Proc. NIPR Symp. Polar Meteorol. Glaciol., 2, 152–160, 1989

GLACIOLOGICAL CHARACTERISTICS OF CORES DRILLED ON JOSTEDALSBREEN, SOUTHERN NORWAY

Toshiyuki KAWAMURA[1], Yoshiyuki FUJII[2], Kazuhide SATOW[3], Kokichi KAMIYAMA[4], Kaoru IZUMI[5], Takao KAMEDA[6], Okitsugu WATANABE[2], Sadao KAWAGUCHI[2], Bjørn WOLD[7] and Yugvar GJESSING[8]

[1]*Institute of Low Temperature Science, Hokkaido University, Kita-19, Nishi-8, Kita-ku, Sapporo 060*
[2]*National Institute of Polar Research, 9–10, Kaga 1-chome, Itabashi-ku, Tokyo 173*
[3]*Nagaoka College of Technology, 888, Nishi-katagai-cho, Nagaoka 940*
[4]*Geophysical Research Station, Kyoto University, Noguchihara, Beppu 874*
[5]*Research Institute for Hazards in Snowy Areas, Niigata University, 8050, Igarashi-nino-machi, Niigata 950–21*
[6]*Faculty of Engineering, Hokkaido University, Kita-13, Nishi-8, Kita-ku, Sapporo 060*
[7]*Norwegian Water Resources and Energy Administration, P.O. Box 5091, Maj., 0301, Oslo 3, Norway*
[8]*Department of Geophysics, University of Bergen, N-5007 Bergen, Norway*

Abstract: Glaciological investigation was carried out on Jostedalsbreen (61°43′N, 7°08′E), Southern Norway, in early May, 1987, as a study of the Japanese Arctic Glaciological Expedition (JAGE 1987) which intended to define the glaciological characteristics in the maritime cryosphere. The 46.9 m full depth ice core was recovered at a dome of the glacier (1960 m a.s.l.). Then glaciological and geochemical *in situ* analyses of the cores were made to clarify the past climatic change. The cooperative study was with institutions of Norway. Several dirt layers were found in the cores; the dirt layers in the upper part indicate the corresponding maximum values of electrical conductivity, different from layers in the lower part. Infiltrating water of about 1 m thick appeared in the borehole, showing a confined aquifer on the bedrock. The temperature of the borehole was nearly 0°C through the entire depth except at the upper part and the firn transformed abruptly into ice at 29.5 m; these results implied that the whole glacier has the property of a temperate glacier. The grain size increased one order of magnitude in a short interval just below the firn-ice interface, probably due to immersion of ice body into 0°C water. A significantly large dip of foliation at the middle layer suggested existence of glacier flow at the boring site. The annual layers were not identified from seasonal variations of *in situ* analyses. However, from accumulation data for the last 20 years, the age of bottom ice was estimated to be about 17 years before the present investigation.

1. Introduction

The first Japanese Arctic Glaciological Expedition (JAGE 1987) was carried out in 1987 on maritime glaciers at different latitudes under an overall research program of the JAGE 1987–1992. The expedition was made as cooperative research works in Southern Norway with the Norwegian Water Resources and Energy Administration (Norges Vassdrags- og Energiverk in Norwegian, NVE) and University of Bergen, and in Svalbard with Norwegian Polar Research Institute (Norsk Polarinstitutt). Objectives of the JAGE and outlines of the field work in 1987 have been reported by WATANABE and FUJII (1988).

The investigation in Southern Norway was conducted at a dome of Jostedalsbreen, a glacier in Southern Norway, in early May, 1987 as a study of JAGE 1987. Jostedalsbreen is situated in the southern part of the east Atlantic sector in the Arctic cryosphere, in contrast with the glaciers in Svalbard located in the northern part. In order to define the past climatic changes, we made glaciological and geochemical *in situ* analysis of the ice cores recovered completely down to the glacier bed and could understand the metamorphisms of snow and its transformation to ice. We also collected core samples to analyze the chemical and physical properties in the laboratory.

Mass balance study at Jostedalsbreen has been made by NVE since the beginning of the 1960's, as well as at a number of glaciers in various parts of Norway (*e.g.*, SÆTRANG and WOLD, 1986; HAAKENSEN, 1986; ØSTREM, 1986). Drilling to collect ice cores, however, has not yet been performed on glaciers in Norway. Hence, one of the purposes of our cooperative study with Norwegian glaciologists was to obtain basic glaciological information for the NVE measurements.

This paper presents preliminary results of the *in situ* analysis of ice cores drilled on Jostedalsbreen, Southern Norway.

2. Drilling Site and Details of the Ice Core Analyses

The investigation was carried out in early May, 1987, on Jostedalsbreen, the largest glacier in Europe, about 300 km northwest of Oslo (Fig. 1a). The mean air temperature during the drilling operation in two weeks was about −6°C. This glacier covers an area of approximately 470 km^2, consisting of huge smooth ice caps and several outlet glaciers flowing down into deep valleys. The ice core of 46.9 m in length, drilling down to the bedrock, was recovered at a flat ice dome (1960 m a.s.l.) in the accumulation area in Nigardsbreen, one of the largest branches of Jostedalsbreen (Fig. 1b). The glaciological elements of Nigardsbreen are summarized in Table 1 (IAHS(ICSI)-UNESCO, 1977).

For Jostedalsbreen, meteorological data as well as accumulation data are available. NVE has maintained an observation hut on the glacier at Steinmannen (1633 m a.s.l.), about 5 km below the drilling site, and has continued meteorological observations through the summer since 1964. Since 1983, data such as temperature, precipitation, humidity, wind velocity, etc., have been recorded automatically throughout the year. Thus, the history of the glacier over the last 25 years is known.

The following analyses of the cores were conducted during drilling operation:

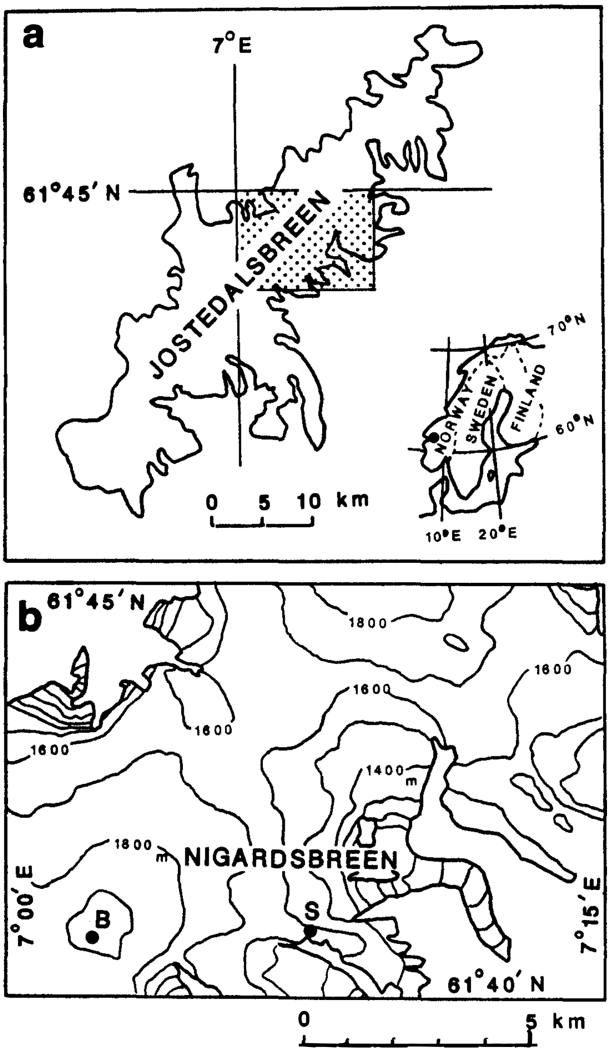

Fig. 1. (a) Location map of Jostedalsbreen. (b) Topographical map, an expanded view of the dotted area of (a), around Nigardsbreen, one of the largest branches of Jostedalsbreen. B, drilling site; S, meteorological observation point at Steinmannen.

Table 1. Glaciological elements of Nigardsbreen.

Minimum elevation	330 m a.s.l.
Maximum elevation	1960 m a.s.l.
Equilibrium line elevation	1460 m a.s.l. (mean for 1970–1974)
Total area	47.0 km^2 (mean for 1970–1974)
Length	8.7 km
Ratio of accumulation area to total area	78% (mean for 1970–1974)

after IAHS (ICSI)-UNESCO (1977)

(1) stratigraphic observation and photographic description; (2) measurements of bulk density and electrical conductivity; and (3) thin section analysis of the crystallographic structure and grain size. The temperature of the borehole was measured at 2.5 m intervals with a thermistor in contact with the wall.

Ice and melt-water samples were collected for laboratory analyses. Analysis of the following items is planned: (1) stable oxygen isotope content ($\delta\ ^{18}O$) and major ion composition, (2) tritium and radio isotopes contents, (3) pH, (4) concentration of microparticles, and (5) total gas content. Item (1) will be analyzed at the Geophysical Institute, University of Bergen.

3. Results and Discussion

3.1. Stratigraphy

An outline of the stratigraphic profile of a 46.9 m-long core is shown in Fig. 2. The firn transforms abruptly into ice at a depth of 29.5 m. In the upper part of the temperate firn down to about 16 m, ice layers are developed with a maximum thickness of 150 mm and granular snow layers of a few mm. Below this layer, refrozen structures of water channels together with ice plates appear in place of the granular snow layers.

In the firn down to 20 m, well-defined dirt layers exist indicating the maximum values of electrical conductivity, whose profile takes higher values with wide variations (Fig. 3). On the contrary, the dirt layers found out in depths of 32 m to 34 m do not indicate the corresponding high values of electrical conductivity. The constituents of the dirt layers in the upper and lower parts, therefore, differ from each other. There seems to exist an environmental difference at the time of their deposition. It is notable that singular dirt layers consisting of small red particles were observed at 9.0 m and 18.8 m.

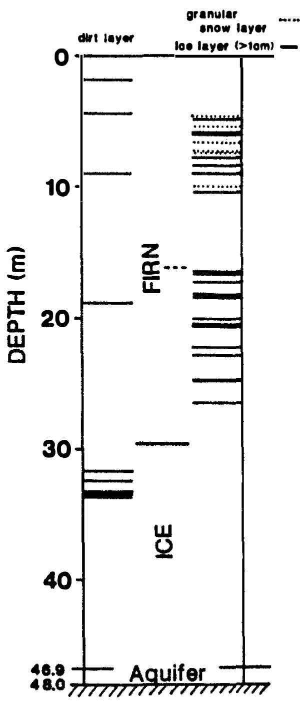

Fig. 2. Outline of structure and stratigraphy of a core from Jostedalsbreen. Major stratigraphical structures are shown in the right part. The structure in the firn is changed slightly at a depth of about 16 m.

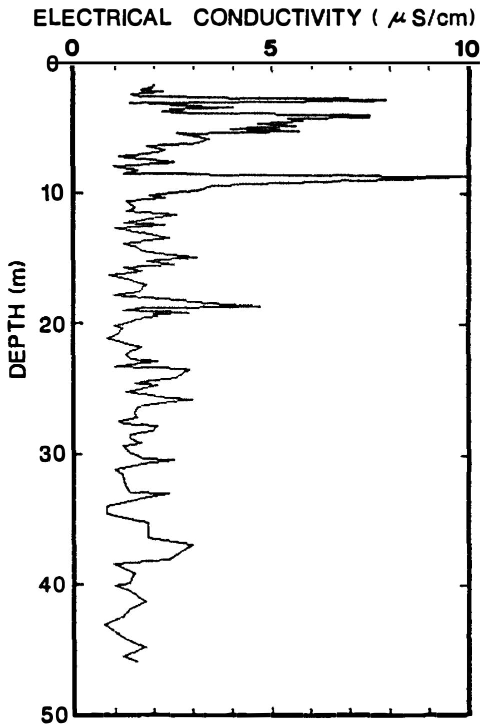

Fig. 3. Profile of electrical conductivity of melt-water from cores.

3.2. *Aquifer on the bedrock*

Infiltrating water appeared in the borehole at depths of 46.9–48.0 m, showing a confined aquifer on the bedrock. The water level in the borehole rose rapidly to an equilibrium water level up to 5.6 m above the bedrock (Fig. 2). Fluctuations in the water level and the amout of melt-water have been examined in the borehole by NVE after drilling. Aquifers have been found in the ice of other temperate glaciers. We found no aquifer at the ice-firn interface, different from Himalaya (IIDA *et al.*, 1984) and Patagonia (YAMADA, 1987), probably bacause our drilling was made in early summer. It is presumed, however, that water which permeates from the upper firn layer forms an aquifer on the impermeable ice layer in the maximum melt season.

3.3. *Temperature profile*

The temperature of the ice was nearly 0°C through the whole depth except in the uppermost firn layer, as shown in Fig. 4. Based on the observed temperature distribution and the abrupt transformation of firn to ice, the ice body of Jostedalsbreen could be classified as a temperate glacier. It is notable that the transformation depth in this glacier is similar to that in the Alps (VALLON *et al.*, 1976) and in Patagonia (YAMADA, 1987). An abrupt transformation at 17 m has also been found in a Himalayan glacier (IIDA *et al.*, 1984). Based on the experimental studies of superimposed ice mechanism by WAKAHAMA (1965) and TSUSHIMA (1978), Iida proposed that it is caused by a densification of snow immersed in water at 0°C. The same process is supposed to occur in Jostedalsbreen as a temperate glacier.

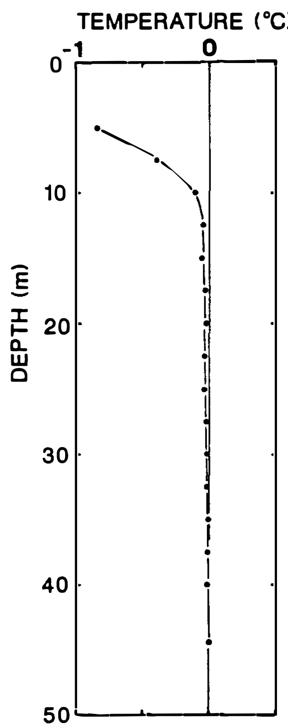

Fig. 4. Profile of borehole temperature.

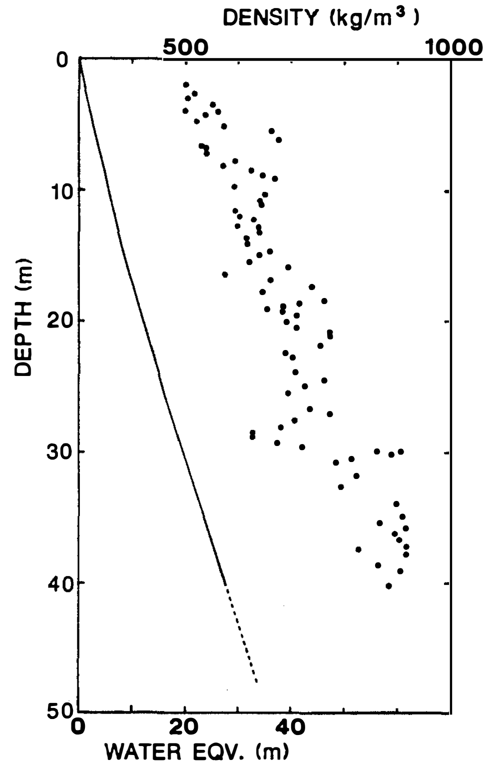

Fig. 5. Profile of density of cores from Jostedalsbreen and cumulative water equivalent.

3.4. *Density profile*

The vertical profile of density and the cumulative water equivalent are shown in Fig. 5. The density increased gradually in the first 26 m, and the discontinuous increase of the density profile is shown at the firn-ice interface at 29.5 m depth. The firn layer just above the ice showed the smaller values of density associated with the low strength of ice cores and the difficult drilling operation.

3.5. *Grain size distribution*

Photographs of four vertical thin sections of the cores are shown in Fig. 6. In the firn layer, grain size showed a nearly constant 0.5–2.0 mm in diameter, as shown in the example in Fig. 6a. Then, in the ice, the grain size increased from 3 mm at 30.1 m to approximately 30 mm at 34.6 m, and thereafter remained nearly constant to the bottom (Fig. 6b–d).

It is notable that the grain size increased one order of magnitude in the short

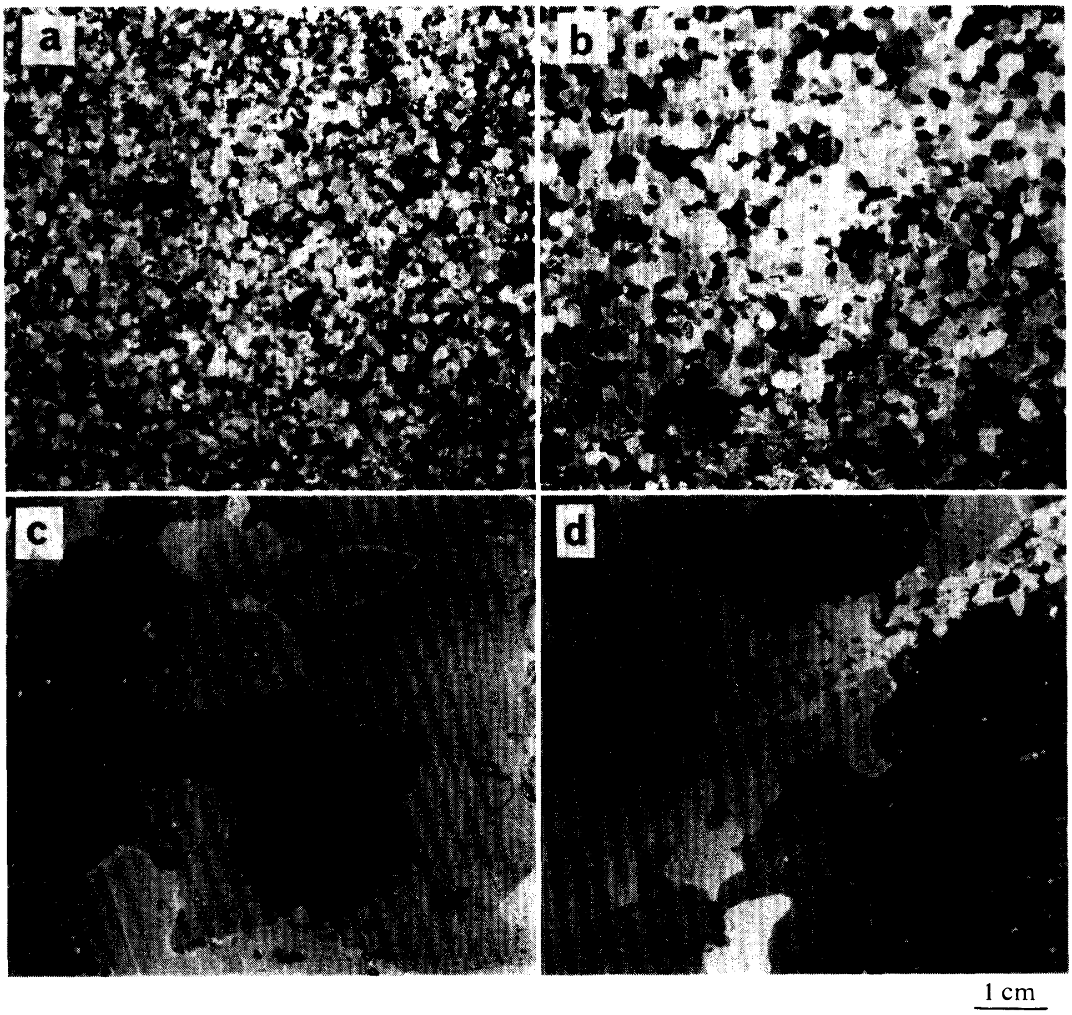

Fig. 6. Photographs of vertical thin sections of cores at depths of (a) 17.0 m, (b) 30.3 m, (c) 34.6 m, and (d) 43.6 m.

interval. In an Alpine glacier, VALLON *et al.* (1976) observed that the average grain size of ice crystals jumped from 1 or 2 mm to 10 or 20 mm between 50 and 80 m. He supposed that the rapid growth was attributed to the particularly active layer containing much free water. According to the experiments by WAKAHAMA (1965) and TSUSHIMA (1978), the immersion of snow into 0°C water results in sudden grain coarsening. On the basis of mass balance data of the last 25 years, the thickness of the abrupt grain growth layer in the core between 30.1 m and 34.6 m corresponded to about 2 years, which is longer than the duration of the experiments. The same grain coarsening process most likely took place in the active layer of Jostedalsbreen.

3.6. *Profile of dip of foliation*

Figure 7 illustrates the variation of the dip as considered by the discontinuous planes, such as ice plates, bubble layers, and dirt layers. The dip increased sharply from 0 degrees over the first 14 m to a maximum value of 60 degrees at 25 m and then decreased to values below 20 degrees at the lowest parts.

The drilling site was located at a flat ice dome as described in the preceding section. However, since a nunatak appears on the ice cap about 200 m away, the bedrock around this site is probably inclined. Figure 6d shows a belt of recrystallized small grains together with a belt of elongated air bubbles, suggesting existence of glacier flow. Thus, it is suggested that the drilling site is not in a source area of glacier flow in spite of being at the top of Jostedalsbreen. The core from Jostedalsbreen was characterized by an extremely large dip, but the exact mechanism is still unknown.

3.7. *Accumulation*

Another characteristic of Jostedalsbreen is that it has a large amount of snow fall

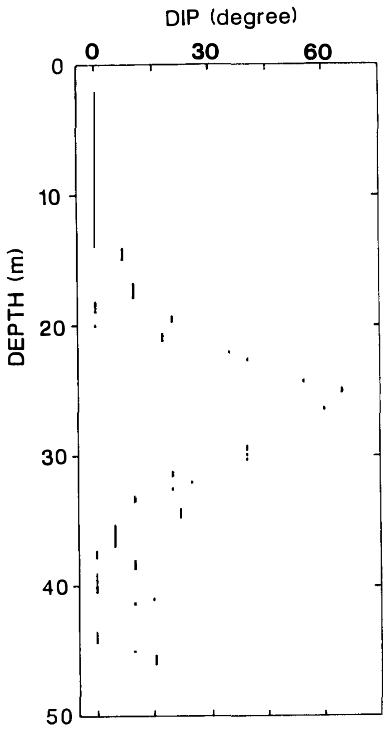

Fig. 7. Profile of dip of foliation in cores.

(about 8 m thick) caused by geographical and climatological conditions similar to those in the mountainous region of Japan facing the Japan Sea. Accumulation amount at altitude intervals has been obtained in Nigardsbreen since 1962 by NVE. Annual accumulation rate and ablation rate are 2.63 m and 0.71 m water equivalent in average, respectively, at the drilling site with a large interannual variation (N. HAAKENSEN, pers. commun.). The data indicate that net accumulation was 0 m in water in 1979–1980; this implies that a plane was exposed at the surface in the two summers of 1979 and 1980, possibly resulting in a quite thick ice layer. There was an extremely thick ice plate, 150 mm, in the core at 18.3 m, thicker than other plates which had a maximum 50 mm. By comparing the stratigraphy with accumulation data of each year, we pursued annual ice layers from the surface, some of which were not recognizable definitely, and the ice plate agreed with the layers for 1979 and 1980. If lateral glacier flow was neglected, the bottom of the core, which is the cumulative water equivalent of 32 m, as seen in Fig. 5, could be calculated to be about 17 years before the present investigation, from the average net accumulation data of 1.9 m water equivalent.

In temperate glaciers, it is difficult to estimate annual layers or amounts of net accumulation from seasonal variations in chemical compositions, because percolated water makes the chemical compositions in the ice uniform. Comparing known accumulation data with results of the chemical analysis of samples brought back, we expect that more information for glaciological study will be obtained.

Acknowledgments

The authors are indebted to Dr. N. HAAKENSEN, Messrs. A. SÆTRANG, M. KENNETT and B. KJØLMOEN, of the staff of the Hydrology Department of the Norwegian Water Resources and Energy Administration for their suggestions and logistic support to our expedition. Thanks are also expressed to Mr. A. TAKAHASHI of Geotechnical Inc. for his assistance with the drilling operation.

The expedition was planned by the Arctic Research Committee of the Japanese Society of Snow and Ice, and was supported by a Grant-in-Aid for Overseas Scientific Research (No. 62041076) "Arctic Ice Coring Project 1987" from the Japanese Ministry of Education, Science and Culture. We would like to express our sincere thanks to them for affording us the opportunity of the expedition.

References

HAAKENSEN, N. (1986): Glacier mapping to confirm results from mass-balance measurements. Ann. Glaciol., **8**, 73–77.

IAHS(ICSI)-UNESCO (1977): Fluctuations of Glaciers 1901–1975. Paris, International Commission on Snow and Ice of the International Association of Hydrological Sciences and UNESCO.

IIDA, H., WATANABE, O. and TAKIKAWA, M. (1984): First results from Himalayan glacier boring project in 1981–1982, Part II. Studies on internal structure and transformation processes from snow to ice of Yala Glacier, Langtang Himal, Nepal. Glacier Studies in Langtang Valley. Data Center for Glacier Research, Japanese Society of Snow and Ice, **2**, 25–34.

ØSTREM, G. (1986): Repeated glacier mapping for hydrological purposes; Water power planning.

Ann. Glaciol., **8**, 135–140.
SÆTRANG, A. C. and WOLD, B. (1986): Results from the radio echo-sounding on parts of the Jostedalsbreen ice cap, Norway. Ann. Glaciol., **8**, 156–158.
TSUSHIMA, K. (1978): Mizu ni tsukatta yuki no sodaika (Grain coarsening of ice particles immersed in pure water). Seppyo (J. Jpn. Soc. Snow Ice), **40**, 1–11.
VALLON, M., PETIT, J.-R. and FABRE, B. (1976): Studies of an ice core to the bedrock in the accumulation zone of an Alpine glacier. J. Glaciol., **17**, 13–28.
WAKAHAMA, G. (1965): Mizu wo fukunda sekisetsu no hentai (Metamorphisms of wet snow). Teion Kagaku, Butsuri-hen (Low Temp. Sci., Ser. A), **23**, 51–70.
WATANABE, O. and FUJII, Y. (1988): Outlines of the Japanese Arctic Research Expedition in 1987. Bull. Glacier Res., **6**, 47–50.
YAMADA, T. (1987): Glaciological characteristics revealed by 37.6-m deep core drilled at the accumulation area of San Rafael Glacier, the Northern Patagonia Icefield. Bull. Glacier Res., **4**, 59–67.

(Received March 18, 1988; Revised manuscript received September 7, 1988)