SOME RESULTS ON OXYGEN ISOTOPE AND STRATIGRAPHIC ANALYSES OF FIRN IN MIZUHO PLATEAU, EAST ANTARCTICA

Okitsugu WATANABE, Kikuo KATO

Water Research Institute, Nagoya University, Chikusa-ku, Nagoya 464

and

Kazuhide SATOW

Nagaoka Technical College, Nishi-katakai-machi, Nagaoka 940

Abstract: Oxygen isotope ($\delta^{18}O$) and stratigraphic analyses of the 2 m deep pits and the 10 m deep cores from the coast to the high-inland region of Mizuho Plateau have been done. A seasonal diagram of $\delta^{18}O$ of drifting snow in connection with the elevation was obtained from the $\delta^{18}O$ values of fallen snow and drifting snow. The regional characteristics of the relations between the $\delta^{18}O$ profiles and the firn layering structures were examined.

The seasonal cycles of $\delta^{18}O$ are only found in the $\delta^{18}O$ profiles in the firn of the coastal region and in the specified places of the katabatic slope region. The $\delta^{18}O$ profile in the most of the katabatic slope region is largely controlled by the season of formation of the surface snow layer and the snow metamorphosis such as the formation of loose and hard depth hoar.

Similar tendencies are found in the profiles of the running means of $\delta^{18}O$ in the cores of the costal region and of the katabatic slope region, respectively. These tendencies may reflect the change of glaciological environment spread over each region.

1. Introduction

The identification of the annual layer from the seasonal cycles of the oxygen isotopic composition ($\delta^{18}O$) have been applied to the pits and the cores from the various places in the Greenland and Antarctic ice sheets. In the Camp Century core it was found that the obvious seasonal cylces of $\delta^{18}O$ are preserved to a depth of 1000 m (JOHNSEN *et al.*, 1972). This method of identifying the annual layer from the seasonal cycles of $\delta^{18}O$ is based on the fundamental idea that the $\delta^{18}O$ of precipitation varies seasonally with its temperature of formation.

On the other hand, as described by PICCIOTTO *et al.* (1968), the accumulation estimated from the cycles of $\delta^{18}O$ in the pits from the Pole of Relative Inaccessibility would be three times larger than that estimated from the other methods such as the stake measurement and the gross β-radioactivity determination. KATO and WATANABE (1977) pointed out that, in Mizuho Plateau, the seasonal cycles of $\delta^{18}O$ are found in the $\delta^{18}O$ profile in the firn of the coastal region, while are not found in that of the katabatic slope region.

As WATANABE (1978a, b) pointed out in this region, the processes of the surface layer formation vary with the region as well as with the climatic conditions. The occurrence of hiatus (interruption in the layer formation) shows striking regional contrasts. The hiatus rarely occurs in the coastal region while frequently occurs throughout the katabatic slope region.

Such regional characteristics in the surface layer formation may affect the $\delta^{18}O$ profile in the firn. The surface snow cover formed during active layer formation shows various $\delta^{18}O$ values reflecting fairly abundant snow depositions (WATANABE, 1978b). In the surface snow cover formed during a long-term hiatus, the initial profile of $\delta^{18}O$ in the firn may be strongly affected by sublimation and depth hoar formation.

In the present study, oxygen isotope and stratigraphic analyses of the 2 m deep

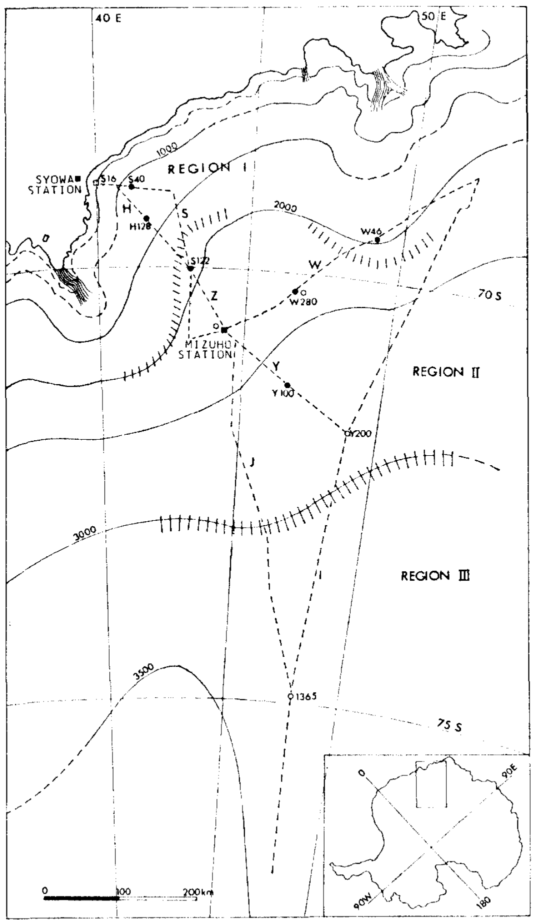

Fig. 1. Glaciological divisions with sites of 2 m deep pit observations (●) and 10 m deep cores (○) on Mizuho Plateau. The traverse routes H, S, Z, W, Y, J and I are shown by the broken lines. The tentative boundaries of the regions are shown by the belt-shaped oblique lines.

pits and the 10 m deep cores from the coast to the high-inland region of Mizuho Plateau have been done to interpret the relation between the $\delta^{18}O$ profile and the firn layer structures.

2. Glaciological Environments and Their Division on Mizuho Plateau

Glaciological environments of Mizuho Plateau, especially the regional tendency of mass balance, were studied during the 10th Japanese Antarctic Research Expedition (JARE-10) to JARE-15 in 1968–1975 from the glaciological, meteorological and geochemical points of view.

As seen in Fig. 1, Mizuho Plateau can be divided into three characteristic regions (WATANABE, 1978a). The description of brief glaciological aspects and the stratigraphic observation sites are shown in Table 1.

These glaciological aspects mentioned in Table 1 reflect basically topographic and climatic conditions and then the stratigraphic structures of the firn vary with the

Table 1. Glaciological divisions of Mizuho Plateau.

Region	Range of elevation	Glaciological aspects	Sites of 2 m deep pit observation and 10 m deep coring in 1973–1976 (elevation in m)
Region I the coastal region	lower than 1800–2000 m	Active annual layer formation with high annual accumulation rate	W46(1958)**
		Continuous distribution of the thick annual layering	S40(1142)***, H128(1378)*** H228(1657)*, W46(1958)***
Region II the katabatic slope region	between 1800–2000 m ~ 3000–3200 m	Common occurrence of the hiatus of the annual layer formation Sporadic distribution of the annual layering with large regional deviation in annual accumulation rate	Mizuho Station (2230)***, W280 (2405)***, Y100 (2606)*, J364 (2613)**, Y200 (2880)***
		Highly developed glazed surface distributed in the region between 2500–3100 m in elevation	S122(1910)***, Z30 (2056)*, W280 (2405)***, Y100 (2606)***, Y200 (2880)*
Region III the high-inland region	higher than 3000–3200 m	Thin unit layer characteristics with uniform and continous layering (Gow, 1965; WATANABE *et al.*, 1979)	J225 (3039)*, I235 (3199)*, I365 (3310)***, I485 (3382)**, I600 (3408)*
			J225 (3039)*, I115 (3049)*, I235 (3200)*, J95 (3253)*, I355 (3304)*, I485 (3382)*

* Reported in WATANABE (1977). ** Reported in WATANABE (1978b).
*** Reported in the present paper.

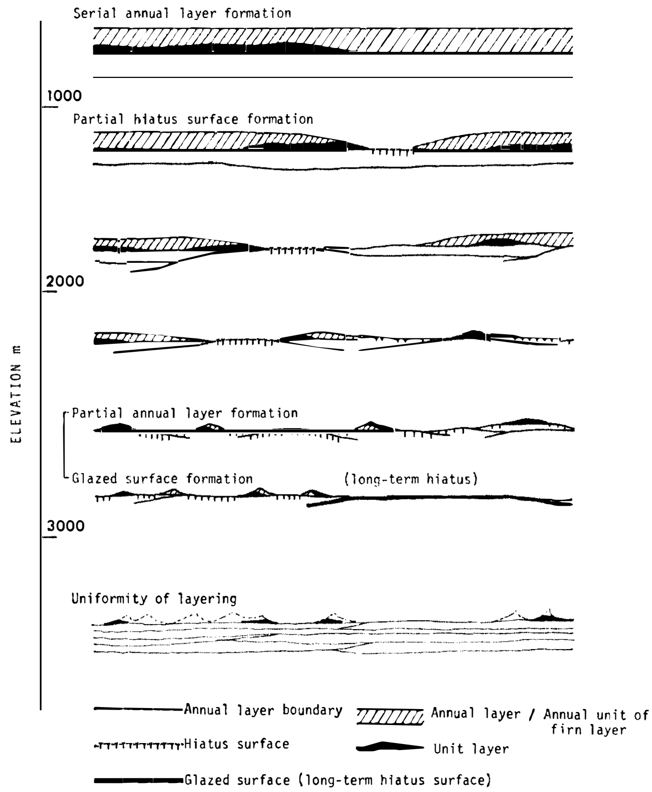

Fig. 2. Schematic model of regional stratigraphic aspects of the snow cover indicated by occurrence and distribution of the annual layers, the unit layers and various types of layer boundaries.

region. These structures are commonly complicated, so that simplified stratigraphic units are adopted for easy understanding of the stratigraphy. In Fig. 2, a schematic conceptional model of the regional stratigraphic aspects is shown by using the terms of unit layer, annual layer (unit) and hiatus surface (WATANABE *et al.,* 1978). A snow layer superimposed upon the previous surface is defined as a unit layer (WATANABE, 1978b).

The scale and shape of unit layer and the frequency of its formation in a year depend on the climatic conditions. The large scale of unit layer and the frequent occurrence of unit layer formation, in general, are seen in the coastal region and the opposite tendencies increase inland. Such regional characteristics of unit layer formation are considerd to be important in interpreting the relation between the $\delta^{18}O$ profile and the stratigraphy in the firn.

3. Analytical Procedures

3.1. Sites of the pit work and coring

The sites of eleven 2 m deep pit works in 1974–1975 and fifteen 10 m deep corings in 1973–1976 are shown in Fig. 1 and Table 1. However, due to extreme development of depth hoarization in the high-inland region, higher than 3200 m in elevation, the recovery of cores by means of hand auger became to be inefficient.

For all of these pits and cores, prelimenary stratigraphic analyses such as stratigraphic description and physical properties were already reported (WATANABE, 1977, 1978b).

3.2. Oxygen isotope determination

The samples from the walls of the pits for the oxygen isotope determination and the cores were brought back to Japan in a frozen state. One to five samples for the oxygen isotope determination were taken from each unit layer throughout the core, after the stratigraphic observations of the cores.

The experimental procedures for the oxygen isotope determination are essentially the same as described by EPSTEIN and MAYEDA (1953). The $^{18}O/^{16}O$ ratio of CO_2 equilibrated isotopically with a water sample was measured with a double collector mass spectrometer (Varian MAT CH-7) at Department of Earth Sciences, Nagoya University, for the pit samples (KATO, 1977) and with a triple collector mass spectrometer (Varian MAT 250) at Water Research Institute, Nagoya University, for the core samples. Analytical results are given in $\delta^{18}O$ notation (CRAIG, 1961) and the analytical error is $\pm 0.2‰$.

Since oxygen isotopic fractionation may take place within the cores during long time storage in a cold room, such $\delta^{18}O$ data from the cores, which were most recently analyzed, are neglected.

3.3. Stratigraphic interpretation of annual layer

One of the most important purposes of the stratigraphic study is the interpretation of annual layer. Such stratigraphic data as the mean annual balance, processes of surface layering, successive change of surface conditions and so on are obtained on the basis of the annual layer sequence interpreted for a sufficient number of years. These factors are important to know the glaciological environments at a given place.

The annual layers are inferred on the basis of the stratigraphic aspects as follows:

1) Periodicity of physical and geochemical properties in the firn layer: profiles of density and $\delta^{18}O$ are very useful.

2) Seasonal characteristics of the unit layer: hard wind-packed layer formed during the end of summer and beginning of autumn, and thick winter layer with relatively simple structure are good indicators of the seasons. These layers are also

inferred by using the profile pattern of grain size.

3) Seasonal characteristics of the surface conditions: a flat layer boundary with the thick and clear ice crust is a structural indicator of the summer surface leveling. This criterion for determination of the summer surface is effective in the pit wall observations in particular.

These seasonal cycles and the stratigraphic criteria for the specific seasons are regional, not universal, so that the application should be done respectively within each region.

4. Seasonal Diagram of Oxygen Isotopic Composition of Snow

Fallen and drifting snow samples collected for the oxygen isotope determination (KATO, 1977) are as follows: 1) Fallen snow samples, some of which include partly drifting snow, collected at Syowa Station in February–December 1974. 2) Drifting snow samples collected at Mizuho Station in January 1974–February 1975. 3) Drifting snow samples collected at various places during the traverses of JARE-15 in 1974–1975.

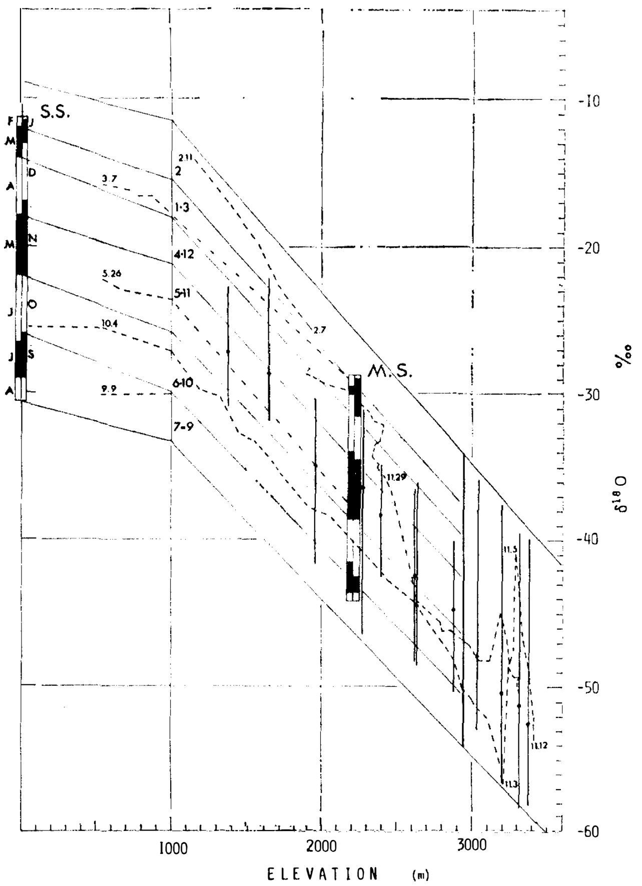

Fig. 3. Seasonal diagram of the relation between $\delta^{18}O$ of fallen and drifting snow and the elevation along the traverse routes S-H-Z-Y-W-I-J of JARE-15. The dark and open parts of the bar graph at Syowa Station (S.S.) and Mizuho Station (M.S.) indicate the monthly range (e.g. F: February) of $\delta^{18}O$ of fallen snow and drifting snow, respectively. The vertical straight lines show the $\delta^{18}O$ range in the 2 m deep pits. The broken lines show the variation of $\delta^{18}O$ of drifting snow collected during the JARE-15 traverses carried out in the various seasons of 1974–1975.

Seasonal variations and regional characteristics of $\delta^{18}O$ of fallen and drifting snow were studied by KATO (1977, 1978, 1979) and KATO *et al.* (1977, 1978, 1979). From such various data was inferred a seasonal diagram of $\delta^{18}O$ of drifting snow in connection with the elevation along the traverse routes of JARE-15 shown in Fig. 1. This diagram is shown in Fig. 3.

The bar graph shows the annual range of $\delta^{18}O$ of fallen snow sampled at Syowa Station (S.S.) and that of drifting snow sampled at Mizuho Station (M.S.), respectively. The dark and open parts of these bar graphs indicate the monthly range of $\delta^{18}O$ (*e.g.* F: February). The variation of $\delta^{18}O$ of drifting snow collected during the JARE-15 traverses carried out in the various seasons of 1974–1975 is shown by each broken line in Fig. 3. The monthly ranges of $\delta^{18}O$ of drifting snow in connection with the elevation along the traverse routes, which are inferred from the various data above mentioned, are shown by using the oblique lines.

It is seen from this diagram that Mizuho Plateau can also divided into three characteristic regions according to the variation with elevation of $\delta^{18}O$ of drifting snow, as pointed out by KATO *et al.* (1977, 1978, 1979) and KATO and HIGUCHI (1979). The first region ranges in elevations from the coast to 100 m with steep slope topography and shows $-4\sim5‰\cdot1000\,m^{-1}$ in the $\delta^{18}O$ gradient. The second region, ranging between 1000 m and 3000 m in elevation and $120\sim130$ km and $200\sim300$ km in distance from the coast, is mostly correlative with the katabatic slope region. The $\delta^{18}O$ gradient, $-10‰\cdot1000\,m^{-1}$, in the second region is twice as large as that in the first region. In the third region, higher than $3000\sim3200$ m in elevation, the variation with elevation of $\delta^{18}O$ of drifting snow shows a large anomaly as seen in Fig. 3. The amplitude of the $\delta^{18}O$ range in the firn at Mizuho Station, shown in the diagram with a vertical straight line, is almost the same as that of drifting snow. The difference between these $\delta^{18}O$ ranges is only 2‰. Accordingly, this diagram may be effective in determining the season of the layer formation.

5. Analyses of 2 m Pits

The pit wall observation is the most effective and easiest in the stratigraphic observations of the surface snow layer. Annual layer boundaries (summer surface of every year) were *in situ* determined by means of the layering structures.

The stratigraphic and oxygen isotope analyses of the pits dug at W46, J364 and I485 were already reported (WATANABE, 1978b). In the present study, the stratigraphic structures and the profiles of $\delta^{18}O$ and density in the pits of W280, Y200, I365 and Mizuho Station are shown in Fig. 4.

According to the glaciological division above mentioned, W280 and Y200 are in the katabatic slope region and I365 is in the high-inland region. The analytical results at these stations show the typical ones in the both regions. However, that at Mizuho Station in the katabatic slope region is an example of the surface snow cover formed due to the installation of the huts. This example shows that a mode of snow accumulation depends largely on the surface conditions (WATANABE, 1978a) and snow can accumulate in all seasons under the surface conditions favorable to snow accumulation (WATANABE *et al.*, 1978).

The annual layer boundaries *in situ* determined are indicated by arrows in Figs. 4a ~ c. The relatively flat surface with thick ice crust formed during the summer surface leveling is determined as an annual layer boundary, taking into the consideration the depth and domain of loose and hard depth hoar development and the seasonal characteristics of layering.

The annual mean accumulations to a depth of 205 cm at W280 and of 195 cm at Y100 are 41 cm and 32 cm of snow, 18 mm and 13 mm of water, respectively. These values are fairly high in comparison with the general trend of accumulation in the katabatic slope region. The shaded parts in the $\delta^{18}O$ profiles indicate the $\delta^{18}O$ ranges of precipitation in May and November, which were determined from the seasonal diagram of $\delta^{18}O$ of drifting snow (Fig. 3). This may indicate that a large amount of precipitation in the autumn and the spring is accompanied by active penetrations of cyclonic disturbance inland of Mizuho Plateau in these seasons.

The seasonal cycles of $\delta^{18}O$ are found in the $\delta^{18}O$ profile of W280, just as found in that of W46 in the coastal region (WATANABE, 1978b). The annual layer boundaries, shown by the arrows in Fig. 4, determined from the stratigraphic analyses of the W280 pit correspond almost to the maxima of $\delta^{18}O$ and also to the minima of density, respectively. This fact shows that snow accumulation occurs in every season at W280 and then the annual accumulation is extremely larger than those at the other stations in the katabatic slope region.

On the other hand, the seasonal cycles of $\delta^{18}O$ are not found in the $\delta^{18}O$ profile of the Y200 pit. An obvious contrast between the stratigraphic structures of the W280 and Y200 pits is also found: flat layer boundaries and cyclic seasonal layering at W280 while irregular layer boundaries and complicated textures at Y200. These differences of the stratigraphic aspects and the profiles of $\delta^{18}O$ and density between these two stations reflect the differences of the glaciological environments.

As KATO and WATANABE (1977) pointed out, $\delta^{18}O$ in the firn at Y200 may be controlled by the following factors: 1) Snow does not always accumulate in every season. 2) Glazed surface is occasionally exposed over one year and subsequent movement of water vapor in the firn occurs during depth hoar formation.

The stratigraphic structures at I365 show typical features of the high-inland region: flat layer boundaries and thin unit layering with partial development of hard depth hoar. The annual layer boundaries were *in situ* determined. The annual mean accumulation is 18 cm of snow, 6 cm of water to a depth of 195 cm.

In the $\delta^{18}O$ profile of the I365 pit, the observed cycles of $\delta^{18}O$ are not seasonal ones. The peaks found at depths of 40 cm, 80–90 cm, 120–130 cm and 170 cm may be rather related to the formation of depth hoar.

From the oxygen isotope and stratigraphic analyses of the 2 m pits in the present study and the previous study (WATANABE, 1978b) are seen the followings:

1) In the coastal region where a larger annual accumulation usually occurs, snow accumulates in every season and then an annual layer can be determined from

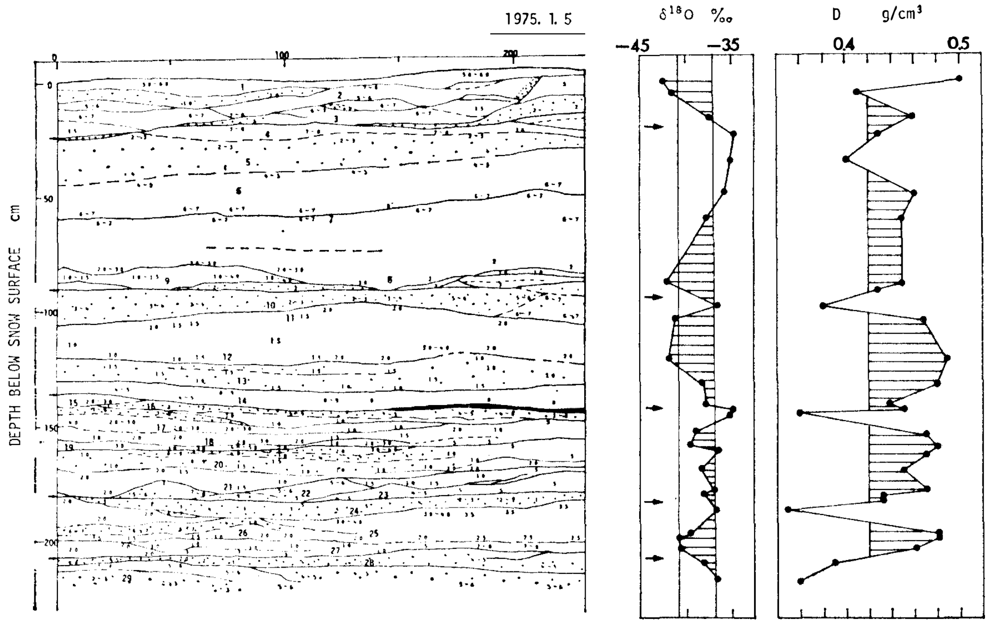

Fig. 4a. W280.

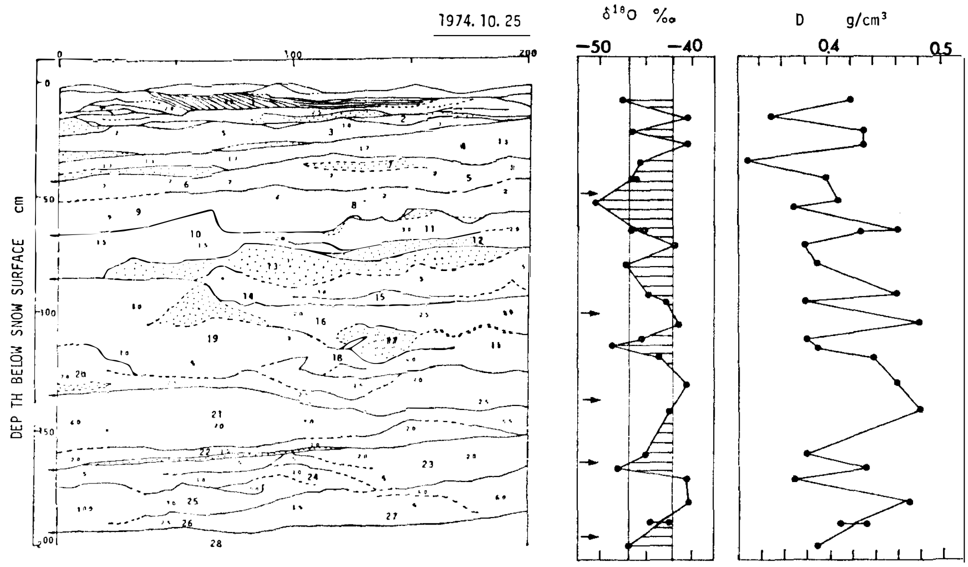

Fig. 4b. Y200.

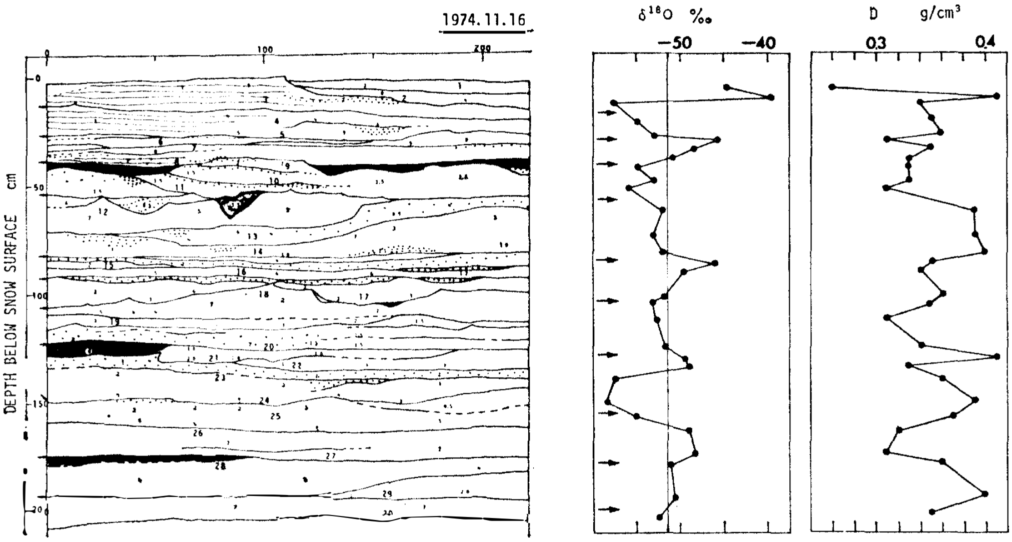

Fig. 4c. 1365.

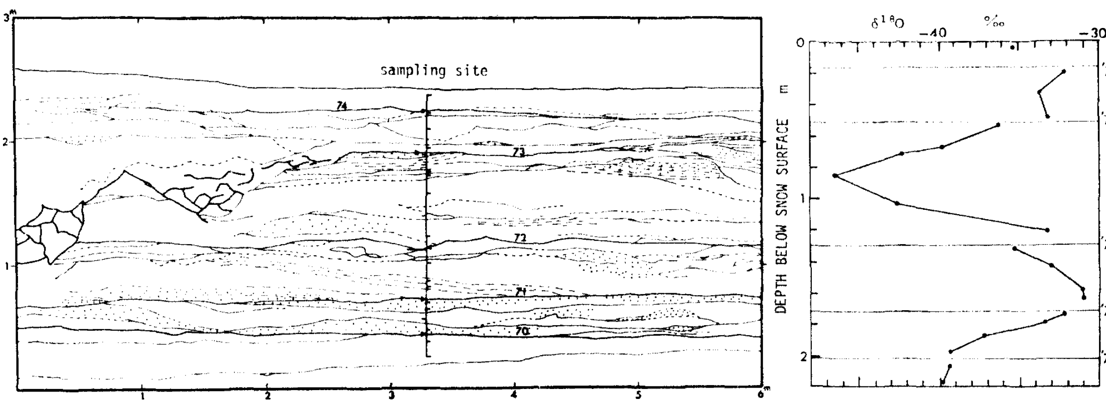

Fig. 4d. Mizuho Station.

Fig. 4. Stratigraphic diagrams and $\delta^{18}O$ profiles in the 2 m deep pits at W280, Y200, 1365 and Mizuho Station.

1) In the stratigraphic diagram, arrow: annual layer boundary; continuous line (broken line): layer boundary with ice crust (without ice crust); darkened layer: thin and very hard layer; dotted parts: depth hoar developed; and the small and large numerical figures are hardness by Canadian gauge (kg/cm²) and $\delta^{18}O$ sample number respectively.

2) The shaded parts seen in $\delta^{18}O$ profiles indicate the range of autumn and spring precipitation according to Fig. 3.

the seasonal cycles of $\delta^{18}O$.

2) In the katabatic slope region, the minima of $\delta^{18}O$ may show those of autumn-winter layers and the maxima of $\delta^{18}O$ are occasionally caused by the local develop-

ment of depth hoar, except for the specified places where an annual accumulation is more than about 40 cm snow and the seasonal cycles of $\delta^{18}O$ are seen.

3) In the high-inland region, the cycles of $\delta^{18}O$ are not governed by the annual layer formation and may be affected by snow metamorphosis such as the formation of loose and hard depth hoar.

6. Analyses of 10 m Cores

Oxygen isotope determinations have been done on the six 10 m cores (S40, H128, W46, S122, W280 and Y100). The former three cores were obtained from the coastal region, and the latter three from the katabatic slope region. Although the elevations of W46 and S122 are almost same, it can be considered that W46 is located within the coastal region and S122 corresponds to the lower limit of the katabatic slope region, judging from the tendencies of the annual accumulation and the surface conditions in each region.

Simplified stratigraphic diagrams and $\delta^{18}O$ profiles of these cores are shown in Fig. 5. The annual layer boundaries estimated from the stratigraphic and $\delta^{18}O$ analyses are shown by arrows, respectively.

6.1. The coastal region

As shown in the S40 core diagram in Fig. 5, 17 annual layers to a depth of 960 cm are independently determined from the stratigraphic and oxygen isotope analyses. The mean annual accumulation estimated from these determinations is 56 cm snow. This value is nearly equivalent to 50 cm snow determined from the stake measurements in 1973 and 1974 (YAMADA *et al.*, 1978).

However, the annual layer boundaries determined independently from the stratigraphic and oxygen isotope analyses do not always coincide. This is because the maximum of $\delta^{18}O$ is not only related to the summer precipitation but also to the development of depth hoar.

In the H128 core, 17 or 19 annual layers were found to a depth of 960 cm. The estimated mean annual accumulation of 56 or 50 cm snow is almost twice as much as that of 30 cm snow determined from the stake measurements (YAMADA *et al.*, 1978). However, as pointed out by KATO and WATANABE (1977), the determinations of annual layer by means of the stratigraphic and oxygen isotope analyses show a good agreement with that by using of the reference horizon of the 1964–1965 summer surface obtained by the gross β-radioactivity measurements (KATO, 1977). A larger value of 43 cm snow was also found in 1978–1979 in the data of stake measurements.

The vicinity of W46 is a particularly high accumulation in the coastal region. This is considered to be due to the topography favorable for penetration of cyclones. According to the pit observation at W46 (WATANABE, 1978b), the mean annual accumulation is estimated 70 cm snow. By means of the stratigraphic and oxygen isotopic

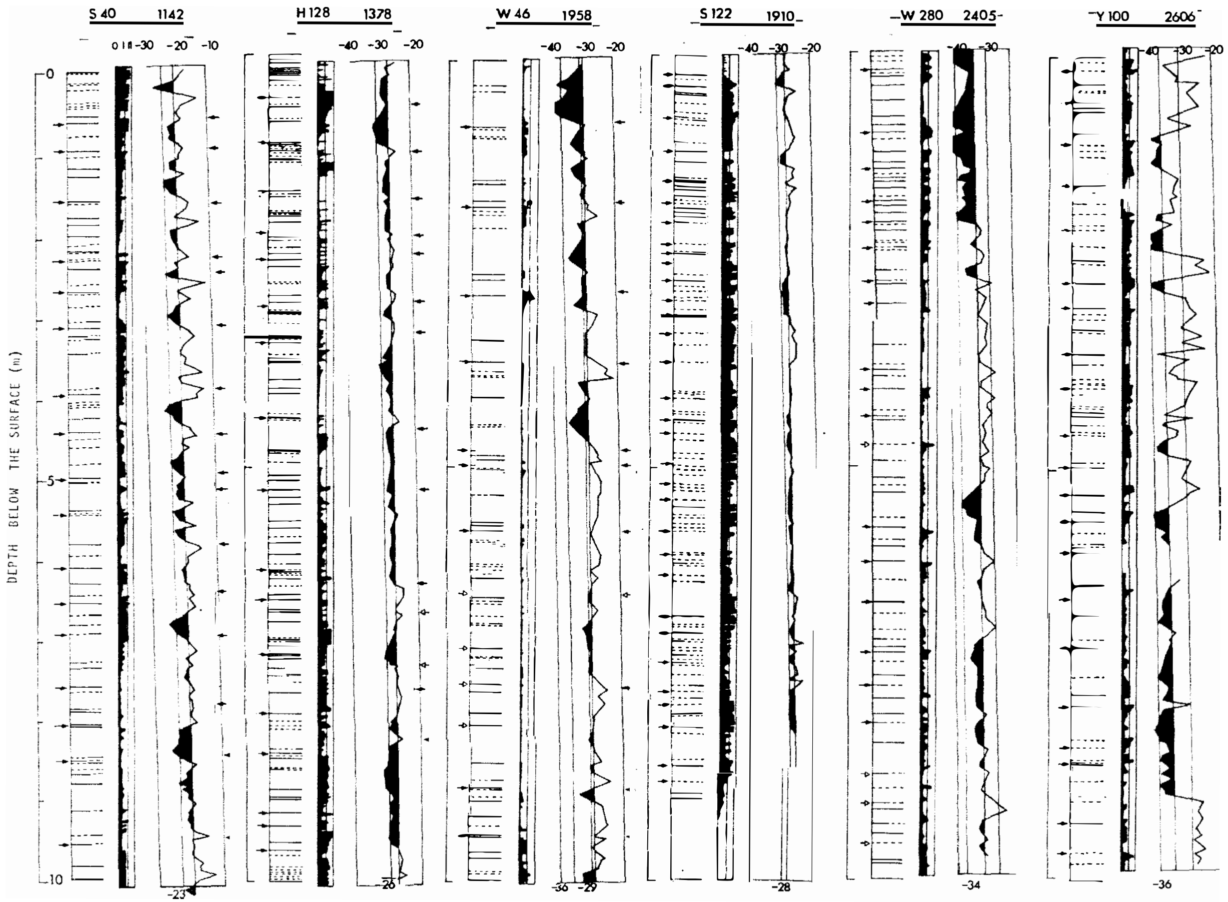

Fig. 5. Simplified stratigraphic diagrams and $\delta^{18}O$ profiles in the 10 m deep cores from Mizuho Plateau. Arrow: annual layer boundary (◀: likely, ◁: doubtful) estimated by stratigraphy (left) and $\delta^{18}O$ profile (right); continous line (broken line) in the stratigraphic diagram indicates layer boundary with ice crust (without ice crust); O, I and II in the median column indicate the level of depth hoar development, i.e., level II is strongly metamorphosed firn, O is initial stage of transformation and I is an intermediate level between O and II.

analyses including the density profile method, 12 annual layers with the mean annual accumulation of 70 cm snow were estimated to a depth of 950 cm.

6.2. The katabatic slope region

The annual accumulation at S122 determined from the stake measurements in 1968–1980 were 0 or negative, except for 28 cm snow in 1970–1971 and 29 cm snow in 1975–1978. So, the purpose of the S122 core analyses was mainly to know the $\delta^{18}O$ profile in the firn under such a glaciological environment. As is obvious from the profile of depth hoar intensity (D.H.L.), the depth hoar is highly developed in the depth range between 2 m and 7 m. In this depth range the variation of $\delta^{18}O$ shows a smaller amplitude and a lower frequency. Even obvious cycles of $\delta^{18}O$ are not seen in the S122 core.

From the stratigraphic interpretation, excluding the periods of hiatus of the annual layers, 32 annual layers with the mean annual accumulation of 28 cm snow were estimated to a depth of 900 cm in the S122 core.

In the W280 core, 21 annual layers were estimated to a depth of 970 cm. From this result the mean annual accumulation at W280 is estimated 46 cm, which fairly agrees with that from the stratigraphic and oxygen isotope analyses of the 2 m pit. The seasonal cycles of $\delta^{18}O$ with the broad winter minima are remarkable to a depth of 2 m in the $\delta^{18}O$ profile.

The vicinity of Y100 and Y200 shows a typical katabatic slope environment, where rough surface composed of sastrugi and dune with the various shapes and scales is distributed. The stratigraphy of such a rough surface region is very complicated, as mentioned in the section of the 2 m pit.

6.3. Regional comparison of oxygen isotope profiles

The profiles of running means of $\delta^{18}O$ in five cores, except for the S122 core, are shown in Fig. 6. The lines in this figure show the depths of the 5, 10, 15 and 20 annual layer levels below the summer surface of 1974–1975.

Although the coring sites, W280 and Y100, show the relatively high accumulations in the katabatic slope region, the existence of hiatus of the annual layer formation should be taken into consideration. Accordingly, the annual layer levels in Fig. 6 obviously become more shallow inland, except for W46 with the exceptional topography and accumulation rate. This shows a good concordance with the general trend of the accumulation rate.

Similar tendencies are found in the profiles of the running means of $\delta^{18}O$ in the cores of the coastal region and of the katabatic slope region, respectively. These tendencies may reflect the change of glaciological environment spread over each region rather than that of local surface conditions.

The straight line in each diagram of Fig. 6 is a linear regression line ($y=ax+b$) of each profile. The gradients (a) are nearly zero in the profiles of the S40 and H128

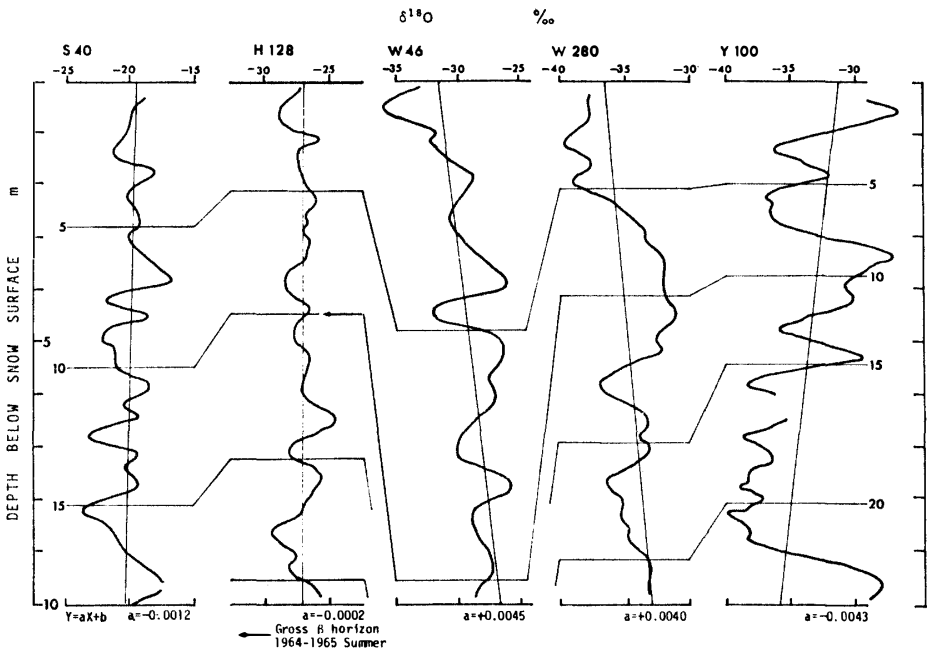

Fig. 6. Profiles of running means of $\delta^{18}O$ in the 10 m deep cores from Mizuho Plateau. Counting of the annual layers (5, 10, 15 and 20) is done from the 1974–1975 summer level, assuming 1973–1976 accumulation at H128 from stake measurement data, where the coring was done in the summer of 1973. The straight line in each diagram is a linear regression line ($y=ax+b$) of each profile.

cores, positive in those of the W46 and W280 cores, and negative in the Y100 core. The regional differences of the gradients which was found in the $\delta^{18}O$ profiles in the 2 m pits by KATO and HIGUCHI (1979) are recognized. These differences are considered to reflect the differences in the glaciological environments of these region.

7. Concluding Remarks

Oxygen isotope and stratigraphic analyses of the 2 m pits and 10 m cores from the coast to the high-inland region of Mizuho Plateau have been done. A seasonal diagram of $\delta^{18}O$ of drifting snow in connection with the elevation was obtained from the $\delta^{18}O$ values of fallen and drifting snows. The regional characteristics of the relations between the $\delta^{18}O$ profiles and the firn layering structures were examined.

The following concluding remarks may be drawn: The seasonal cycles of $\delta^{18}O$ are only found in the $\delta^{18}O$ profiles in the firn of the coastal region and in the specified places of the katabatic slope region where high accumulations occur. The $\delta^{18}O$ profile in the most of the katabatic slope region is largely controlled by the season of formation of the surface snow layer and the snow metamorphosis such as the formation of loose and hard depth hoar.

Similar tendencies are found in the profiles of the running means of $\delta^{18}O$ in the cores of the coastal region and of the katabatic slope region, respectively. These tendencies may reflect the change of glaciological environment spread over each region rather than that of local surface conditions.

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