STRATIGRAPHIC STUDIES OF THE SNOW COVER IN MIZUHO PLATEAU

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Abstract: This paper is concerned with the stratigraphic investigations conducted by means of pits and snow cores on the snow cover of Mizuho Plateau in 1970–1971 and 1974–1975. The snow cover is basically composed of the unit layer (minimum structural units) and the layer boundaries caused by hiatus phenomena. The natures of these two stratigraphic elements are revealed through the studies of structural and physical properties, as well as oxygen isotope ratios. In the high accumulation region lower than 1700–2000 m a.s.l., the characteristics of the unit layer corresponded well to the seasonal changes of climatic conditions. In the inland region of less accumulation, the hiatus frequently occurs in the formation of the annual layer and almost all of the stratigraphic elements are strongly deformed by metamorphic processes. Determination of the annual accumulation rate was investigated by means of the stratigraphic interpretation, seasonal variation of oxygen isotope ratios and detection of the reference horizons by vertical profiles of gross β activity. The oxygen isotope method is not so effective in the estimation of the annual accumulation rate in areas other than high accumulation region. Accumulation shows a regional distribution such as 60 cm snow per year in the coastal region and 15 cm snow per year at 3400 m a.s.l. According to the regional variation of snow stratification, the snow cover in Mizuho Plateau is divided characteristically into three regions with elevation boundaries lying in 1900–2100 m and 2800–3200 m a.s.l.

1. Introduction

The purpose of the stratigraphic studies on the surface snow layer is to clarify the annual process of the mass balance in Mizuho Plateau on the basis of investigations of surface conditions and the direct measurements of accumulation with the snow stake method. The annual process should be investigated from the following phenomena: snow accumulation rate over Mizuho Plateau and its annual and regional variations, and regional characteristics of the formation processes of the surface layer.

The surface snow layer results from the piling up of the annual mass balance over a long period; so the stratigraphic structures of the layer show the process of air - snow surface interaction.

Stratigraphic investigations were made by the observation of 2- and 1-m pits

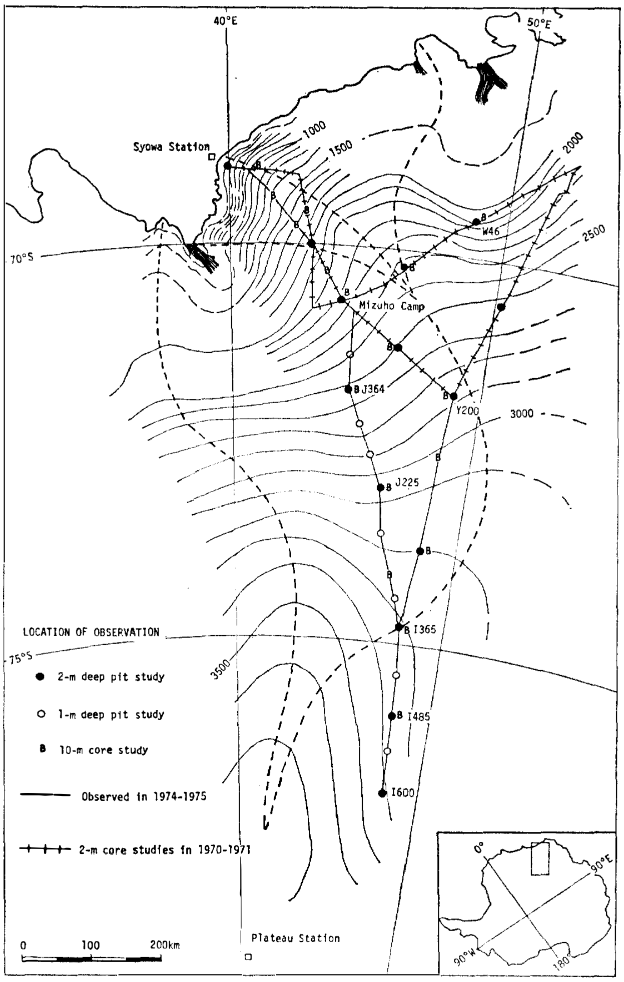

Fig. 1. Locations of stratigraphic investigation.

and 2- and 10-m auger cores obtained along the traverse routes in 1970–1971 and in 1974–1975. Observations were made at interval of about 100 km in almost all areas of Mizuho Plateau. The sites and areas of stratigraphic investigations are shown in Fig. 1 and the methods and items of observations are summerized in Table 1. The whole data obtained from these investigations and observations were reported in JARE Data Reports, No. 17 (1972), No. 27 (1975) and No. 36 (1977).

Stratigraphic studies on the surface snow layer have been made by many investigators over the Antarctic ice sheet since the IGY, and much knowledge has been obtained on the formation processes and properties of the surface snow layer.

But, on metamorphic processes of snow many problems remain unsolved, especially an evaporation-condensation process and a phenomenon of missing

Table 1. Items and methods of stratigraphic investigations.

1970–1971	2-m pit study (6 stations)	2-m core study (44 stations)	10-m core study (7 stations)	Ram sonde
Route S-Z-Y-W-X-S (Sandercock Traverse)	Snow stratigraphy Density Grain size	Snow stratigraphy Density Grain size	Snow stratigraphy Density	Profiling along traverse routes
	Reference: JARE Data Reports, No. **17** (1972) and No. **27** (1975)			
1974–1975	**2-m pit study (11 stations)**	**1-m pit study (7 stations)**	**10-m core study (15 stations)**	**Ram sonde**
Route S-H-Z-Y-I-J (Highland and Traverse) and Route W	Snow stratigraphy Density Grain size Hardness with Canadian gage Oxygen isotope ratio Gross β activity	Snow stratigraphy Density Grain size Hardness with Canadian gage	Snow stratigraphy Density Grain size (0.1 mm grade) Oxygen isotope ratio Gross β activity Texture analysis by micro-photographs	Profiling along traverse routes
	Reference: JARE Data Reports, No. **36** (1977)			

annual layers. These problems will be discussed in this paper on the basis of the observational results in Mizuho Plateau.

Another fundamental problem in the snow stratigraphy results from a confusion in the description of stratigraphic structures and phenomena. So, at first, the descriptive methods are proposed from the viewpoint of genetics. Then regional characteristics of the surface snow layer will be discussed from the stratigraphical, physical and geochemical properties. An accumulation rate over an area was estimated by means of stratigraphic analyses and regional characteristics of formation processes of the surface snow layer.

2. Process of Layer Formation

Surface conditions of the ice sheet are in various stages of the "deposition-erosion process" which represent the formation processes of the surface layer, as discussed in another paper (WATANABE, 1978).

When a surface condition attains the stage of equilibrium (stable) in the process between the actions of deposition and erosion, the residue, namely a difference between the deposited and eroded amounts during the process, corresponds to net balance. From a snow stratigraphic viewpoint, the residue should be presumed as a unit of snow stratification which is superimposed upon the previous surface. This unit of stratification will be called a "unit layer" in this paper.

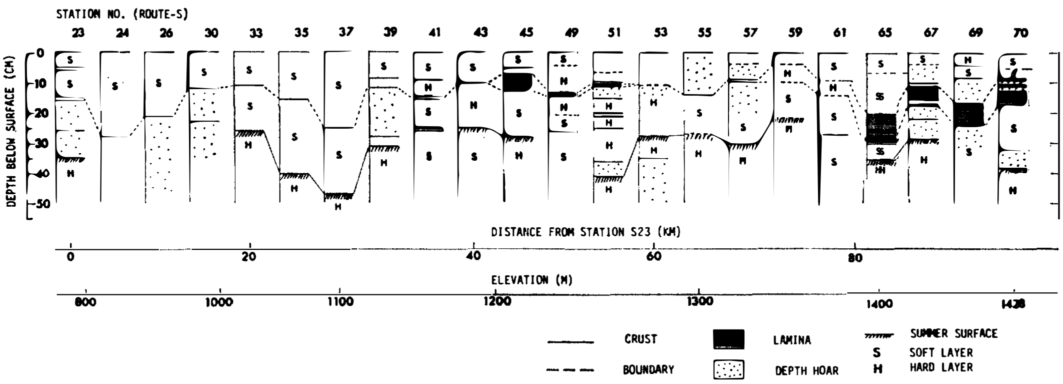

Fig. 2. Regional variations of autumn layer in 1970 along Route S (region between S23 and S70).

The upper boundary of the unit layer is formed under a hiatus in the accumulation process, whereby the dimension of a layer boundary shows the duration of the equilibrium (stable) stage in the process.

The snow stratification can be considered as representing a sequence of snow layer formation, that is, a combinations of the hiatus and the accumulation.

A unit layer has inner structures of sastrugi and/or dunes at the surface indicating various stages of the deposition-erosion process relating to a climatic condition at a place where the unit layer has been formed.

Surface snow layers observed between S23 (788 m a.s.l.) and S70 (1428 m) are shown in Fig. 2.

Since this observation was made in May 1970, these surface snow layers are considered to have been formed during the period from the end of summer to autumn of 1970. Although these layers were formed during a relatively short period, the natures and numbers of the unit layers vary from place to place. The natures of the surface snow layers in this region can be divided into six groups with the ranges of 100 m in elevation and 20 km in distance.

From the figure and other results by OKUHIRA and NARITA (1978), the unit layer has the characteristics of dimension, orientation and shape restricted by regional and seasonal meteorological conditions related to the topographical condition at a given site. These morphological characteristics of the unit layer must correspond to the surface features at the same site reflecting the seasonal variation of climatic conditions. The term of "annual layer" used in the snow stratigraphic study corresponds to an aggregation of the unit layers formed during a given year.

Unit layers are adjacent to one another with layer boundaries which were formed during hiatuses in snow deposition. The thickness of a layer boundary depends on the duration of a hiatus. In the coastal region where large numbers of unit layers are found in an annual layer, the thickness of a layer boundary is thinner, showing a relatively short-term hiatus less than one month. On the other hand, a thicker layer boundary with ice crust such as the summer surface was formed during a relatively long-term hiatus. In general, ice crust is formed by sintering of snow particles and melting thereof due to radiation (NARITA and WATANABE, 1977). A multilayered ice crust indicates a long-term hiatus over several years. The glazed surface found in the vicinity of Mizuho Camp was composed of a six-layered ice crust (WATANABE and YOSHIMURA, 1972). The basic elements of stratigraphical structures observed in a vertical section of the surface snow cover are the unit layers and the hiatus structures, together with relatively small-scale structures reflecting deposition processes and the metamorphic processes that take place after stratification. In a limited area of the coastal region, the phenomenon of melting at the surface presents another important structure.

The descriptive legend of snow stratigraphy based on the method adopted in this paper is shown in Fig. 3. Conventional methods of representing the descrip-

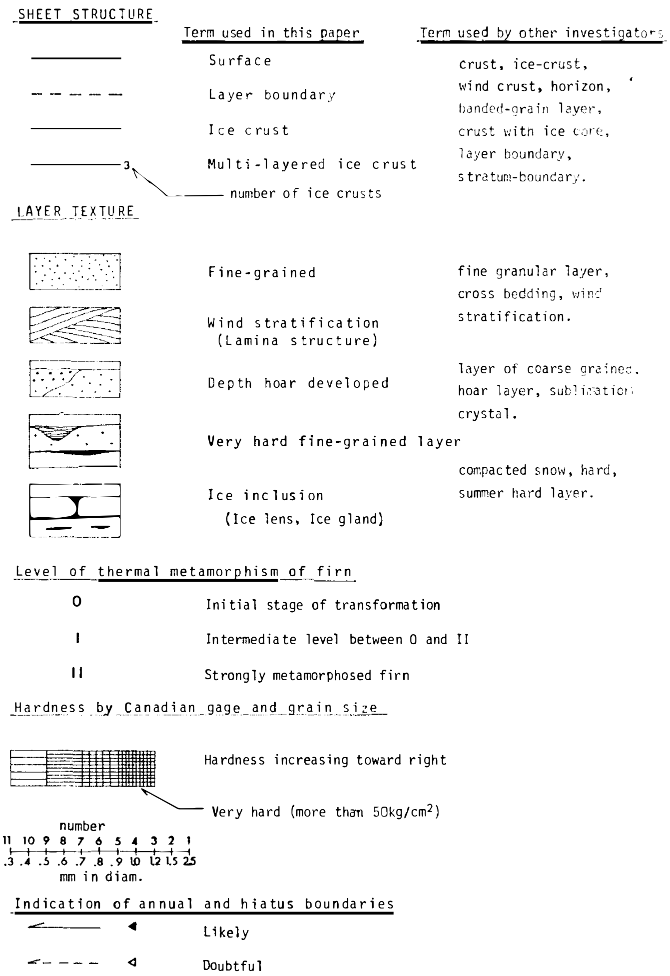

Fig. 3. Descriptive legend of snow stratigraphy.

tion have not been established yet. Descriptive terms which were used previously by many investigators are shown in the right-hand column of Fig. 3 for comparison.

3. Regional Characteristics of Snow Stratigraphy

Structures of the unit layer originate from various conditions of the deposition-erosion process at the surface. These structures can be analyzed by the following elements:

a) horizontal and vertical dimensions of the unit layer indicating meteorological conditions during the formation; b) a cross sectional appearance on the wall of a snow pit showing previous surface conditions; c) the structure of the layer boundary which is a reflection of the dimension of a hiatus during the formation of a unit layer; d) the microstructure and texture of the unit layer indicating a variation of meteorological conditions during the formation.

Another structural element such as the summer surface characterized by extensive leveling is important for a stratigraphic analysis. The occurrence and nature of these structural elements observed in a unit layer at a given place can be considered to indicate the regional characteristics of the mass balance. The results of stratigraphic observations made at Mizuho Plateau during 1970–1975 were examined by taking the foregoing into account.

3.1. Snow stratigraphy in the coastal region

Since the region lower than 1700–2000 m a.s.l. is strongly affected by cyclonic disturbances, a relatively high accumulation occurs (YAMADA *et al.*, 1978; WATANABE, 1978). The results of stratigraphic observations made in this region are shown by six stratigraphic diagrams in Fig. 4. One diagram is of snow accumulation (1974) on the sea ice near Syowa Station and five diagrams are of surface layers (1970) between the firn line and the dry snow line (BENSON, 1962). Snow accumulations on the sea ice melted away before the end of summer (YOKOYAMA *et al.*, 1978). The recent climatic condition is such that the elevation of the firn line on the ice sheet is around 500 m a.s.l., varying annually in the range of 100 m. The location of S16 (554 m) is just above the firn line in 1970. The stratigraphic diagrams at S16, S19 and S21 are characterized by the inclusion of ice due to melting and by a relatively thick snow layer. It is reasonable to consider that melting occurred as that the dry snow line was located between S21 (708 m) and S23 (788 m) in 1970. The occurrence of relatively large and numerous unit layers in an annual layer is found in this region. The uniform layering of unit layers is also one of the characteristics of this region. Lightly compacted and fine-grained snow were found generally with depth hoar developed on a very small scale, whereas coarse-grained granular snow was found in the subsurface layer of the summer surface. Ice crusts with ice lenses resulting from

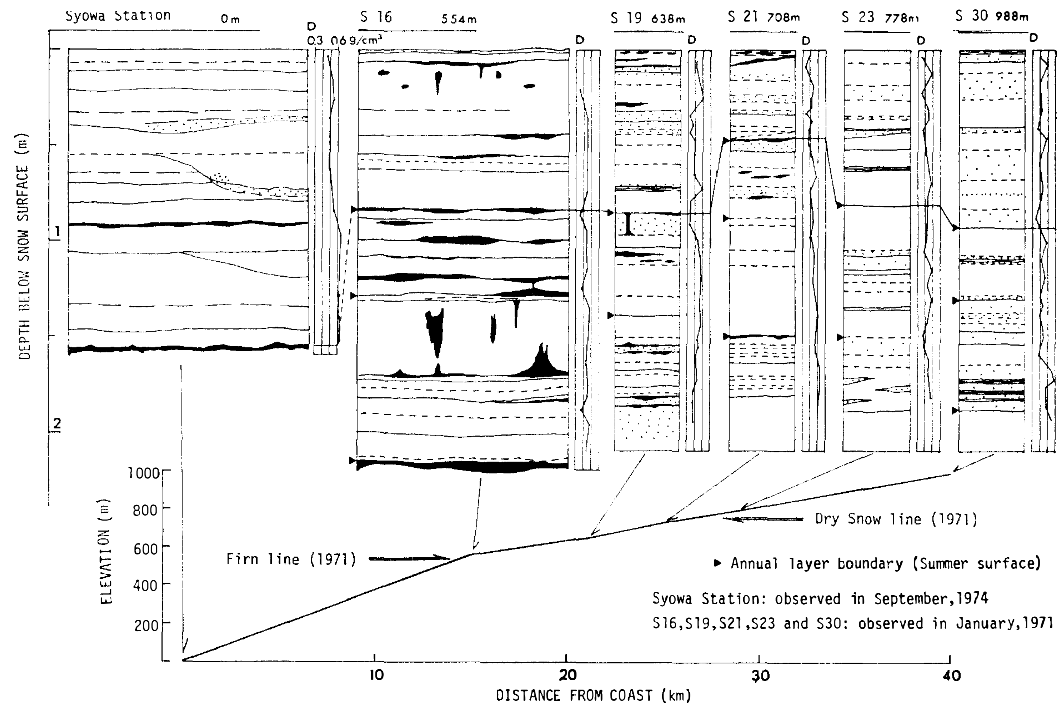

Fig. 4. Stratigraphic diagrams of the coastal region.

melting are well developed, but ice crusts formed under a long-term hiatus were not found. Therefore, it is considered that the missing of an annual layer or layers has not occurred in this region.

3.2. Snow stratigraphy in the inland region

Three stratigraphic diagrams to show the layers from the surface to a 2-m depth observed in the inland region are shown in Fig. 5 with the vertical variations of oxygen isotope ratio, density and hardness. These three diagrams selected from the eight results obtained by observations during summer of 1974–1975 represent typical stratigraphic features of the inland surface snow cover. According to the result of snow-stake measurements (YAMADA *et al.*, 1978) and surface feature observations (WATANABE, 1978), the region above 1800–2000 m a.s.l. was strongly affected by katabatic winds, and the same climatic characteristics continue with elevation as high as 3000–3200 m a.s.l. In this region the annual processes of accumulation are quite different from place to place; besides, a hiatus lasting one or more years frequently occurs in annual layer formation in this region. The annual accumulation rate (70 cm or more snow per year) at W46 estimated by stratigraphic methods was of the same order as at the region lower than 1500 m a.s.l. along Route S. This accumulation rate at W46 is considerably high in comparison with the general trend of accumulation related to the elevation, and may be ascribed to the topography around W46, where

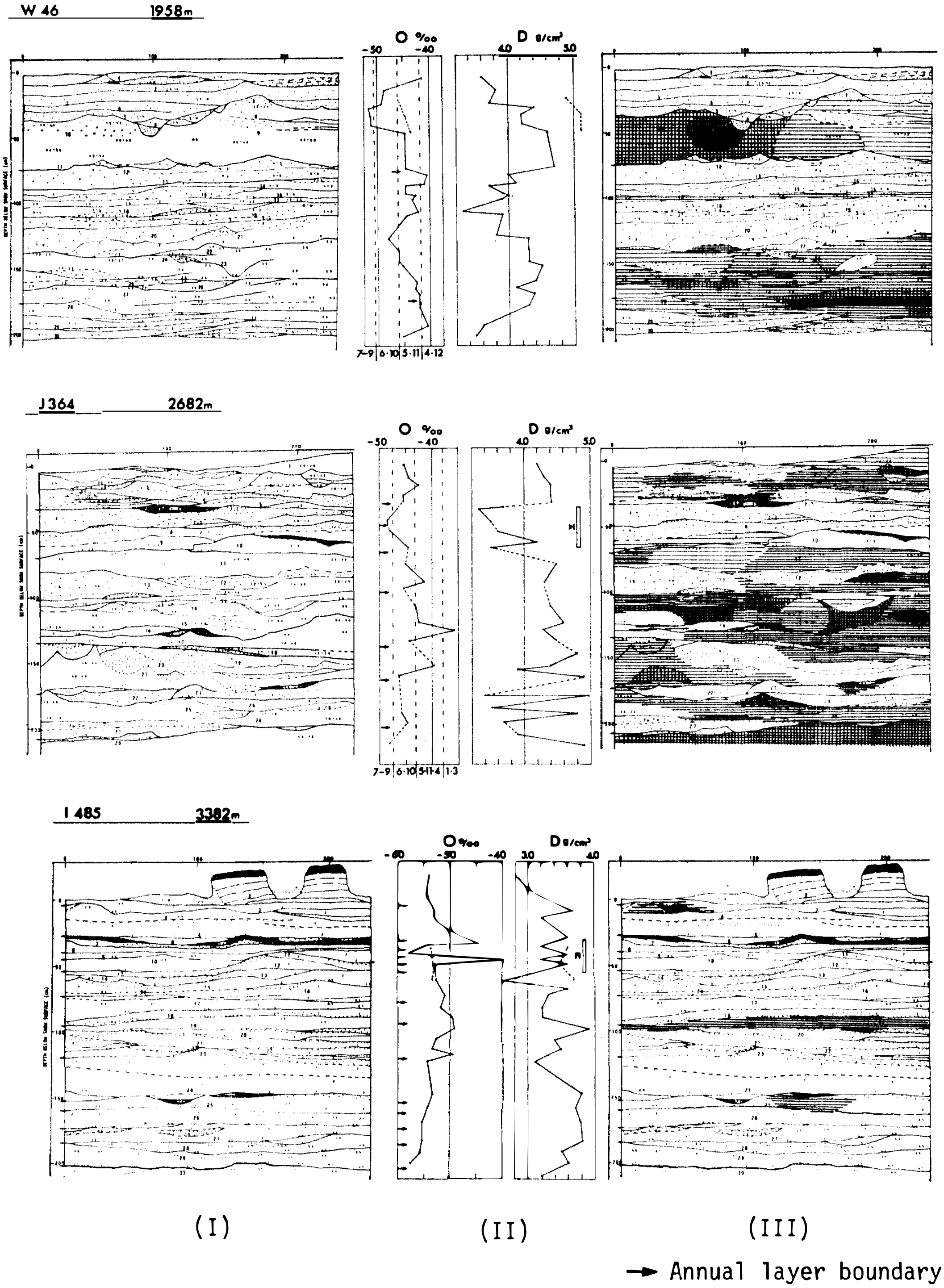

Fig. 5. Stratigraphic diagrams of the inland region.
(I) Stratigraphy, (II) Oxygen isotope ratios (O) and Density (D), and (III) Hardness (kg/cm²) by Canadian gage.

a valley-shaped landform is well developed down to the coast due to the flow of the Rayner Glacier; this landform acts as an accelerating factor for penetration of a cyclone to the inland of the ice sheet. As seen in the stratigraphic diagram at W46, the occurrence and nature of structural elements indicate the typical seasonal variation as follows: For the determination of an annual accumulation, traditional stratigraphic methods were adoptable with a high accuracy. Estimating from the oxygen isotope ratios, a thicker unit layer with a higher density is considered to have been formed during autumn and winter, and a thinner unit layer with an irregular shape to have been formed from spring up to early summer. Differences among these characterized layers are well reflected in the areal distribution of hardness shown in the left-hand column of the diagram.

The location of J364 is in the region where the surface conditions are strongly controlled by both the erosional and depositional wind systems, the former being considered as the "pure katabatic" (WATANABE, 1978). The unit layers of J364 are characterized mainly by these irregularities in dimension and shape. These characteristics are considered to have resulted from a rough condition with developed sastrugi. Since distribution of hardness is not uniform, the unit layers with high and low hardness values coexist in the same level, and this coexistence indicates that the layers were formed at different times because the hardness of each layer depends on the season during which it was formed. The average hardness of the surface layer, on the other hand, is higher than that in other regions. An annual layer consists of a few (one to three) unit layers and the sequence of their formation is not in a seasonal order; hence the vertical variation of oxygen isotope ratios is invalid for the analysis of annual layers.

The location of I485 is 900 km apart from the coast and its elevation (3382 m) is very near the highest place of the investigated region. Characteristics of the snow stratification distributed above 3000–3200 m a.s.l. is remarkably different from those of the lower region. Relatively uniform shaped and thin unit layers are common in this region. The same tendency was observed by Gow (1965) in the South Pole region, as noted in the following:

"It was somewhat surprising at the time to observe a relatively uniform and systematic stratigraphy in the pit wall since, with the relatively low rate of accumulation (20 cm snow per year) and occurrence of some high sastrugi in the immediate vicinity of the pit, rather irregular layering might have been expected".

As seen in the figure, the occurrence of the surface feature seen at the top of the snow cover and the structure of the snow layer of I485 coincided closely with the condition described by Gow (1965), who explained this uniform stratigraphy by the widespread leveling of the surface feature during summer. When observations were made at the beginning of summer, the surface conditions of this region were still in the active stage of the deposition-erosion process.

The low values of both density and hardness due to well developed depth hoar are one of the typical characteristics of snow layers in this region. An interrelation between vertical variations of oxygen isotope ratio and density coincides in both figures of J364 and I485; low value of the oxygen isotope ratio correspond to low values of density, while the reverse also holds. The mark H in the figures of J364 and I485 indicates the layer affected by a long-term hiatus condition when the position of the level was at the surface. A distinct process of development of depth hoar at the subsurface layer, and also thin hard layers with thick ice crusts were found in these cases.

4. Physical Properties and Oxygen Isotope Ratio of the Snow Cover

4.1. Physical properties

Physical properties such as density, hardness, grain size and depth hoar development in the snow cover were measured as the elements to determine annual layers and regional characteristics of snow stratification. The methods and items of stratigraphic investigation of pits and cores are shown in Table 1.

4.1.1. Density profiles

It has been believed that the density in the surface snow layer provides an indicator of the season during which it was formed. Some results of density measurements made in 2-m pits and core analyses are shown in Figs. 4 and 5. As seen in these figures, change in density in the vertical profiles were found in the coastal region, whereas irregular changes were common in the inland region. The densification of the subsurface layer from the surface to a 2-m depth was examined by calculating a load at each level from the depth and density of snow. The load-density relation and the load-depth relation are shown in Fig. 6, in

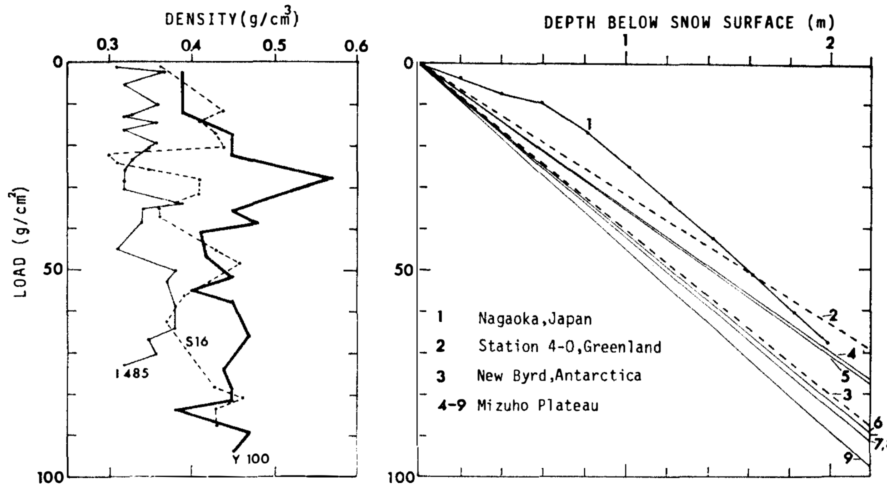

Fig. 6. Load-density and load-depth relations from the surface to a 2-m depth. (4-9 Mizuho Plateau): 4. I485, 5. I600, 6. Y100, 7. W46, 8. J364, 9. S16.

which three profiles at S16, Y200 and I485 are selected as examples. As seen in this figure, correlations between density and load are not clear. A larger variation of density is seen in the vertical profile of Y100, while the profiles of S16 and I485 both show relatively smaller variations in connection with the uniform stratification of the two regions. Despite the lack of a close relation between density and load, the load-depth relation falls on a straight line (Fig. 6). In this figure, the relations obtained at the New Byrd Station (which used to be called Byrd Station) in Antarctica, Station 4-0 in Greenland (BENSON, 1971), and Nagaoka in Japan are also shown. On the different values of inclination of these straight lines obtained from the observations in Antarctica and Greenland, BENSON (1971) noted as follows:

"Two factors seem to be involved: wind action and range of temperature...... They vary significantly between Byrd Station and the Greenland stations considered here. Byrd Station is windier and has a smaller temperature range; these

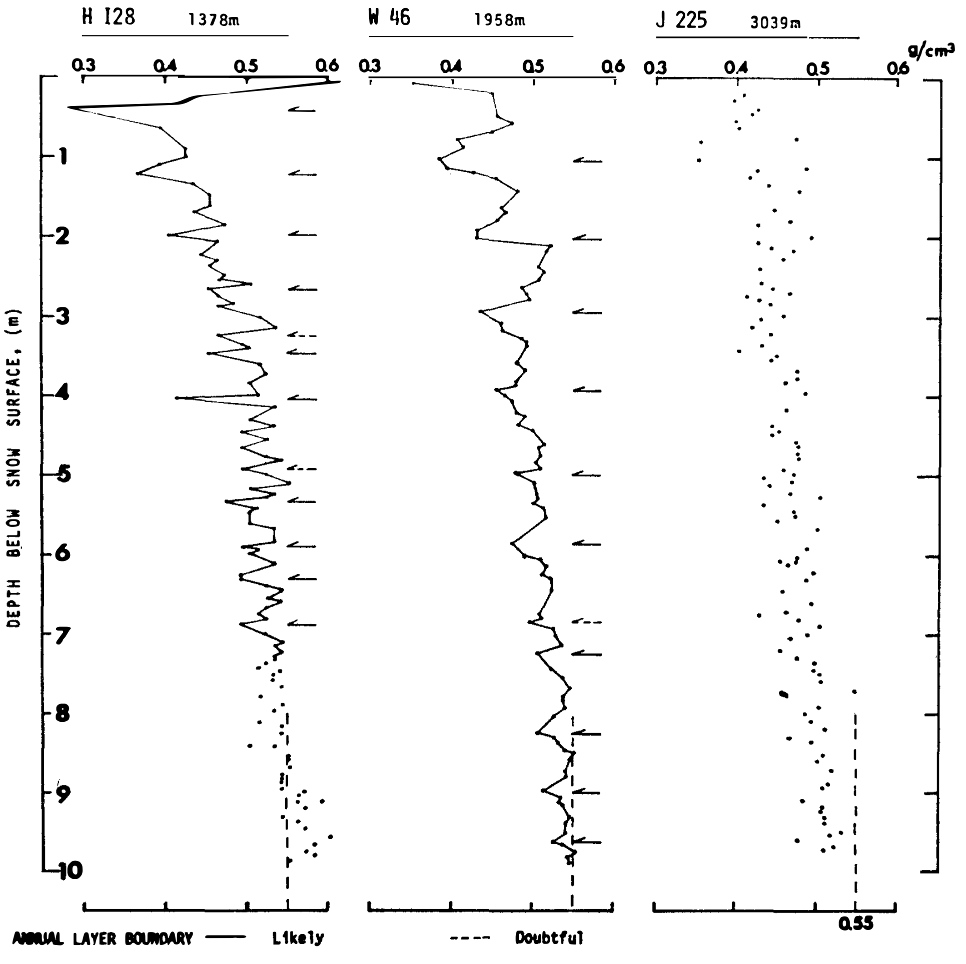

Fig. 7. Depth-density relations from the surface to a 10-m depth.

differences favor the development of denser, harder, snow at Byrd".

This explanation cannot be applied fully to the relation in Mizuho Plateau, because the low ratio of the load-depth relation obtained from the most of the inland region resulted from the high development of depth hoar as shown by the result of stratigraphic studies. The ratio of relation between load and depth varies from 0.44 at the coast to 0.35 in the innermost inland observed: hence, the load at a 2-m depth in I600 is 70g/cm^2, which corresponds to 80% of the value of S16.

The depth-density profiles from the surface to a 10-m depth are shown in Fig. 7, which are selected from many data obtained in Mizuho Plateau. The two

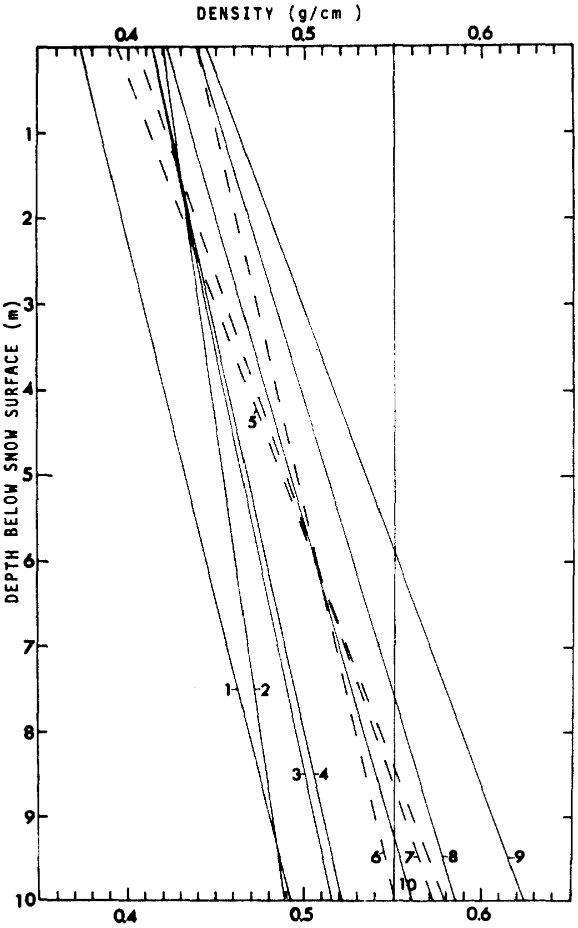

Fig. 8. Linear regression lines of depth-density relation from the surface to a 10-m depth.
1. I355, 2. I235, 3. J225 4. Y210, 5. Z30, 6. W46. 7. S122, 8. H228, 9. S97, 10. H128.

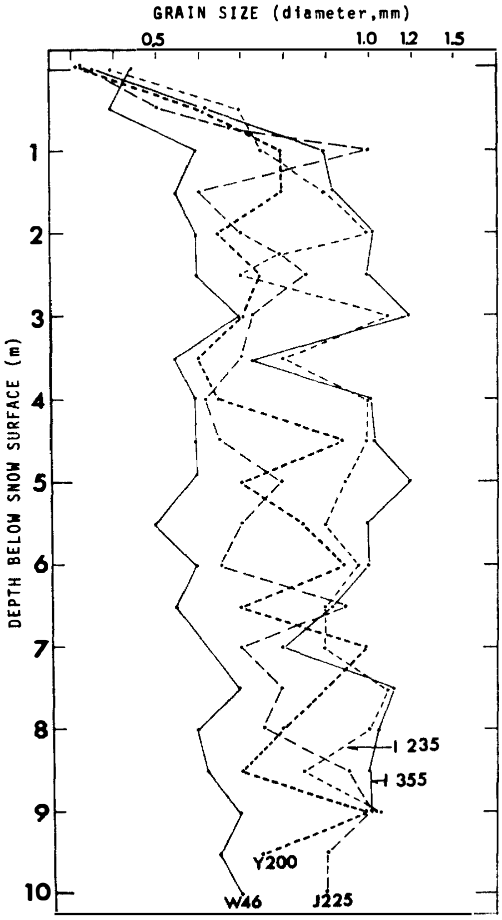

Fig. 9. Vertical variations of grain size from the surface to a 10-m depth.

(H128 and W46) among the three in this figure were obtained in the coastal region and the other (J225) in the inland region.

The systematic variations were well preserved in the profiles of H128 and W46. It is evident from the stratigraphic analysis that these intervals correspond to each of the annual layers indicated by an arrow. The vertical density profiles obtained from the inland region, as plotted in the figure for J225, as an example, do not indicate such a systematic variation.

According to the stratigraphic analysis of a deep ice core from Site 2 in Greenland (LANGWAY, 1970), change in the slope of the relation between density and depth occurs at about the 10-m depth with a density of about 0.55 g/cm^3, which is considered as the limiting density for the initial densification process (ANDERSON and BENSON, 1963).

In Mizuho Plateau, the density at the surface and 10-m depth varied from place to place and increased almost linearly with depth at various rates in the range from 0.007 to 0.018 g/cm^3 per meter. Linear regression lines obtained from the depth-density relation in Mizuho Plateau are shown in Fig. 8 for a comparison of densification in the various regions.

4.1.2. Grain size and depth hoar development

In the 10-m core studies, the grain size (diameter) was measured continuously from the surface to a 10-m depth with a scale graduated in 0.1 mm. The detailed methods used in core analysis were reported in JARE Data Reports, No. 36 (1977).

Vertical variations of grain size in 10-m cores are shown in Fig. 9. As seen in this figure, the grain size increased linearly until the depth reached 1 m, but such a tendency is not so clear below it. The minimum of the increase of the grain size, 0.15 mm, between the surface to a 1-m depth was found in W46; larger amounts, 0.6–0.7 mm, occurred in the region higher than 3000 m a.s.l.

From an analogy with the sintering process of isothermal grain growth in metallurgy and ceramics, some investigators (STEPHENSON, 1968; GOW, 1969) have represented the growth relationship by an empirical equation of the form

$$Dt^2 - Do^2 = AT \exp(-Q/RS),$$

where D represents area and t is time, T is the absolute snow temperature, A is a constant, and Q and R are the activation energy and gas constant, respectively. GOW (1969) pointed out that crystal growth rates in Antarctica could be expected to vary with temperature by at least two orders of magnitude—from a rate of 0.0003 mm/year at -60°C to 0.03 mm/year at 15°C.

Although the annual mean air temperature at each location shown in Fig. 11, estimating from the snow temperature at a 10-m depth, varies from -20.8°C at H128 to -51.9°C at I 355 (YAMADA and NARITA, 1975; SATOW, 1970), the growth rates of the grain size between the 1-m and 10-m depths do not differ much with places, as shown in Fig. 9. Moreover, though the t at a 10-m depth in the inland region can be assumed as 3 or 5 times longer than that in the coast region, the regional variation of the grain size is not expected to be more than one order.

In the layer from the surface to a 10-m depth, the evaporation-condensation process is more effective than the sintering process. Depth hoar development is the most important process in snow metamorphism in the surface snow cover of Antarctica. Depth hoar develops at the layer just below the glazed surface, where one could find loose and coarse grains with automorphic crystals and well-developed porous parts elongated vartically, and the initial stratigraphical structures almost diminished.

From many observations of snow textures, the depth hoar in the snow cover can be classified broadly into two; loose type and hard type. From the results of his systematic laboratory experiments, AKITAYA (1974) has classified the depth hoar into two types; solid type and skeleton type, which are formed in both the isolated and mixed states; he also has found another type of depth hoar, namely, "hard depth hoar", in a sample of less porous snow under a strong temperature gradient.

The hard type depth hoar observed in Antarctica can be considered to correspond to this "hard depth hoar" from an analogy between the experimental condition and the actual circumstance of layer formation in which densities increase as a result of wind packing together with strong temperature gradient which provides another factor helping its formation.

The distinct contrast in the occurrences of loose and hard depth hoars is seen in the stratigraphic diagram of J364 shown in Fig. 5 and the occurrence of well developed loose depth hoar is seen in that of I485.

As a trial to make relative grading of depth hoar development, the levels of thermal metamorphism of firn defined in Fig. 3, are used as criteria. Interrelations among depth hoar development, grain size and density are shown in Fig. 10 on the basis of results obtained from the 10-m core analysis.

As seen in the figure, a good agreement is found between depth hoar development and grain size, while a good inverse agreement between either of them and density. The low development of depth hoar in W46 may have been caused by a high accumulation rate, the systematic occurrence of low development at each spring-summer layer is useful as an indicator of an annual boundary. The high development of depth hoar in S122, by contrast, may have been caused by a widely distributed long-term hiatus at the surface in this region.

Regional characteristics of physical properties including the direction of crystal growth in the evaporation-condensation process in Mizuho Plateau are shown in

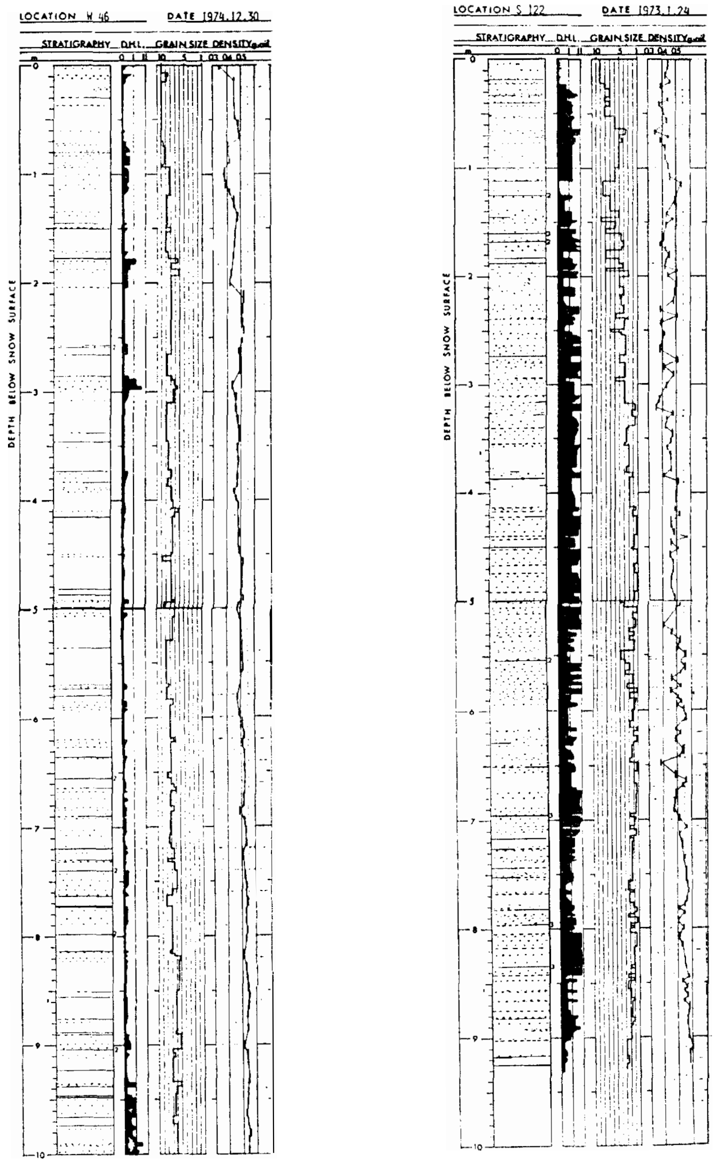

Fig. 10. Stratigraphic diagrams of 10-m cores from the surface to a 10-m depth.

Fig. 11 in which the growth direction is shown by an arrow mark. The sequentially localized development of depth hoar seen in the profiles of H128 and Z30 is considered to have resulted from a secular change in surface conditions. The ratio of upward to downward crystal growth increased with elevation above J225. Although the cause of this tendency has not been made clear, the seasonal changes of the surface temperature and the rate of accumulation should be related to this phenomenon.

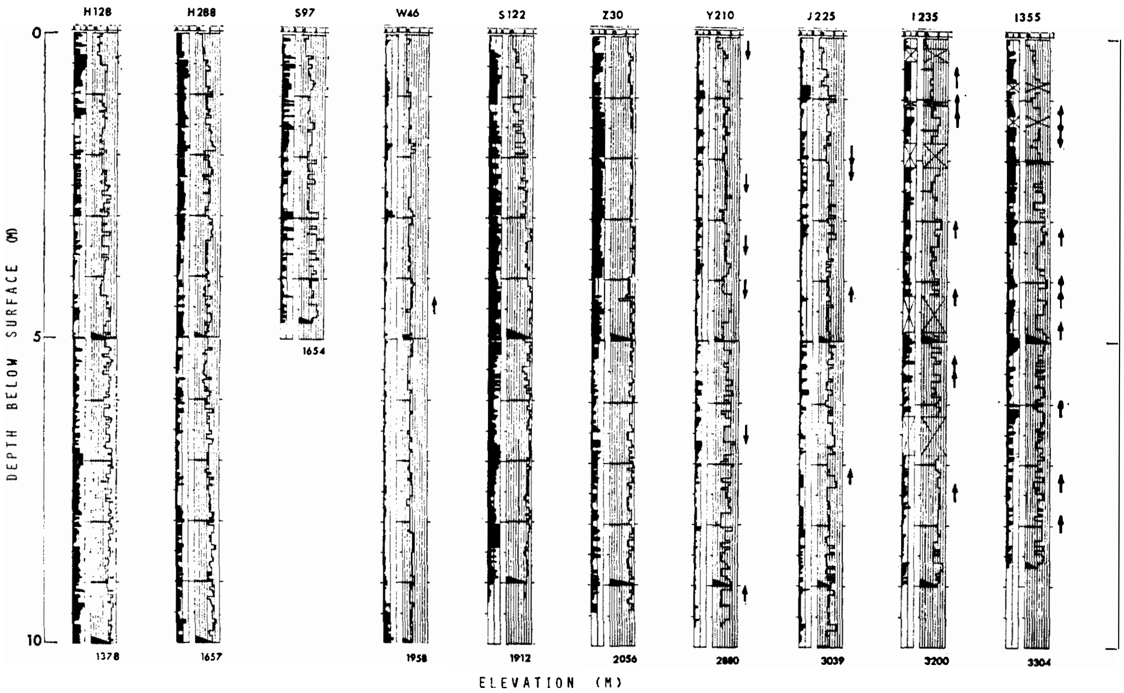

Fig. 11. Vertical profiles of depth hoar development accompanied by profiles of grain size and direction of crystal growth shown by an arrow mark.

4.2. Oxygen isotope ratio

Observations were made of the isotope ratio ($\delta^{18}O$) in the surface snow layer for an application to the stratigraphic interpretation of an annual balance. For this purpose, the following observations were made during 1974–1975:

i) Continuous collection of falling and drifting snow samples at Syowa Station and Mizuho Camp,

ii) Collection of samples of drifting and settled snow on the surface during every oversnow traverse including trips between Syowa Station and Mizuho Camp made in various seasons,

iii) Measurements of oxygen isotope ratio in each unit layer studied with samples from 2-m pits and 10-m cores.

Results of i) and ii) were reported by KATO *et al.* (1978). The oxygen isotope ratios of falling and drifting snow samples collected at the two stations showed a systematic change indicating a good correlation with seasonal air temperature; therefore the $\delta^{18}O$ of a unit layer can be used as an indicator of the season which favored the accumulation process.

Results of vertical profiles of $\delta^{18}O$ in the surface snow cover are shown in Fig. 5. As is obvious from the figure, evident seasonal changes of $\delta^{18}O$ are seen only in the profile of W46, in which an inverse correlation can be found between $\delta^{18}O$ and density. This provides traditional physical stratigraphic criteria, namely,

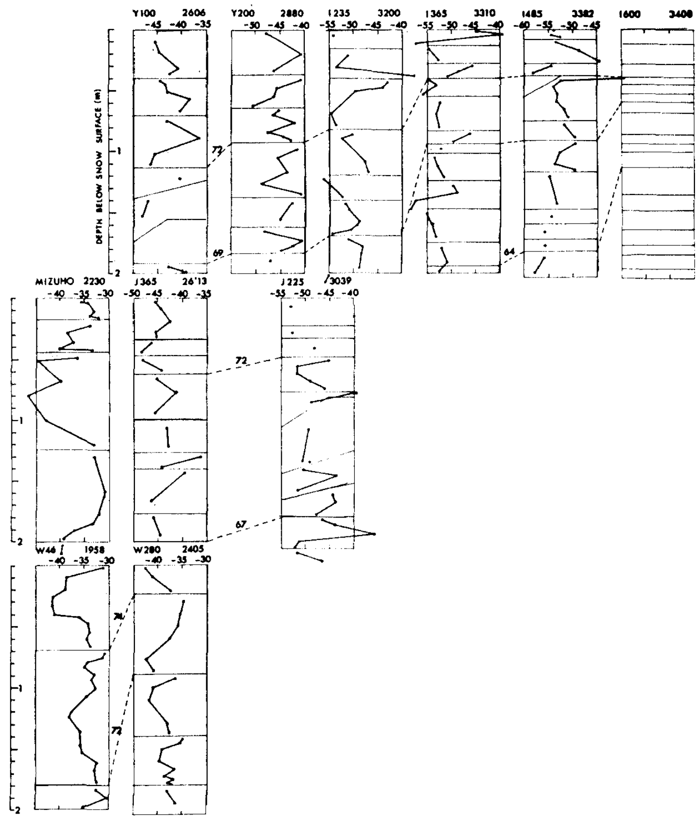

Fig. 12. Regional variation of vertical profiles of oxygen isotope ratio in 2-m pits relating to the annual layer estimated by snow stratigraphy.

finer grained, hard and high density in winter; coarse grained, soft and low density in summer (LANGWAY, 1970; SHIMIZU, 1964).

From the $\delta^{18}O$ characteristics that depend on the air temperature during snow condensation and accumulation sequences, the profile of W46 indicates that accumulation started in a warm season, and occurred predominantly in a cold season, followed by another warm one (warm-cold-warm type).

The vertical changes in $\delta^{18}O$ at J364 and I485 in Fig. 5 cannot correspond to the annual layers estimated from the stratigraphic interpretation, but are strongly correlated to the change in density. The relatively low contents of oxygen isotope are correlated to the low density layer. The characteristics of a profile and the relations among density, hardness and snow texture suggest the occurrence of vertical mixing of water vapor in metamorphic processes of a snow layer.

All of the results obtained by studies of oxygen isotope ratio in Mizuho Plateau are shown in Fig. 12. Seasonal changes in $\delta^{18}O$ are seen at W46 and W280, where accumulation rates are considered high. The profile at Mizuho Camp indicates the characteristics of drift formed around the hut.

The vertical profiles of $\delta^{18}O$ at other sites do not correspond to the stratigraphic

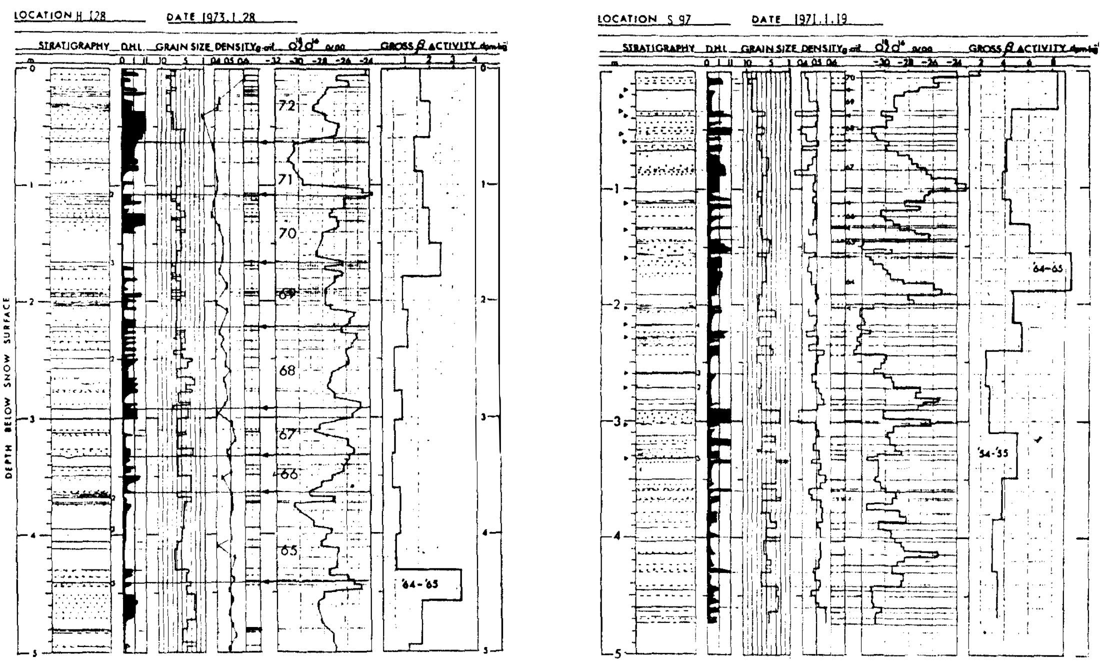

Fig. 13. Vertical profiles of oxygen isotope ratio and gross β activity together with vertical profile of stratigraphic elements.

interpretation, excepting the parts of the profiles of Y100 and J225 which show a similar tendency to the seasonal change. The changing patterns of $\delta^{18}O$ at Y100, Y200, Y365, J225 and I235 indicate that accumulation started in a cold season, and occurred predominantly in a warm season, followed by another cold one (cold-warm-cold type). Therefore, these regions are in the environment where a spring-summer accumulation was predominant, differing from the environment where a winter accumulation was predominant in the warm-cold-warm type.

In the region higher than 3200 m a.s.l., the number of unit layers contained within an annual layer is very few (one or two), while unexpected fluctuation of $\delta^{18}O$ of drifting snow was observed during a short period in the 1974 traverse. Such an abnormal fluctuation was not observed in the case of seasonal changes in $\delta^{18}O$ at Syowa Station and Mizuho Camp (KATO *et al.*, 1978). Hence, the $\delta^{18}O$ cannot be used as an indicator of a season in this area.

Fig. 13 shows results of the 10-m core analysis such as the oxygen isotope ratio, gross β activity and physical properties of snow. As seen from the case of H128 in the figure, the estimation of an annual layer by the $\delta^{18}O$ change coincides considerably with the results by stratigraphic methods and the reference horizon obtained by the gross β activity.

In the diagram of S97, however, an agreement between the $\delta^{18}O$ change and other elements was not so good. Explanation of the difference between H128 and S97 can be given by the environmental difference between these two sites;

that is, H128 (1378 m) is located in the coastal region where a high accumulation without hiatus phenomena was observed by means of stake measurements, whereas S97 (1645 m) is located in the region with a less accumulation, where hiatus phenomena may occur occasionally due to a local topographical condition. The change in $\delta^{18}O$ value in the S97 profile can be explained by isotope fractionation under the evaporation-condensation process.

5. Estimation of Annual Accumulation

5.1. Regional variation of stratification

The regional variation of mass balance at the snow surface can be related to regional climatic and topographic conditions. The characteristics of these regional variations should be considered from the following stratigraphic phenomena:

5.1.2. Unit layer formation

The "deposition-erosion process" in this paper means that all of depositional and erosional processes on the surface originate from a direct interaction between the snow surface and the air (WATANABE, 1978). The wind systems taking part in the interaction are cyclonic in the coastal region and katabatic in the inland region lower than 3000–3200 m a.s.l.

Much accumulation is brought to the coastal region from the sea by a cyclonic wind, but less accumulation occurs in the inland region.

The deposition-erosion process in the innermost inland region higher than 3000–3200 m a.s.l. is not investigated yet and so it remains unknown, but it may be possible that the phenomenon described by GOW (1965) occurs in the region.

5.1.1. Deposition-erosion process

The snow residue after a cycle of the deposition-erosion process forms the uppermost layer of the snow surface as a unit layer. The boundary structure is formed during the hiatus between the formation periods of unit layers. The frequency of the formation and the dimension of the unit layer varied with regional climatic and topographic conditions; the unit layers in the coastal region were thicker in width and larger in numbers in an annual layer, and the opposite tendency occurred in the inland region.

As for the snow cover of the katabatic region, its snow stratification was not uniform in general, and shows such surface conditions at the time of formation of a unit layer that the deposition-erosion process was active, inactive or stable.

5.1.3. Annual layer formation

An annual layer represents an integration of the unit layers formed during a year. The physical properties and oxygen isotope ratios of a unit layer indicate a climatic condition when the unit layer was formed (Fig. 5).

In the region lower than 1700–2000 m a.s.l., the annual layers were continuous, but their thickness is different depending on the amount of accumulation. The average value of accumulation in terms of net balance obtained by means of snow stakes or snow stratigraphy shows the tendency of net balance in the observed area.

In the region higher than 1700–2000 m a.s.l., the unit layers are discontinuous and the missing of an annual layer or layers occurred frequently. Such a long-term hiatus in annual layer formation as the glazed surface was seen in some places of this region. The term "annual net balance or annual layer at a place" is not suitable to describe a mass balance in these places but the term "increasing rate of relative height of the snow surface" is rather reasonable.

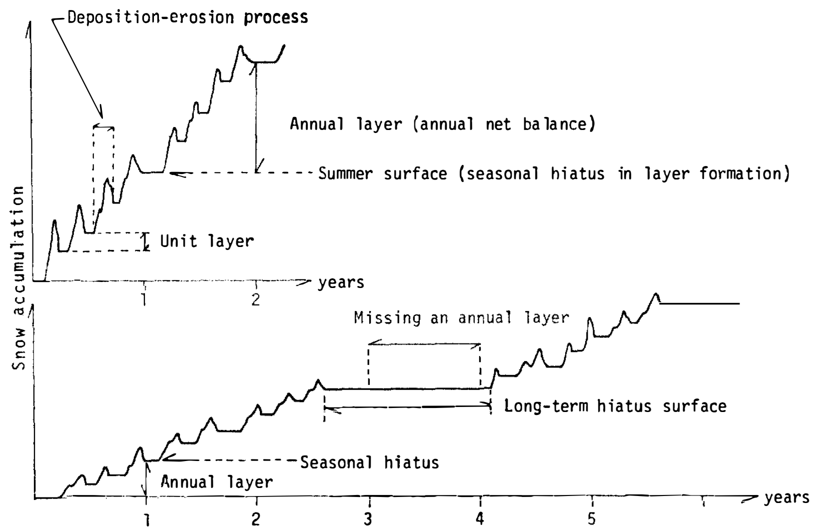

Fig. 14. Regional characteristics of surface formation and explanation of stratigraphic terms.

A model of an increasing process in the relative height of the snow surface is shown in Fig. 14 on the basis of the regional characteristics of the surface formation described in items i)–iii). This figure is indicative of relations among such stratigraphic terms as the deposition-erosion process, the unit layer, the annual layer and the hiatus phenomena.

The major object of stratigraphic studies on the surface snow cover is to make clear these regional and seasonal characteristics of these relations.

Fig. 15 shows the characteristics of unit layers in an annual layer from the following three criteria. Using a criterion for the season during which formation takes place, a unit layer can be distinguished by its belonging to spring-summer formation, winter formation or autumn formation. When the layer structure is used as another criterion, the unit layer can be described as belonging to ice

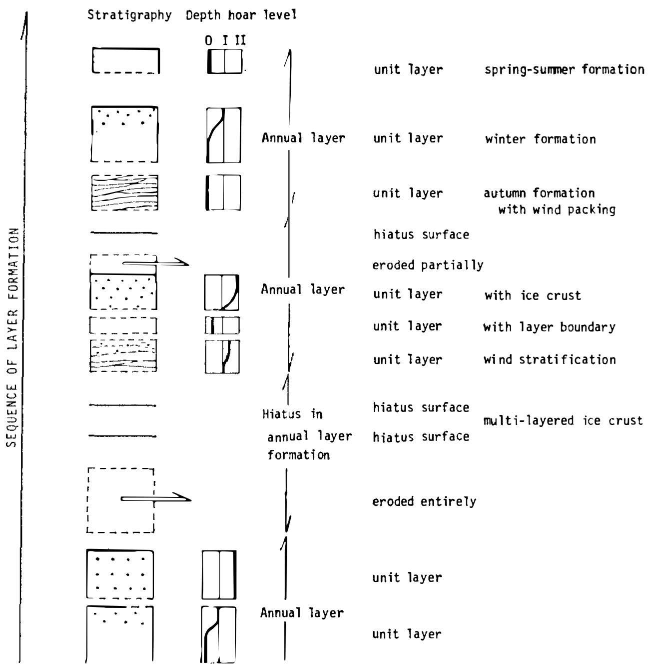

Fig. 15. Schematic model of snow stratification and descriptive methods of the unit layer.

crust, layer boundary, wind stratification, etc. When the texture of snow is used as the third criterion, the degree and occurrence of metamorphism such as new snow, well developed depth hoar, or partial and entire development of depth hoar can be represented by the depth hoar level.

5.2. Stratigraphic methods and results of annual layer estimation

The methods of stratigraphic interpretation of the annual layer used in this study can be divided into the following three categories: i) interpretations of stratigraphic diagrams revealed in walls of pits and in snow cores, ii) oxygen isotope analysis, and iii) detection of marker horizons of a known age by measurements of gross β activity.

The relation among these methods and stratigraphic elements applied to the stratigraphic interpretation of the annual layer are shown in Table 2 with illustrations of the application. The relation between elevation and annual accumulation obtained by the stratigraphic observation of surface snow layer is shown in Fig. 16. It was found that accumulation was large (60 cm snow per year) in the coastal region and small (15 cm snow per year) at 3400 m a.s.l.

The problems of each method in application to determination of an annual layer will be discussed in the following paragraphs:

Table 2. Methods and stratigraphic elements for interpretation of annual accumulation.

	Stratigraphy	Observation	Phenomena	Agent factor
1. Stratigraphic interpretation				
1.1. Structural and texture analysis	Unit layer	numbers	melting phenomena*	
		dimension	new snow	
		shape	hard-compact-wind packing	seasonal variation of climatic condition
		snow characteristics	loose-depth hoar	surface condition
	Layer boundary	structure	smooth surface (spring-summer surface)**	surface leveling (states of Deposition-Erosion Process)
			rough surface (autumn-winter surface)	
		texture	layer boundary without ice crust	hiatus phenomena in layer formation
			ice crust (summer surface)***	
			multiple-layered ice crust (long-term hiatus surface)	
1.2. Physical and chemical analysis	Unit layer	physical properties	density, grain size, hardness — periodical change****	initial condition (indicator of season)
			density, grain size, hardness — metamorphic process	depth hoar development
		oxygen isotope ratio	periodical change*****	sequence of accumulation (indicator of season)
			temperature indicator	isotope fractional process
		chemical component		
	Layer boundary	micro particles	physical properties	
			chemical properties	
2. Detection of reference horizon		gross β activity	periodical change	
			reference horizon of a known age******	

Illustrations of application to annual layer interpretation

* S16, S19, S21 (Fig. 4)

** W46, J364 (Fig. 5)

*** W46, J364, I485 (Fig. 5)

**** W46 (Fig. 5), H128, W46 (Fig. 7), W46 (Fig. 10)

***** Mizuho Camp, W46, W280 (Fig. 12), H128 (Fig. 13)

****** H128, S97 (Fig. 13)

5.2.1. Interpretations of snow stratigraphy

The physical properties such as density, grain size and hardness of the unit layer indicate the surface condition during the layer formation and the metamorphic process thereafter.

In a relatively higher accumulation region, the physical properties of the unit layer were well preserved in the state in which formation took place, and so the vertical profiles of these properties may indicate the seasonal condition. On the other hand, in a region with a less accumulation, difficulties have been experienced in interpreting snow stratification, because the properties may change depending on active metamorphic processes. The development of depth hoar occurred commonly in the subsurface layer in a large area of Mizuho Plateau. Therefore, the direct application of the traditional interpretations is generally not effective to the determining of an annual layer, but such interpretations are

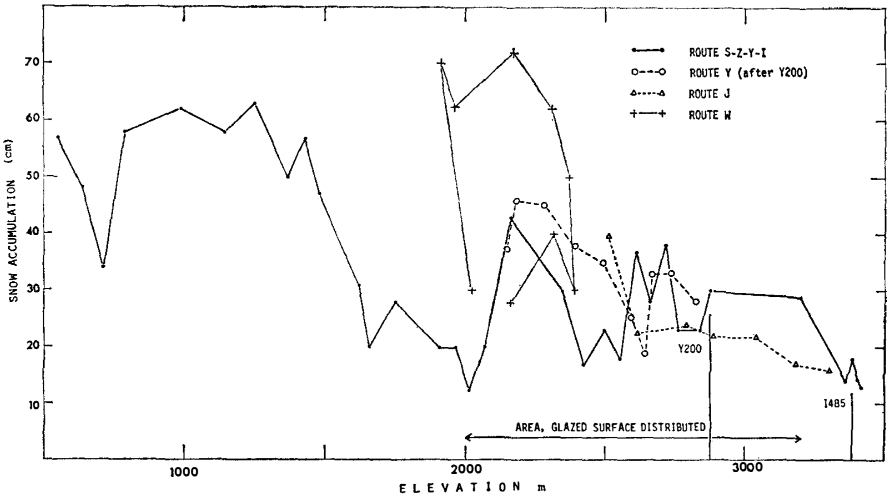

Fig. 16. Relation between elevation and annual accumulation obtained by stratigraphic observations.

applicable when the properties resulting from metamorphic processes themselves provide also an indication of seasonal conditions.

5.2.2. Oxygen isotope studies and gross β activity measurements

Studies of oxygen isotope ratio have been regarded to be effective in the determining of annual accumulation, since the periodical variations of $\delta^{18}O$ in the vertical profiles have been believed to reflect the seasonal changes of the $\delta^{18}O$ of precipitation elements. According to the results of the isotope studies in Mizuho Plateau, a considerable difference was found in the annual accumulation rates estimated from isotope analyses and those from stratigraphic interpretations.

This disagreement in determination by the different methods can be explained by the following two causes: One of the causes is the fractionation process of oxygen isotopes in snow metamorphism under a condition of less accumulation, which was confirmed experimentally (SATOW *et al.*, in preparation). The other cause is the lack of a seasonal sequence in layer formation. The layer formation is not enough to record the seasonal sequence in the area of less accumulation in most of the inland region.

Measurements of gross β activity of the snow samples collected from pits and cores in Mizuho Plateau are still in progress, except cores from two stations (S97 and H128). A good agreement was found between the marker horizon of a known age detected by gross β activity and the sequence of snow accumulation deduced from the other stratigraphic methods. This method is very effective in the estimation of the average rate of snow cover formation during a considerably long period, and especially in the application to the lower accumulation region, where the missing of an annual layer or layers frequently occurs.

5.2.3. The missing of annual layers and disappearance of stratigraphic structure

As described in the previous section, the major difficulty in determining the annual accumulation is that it is hard to find out how many annual layers are missing and the disappearance of the stratigraphic structures related to the missing. In the estimation of the annual accumulation shown in Fig. 16, such missing of layers was not included. In the process of the snow cover formation, the duration of the hiatus in layer formation is considerably longer than that of snow accumulation. Therefore, the estimation of duration of various hiatus phenomena will be most important in future snow stratigraphic studies.

The analysis of micro particles that were deposited during the hiatus and the precise study on the quantitative mechanism of the metamorphic process will contribute to such studies.

6. Regional Characteristics of the Snow Cover

The formation process of the snow cover is characterized by the climatic and geomorphological conditions in the region.

In order to show the regional variation of layer formation, stratigraphic

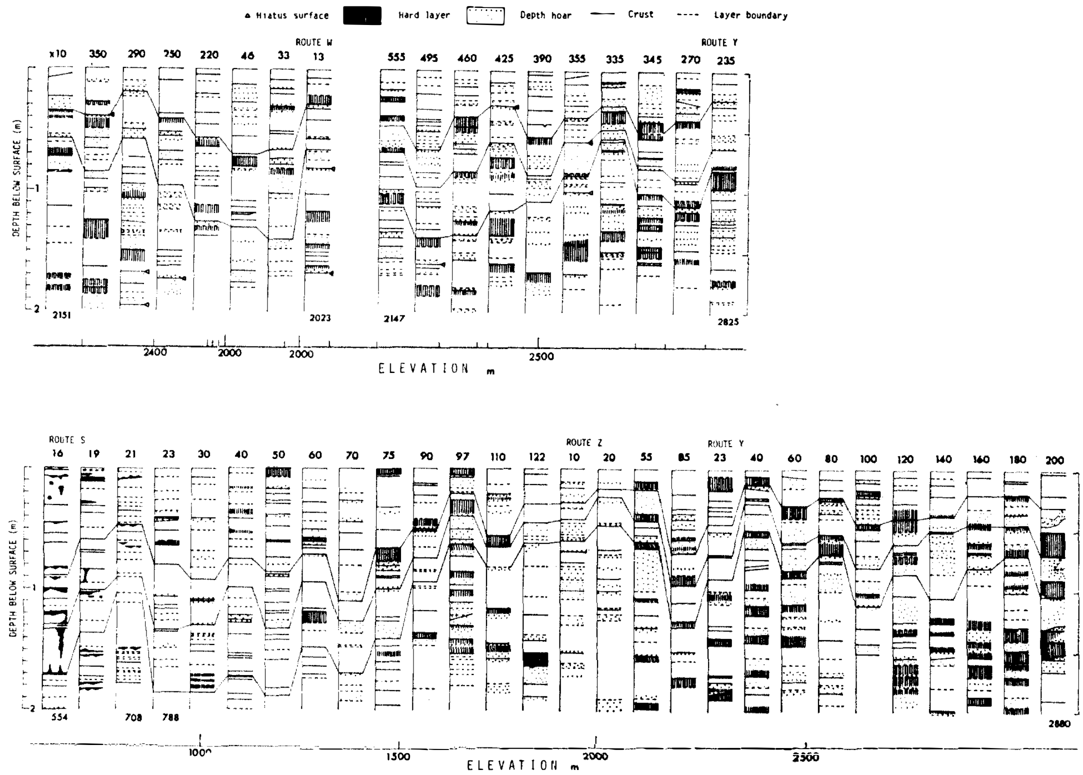

Fig. 17. Regional characteristics of surface snow layers in Mizuho Plateau.

diagrams of 2-m cores are shown in Fig. 17, in which the stratigraphic elements are simplified for the purpose of a direct comparison of regional characteristics. The properties of snow are indicated as hard, loose, and intermediate. The structures are shown by layer boundaries with or without ice crusts. In this figure the lines connecting each stratigraphic diagram show the annual layers. As for the region higher than 1700 m a.s.l., since the hiatus in annual layer formation occurred frequently, it is not sure that the lines indicate the same year.

What are evident from this figure are as follows: i) The thicknesses of the unit layers and their number contained within an annual layer decreased as the distance from the coast and the elevation increased. Such a tendency can be correlated to the accumulation rate at a given place. ii) The ratio between the thickness of a hard layer and that of a loose layer at a given site along Routes S, Z and Y increased suddenly when the elevation reached 1500–1700 m a.s.l. The marked variations in vertical profiles of the physical properties such as the density and hardness were seen simultaneously. A comparison of these phenomena in the regions of Route S-Z-Y and Route W disclosed a different tendency between the two regions as follows: The elevation where the stratigraphic characteristics changed was 1900–2500 m a.s.l. in the region of Route W, but 1500–1700 m a.s.l. in the region of Route S-Z-Y.

Considering this fact, the regional environment related to the stratigraphic characteristics would be controlled not only by elevation but also by other geomorphological factors.

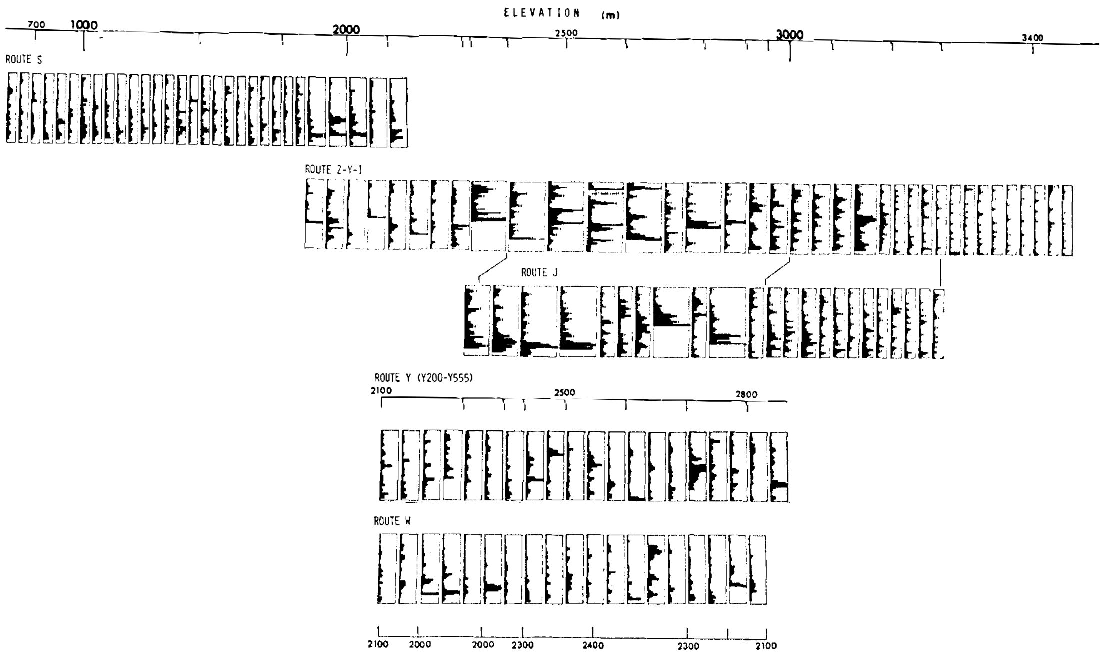

Fig. 18. Regional variations of Ram hardness profiles.

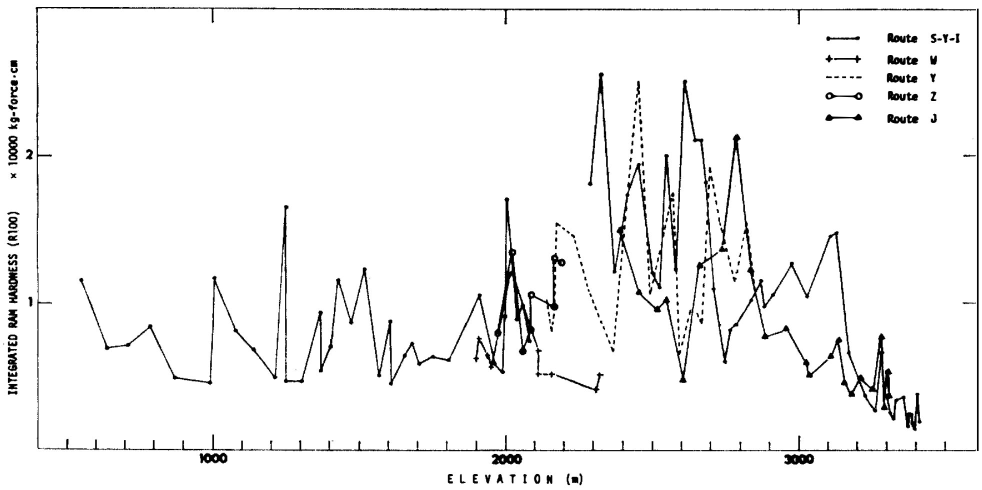

Fig. 19. Regional variations of integrated value of Ram hardness from the surface to a 1-m depth.

The vertical profiling of Ram hardness from the surface to a 2-m depth was made at intervals of 20–40 km along the traversed routes. The purpose was as follows: i) tracing of snow stratigraphy under the similar environmental conditions; ii) determination of regional characteristics of depth hoar formation.

All the results of Ram hardness profiling along the route traversed in 1970–1971 and 1974–1975 are given in Fig. 18. The stratigraphic diagrams of 2-m cores in Fig. 17 correspond to the Ram profiles along Route S-Z-Y-I and Route Y (Y200–Y555)–W. The marked development of hard and loose layers was seen from the variations of Ram hardness which were obtained in the area between 1900–2800 m a.s.l.

In the coastal region, the stratigraphic diagrams were well correlated to the Ram profiles despite the relatively small variations of values; hence, the profiles are effective to trace the reference horizon indicating a fixed year. In the region higher than 3200 m a.s.l., strongly developed depth hoar was observed, whereby considerably small values of Ram hardness were seen consequently. The regional variations of the integrated values of Ram hardness of the snow layer to a 1-m depth are shown in Fig. 19. As seen in this figure and Figs. 17 and 18, Mizuho Plateau can be divided stratigraphically into three regions with boundaries at 1900–2100 m and 2800–3200 m a.s.l.

The snow cover in the lowest region is characterized by high accumulation without the hiatus phenomena and by poor development of depth hoar. The typical characteristics of the snow cover in the intermediate region are the alternating occurrence of hard and loose layers in the snow cover relating to a katabatic climate, and the frequent hiatus phenomena. The snow cover in the highest region is characterized by low accumulation with frequent hiatus and by high development of depth hoar.

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