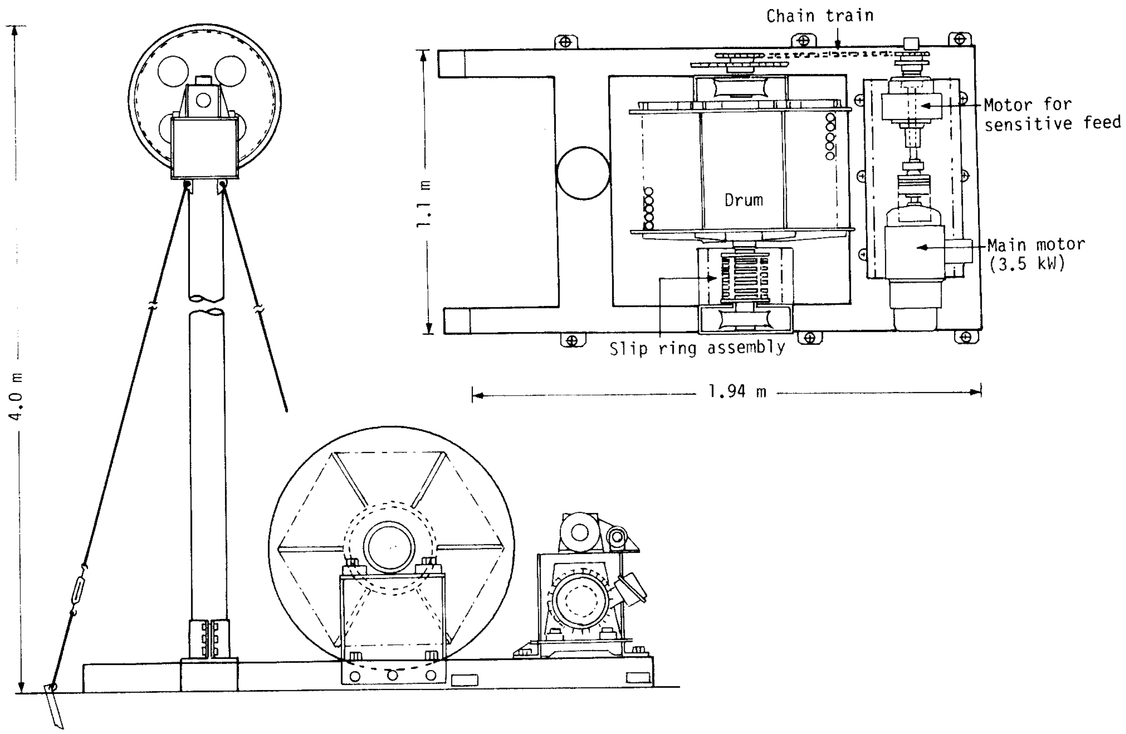

Fig. 2. Plan of the 730-m winch.

(d) Thermal drills: The thermal drills were an improved version of the drill used by JARE-15 (SUZUKI and TAKIZAWA, 1978). Two types of drill were designed with different outer diameters and lengths. Specifications of the drills are given in Table 1 and a schematic plan of the drill is shown in Fig. 3. Both drills are similar to the CRREL thermal drill (UEDA and GARFIELD, 1969). The drill consisted of six blocks: (1) suspension, (2) monitor, (3) air (vacuum) pump, (4) water tank, (5) core barrel, and (6) main heater (drill head).

(1) Suspension block: There is an optimum value of pressure to maximize the penetration rate of the drill. The thermal drill is too heavy to provide the optimum borehole bottom pressure. Therefore, in order to have a plumb borehole the drill must be partly supported by the cable. For this purpose, a micro-switch assembly (see tension switch in Fig. 3), is operated with a suspension spring. The elongation of the spring is

Table 1. Specifications of thermal drills in JARE -24 and -25.

Type	Length (m)	Weight (kg)	Core size diameter/length (mm)	Heater ring O.D./I.D./height (mm)	Heater elements (kW)	Power per unit area (kW/m²)
TD-170	3.5	60	127/1600	168/132.8/60	200V 1.5×2	700
TD-140	2.8	40	120/1400	145/128/60	200V 1.25×2	700

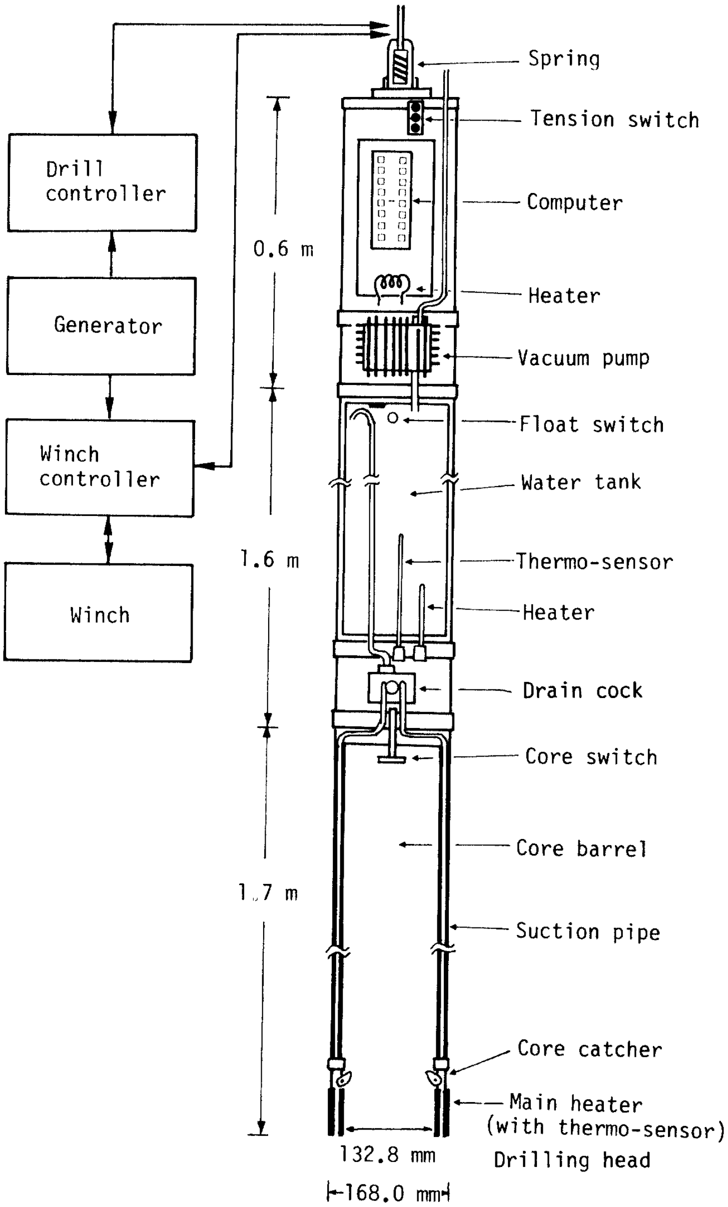

Fig. 3. Schematic of the thermal drill (TD-170 and TD-140).

proportional to three levels of pressure: small, normal, and large. The microprocessor converted these logic inputs into digital signals and transmitted them to the control panel. The optimum load of the suspension spring was found to be in the range of 13.5 to 23.5 kg.

The drill head reached an optimum regime at 15 A current. Figure 4a shows traces on the surface of the core produced by melting due to hot water, when the drill penetrated ice under the optimum conditions. A stripped pattern means that the top water level and the distance of patterns coincide with intervals of the lowering. The bottom of the valley in striped patterns shows the position of the meltwater inlet on the drill head. The water level is balanced on both sides of the inlet. Figure 4b shows the pattern of the trace at the main heater current of 20 A. Then the water level became too unbalanced on both sides and was disordered. This means that the water flow was not stationary. The drilling in such conditions will lead to inclination of the borehole.

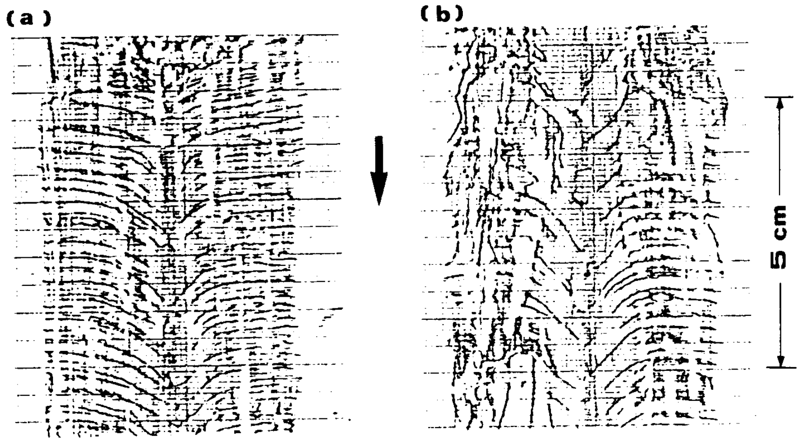

Fig. 4. Traces on the surface of an ice core. The traces were copied by pencile-rubing on the surface core. (a) heater current: 15 A and (b) heater current: 20 A. Contact load is 13.5 - 23.5 kg. The arrow shows the direction of drill penetration.

(2) Monitor: The monitored items were as follows: temperature of the drill head and inside the water tank, voltage of the drill head and air pump (as digital data), active switch on the suspension assembly, core switch and float switch in the tank. The computer sends these continuous data to the surface.

(3) Air pump: In order to suck the meltwater from the borehole, bottom air pressure inside the water tank was reduced, by a linear-type air vacuum pump (Model A1017-S, Medo Industries Co. Ltd. Tokyo) capable of providing an air pressure of 290 mmHg. That allowed water flow of above 1.2 *l*/min.

(4) Water tank: The tank was made of a 2.0-mm-thick stainless steel pipe 139.8 mm in outer diameter and 1.6 m in length. Two copper pipes 3 mm in inner diameter lead to inlets of the drill head from the tank. The melted water moved up through the pipes. A float switch was mounted at the top in side the tank. An electric heater of 0.03 kW and a temperature sensor were mounted at the tank bottom. During the operation, the temperature of water in the tank was about 23°C.

(5) Core barrel: The barrel was made from 2.1-mm-thick stainless steel pipe, of 139.8 mm outer diameter, with a core catcher block. The lower flange of the block supports the drill head. The barrel was connected to the water tank by 4 bolts welded at the upper flange of the barrel. The core was taken out of the borehole by erecting the catcher into the core.

(6) Drill head: The main heater was molded of aluminum alloy, as described by

SUZUKI and TAKIZAWA (1987). The heater had two heating elements inserted into a stainless steel tube. Several inlets for water were arranged near the bottom as shown in Fig. 5. A groove pattern was machined on the bottom face of the heater as a water channel.

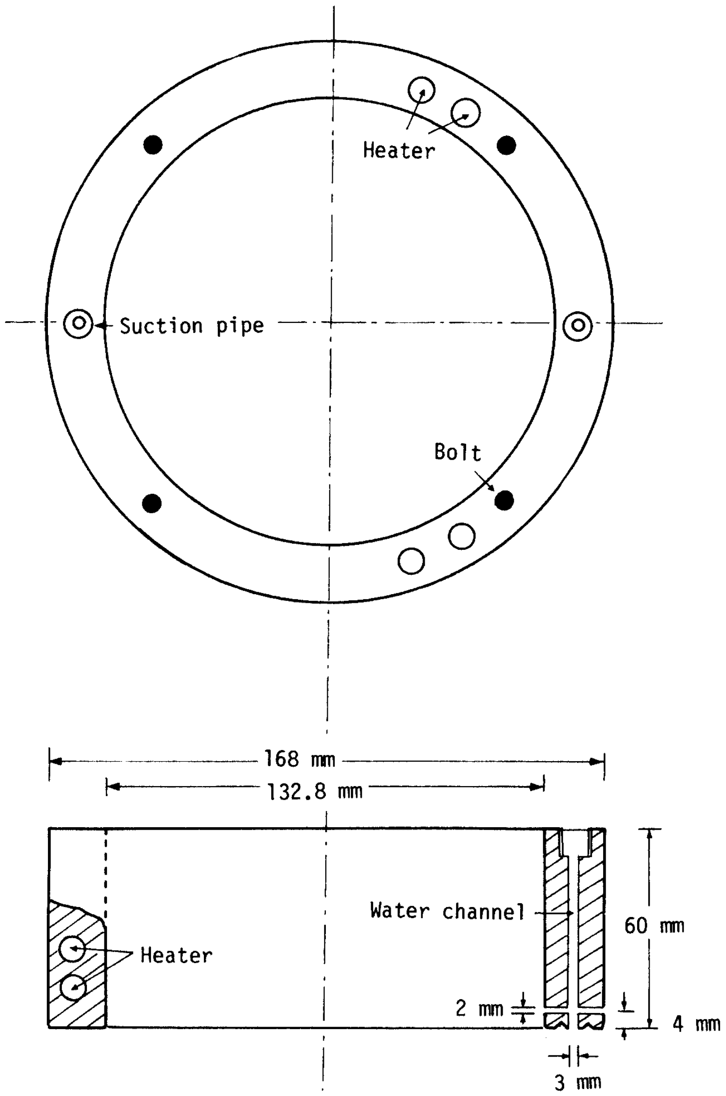

Fig. 5. The water-inlets and -channels in the drilling head.

3. Drilling Operations

3.1. Drilling operation in 1982-84 (JARE-24)

On January 13, 1983, JARE-24 personnel arrived at Mizuho Station. The average annual temperature here is –34.5°C. A drilling hut of 5 × 5 × 5 m was made already by JARE-23. Foam sheets covered site wall to keep heat inside the drilling hut. The drilling pit was warmed by heat from the generator cooling system. We could keep the temperature in hut at –10°C but it was about –22°C in the pit. The generator, mast, winch, control panel and thermal drill were mounted in the site. The construction of the drilling system and tests were finished on April 4. In Fig. 6a shows the arrangement of the system in the drilling hut. Figure 6b shows the location of core storage and the drilling site at Mizuho Station. The deep drilling began from April 22. A record of drilling progress is shown in Fig. 7. The causes of trouble in the early stage were due to computer errors and failure of the winch control inverter. The average speed of drilling was about 1.25 m/hr. Average lowering and raising speed was 2500 m/hr. As shown in Fig. 7, actual drilling time occupied about 54 % of the drilling procedure, 22 % and 24 % were used for lowering and raising the drill in the borehole, and for preparation (service) and core dispo-sition, respectively. Time spent on trouble solving was 2-3 % of total working time.

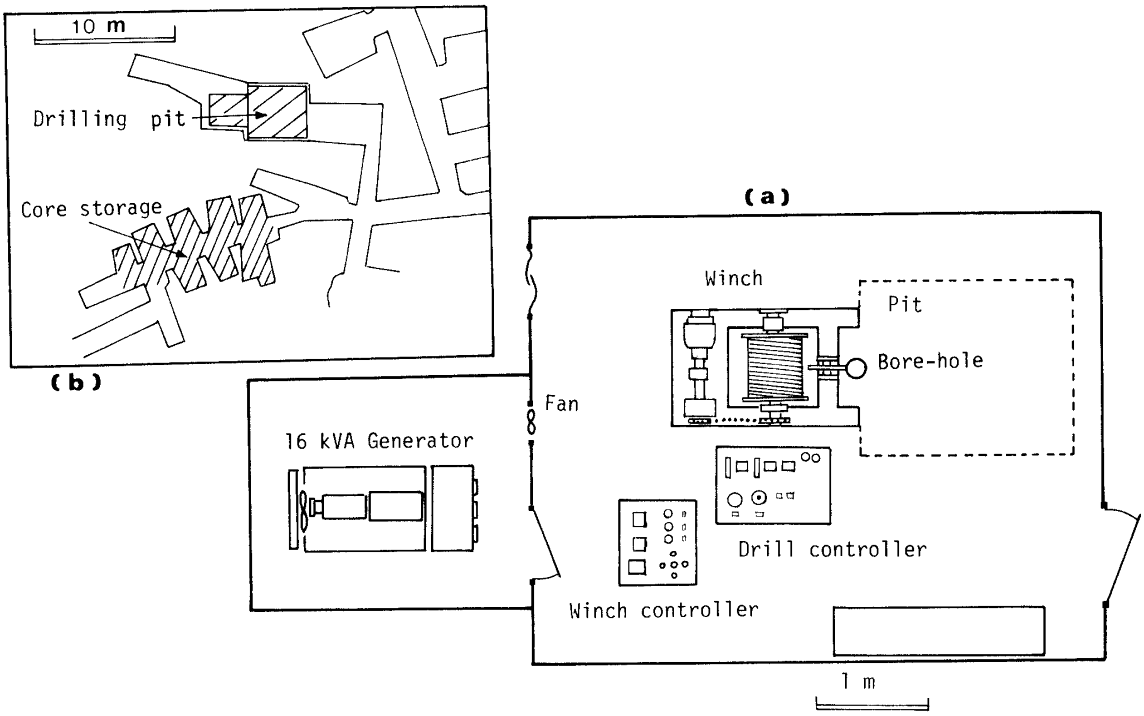

Fig. 6. (a) The arrangement of the drilling site and (b) Locations of drilling site and core storage.

We began to feel some shocks through the cable from July 9, when the drill reached the depth of 358 m. The shocks arise when the drill passes through the borehole contractions. The number of shocks increased with depth and the time. The relationship between the depths of the shocks and dates of drilling is shown in Fig. 8. Points along a vertical line show the depths of the shock in one drill lowering and raising. When the borehole depth was 358 m, the number of shocks was small and the deepest borehole contraction was at 311 m. The difference between the deepest contraction and the borehole depth gradually became smaller. On July 22, the contraction was occurred during 1.5 hours after retrieval of the last segment of ice core. The clearance between the borehole wall and the outer diameter of the drilling head is about 2 mm. Hence, the borehole closure rate is about 0.33 mm/day at 400 m depth. If the clearance is less than 2 mm and the drill swing horizontally during lowering and raising, the shock might occur even without borehole closing. Drilling in this condition might cause the drill to stick. The drilling operation in JARE-24 was closed at this time.

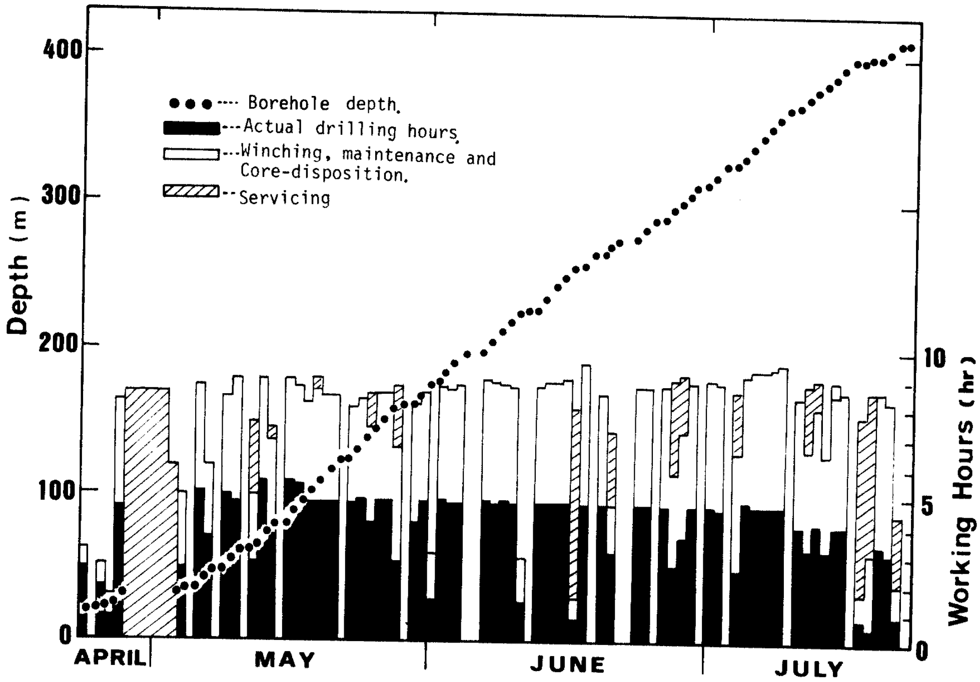

Fig. 7. The record of drill-processing in JARE-24.

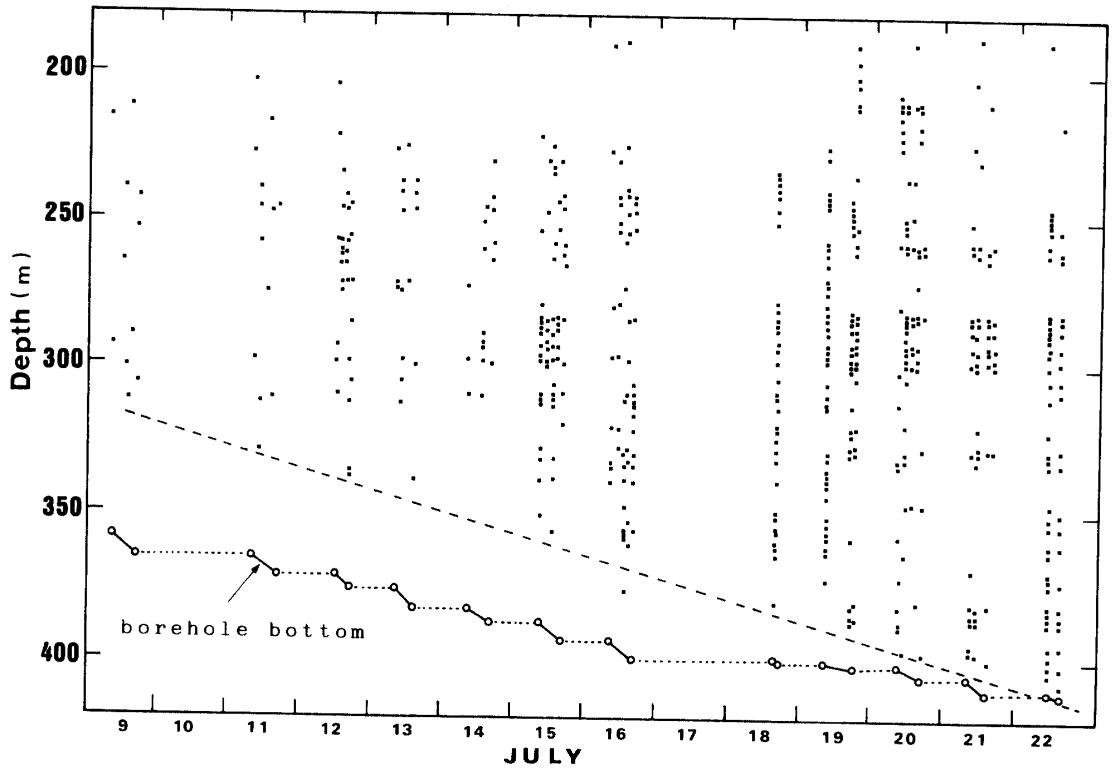

Fig. 8. The relationship between the depths and numbers of the shocks during lowering and raising of the drill in the borehole.

3.2. Drilling operation in JARE-25 (1983–85)

In January 1984, the diameter of the first borehole was measured. It was found that the borehole was shrinking. According to the measurements on March 24, the diameter of the borehole at 200, 300 and 400 m had shrunk by 1.0, 10.8 and 27.6 mm, respectively. In the second stage of the drilling operation, reaming of the borehole was done by thermal and electro-mechanical drills. However, they were not able to ream the original hole through the total depth. Only 133.5 m depth was accessible. The total time for the reaming procedure was 81 hours.

The drilling in JARE-25 was carried out successively from 133.5 m depth. The drilling must proceed to the target depth before the borehole shrinks to the diameter of the drill. According to the measurements of the borehole diameter at the proper intervals, the closure rate was stationary. Therefore, the borehole closure rate was assumed to follow Glen's flow law:

$$\dot{\varepsilon} = A\tau^{n}. \tag{1}$$

Here, $\dot{\varepsilon}$ is effective strain rate (s^{-1}), A and n are constants and τ is effective shear stress:

$$\tau = \frac{g\int_{o}^{h} \rho \, dh}{n} \times 10^{-3}, \tag{2}$$

where ρ is density of ice, g is the acceleration of gravity and h is the depth of the borehole bottom. We assume that the initial borehole diameter was from 172 to 176 mm, n = 3 and $A = 4.0 \sim 6.0 \times 10^{-18}$ (s^{-1} kPa^{-3}). With these parameters, the calculated closure rate is close to measured values. Table 2 presents the closure rates which were calculated from eq. (1) with n = 3 and $A = 5 \times 10^{-18}$. The total time for core drilling T was estimated from the following equation:

$$T = \frac{D}{v} + \frac{SD}{L} + \frac{2D^{2}}{VL}. \tag{3}$$

Here, D is the hole-depth, v is the penetration rate, V is the drill travel time, and L and s are the core length and the drill servicing time during one run, respectively. In order to drill a 700 m deep dry borehole under conditions of borehole closure the working time and borehole diameter were calculated from eqs. (1), (2) and (3).

Table 2. Closure rate of the borehole.

Depth (m)	200	300	400	500	600	700
Closure rate (mm/day)	0.01	0.05	0.11	0.23	0.40	0.65

In Fig. 9 shows changes of borehole diameter for working time of 15 hours per day. According to the figure, when the drilling is carried out by the TD-170, the borehole diameter becomes equal to the drill diameter at 540 m. When the borehole depth was 200 m the working time was increased to 16 hours per day. Two teams of three persons each continued drilling in 8-hour shifts. Furthermore, the drilling was carried out with increased borehole diameter. To increase the clearance, the vertical position of the melt-water inlets

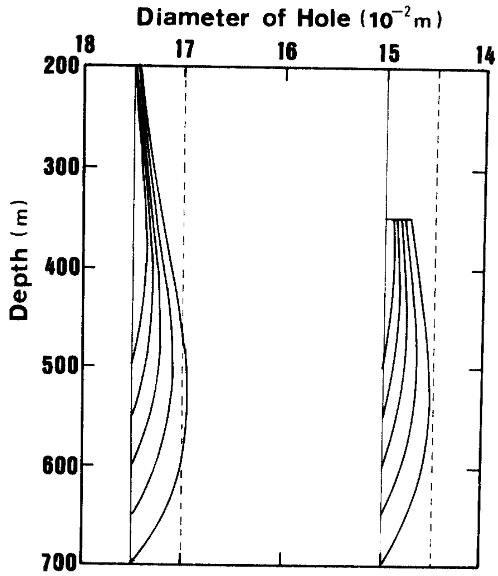

Fig. 9. *The closure rate of the hole: the left curve shows drilling by TD-170 drill and the right curve drilling by TD-140 drill.*

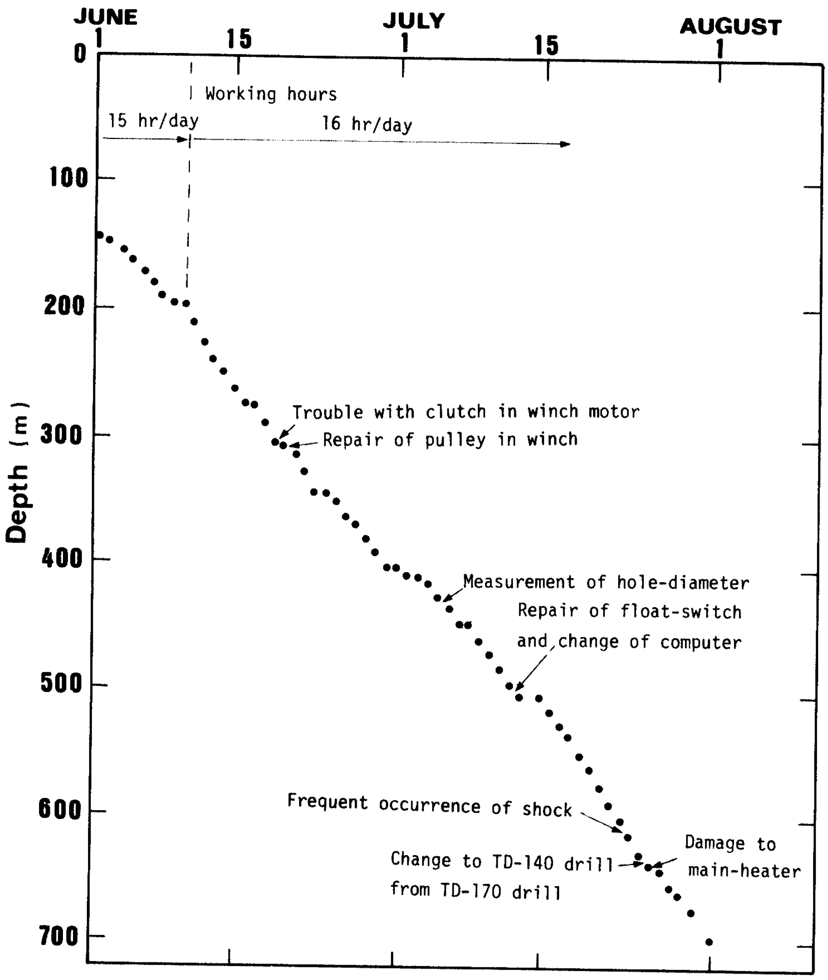

Fig. 10. *The record of drill-processing in JARE-25.*

on the side face of the drill head was changed from 4 mm to 14 mm from the base of the drill head. Then, the melt-water level in the borehole bottom increased. As a result, the drilling made fairly smooth progress from July 23, when the borehole depth exceeded 600 m. The drilling below 625 m was carried out by the TD-140. On August 1, the drilling depth attained 700.63 m. All of the cable in the winch-drum had been used. Figure 10 shows the conditions of the drilling process in JARE-25.

Total time working time for drilling from 133.5 m to 700.63 m was 1014 hours. The drilling time was 364 hours. Therefore, the average drilling speed was 1.55 m/hr. The 567 m ice core in JARE-25 was obtained during two months.

4. Core Quality

The ice core recovery was almost 100%, that is, continuous core from surface to

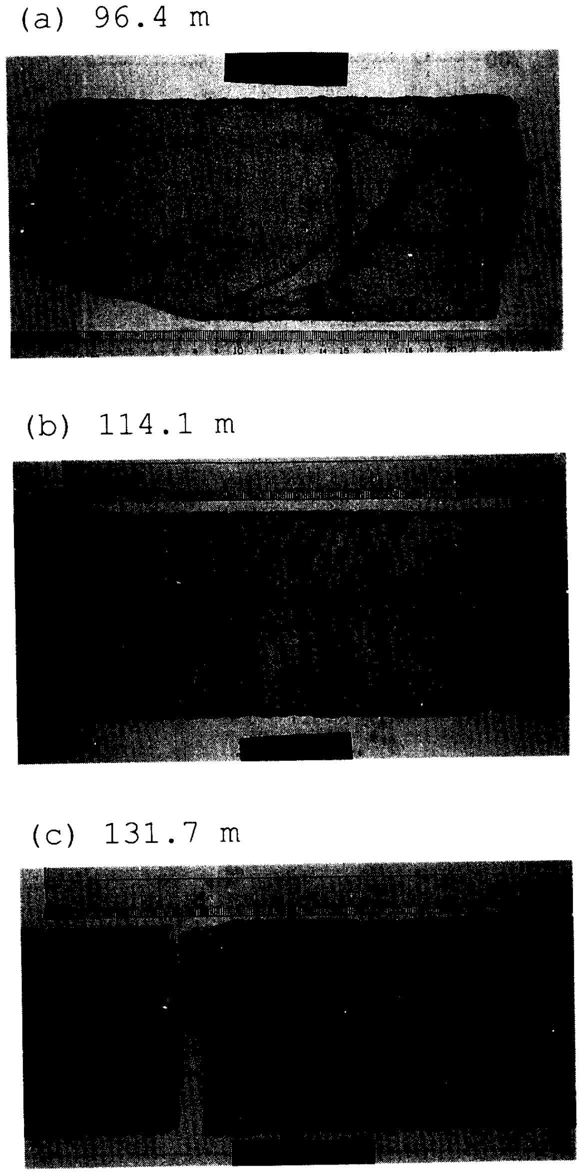

Fig. 11. Photographs of thermal cracks in the ice core.

700.63 m depth. The core quality was perfect from the surface to about 96 m. Cores recovered from greater depth contained many cracks. From 96 to 110 m, most cracks were introduced diagonally at intervals of about 0.15 m, as shown in Fig. 11a. In the deeper core only horizontal cracks were found. Around 110 m depth they were concentrated in 0.1 m thick bands (Fig. 11b); in deeper cores such cracks were distributed equally with intervals of about 5 mm (Fig. 11c).

5. Concluding Remarks

Three JARE drilling operations were conducted at Mizuho Station during 1971-1975. The maximum drilled depth was 145.7 m. In 1980, the Glaciological Research Program in East Queen Maud Land, Antarctica in JARE was started and a working group was established to develop a new thermal drill. It was our target to accomplish ice core drilling to 500 m depth during 1982–1985 (JARE-24 and -25).

On June 1983 (JARE-24), the actual drilling started at Mizuho Station. During the first year, a 411.7-m long ice core was recovered. However, we had to stop the drilling for reason of borehole closure. The next year (JARE-25) the drilling team reamed the borehole to 133.5 m. They continued the drilling from that depth with consideration of the conditions of the borehole closure. Optimum clearance between the borehole and the drill, and speed were calculated. The 700.63 m deep borehole took about 2 months to drill.

The drilling operation succeeded in fulfilling the intended functions of the drill. However, the thermal drill system consumes power, and drilling speed is slower than that of electrical mechanical drills. Based on this technical experience we are considering designing a light weight mechanical drill. We think that it can be adopted for intermediate depth core drilling with ability to obtain good quality cores.

Acknowledgments

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