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Glaciological characteristics revealed by 37.6-m deep core drilled at the accumulation area of San Rafael Glacier, the Northern Patagonia Icefield

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Abstract

Glacier drilling was conducted for the first time to the depth of 37.6 m in the accumulation area of San Rafael Glacier (46° 44′ S, 73° 32′ W, 1296 m a. s. l.) in the Northern Patagonia Icefield (Hielo Patagónico Norte) in the end of November, 1985. Snow and firn consisted of wet granular snow with abundant ice crusts and ice layers. Dry density ρ_d and the rate of ρ_d increment to depth increment ($d\rho_d/dz$) gradually increased with increasing depth z until around 19.7 m in depth. In the firn between the depths of 19.7 m and 26.7 m, the dry density was kept fairly at the constant value of 0.75 Mg/m^3. At the depth of 26.7 m, firn abruptly transformed into ice. The unconfined aquifer was found with the thickness of 1.8 m at depths from 26.7 m to 24.9 m on the firn-ice interface. This singular densification process is attributable to the effect of water percolated into firn. The annual layer was not identified by stratigraphic observations because of no visible dirt layers and no seasonal variations in snow texture, density and chemical characteristics. But discontinuities in the relation between density and depth apparently suggest the existence of the annual layer boundary, *i. e.*, summer surfaces, with the support of the variation trend in $\delta^{18}O$ profile, wherefrom, the annual net accumulation in 1984 was derived as 3450 mm. Permeability coefficient of the aquifer was revealed as $4x10^{-7}$ m/s by means of the auger hole method.

1. Introduction

The Patagonia Icefield, located in the range of latitudes, 46° 30′ S – 51° 30′ S, on the southern part of South America is covered by large ice masses over the area of some 18,000 km^2, which ranks third in size of the area covered with ice in the world following Antarctica and Greenland. The glaciological and meteorological conditions of this region, however, have remained unknown yet because of the difficulty in accessibility. Thus the region has attracted people for mountaineering and exploration activities for a long time.

Recently, we organized the first systematic glaciological expedition to San Rafael Glacier and Soler Glacier, respectively on the western and eastern sides of the Northern Patagonia Icefield (Hielo Patagónico Norte) (Nakajima, 1985). On the basis of the reconnaissances in this research expedition, the first attempt of glacier drilling was planned to make clear the amount of annual net accumulation, structure of ice masses, densification process from firn to ice and other general characteristics of the accumulation area in the Northern Patagonia Icefield.

The drilling operation was successfully completed to the depth of 37.6 m through firn to ice in the end of November, 1985. The following were made : a) observations of stratigraphy and snow temperature through firn to ice ; b) measurements of density profile ; c) observations of grain size and shape by photographs of thin sections taken *in situ* ; d) measurements of pH, DC-electric conductivity and density of water taken from cores ; e) pumping tests of the englacial unconfined aquifer. For analyzing stable oxygen isotope ratios and chemical compositions, samples were obtained from the cores and the surface snow layers. The water samples were brought back to the laboratory in Japan.

Presented in this paper are the preliminary results of analyses of the glaciological characteristics in the accumulation area of the Northern Patagonia Icefield. A technical report of the drilling operation is given by Yamada *et al.* (1987) in the same issue as this paper.

2. Drilling site

The drilling site is situated at the accumulation area of San Rafael Glacier, a relatively flat snow field (46° 44′ S, 73° 32′ W, 1296 m a. s. l.), some 25 km in straight distance from the glacier terminus as shown by DS in Map 2 (folded in). As seen in the map, the drainage basin of San Rafael Glacier is mostly covered by ice masses, accounting for in 91% of the total area of 804. 3 km^2. The glacier overflows from the icefield into the sea level, Lagoon San Rafael being at the end of Fjord Elefantes, and calvings occur frequently at the terminus, while the highest point of the drainage is 3970 m in Mt. San Valentin. Mean annual air temperature and annual precipitation at the drilling site are estimated as −0.2°C and 7,500−10,000 mm, respectively, on the basis of altitudinal lapse rate of air temperature (Inoue *et al.*, 1987) and altitudinal distribution of precipitation (Fujiyoshi *et al.*, 1987) observed in the current glaciological expedition, and 7.6°C and 3,700 mm of them obtained near the glacier terminus, where surface meteorological observations have been made by the Chilian Air Force (BH in Map 2) since 1981.

3. Structural characteristics

The outline of structure in the snow cover and glacier ice is illustrated in Fig. 1. The surface layer to the depth of 50 cm consisted of new snow which had deposited just before we reached the site. Below this layer, snow texture changed discontinuously into wet granular snow. As will be mentioned later, firn transformed into ice at the depth of 26.7 m. Immediately above the firn-ice interface, an unconfined aquifer was found out and the borehole was filled with water, the water head coming up to the depth of 24.9 m. Moreover, the firn layer between depths of 19.7 m and 24.9 m was soaked with water, which was recognized by spilling water from cores in the barrel immediately after the core was lifted up from the hole. It may correspond to a capillary water zone in soil. The melting point remained the same at all depths in spite of accumulation area.

The stratigraphic profile of a core 37.6 m long is

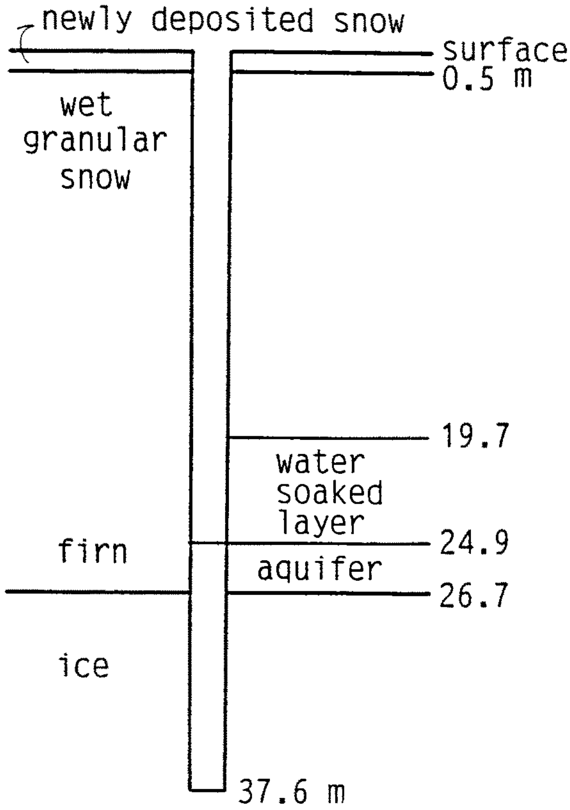

Fig. 1. Outline of structure in snow and ice of accumulation area in the Northern Patagonia Icefield.

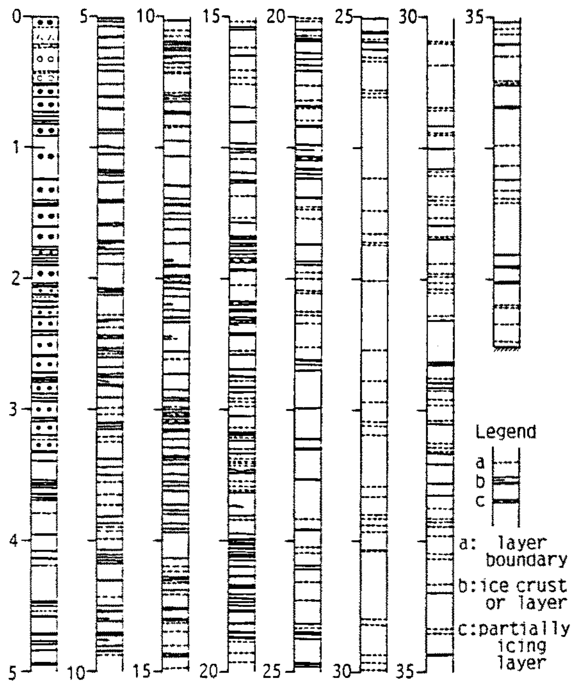

Fig. 2. Stratigraphy of a core 37.6-m long.

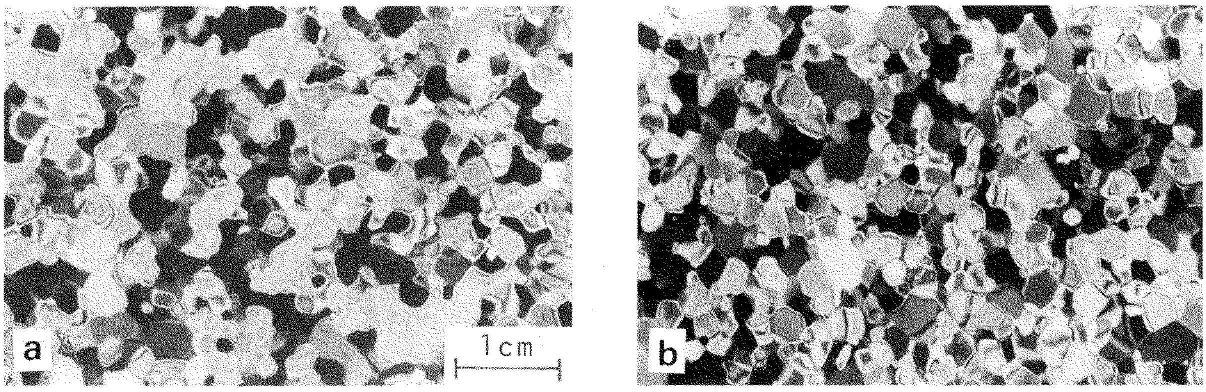

Fig. 3. Horizontal thin sections of the core at depths of 16.5 m (a) and 32.3 m (b).

shown in Fig. 2. The snow cover was composed of wet granular snow except the surface snow layer. In the granular snow layer, a number of ice crusts and ice layers abundantly existed with the thickness of 0.5–35 mm. Visible ice crusts/layers tend to decrease in number as they densify with increasing depth. Throughout the entire depth, we found no dirt layer and no cyclic variation in firn texture. An attempt to decide the annual layer only by stratigraphic observations resulted in failure. Also we found no lineations and no foliations of snow crystals and bubbles ; it suggests no active glacier flow in this site. The crystal size of firn and ice showed no remarkable growth with increasing depth but showed the almost constant size of 1–5 mm as shown in Fig. 3. As a result, the snow cover in the accumulation area of the icefield is characterized by wet granular snow containing many ice crusts/layers without dirt layers.

4. Results of core analyses

4. 1. The vertical profiles of Oxygen isotope content, pH-value, DC conductivity and water density

For obtaining information on the geochemical background and the seasonal fluctuation of the depositional environment on the icefield, the water samples taken from cores were examined in the laboratory. Oxygen isotope content was analyzed in Water Research Institute, Nagoya University, with the error of ± 0.2 per mil, and other three kinds of measurements were carried out in the room temperature of 20° C in Geophysical Research Station, Kyoto University. Water density is considered to depend on the amount of stable isotope (H^2 and O^{18}) and dissolved substance

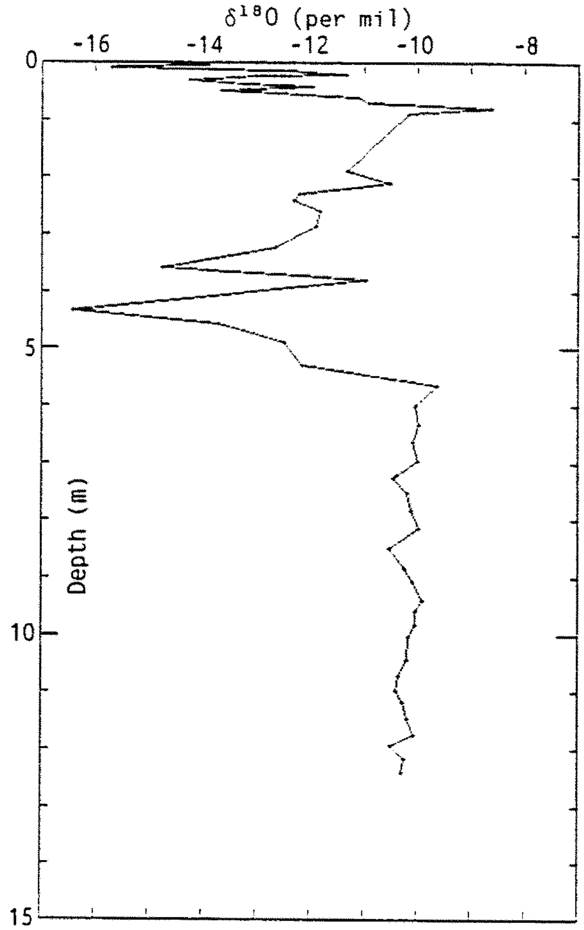

Fig. 4. Profile of oxygen isotope content.

in water.

The vertical profiles of oxygen isotope content, pH-value, DC conductivity and water density are respectively presented in Figs. 4, 5, 6 and 7. The

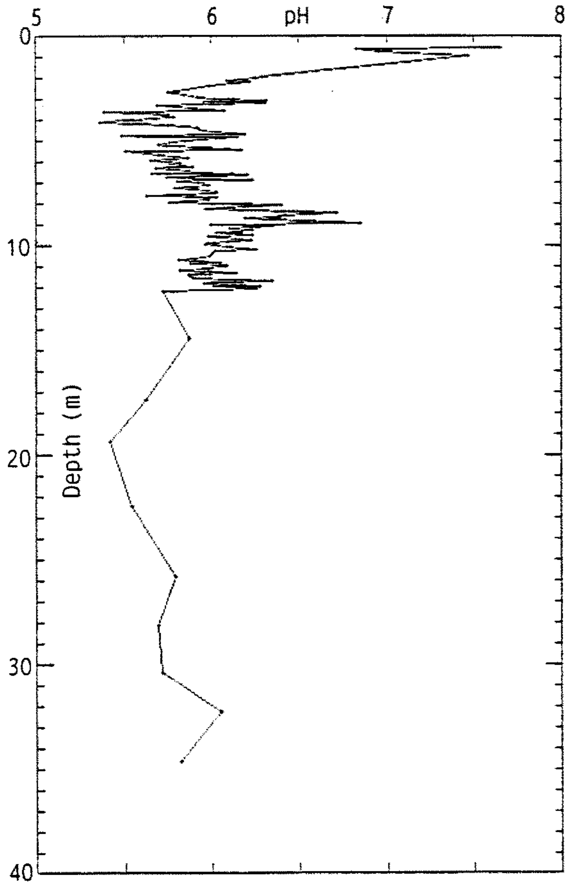

Fig. 5. Profile of pH.

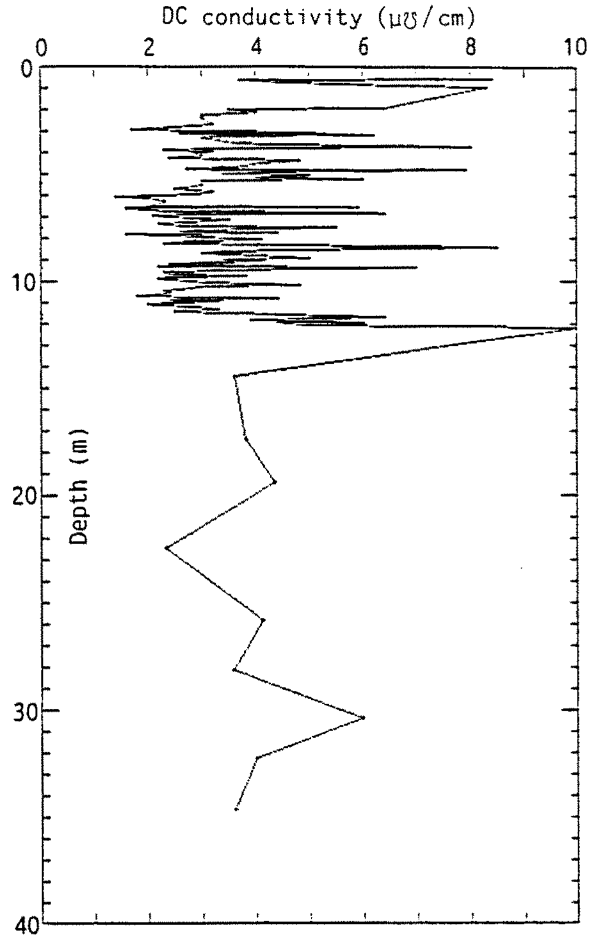

Fig. 6. Profile of DC electric conductivity.

oxygen isotope content given in $\delta^{18}O$ notation is characterized by a relatively large fluctuation from -17 per mil to -8 per mil in the upper layer above the level around 6 m deep and fairly constant at some -10 per mil in the lower layer below it. This discontinuity was not found in the profiles of pH, DC conductivity and water density, but another common level of discontinuity was found at the level around 2 m deep, above which values of pH and water density are larger and below which they are smaller. The interpretation of this discontinuity is still pending.

According to the results revealed from a Himalayan core (Watanabe *et al.*, 1984), the profiles of $\delta^{18}O$, pH and DC conductivity showed a relatively small scale oscillation and had no relation to the seasonal variation. The profiles below the level 2 m deep in the figures also show the same trend as the glacier in the Himalaya. The original distribution of chemical composition may have been disturbed and homogenized by the infiltration of abundant meltwater and rainwater, as is discussed in section 5.

4. 2. Density profile

Density was measured by means of the weight-volume method. Snow contained meltwater in its framework after coring. The wet density profile is shown by crosses in Fig. 8 with the profile of cumulative mass by a solid line. The wet density profile is much different from that in polar glaciers. In the polar glaciers, the increasing rate of density gradually decreases with increasing depth, and also firn gradually transforms into ice. The densification rate of wet snow in the icefield, on the contrary, apparently increases with increasing depth until the level approximately 19.7 m deep and the density of firn deeper than it is kept fairly constant at around 0.85 Mg/m^3 as seen

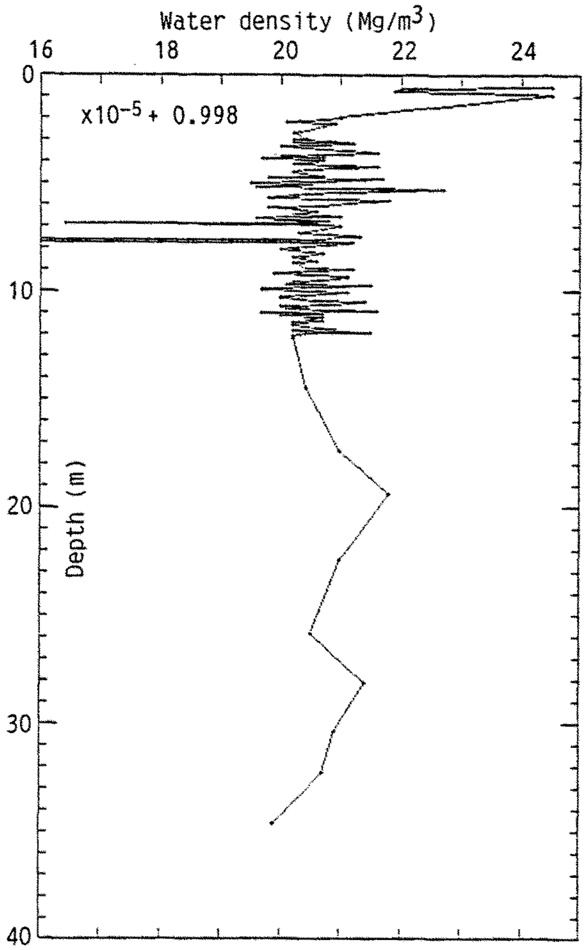

Fig. 7. Density profile of water melted from the core.

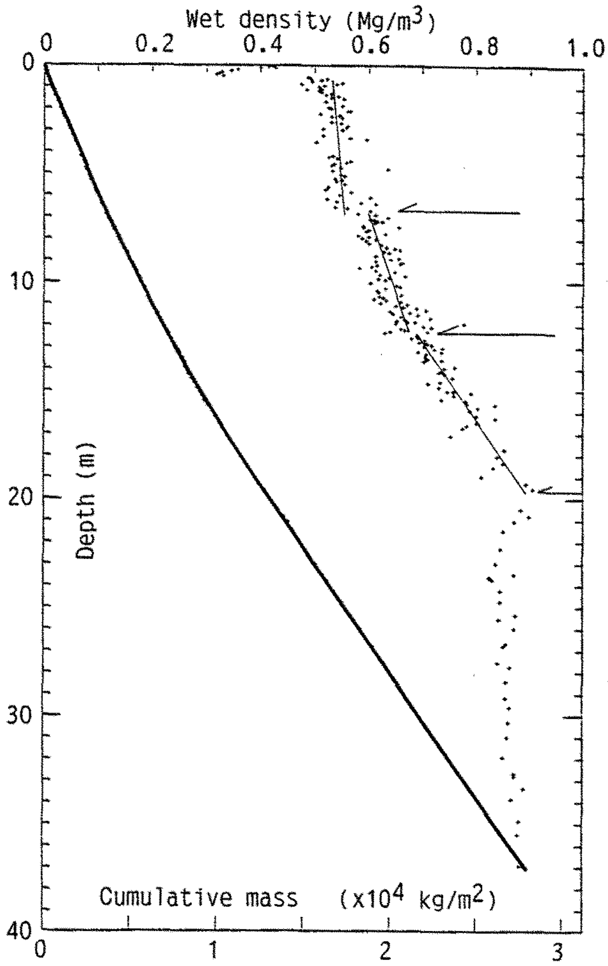

Fig. 8. Profile of wet snow density.

in Fig. 8. Cumulative mass calculated from the wet density profile shows a rapid increase with increasing depth, the increasing rate being larger than that in a usual polar glacier.

When the density profile is carefully examined, discontinuities are found in the relation between density and depth at levels around 6.8 m, 12.3 m and 19.7 m deep as shown by arrows in Fig. 8. These discontinuities will be discussed later.

5. Observation of aquifer

An aquifer found out during the drilling operation was an apparently unconfined one because of no impermeable layer over it. For obtaining the permeability coefficient of the aquifer, a pumping test was conducted by means of the auger hole method (Kirkham, 1954). Permeability coefficient k was determined from the equation :

$$k=0.617\frac{r}{Sd}\frac{\Delta h}{\Delta t},$$

where S is a geometrical function (see p. 83 in Kirkham, 1954). The radius of drilling hole r was 5.4 cm and the thickness of aquifer d was 176 cm in the pumping test. Measured was the level of water head h in the hole as a function of time after bailing water out of the hole to 32.45 m level of the water head. The value of k was calculated from time Δt needed for water to rise a distance of Δh in the hole.

The result of the observation is shown in Fig. 9. The water level rose up almost linearly with time during some 500 minutes after the start of measurement. As the water level passed up through the 26.7 m deep level, the rising rate began to decrease exponentially. Then the firn-ice interface existing at this

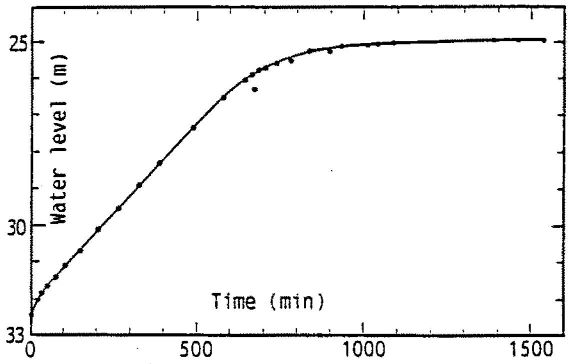

Fig. 9. Recovery of waterhead in the borehole.

level was decided. Permeability coefficient was derived as 4×10^{-7} m/s or 0.035 m/day, which corresponds to that of silt or sandstone. The value is one order greater than those obtained in the ablation area of Mendenhall Glacier in Alaska, 6.0×10^{-8} m/s (Takahashi and Wakahama, 1970) and in the accumulation area of Yala Glacier in Nepal Himalaya, 3.5×10^{-8} m/s (Iida *et al.*, 1984).

6. Discussion

The conspicuous and important characteristics of the accumulation area of the Northern Patagonia Icefield are the existence of abundant water in firn and glacier ice. The contained water may remain there throughout the year except in the surface layer, because monthly mean air temperature there is estimated as approximately -6°C even in the coldest months from the altitudinal lapse rate of air temperature (Inoue *et al.*, 1987) and data obtained at Chilian Air Force Meteorological Station (BH in Map 2), and it may be difficult for winter cold to penetrate the deeper layer.

As seen in the previous section 4.2., the densification process of wet snow is much different from that of polar snow. Since compactive viscosity of polar snow is expressed by the positive exponential of density (Kojima, 1964), the densification rate decreases with increasing density. However, the density profile in Fig. 8 suggests that the densification process in the Patagonia Icefield must be controlled greatly by stress, *i. e.*, overburden pressure and that its dependence on density is rather minor. Although the densification process of wet snow has partially been investigated (Ohmae and Wakahama, 1980), no sufficient experimental studies have been made, leaving it almost unknown.

For making clear the actual state of the densification process, dry density ρ_d is calculated from the measured wet density ρ_w and the estimated range of possible water content W, using the simple equation :

$$\rho_d = (1 - W)\rho_w.$$

Because of no measurement of the water content *in situ*, approximation was made by measuring water contents of wet snow in the perennial snow patch, in which an aquifer existed, in the Daisetsu mountain range, Japan, during the ablation season in 1986. Maximum and minimum values of water content were assumed as 4 to 8 % in the upper wet firn layer to the depth of 19.6 m, as 10 to 15 % in the firn layer of water soaked and the aquifer of 19.7 to 26.7 m in depth and as almost 0 % in the ice body below it. The calculated

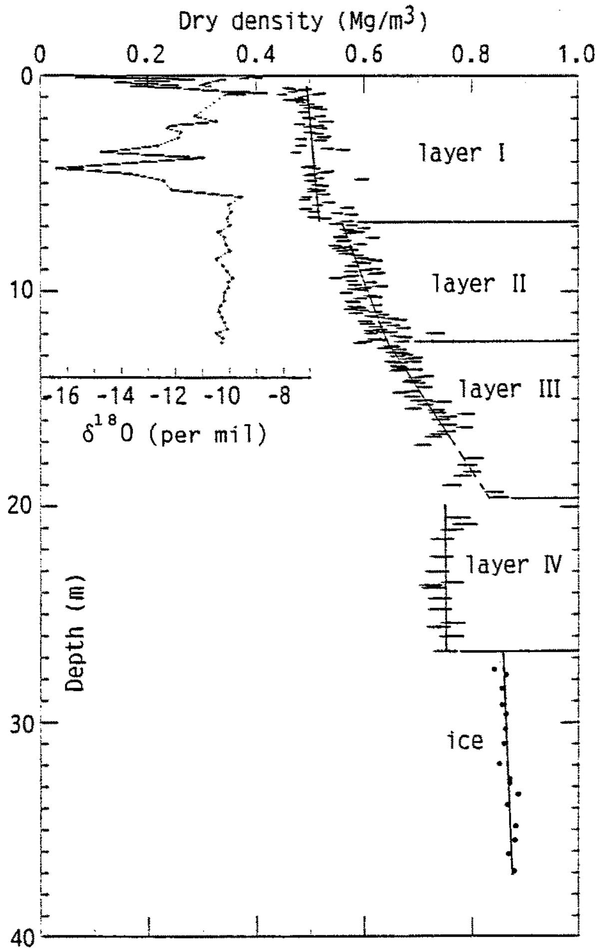

Fig. 10. Profiles of dry snow density calculated (horizontal bar) and Oxygen isotope content.

dry density profile is presented by the horizontal bar in Fig. 10 with $\delta^{18}O$ profile already shown in Fig. 4. Discontinuities in densification process are recognized in the profile. Upper three discontinuities are the same as those of wet density profile in Fig. 8.

Firn is divided into four layers denoted by layers I, II, III and IV in respect of the densification process. Density seems to increase linearly with increasing depth in each layer as shown by thick solid lines in Fig. 10. The density profile in uppermost layer I looks similar to that of the seasonal snow cover consisting of wet granular snow in the melting season. It is well known that a large fluctuation in the density profile in the winter snow cover decreases drastically and converges to the relatively constant density of 0.45−0.55 Mg/m^3 through the entire depth, due to wet metamorphism. The density profile of layer I suggests strongly that the layer should be deposited during the austral winter of 1985. This fairly constant density layer will be densified as the same density profile as that of layer II due to the successive winter accumulation mass.

Furthermore, the oxygen isotope content fluctuates between −17 and −8 per mil in layer I and this large fluctuation decreases drastically in layer II, showing the fairly constant value of −10.2 per mil. In general, the value of $\delta^{18}O$ in precipitation is smaller in winter than in summer ; that is, the amount of O^{18} in precipitation is richer in summer than in winter. When O^{18}-rich summer water percolates into an O^{18}-poor winter snow layer, the value of $\delta^{18}O$ gradually increases with time, as is well known. It is assumed that the $\delta^{18}O$-profile in layer I still kept the small winter value because it was measured in November 1985, the beginning of austral summer. A remarkable amount of water infiltrates during the summer in this region as is discussed later. Due to the infiltration of O^{18}-rich summer water such as rainwater and meltwater of snow temporarily deposited in summer, the small winter value of layer I should be shifted to the almost constant value of about −10 per mil as seen in layer II, which may be the annual mean value of $\delta^{18}O$ in this region.

As the conclusion of the above arguments, it can be predicted that discontinuity levels of 6.8 and 12.3 m in depth implies summer surfaces in the end of 1984−85 and 1983−84 austral summers, respectively, and layer I is deposited after 1984−85 summer, *i. e.,* in the winter season of 1985. Thus layer II stands for the annual layer during the above two summers, from which 3450 mm is calculated as an annual net accumulation in 1984.

The relative constant density profile in layer IV may be produced by the rising up of the water level of the aquifer or the water soaked layer to 19.7 m deep level in the previous summer. Then layer IV might be entirely soaked with water. In general, if the snow layer is filled with water, buoyancy is generated in the snow mass due to a difference in density between ice and water, which results in almost the same stress conditions through the snow layer. When the same stress conditions continue for a fairly long time, the equilibrium density to the stress is realized in the snow layer. A necessary amount of water for filling the spaces in layer IV is evaluated only as 1350 mm, if the en-glacial flow is negligibly small. In this area, the amount of percolated water is estimated at least as over 3000 mm in the summer season (Kondo and Yamada, 1987). Therefore layer IV may be entirely soaked with water. Then layer III may not be an annual layer because the boundary of layers III and IV at the discontinuity level of 19.7 m may not be the summer surface but the expected upper level of the aquifer or water soaked layer in 1984−85 austral summer.

The sudden transformation from firn to ice at the bottom of an aquifer should be essentially important to an ice formation process in temperate glaciers. Vallon *et al.* (1976) observed an ice formation process from firn to ice in an aquifer found in an Alpine glacier, reporting that about 3 m thick firn transformed into ice in the aquifer during the summer. Wakahama (1975) also found out that water soaked snow with the density of 0.46 Mg/m^3 transformed very quickly into ice during only one week under a fairly low stress of some 1000 kg/m^2. I also attempted to observe a densification process in the aquifer found in the perennial snow patch in Mt. Daisetsu during the summer season of 1986 ; I was not able to recognize transformation from firn to ice, however, observing only a high rate of densification there, despite that the stress was sufficiently large.

Transformation from firn to ice under the condition of submersion may depend on density, overburden pressure and time. Quantitative relationships between them are still unknown. The process should be experimentally investigated in future.

Acknowledgments

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Resumen

Características glaciológicas reveladas por la perforación a 37,6 m de profundidad en el área de acumulación del Glaciar San Rafael, Hielo Patagónico Norte (HPN)

A fines de Noviembre de 1985 se llevó a cabo la primera perforación glaciar en el HPN hasta una profundidad de 37,6 m. Los objetivos eran conocer la acumulación neta anual, la estructura del cuerpo de hielo, el proceso de densificación de neviza a hielo y otras características generales del área de acumulación del HPN. El sitio de perforación (DS en el Mapa 2 anexo a esta publicación) fue ubicado en el área de acumulación del Glaciar San Rafael (46°44' S, 73°32' W, 1296 m. s. n. m.), a unos 25 km en línea recta del frente del glaciar, sobre el relativamente plano campo de hielo.

San Rafael es un típico glaciar temperado y el hielo se encuentra al punto de fusión en todo su espesor. El estrato de nieve consiste en nieve granular húmeda con un tamaño de grano de 1-5 mm (Fig. 3), el cual no tiende a aumentar can la profundidad. Se encontró numerosos lentes y costras de hielo de un espesor de 0,5 a 35 mm, excepto en la capa superficial de nieve recientemente depositada (Figs. 1 y 2). La capa anual no pudo ser reconocida por observación estratigráfica debido a que no existían estratos visibles de impurezas ni tampoco variación en la textura, densidad o características químicas de la nieve (Figs. 2, 4, 5, 6, 7, y 8).

La densidad seca ρ_d se calculó a partir de la densidad medida in situ (Fig. 8) y estimaciones del contenido de agua mínimo y máximo posible. La densidad seca aumentó gradualmente con la profundidad hasta los 19,7 m, y luego la neviza mostró un valor constante de alrededor de 0,75 Mg/m^3 hasta los 26,7 m (Fig.10). El gradiente $d\rho_d/dz$ aumenta con la profundidad al contrario de los glaciares polares. La

neviza se transforma de súbito en hielo a partir de la superficie de contacto neviza-hielo a los 26,7 m. Tal proceso de densificación caracteriza al campo de hielo Patagónico y se debe al efecto de abundante agua que percola a través de la nieve y neviza, estimándose un total anual de 3.000 mm producto de aguas lluvias y derretimiento. Se consideró que las dos discontinuidades superiores de las tres en total encontradas en la nieve y neviza corresponden a la superficie del verano austral de 1984-85 y 1983-84, por simple añalisis con apoyo de datos de variación del perfil de δ^{18} O. Así se encontró una acumulación anual neta de 3.450 mm para la capa de 1984.

En el contacto neviza-hielo, se encontró un acuífero no confinado de un espesor de 1,8 m entre los 26,7 m y 24,9 m de profundidad. Mas aún, se encontró una capa saturada sobreimpuesta al acuífero entre los 24,9 m y 19,6 m de profundidad (Fig. 1). Por medio del método de perforación Auger se determinó que el coeficiente de permeabilidad del acuífero es de $4 \cdot 10^{-7}$ m/s.