Abstract

Glaciological studies of the upper 10 m of the ice sheet in East Antarctica were made during the JARE South Pole Traverse 1968–1969. The glaciological studies consisted of studies of surface snow and subsurface snow by means of pits as well as analyses of snow cores.

Conditions of surface snow such as accumulation, roughness, density and hardness are described in this paper. It is found that the conditions are distinctly different in four regions along the route from Syowa Station to the South Pole, and that they have a close connection with the slope inclination. Relationship between the snow conditions and the slope inclination is discussed in terms of the dependence of wind speed on the slope inclination. Thus, it is concluded that the conditions of surface snow are mainly controlled by wind speed.

Measurements of annual snow accumulations disclose that local variations in accumulations take place in a strong wind region, and coincide with local topography of the region. Also, distinct regional differences in accumulations during the summer season are discussed from the differences between cyclonic and anticyclonic precipitations.

Studies of subsurface snow in 2 m deep pits indicate that regions located in the north and south of 73°S are characterized respectively by compact fine-grained snow and well-developed depth hoar.

Analyses of snow cores from the surface to a depth of 10 m revealed the distribution of snow density in the upper 10 m of the ice sheet along the route from Syowa Station to the South Pole. Regional profiles of snow density at the depths of 5 and 9 m were different from those at the surface. This is due to the differences in the mean annual air temperature.

1. Introduction

The JARE South Pole Traverse 1968–1969 carried out a round trip between Syowa Station and the South Pole along the route of 40–43° East Longitude in the Antarctic summer 1968–1969 (Fig. 1). Both the outgoing trip to the South Pole (from 28 September to 19 December 1968) and the returning trip (from 25 December 1968 to 15 February 1969) were made along the same route. Traverse stations were set up at intervals of 2 km between Syowa Station and Plateau Station, and at intervals of 4 km between Plateau Station and the South Pole. Glaciological studies conducted at these stations were as follows:

1) Observations of the surface snow relief such as sastrugi, snow dunes and ripple marks at intervals of 2 or 4 km.

2) Measurements of hardness and temperature of surface snow at intervals of 8 km. Measurements were made twice both during the outgoing and the returning

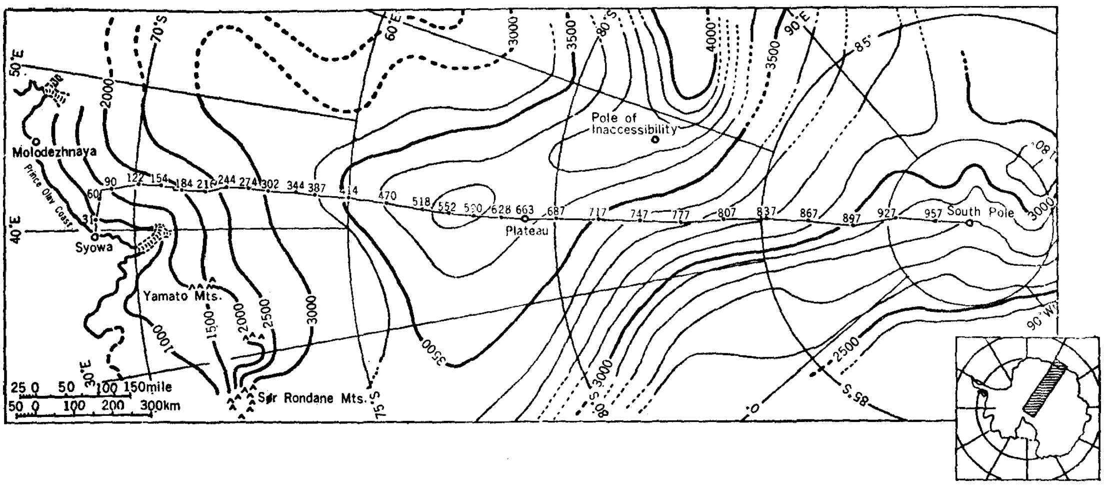

Fig. 1. The route of the JARE South Pole Traverse 1968–1969 and the topography of East Antarctica. The topography was compiled by K. FUJIWARA from the elevation data of the ice sheet obtained by the JARE South Pole Traverse, the Soviet Vostok-Molodezhnaya and Molodezhnaya-Novolazarevskaya Traverses and the U.S.A. Queen Maud Land Traverses. Some of traverse stations are shown by numbers on the route.

trip.

3) Remeasurements of snow accumulations with stakes set up by JARE-8 in December 1967-January 1968 at intervals of 2 km between Syowa Station and Plateau Station, which were carried out twice both during the outgoing and the returning trip. In addition, measurements of surface snow density were made at intervals of 16 km during the returning trip from Plateau Station to Syowa Station.

4) Stratigraphical studies of 2 m deep pits to obtain annual snow accumulations. This study was made at 44 stations.

5) Sampling of snow cores to a depth of 10 m at 23 stations.

6) Measurements of snow temperature at a depth of 10 m.

The main purpose of this paper is to describe conditions of the snow cover in the upper 10 m depth of the ice sheet in East Antarctica along the route of the JARE South Pole Traverse, and to discuss meteorological and topographical factors controlling these conditions. The studies of surface snow are discussed in Sections 2, 3, and 4, and the studies of subsurface snow in Sections 5 and 6.

2. Conditions of Surface Snow in Different Regions of East Antarctica

Conditions of surface snow were investigated by measuring mean annual snow accumulations, height of the surface snow relief, snow density, and snow hardness at the surface along the route of the JARE South Pole Traverse 1968–1969 (FUJIWARA and ENDO, 1971). These values are plotted in the first four diagrams in Fig. 2.

2.1. Mean annual snow accumulations

The annual snow accumulations in Fig. 2 (A) were obtained from stratigraphical studies made in pits. Generally speaking, summer layers are coarse-grained, contain depth hoar and are of low density and of low hardness; winter layers are fine-grained, rather homogeneous, of high density and of high hardness. By paying attention to such a cyclic seasonal variation in snow layers, the boundaries of annual snow layers are distinguished.

Then, stratigraphical features, grain sizes and densities of snow layers were examined in each pit, and the boundaries of annual snow layers were distinguished by the above-mentioned criteria in the field, as indicated by the arrow marks in Appendix 1. The arrow marks with (?) indicate doubtful annual snow boundaries in the cases where the possibility of existence of annual boundaries was only guessed, because of the lack of distinct seasonal variations in snow layers.

In Fig. 2 (A) an upper dot indicates a mean value of annual accumulation based on the arrow marks without (?) in Appendix 1, while a lower dot in the same ordinate indicates a mean value based on both the arrow marks without (?) and those with (?).

As shown in this figure, annual snow accumulations are more than 10 g/cm^2 year near the coast; they decrease toward the center of East Antarctica, and reach the minimum value of 3 g/cm^2 year in the vicinity of the highest point (Station 556, about 77.5°S) on the route. Farther southward, the annual accumulations increase; near the South Pole they become about 7 g/cm^2 year. Such distribution of annual snow accumulations along the route is explained by the penetration of cyclonic storms into the interior of Antarctica. The cyclonic storms are formed over the ocean, and transport heat and moisture into Antarctica. As these cyclones move southward, the moisture condenses and falls in the form of snow. Regions

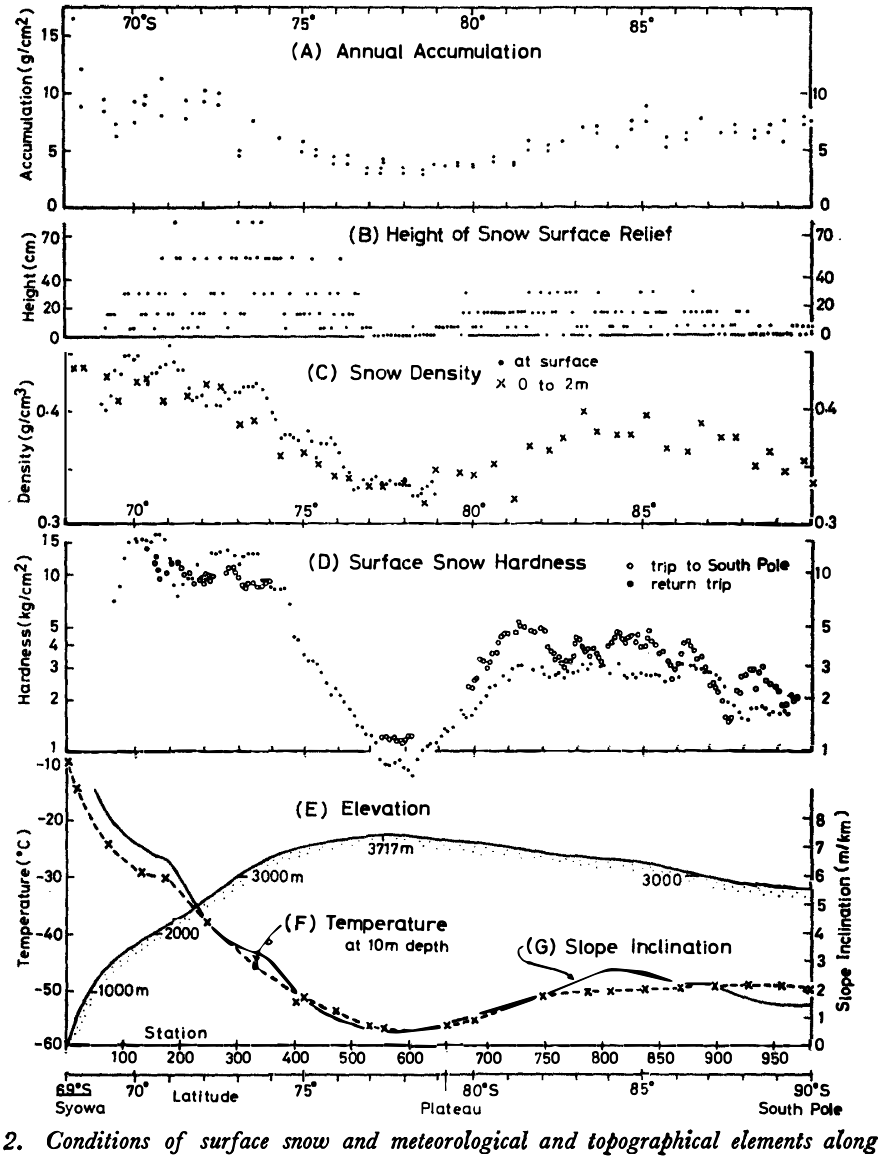

Fig. 2. Conditions of surface snow and meteorological and topographical elements along the traverse route.

(A) Mean annual accumulations obtained by pit studies. (B) Height of the surface relief. (C) Snow density: Solid marks show moving averages over 5 values of the surface snow density measured at intervals of 16 km, and cross marks show average snow densities from the surface to the depth of 2 m in each pit. (D) Snow hardness at the surface shown by moving average over 10 values of hardness measured at intervals of 8 km: Open circles show the hardness measured on the outgoing trip to the South Pole, and solid circles on the returning trip. (E) Elevation. (F) Snow temperature at a depth of 10 m. (G) Slope inclination (gradient of elevation along the direction of the maximum slope) over a distance of about 100 km. The interval of stations is 2 km between Syowa and Station 663 (Plateau Station), and 4 km between Station 663 and Station 982 (the South Pole).

into which the cyclones move tend to have heavier snowfalls than other regions. In East Antarctica, most of cyclones move along the periphery of the continent and do not penetrate into the interior, as they are blocked by the high surface elevation and by the anticyclone existing over this region. Therefore, the annual snow accumulations attain the maximum value near the coast, and decrease rapidly toward the interior. In West Antarctica, some of cyclonic storms move across the continent between the Ross Sea and the Weddell Sea. The South Pole is located on the track of cyclones (ASTAPENKO, 1960). The increase of annual accumulation toward the South Pole, shown in Fig. 2 (A), is due to the cyclonic effects.

In this section, attention is paid to local fluctuations of annual snow accumulation. Figure 2 (A) shows that the values of accumulations in the regions between the coast and 74°S and between 83°S and 87°S differ from place to place, whereas in other regions the values do not fluctuate locally. This is recognized more clearly in the upper dots of Fig. 5, showing annual snow accumulations measured with snow stakes. Detailed studies on accumulations are described in Section 4.

2.2. Height of the surface snow relief

In Fig. 2 (B), height of the surface snow relief such as sastrugi, snow dunes and ripple marks is plotted along the route at intervals of about 10 km. In the coastal region the relief is relatively small. However, in the region between 71°S and 74.5°S the snow surface becomes very rough, and sometimes the relief comes to more than 70 cm in height. Beyond 74.5°S its height decreases rapidly; at the highest location on the route the snow surface becomes smooth, and only ripple marks or other small-scale features are observed. Farther southward, the surface becomes fairly rough, but near the South Pole it becomes smooth again.

2.3. Snow density at the surface

Surface snow densities shown by solid marks in Fig. 2 (C) are moving averages over 5 values measured on the surface at intervals of 16 km. The average snow density from the surface to a depth of 2 m shown by cross marks was measured in pits. In either case, the densities exceed 0.38 g/cm^3 in the north of 74°S. Beyond 74°S, decreasing rapidly, they reach the minimum value of 0.33 g/cm^3 in the highest location on the route. Between 83°S and 87°S, the snow densities come to about 0.38 g/cm^3, but they decrease again, as the South Pole is approached.

2.4. Snow hardness at the surface

Hardness of surface snow was measured with Kinosita's hardness-meter (KINOSITA, 1960). Plotted in Fig. 2 (D) are moving averages over 10 values of hardness measured at intervals of 8 km. Open circles in this figure show the hardness measured during the outgoing trip to the South Pole, and solid circles show the hardness during the returning trip. As shown in this figure, the hardness of surface snow in the interior of East Antarctica measured during the returning trip (midsummer) is smaller than that during the outgoing trip (early summer) to the South Pole. The decrease of the hardness in midsummer may be related with sublimation crystals which were frequently observed on the snow surface in the interior of East Antarctica during the returning trip in midsummer, as reported by Gow (1965) and ORHEIM (1968).

In the north of 74.5°S, the hardness at the surface is about 10 kg/cm²; however, it ranged from 2.3–3.1 kg/cm² on a drift snow surface to 20–50 kg/cm² on a glazed surface. Beyond 74.5°S, the hardness decreases rapidly and shows the minimum value of 1 kg/cm² at the highest location on the route. In the south of 81°S, the hardness is 3–5 kg/cm², but it decreases again beyond 87°S.

2.5. Division of the ice sheet along the traverse route

As mentioned above, four data, which indicate conditions of surface snow, show distinct differences, which depend on regions. Moreover, all of the four data agree with each other in the demarcation of regions. Then we can divide the ice sheet along the route into four regions on the basis of regional variations of conditions of snow at the surface. Table 1 gives the division of the ice sheet along the route in accordance with the grouping of conditions of surface snow. The lowest column in this table is a topographic division, which was made from a topographic viewpoint by FUJIWARA and others (1971). Table 1 shows that two kinds of the divisions which were made from different standpoints coincide. This implies that conditions of the surface snow have a close connection with topography of the ice sheet.

Table 1. Division of the ice sheet in East Antarctica along the route of 40~43°E in accordance with the grouping of surface snow conditions.

Boundary of regions	69°S	74~74.5°S	81~83°S	87°S	90°S
Annual accumulation (g/cm^2 year)	>20 near the coast	0~15 differs from place to place	3~4	5~8 differs from place to place	7
Height of the relief (cm)	< 40 in the north of 70.5°S	>40 frequently	smooth	<40	smooth
Snow density (g/cm^3)	0.40~0.45		0.33 at highest parts	0.38	0.35
Snow hardness (kg/cm^2)	8 ~20		1 at highest parts	3~5	2
Slope inclination (m/km)	>3		<2	2<S<3	<2
Topographic division (after FUJIWARA *et al., 1971*)	Marginal slope (69°S~71°S)	Katabatic slope (71°S~ 74.5°S)	Central core (74.5°S ~81°S)	Interior slope (81°S~87°S)	Interior basin (87°S~90°S)

3. Topographical and Meteorological Factors Controlling Conditions of Surface Snow

3.1. Relationships between conditions of surface snow and the slope inclination

In this section we discuss the main factors causing regional variations in conditions of surface snow. (E) elevation, (F) snow temperature at a depth of 10 m, and (G) slope inclination are chosen as factors affecting conditions of surface snow, and they are shown in the lower part of Fig. 2. (E), elevation, and (F), snow temperature at a depth of 10 m, were measured during the JARE South Pole Traverse (FUJIWARA and ENDO, 1971; FUJIWARA *et al.*, 1971). It is well known that snow temperature at a depth of 10 m gives a good approximation to the mean annual air temperature. (G), the slope inclination, is the gradient of elevation along the direction of the maximum slope, namely the normal direction to a contour line; it is not a gradient along the direction of the traverse route. It was derived from a contour map compiled by FUJIWARA (1971). Values adopted for the slope inclination are averages over a distance of about 100 km.

Should we compare figures (A), (B), (C) and (D) in the upper part of Fig. 2 with (E), (F) and (G) in the lower part, paying special attention to the changes of these curves between the highest point (77.5°S) and the South Pole, we can find that regional variations as regards conditions of surface snow coincide with those of the slope inclination in all regions except the north of 74°S. That is, Fig. 2 indicates that conditions of surface snow such as the density, hardness and so on have little connection with temperature or elevation, but are closely related to slope inclination. The relationships between conditions of surface snow and slope inclination, which are shown in Fig. 2, are outlined as follows:

1) In a range of the slope inclination between 0 and about 3 m/km, the density, hardness and height of the relief of surface snow increase with the increase of the slope inclination. However, on the slope steeper than about 3 m/km, they no longer increase, being nearly constant. In the case of the surface relief, a decreasing tendency is recognized on the steepest slope near the coast.

2) The annual snow accumulations fluctuate from place to place on the steeper slope, but do not fluctuate on the gentle slope.

Table 1 also gives the slope inclination in the four regions divided by conditions of surface snow.

3.2. Relationships between the snow density and the slope inclination

As a good example showing the relationships described in the previous sub-section, the relationships between the average snow density from the surface to a depth of 2 m and the slope inclination are given in Fig. 3. Solid circles in the

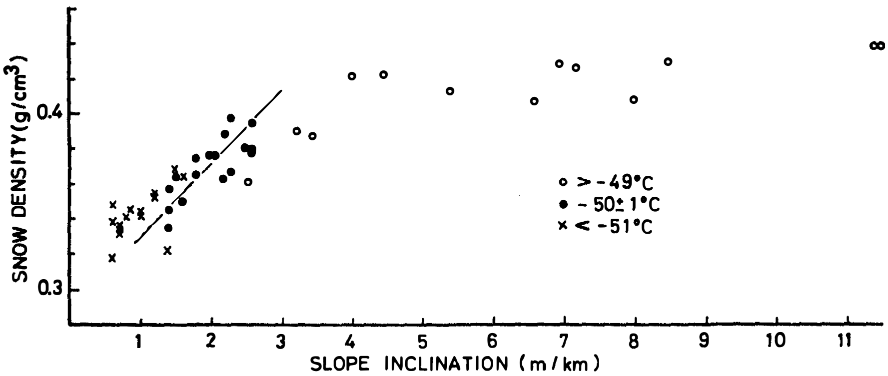

Fig. 3. Relationship between the average snow densisy from the surface to a depth of 2 m and the slope inclination.

Open circles show the densities at places where the annual mean air temperature is above −49°C; solid circles at −50±1°C; cross marks below −51°C. A straight line expressed by $\rho_{-50}(g/cm^3)=0.29+0.042S(m/km)$ was obtained from the solid circles.

figure show the snow densities at places where the mean annual air temperature is −50±1°C; open circles above −49°C; cross marks below −51°C. As shown in this figure, the snow density increases with the increase of the slope inclination in the range of the slope inclination between 0 and about 3 m/km; on the slope steeper than about 3 m/km, the snow density becomes nearly constant, being about 0.42 m/cm³. For the solid circles indicating −50±1°C, the following equation is obtained:

$$\rho_{-50}=0.29+0.042S \qquad (1)$$

where ρ_{-50} is the average snow density (g/cm³) from the surface to a depth of 2 m where the mean annual air temperature is −50±1°C, and S is the average slope inclination (m/km) over a distance of about 100 km. Effects of temperature on the snow density are discussed in Section 3.5.

Similar relationships were found between the snow hardness and the slope inclination.

By the way, the slope inclination itself is not a direct factor affecting the snow density, snow hardness and so on. Therefore, the relationships which exist between conditions of surface snow and the slope inclination are considered to be created by other factors which affect conditions of surface snow and moreover depend on the slope inclination. Wind speed is regarded as one of such factors. Then, dependence of wind speed on the slope inclination is examined in the next subsection.

3.3. Dependence of wind speed on the slope inclination

Figure 4 shows relationships between the mean annual wind speed and the slope inclination on the ice sheet in Antarctica (except ice shelves, peninsulas, extensive rock areas and offshore islands). Plotted in this figure are the data of the mean annual wind speed at all stations (except Eights, Cape Denison, and Port Martin) on the ice sheet, which were given from a paper by MATHER and MILLER (1967). The reasons for eliminating the data of the three stations are that Eights can be regarded as a station located at the root of the Antarctic Peninsula, and that extremely strong katabatic winds at Cape Denison (19.8 m/s) and Port Martin (18.0 m/s) are looked on as exceptional phenomena caused by a special local topography. Values of the slope inclination are adopted averages for a distance of 100–200 km, which were derived from our traverse map (FUJIWARA, 1971) and Antarctic Map Folio Series, Folio 2 (BENTLEY *et al.*, 1964), in order to compare them with Fig. 3.

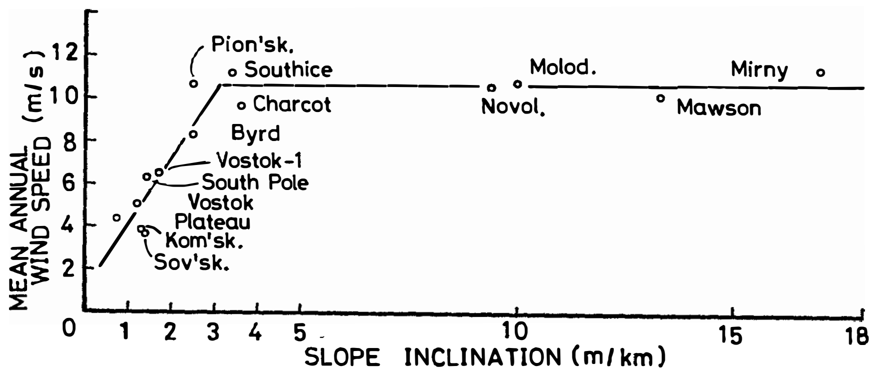

Fig. 4. Relationship between the annual mean wind speed and the slope inclination far Antarctic stations on the ice sheet (except ice shelves, peninsulas, extensive rock areas and offshore islands).

Figure 4 shows that the mean annual wind speed on slopes having an inclination within about 3 m/km increases in proportion to the slope inclination, but on slopes steeper than about 3 m/km it no longer increases, showing a constant value of 10–11 m/s. The relationship in a region of the slope inclination between 0 and about 3 m/km can be expressed by the following equation:

$$W = 1.0 + 3.0S \quad (2)$$

where W is the mean annual wind speed (m/s) and S the slope inclination (m/km).

AGETA (1971) reported that the mean wind speed from September to January was about 8–10 m/s along the route of the JARE South Pole Traverse between the edge of the ice sheet and 72°S (more than 4.5 m/km in the slope inclination) on the basis of weather observations made by several traverse parties of JARE from 1960 to 1970. Wind speed in the coastal region is generally smaller in summer than in winter; the amplitude of seasonal variations in wind speed is ±20 – 30% from the mean (MATHER and MILLER, 1967). Therefore, the annual mean wind speed in this region is considered to be 10–11 m/s. This suggests that the relationships shown in Fig. 4 are applicable to the traverse route. According to Fig. 4, the mean annual wind speed in the north of 73–74°S on the route is 10–11 m/s everywhere.

3.4. Influence of wind speed on conditions of surface snow

From the relationship between the snow density and the slope inclination in Fig. 3 and the dependence of wind speed on the slope inclination in Fig. 4, we shall deduce the relationship between the snow density and the wind speed. Comparing the two curves in Fig. 3 and Fig. 4, we notice that both curves have the same tendency, and bend at the same point of about 3 m/km. We can consider that the constant value of the snow density (0.42 g/cm³)* in the region beyond a slope inclination of about 3 m/km is due to the constant wind speed (10–11 m/s) in this region, and that the snow density is proportional to the wind speed. The proportional relationship can be expressed by solving two equations (1) and (2), as follows:

$$\rho_{-50}=0.27+0.014W \qquad (3)$$

BILELLO (1967) has proposed the following equation to estimate average seasonal (November-March) snow cover density ρ (g/cm³), from the analysis of snow density and climate for 27 stations in North America and Greenland, where average seasonal air temperature T (°C) ranges from –2 to –35°C, and average seasonal wind speed W (m/s) from 1 to 8 m/s:

$$\rho=0.152-0.0031T+0.019W \qquad (4)$$

Applying eq. (4) to a temperature of –50°C, we get

$$\rho_{-50}=0.31+0.019W \qquad (5)$$

The two coefficients in eq. (3) are not comparable with eq. (5), since there is a difference between the snow cover of several years period and the seasonal snow cover. Nevertheless, eq. (3) and (5) are identical in shape, which justifies our consideration. We can conclude that the snow density is proportional to the

*This constant snow density (0.42 g/cm³) might be regarded as the limit of density into which snow packs mechanically due to wind actions.

wind speed when the temperature is constant, and that the relationship between the snow density and the slope inclination, shown in Fig. 3, is due to the wind action.

The relationship between ρ and W is attributed to the following action of wind:

(1) Snow crystals are destroyed by wind into smaller fragments depending on the wind speed (KOTLYAKOV, 1966). Smaller fragments are known to pack more closely than larger fragments.

(2) As wind becomes stronger, the fragments of snow crystals pack into a higher density as a result of the pressure of the flying fragments and the moving air.

In the same way, the snow hardness, the height of the relief and the local fluctuations of the annual accumulations can be related with the wind speed, referring to the description in Section 3.1. and to the dependence of the wind speed on the slope inclination in Fig. 4, as follows: as the wind speed increases, the snow hardness and the height of the relief increase, and the annual snow accumulations fluctuate more largely from place to place. These relations are verified by the following facts generally observed in Antarctica:

(1) In a wind-free condition, snow crystals tend to accumulate uniformly on the snow surface, and make a soft snow layer of low density. Under the action of wind, however, snow crystals are destroyed into smaller fragments and pack into firm, dense layers.

(2) When snow falls in a mild wind condition, it tends to accumulate uniformly on the surface. However, in a strong wind condition, snow is usually deposited in the form of elongated snow dunes, and surfaces snow is sharply eroded. Therefore, the height of the surface relief and the local fluctuation of the accumulation should be related with the wind speed.

We can conclude that the relationship between the condition of the surface snow and the slope inclination is formed by the action of wind and the regionally varying in conditions of surface snow are mainly attributed to different wind speeds.

3.5. Effects of temperature on the density of snow

In the foregoing subsection, it was concluded that the main factor of regional variations in conditions of surface snow is wind speed. However, as shown in BILELLO's empirical equation (4), temperature also must affect snow conditions, especially density and hardness, even though the effect may be slight.

Figure 3 indicates temperature effect on the average snow density from the surface to a depth of 2 m. In a range of the slope inclination below 3 m/km, that is, wind speed below 10–11 m/s, which corresponds to the mean annual air temperature from $-48°C$ to $-60°C$, cross marks indicating below $-51°C$ tend to be located in the left part of a solid line indicating $-50 \pm 1°C$, and open circles indicating above $-49°C$ tend to be located in the right part. This suggests that the snow density at wind speeds below 10–11 m/s and temperatures from $-48°C$

to −60°C decreases with the rise of temperatures, if the slope inclination, that is, the wind speed is the same. This tendency agrees with BILELLO's equation.

Effect of temperature on the snow density in a region having the slope inclination above 3 m/km, that is, a constant wind speed of 10–11 m/s is examined in Fig. 10. In this figure, the average snow densities from the surface to a depth of 2 m are plotted against mean annual air temperature by cross marks. A region having a constant wind speed of 10–11 m/s corresponds to a region between −10° and −48°C in this figure. The distribution of the points between −10° and −48°C shows a tendency for the density to increase as temperature increases.

As mentioned above, the temperature effect on the density becomes completely reverse due to defferences in wind speed and temperature. Such reverse effects of temperature on the snow density are explained by the following three causes:

(1) The size of snow crystals is related primarily to the air temperature: As the temperature rises, the crystals increase in size (KOTLYAKOV, 1966). As small crystals pack more closely than large crystals, the density of newly deposited snow in mild wind conditions has a decreasing tendency with the rising temperature.

(2) In strong wind conditions, snow crystals break into small fragments, its extent being dependent on wind speed and on type of snow crystals. Plane snow crystals (stellar crystal, dendrite, and plate) which are formed at temperatures above −25°C, tend to be destroyed by wind into smaller fragments than columnar crystals (prism and bullet) formed mainly at lower temperatures (KOTLYAKOV, 1966). Consequently, in a strong wind condition the density of newly deposited snow will be larger in high temperature places than in low temperature places.

(3) After deposition, the density of snow gradually increases under its own weight and the weight of the snow above, the rate of densification increasing with the rising temperature. Therefore, the snow density becomes larger in high temperature places than in low temperature places, if the initial density of newly deposited snow is the same.

In the condition with wind speeds below 10 m/s and temperature from 48°C to 60°C, it is considered that the destructive effect of wind (2) and the densification under gravity (3) are negligible because of mild wind and very low temperature. Therefore, in this condition the average snow density from the surface to a depth of 2 m has a decreasing tendency with the rising temperature, as mentioned in (1). On the other hand, at a wind speed 10–11 m/s and temperatures from −10°C to −48°C, (2) and (3) play important roles, resulting in the increase of the snow density as the temperature rises.

4. Snow Accumulations in a Region between Syowa Station and Plateau Station

In December 1967–January 1968, the traverse party of JARE–8 set up snow stakes at intervals of 2 km from Plateau Station to Syowa Station. Measurements of accumulations using these stakes were carried out in April 1968, September–November 1968, and January–February 1969. Upper dots in Fig. 5 show annual

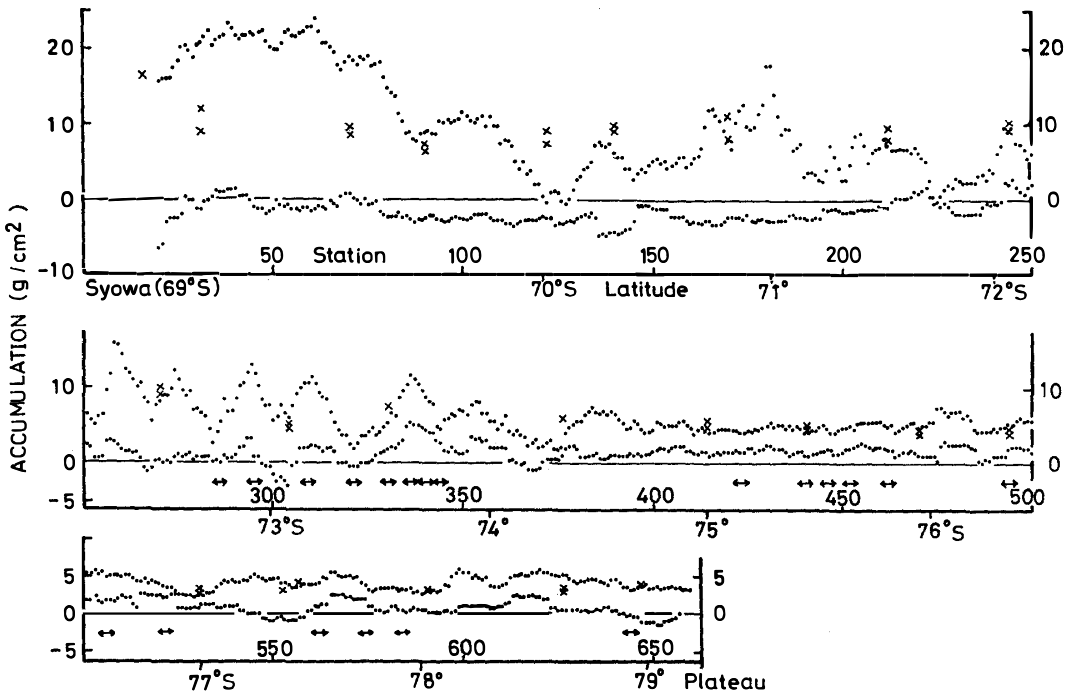

Fig. 5. Snow accumulations measured by stakes along the route from Syowa to Plateau. Upper dots show annual accumulations from December 1967–January 1968 to January–February 1969; lower dots show accumulations in summer from September–November 1968 to January–February 1969. These values are moving averages over 10 values of accumulations measured at intervals of 2 km. Cross marks are mean annual accumulations obtained from pit studies. A line with 2 outward arrow heads at both ends in the lower part shows the location where small ice-crystals were observed during the trips.

snow accumulations from December 1967–January 1968 to January–February 1969, and the lower dots show accumulations in summer from September–November 1968 to January–February 1969 (FUJIWARA and ENDO, 1971). These values are moving averages over 10 values of accumulations measured by stakes set up at intervals of 2 km. Cross marks show mean annual snow accumulations obtained from stratigraphical studies made in pits.

4.1. Relationships between snow accumulations and the local topography

As shown in Fig. 5 annual snow accumulations attain the maximum value of more than 20 g/cm² year in an area between Stations 25 and 65 (30 to 80 km from the coast, 800 to 1350 m above sea level) ; Between 70°S and 74.5°S, annual accumulations vary periodically in places within the range of 0 to 15 g/cm². Especially local variations in accumulations at locations between 72°S and 74.5°S take place at intervals of about 40 km. However, in the south of 74.5°S accumulations are nearly constant at 4 g/cm² year.

As mentioned in Section 3, differences in the values of accumulations observed in the north and the south of 74.5°S, that is, the fluctuation of accumulations and the constant accumulations, are due to differences in wind speed between the two regions. This subsection deals with studies on local changes in accumulations which are characterized by similarities taking place recurrently in the north of 74.5°S.

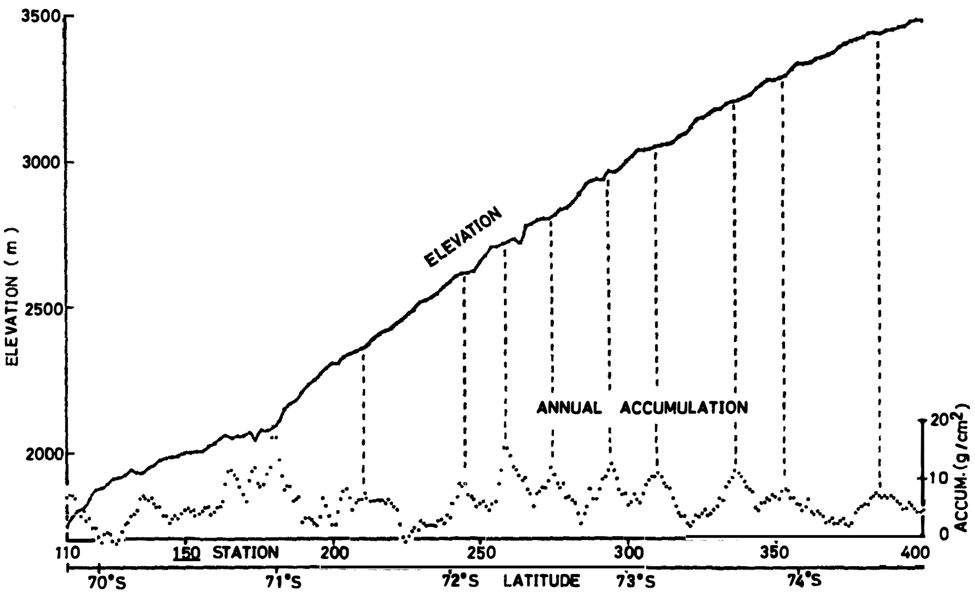

Fig. 6. Annual snow accumulations and elevations along the route from 70°S to 74.5°S.

Figure 6 shows annual snow accumulations and the elevation in the north of 74.5°S. As shown in this figure, the topographical feature of this region is characterized by tiers of fairly steep slopes and flats or shallow troughs. In the south of 74.5°S, however, this topography disappears and slopes become smooth and uniform (FUJIWARA *et al.*, 1971). Figure 6 shows that the changes in accumulations of snow coincide with the tiered topography; accumulations are large in flats or shallow troughs, and small on steep slopes. The following interpretation of this tendency is possible. In the north of 74.5°S where strong winds prevail, new snow on steep slopes is carried away by strong winds, and is deposited on flats or shallow troughs where wind speed may decline; in the south of 74.5°S where the wind is mild and slopes are uniform, new snow accumulates uniformly on the surface.

4.2. Comparison of the values of annual snow accumulations measured by stakes and from snow stratigraphy

Annual snow accumulations in the region between Syowa and Plateau were measured both by stakes and from the snow stratigraphy. Upper dots in Fig. 5 show the annual snow accumulations by stakes, and cross marks show mean annual accumulations from the stratigraphy. As shown in this figure, values of mean annual accumulations from the stratigraphy agree fairly well with values by stakes, except at Stations 30, 70 and 122. However, mean annual accumulations in the region between Plateau and the South Pole, which were obtained from the stratigraphy by the JARE South Pole Traverse, are fairly larger than those derived from the gross β activity measurements by the South Pole–Queen Maud Land Traverses (PICCIOTTO *et al.*, 1968).

4.3. Ablation and accumulation in summer along the route

Lower dots of Fig. 5 show the accumulation or ablation of snow in summer from October–November 1968 to January–February 1969 during the interval of arrivals at a station on both outgoing and returning trips. Therefore, the number of days that lapsed between the previous measurement of accumulations by stakes and the next measurement differs from station to station. For instance, the accumulation (or ablation) at Station 28 is a value extending over 140 days, at Station 400 over 100 days and in the vicinity of Plateau over 70 days. In the lower part of Fig. 5 a line with 2 outward arrow heads at both ends shows the location where small ice-crystals or "diamond dust" crystals in meteorological terms were observed during the trips to and from the South Pole (NISHIBE and SEINO, 1971).

As shown in this figure, a region between Syowa and Plateau in summer is divided at 72–73°S into the ablation region and the accumulation region (2600–3000 m above sea level, 350–450 km from the coast); small ice-crystals were observed only in the accumulation region lying south of 73°S, and never in the ablation region. Moreover, the accumulation rate in the accumulation region seems to be nearly constant throughout the year, from the comparison of accumulations between the summer season and the whole year.

Generally, the ablation rate falls off rapidly with increasing elevation of the ice sheet (BUDD, 1966). However, the above-mentioned facts seem to suggest that differences in accumulations in summer between the two regions are caused not only by the decrease of ablation rate due to the increase of elevation, but also by the following differences in origin of precipitation.

Large cyclonic storms are formed over the sea, and transport heat and moisture into Antarctica. As these cyclones move southward, the moisture condenses and falls in the form of snow. Most of cyclones do not penetrate deeply into the high central region of East Antarctica because they are blocked by the anticyclone that exist there. In the coastal region of East Antarctica, the majority of snowfalls take place during the passing of cyclones. However, as the activity of cyclones weakens in summer, there is little precipitation in summer (KOTLYAKOV, 1966).

On the other hand, the Antarctic anticyclone that exists over the central region of East Antarctica is characterized by the outflow of cold air from the interior in the lowest layer of atmosphere, the sinking movement of air over the highest and coldest part of the continent and, above approximately 600 mb, the inflow of relatively warm and moist air toward the central region. During the sinking movement of relatively warm and moist air into the strong temperature inversion over the surface, water vapor is changed into small ice-crystals, which fall slowly to the surface. The greater part of the total annual accumulations in the central region is produced by this ice-crystal precipitation which is observed almost every day (SCHWERDTFEGER, 1969). In Plateau Station, this ice-crystal precipitation from cirrus clouds or from cloudless skies was observed on 317 days in 1967 (KUHN, 1968).

The characteristics of snow accumulations in the south of 72–73°S, as shown in Fig. 5, are that the accumulations are observed even in summer, the accumulation rate is nearly constant throughout the year, and small ice-crystals are observed in this region. These are characteristics of the anticyclonic precipitation. Therefore, the region south of 72–73°S is considered to be under the action of the anticyclone; the region north of 72–73°S seems to be under the action of the cyclonic precipitation which seldom takes place in summer. The ablation in summer in the north of 72–73°S is regarded as the result of loss of snow by evapolation and wind erosion of the little cyclonic precipitation in summer. Namely, in summer the boundary between the two regions controlled by the cyclonic or the anticyclonic precipitation is considered to lie at 72–73°S (2600–3000 m above sea level, 350–450 km from the coast).

5. Characteristics of Snow in the Upper 2 m of the Ice Sheet in East Antarctica——Results of Pit Studies

The pit studies consisted of observations on stratigraphical features, snow density and grain size. Pit diagrams are given in Appendix 1. Characteristics of snow in each pit are summarized in Fig. 7. Figures 7 (A) and 7 (B) show respectively the proportions of total thickness of snow layers, comprising each snow type and each grain size, from the surface to the bottom of pit. In Fig. 7 (C),

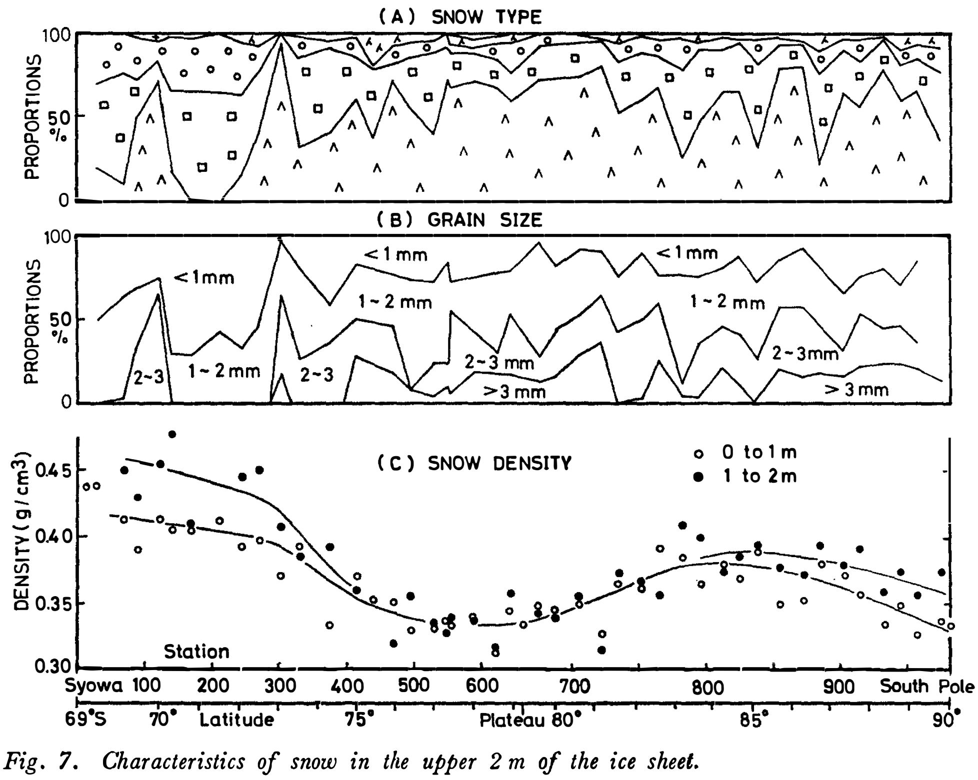

Fig. 7. Characteristics of snow in the upper 2 m of the ice sheet.
(A) Proportion of each snow type composing the snow cover in the upper 2 m; (B) Proportion of each grain size of snow composing the snow cover in the upper 2 m; (C) The average snow densities from the surface to a depth of 1 m (open circles), and from 1 m to 2 m in depth (solid circles).

the average snow densities from the surface to a depth of 1 m and from 1 m to 2 m in depth are plotted on the route. The symbols for the snow types adopted in this figure are as follows:

(++) New snow.
(ʎ ʎ) Very fine-grained snow which has just been metamorphosed from new snow without melting.
(◦ ◦) Compact fine-grained snow.
(□□) Medium-grained depth hoar not developed well: mainly corresponds to a solid type of depth hoar.
(∧ ∧) Coarse-grained, well-developed depth hoar; mainly corresponds to a skeleton type of depth hoar.

5.1. The type and grain size of snow in the upper 2 m

In East Antarctica, the melting of snow takes place only on low elevations near the coast; the greater part of East Antarctica lies in the dry snow zone (BENSON, 1962). Along the route, ice layers, ice lenses and ice glands indicating the results of the melting of snow were observed only at Station 16, the pit nearest to the coast (about 15 km from the coast, 523 m in elevation), and never at the next pit, Station 31 (about 30 km from the coast, 960 m in elevation), as shown in Appendix 1. In addition, Fig. 5 shows that the ablation in summer is less than 3 g/cm^2 in the south of Station 22 (about 25 km from the coast, 720 m in elevation). Consequently, it can be considered that the upper limit of snow melting, namely the dry snow line, lies at 550--700 m in elevation (15–25 km from the coast).

Figures 7 (A) and (B) show that in the dry snow zone lying above the dry snow line, remarkable differences in type and grain size exist between snow in the north of 73°S and snow in the south of same.

(1) In the north of 73°S, the snow cover in the upper 2 m is composed of layers of compact fine-grained snow and medium-grained depth hoar (consisting of solid type crystals). Grain sizes are less than 2 mm in diameter. Exceptional development of coarse-grained depth hoar was observed at Stations 122 and 304. This is due to the absence of accumulations. As shown in Fig. 5, there is little accumulation at Station 122. Station 304 (73°S) had a glazed surface implying low-accumulation.

(2) In the south of 73°S, only a few layers of compact fine-grained snow are observed; the snow cover in pits is composed of layers of medium- and coarse-grained depth hoar. In the region between 77°S and 83°S, most of snow layers are coarse-grained depth hoar.

As mentioned in Section 3.3., the annual mean wind speed in the north of 73–74°S has the maximum value of 10–11 m/s on the route. Also, as mentioned in Section 4.3., most of precipitations in the north of 72–73°S take place during the passing of cyclones. Generally speaking, cyclones in Antarctica are accompanied by strong winds, intensive snowfalls and comparatively high temperatures. For the formation of compact fine-grained snow, strong winds are necessary, but it is uncertain whether strong winds are a sufficient condition or not. Therefore, it can not be decided in this paper whether the north of 73°S, characterized by compact fine-grained snow, corresponds to the region having strong winds of 10–11 m/s or to the region controlled by the cyclonic precipitation.

The reasons why the depth hoar is developed in the south of 73°S are explained next. For the development of large depth hoar it is necessary that large temperature gradients exist in a snow layer of low density. The south of 73°S has this condition. As described in Section 3, the density of newly deposited snow is small in this region having mild winds. Also, larger temperature gradients in snow cover are expected as the result of a larger difference in air temperatures between summer and winter which is observed at interior stations. Moreover, the small annual accumulations in this region can promote the development of depth hoar, because when the accumulation is small a snow layer near the surface remains for a long time near the surface where the largest temperature gradients in the snow cover exists.

5.2. Densification of snow in the upper 2 m of the snow cover

This subsection deals with the increase of density with depth. Figure 7 (C) shows that the increase of density with depth (a difference between the average snow density from the surface to a depth of 1 m and the average density from 1 m to 2 m in depth) is distinctly different in different regions. The traverse route can be divided by differences in the increase of density with depth as follows:

1) Syowa to 73°S: In this region the increase of snow density with depth is larger than in other regions on the route, and it has a tendency to decrease toward the interior.

2) 73°S to 83°S: In this region, the snow density does not increase with depth.

3) 83°S to the South Pole: In this region, the snow density increases slightly with depth. The rate of increase tends to gain toward the South Pole.

The rate of increase in density with depth should be influenced by snow temperature, annual snow accumulation, initial snow density (average snow density from 0 to 1 m in depth) and snow type: It increases as temperature rises; it has a tendency to decrease with the increase of initial density or annual snow accumulation; layers of coarse-grained depth hoar have a tendency to resist gradual plastic deformation. Snow temperature at a depth of 10 m, mean annual snow accumulation, average snow density from 0 to 1 m in depth and snow type along the route are shown in Fig. 2 (F), Fig. 2 (A), Fig. 7 (C) and Fig. 7 (A), respectively.

Referring to these figures, we note that differences in the increase of density with depth among three regions are due to differences in snow type and in snow temperature. Also, the gaining rate of increase in density with depth toward the South Pole in the region between 83°S and the South Pole can be ascribed to the poleward decrease of initial snow density, since the snow temperature, annual snow accumulation and type of snow in this region are almost the same.

6. Distribution of Snow Density in the Upper 10 m of the Ice Sheet along the Route of 40–43°E——Results of Snow Core Analyses

Core drilling to a depth of 10 m was carried out with a SIPRE type hand auger, and snow cores were taken out from the bore holes. However, it was difficult to take out cores in a good shape, especially in the center of East Antarctica (76°S–86°S). The difficulty of core sampling was due to the fact that layers of well-developed depth hoar were very fragile and easily disintegrated during the

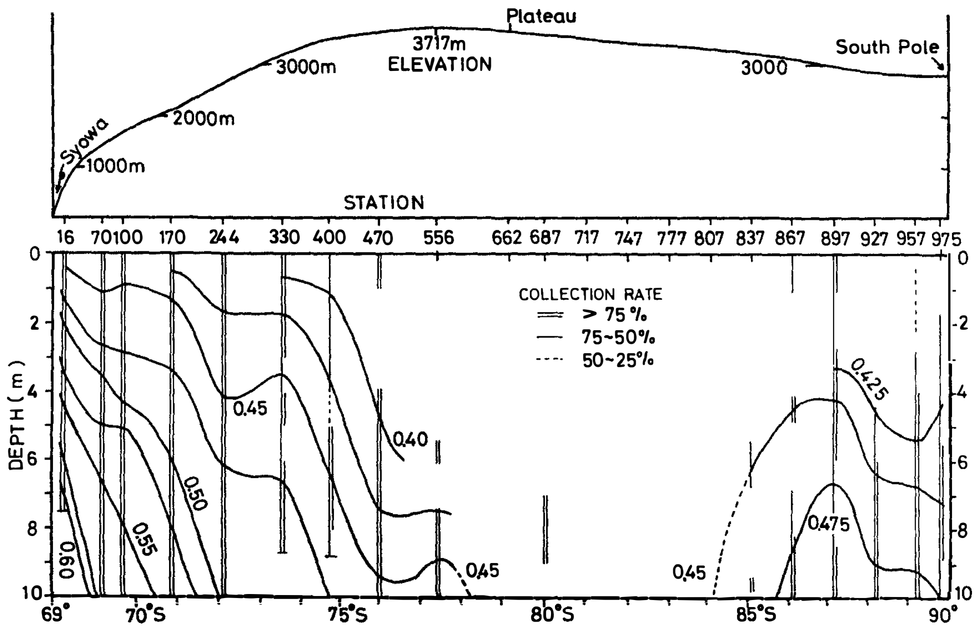

Fig. 8. Distribution of snow density in the upper 10 m of the ice sheet and the collection rate of core samples at each drilling site.

Thick curves are contours of the same density; the number on a contour line shows the snow density (g/cm³). Station numbers along the route indicate drilling sites. The collection rate of core samples at a drilling site is expressed by the ratio in percentage of the total length of snow cores picked up to the depth of a hole: A double thin line shows the degree above 75%; a single thin line 75–50%; a broken line 50–25%; a place with no mark below 25%.

drilling. Therefore, this difficulty may be an indication of the development of depth hoar as well as some of the mechanical properties of snow (for example, shearing strength).

The cores taken out in a good shape were used for measuring the snow density. Resultant density-depth curves at each drilling station are shown in Appendix 2.

Figure 8 shows the collection rate of core samples at each drilling site and the distribution of snow density in the upper 10 m of the snow cover on the route, which was obtained from the density-depth curves in Appendix 2. The collection rate is expressed by the ratio in percentage of the total length of snow cores picked up to the depth of a hole at this site. As shown in this figure, the snow cores were taken out in an almost perfect shape in the north of 73°S. However, in the region between 76°S and 86°S lying on the southwest slope of the East Antarctic Ice Ridge, snow cores were disintegrated during the drilling except the layers of hard and dense snow found at various depths. In the south of 86°S, the ratio becomes higher with depth.

Figure 8 also indicates that snow cores of more than 0.425 g/cm^3 in density are taken out at the higher ratio. Then, in a region between 78°S and 84°S where snow cores are hardly taken out, the snow density at a depth of 10 m might be less than 0.425 g/cm^3.

6.1. Change of regional profiles of snow density with depth

In Fig. 9 snow densities at different depths are plotted for each location on

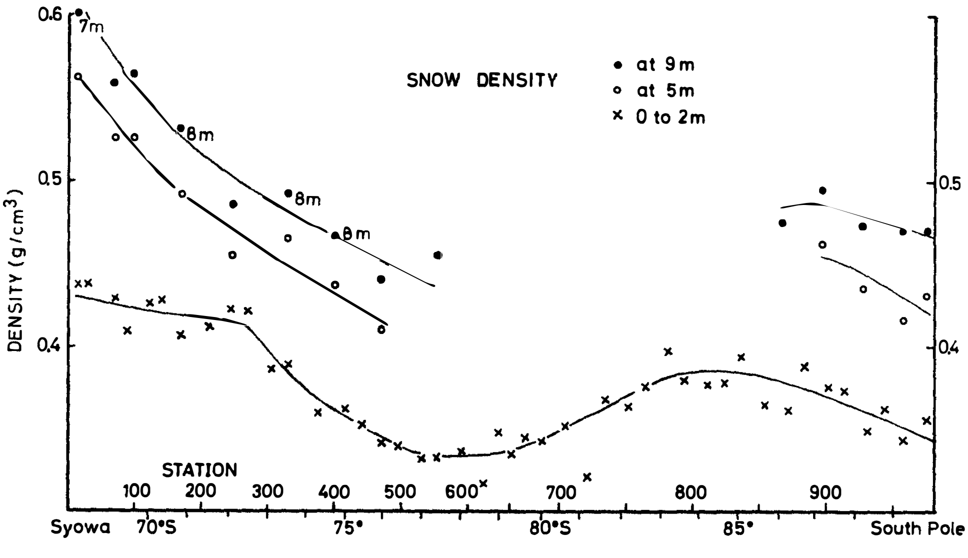

Fig. 9. Regional profiles of snow density at different depths.
Solid circles show snow densities at the 9 m depth; open circles at the 5 m depth; cross marks the average snow densities from the surface to the 2 m depth.

the route. The average snow densities from the surface to a depth of 2 m were obtained from pit studies, and snow densities at the 5 and 9 m depths were measured from snow cores.

Figure 9 shows that the regional profiles of snow density are clearly different between the surface snow and the snow at depths of 5 m and 9 m. A remarkable change is found in the coastal region between the coast and 73°S where the mean annual air temperature rises rapidly toward the coast: while the average snow density in the upper 2 m is about 0.42 g/cm^3 in this region, the snow densities at depths of 5 m and 9 m increase toward the coast. On the other hand, in a region between 85°S and the South Pole where the temperature remains around −50°C, the regional profiles of snow density at depths of 5 m and 9 m are parallel to the regional profile of surface snow density.

From the above mentioned facts, such a change in regional profiles of snow density with depth is considered to be due to the regional differences in the mean annual air temperature.

6.2. Relationships between the snow density at 5 and 9 m depths and the mean annual air temperature

Figure 10 shows relationships between the snow density at different depths

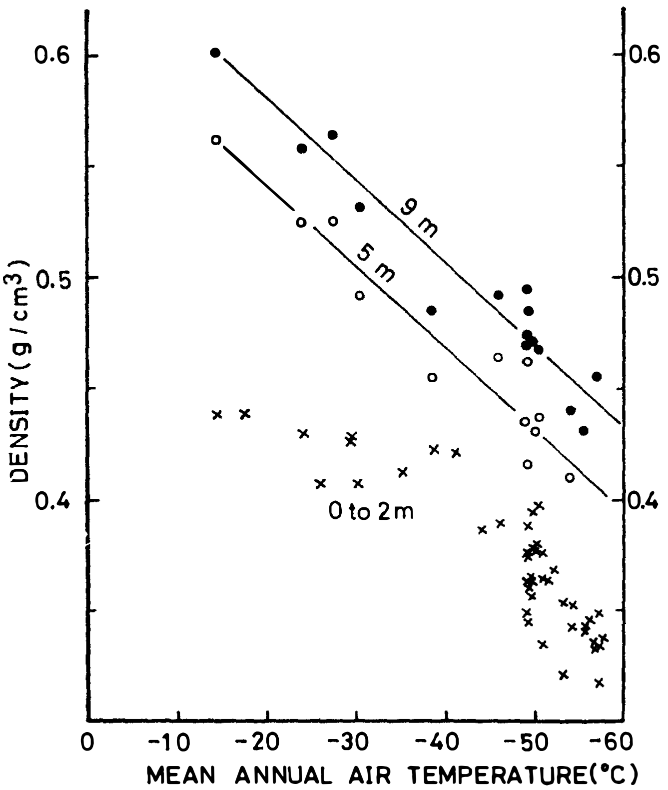

Fig. 10. Relationship between the snow densities at different depths and the mean annual air temperature.

and the mean annual air temperature.

This figure indicates that snow density at 5 and 9 m depths decreases at a rate of about 0.037 $g/cm^3/10°C$, as the temperature decreases.

7. Conclusions

The following conclusions were drawn from the glaciological studies of the snow cover from the surface to a depth of 10 m along the route of the JARE South Pole Traverse 1968–1969:

1) Conditions of snow at the surface of the ice sheet along the route are distinctly different from region to region. By the differences of conditions of snow at the surface, the ice sheet here can be divided into four regions. The conditions of surface snow in these regions are summarized in Table 1.

2) Conditions of surface snow have a close connection with the slope inclination.

3) Wind speed is the main meteorological factor controlling conditions of surface snow along the route. This was revealed by the relationship between the snow conditions and the slope inclination, and by the dependence of wind speed on the slope inclination.

4) Local variation of annual snow accumulations in a strong-wind region (in the north of 74.5°S) coincides with the local topography.

5) A boundary between cyclonic and anticyclonic precipitations seems to lie at 72–73°S (2600–3000 m above sea level, 350–450 km from the coast).

6) The type and grain size of snow constituting the upper 2 m of the ice sheet along the route are different between two regions divided at 73°S. The north of 73°S is characterized by compact fine-grained snow, and the south by coarse-grained, well-developed depth hoar.

7) The distribution of snow density in the upper 10 m of the ice sheet in East Antarctica along the route from Syowa to the South Pole is shown in Fig. 8.

8) Regional variations of snow density at the depths of 5 and 9 m are different from those at the surface due to the differences in the mean annual air temperature.

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APPENDIX I—Pit Diagrams

The following diagrams show the stratigraphy in pits dug during the JARE South Pole Traverse 1968–69.

Symbols for stratigraphy

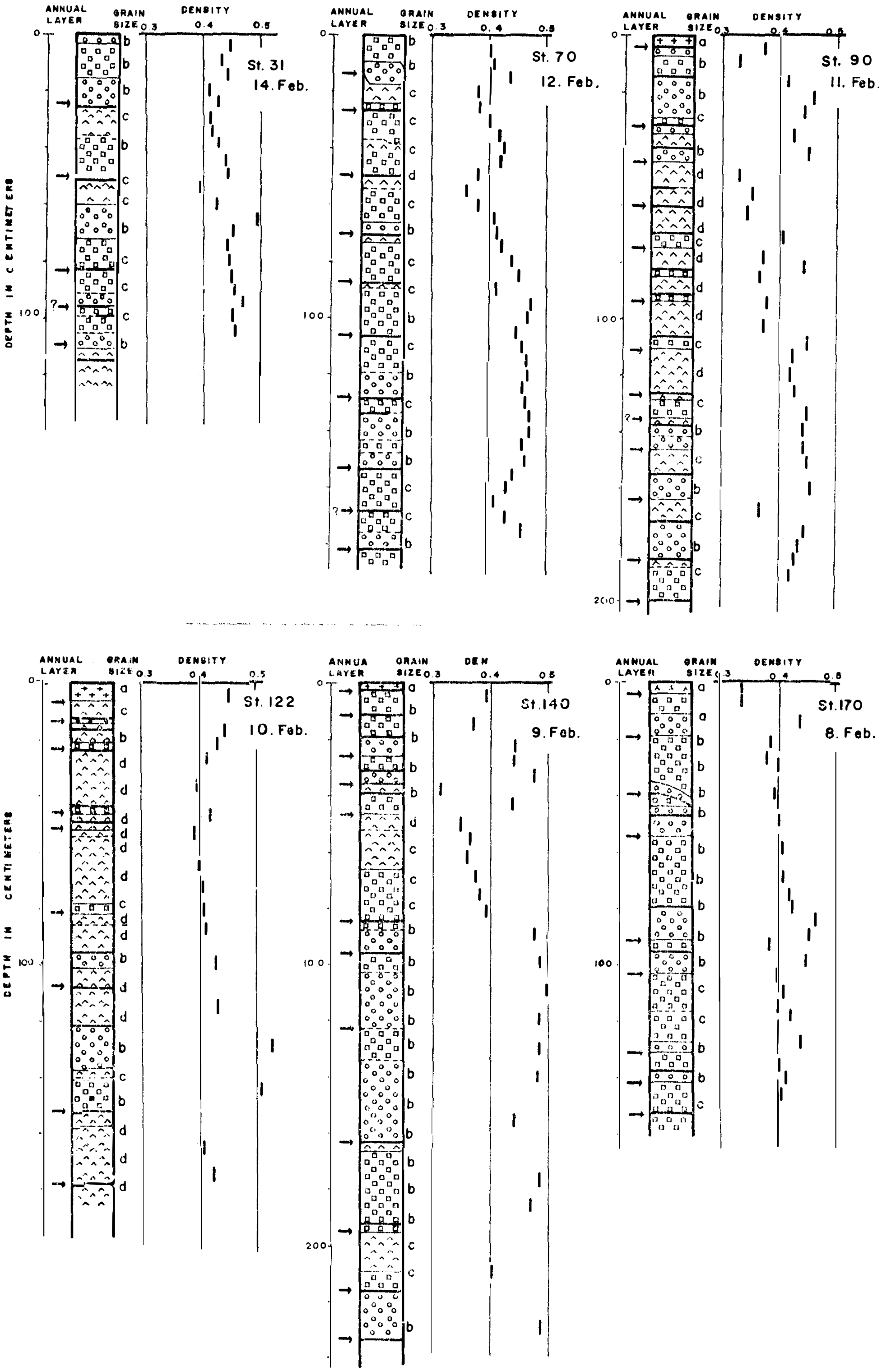
(++)	New snow
(∧∧)	Very fine-grained snow which has just been metamorphosed from new snow without melting
(○○)	Compact fine-grained snow
(□□)	Medium-grained depth hoar not developed well; mainly corresponds to a solid type of depth hoar
(Λ Λ)	Coarse-grained, well-developed depth hoar; mainly corresponds to a skeleton type of depth hoar
(—*i*)	Ice layer or ice lense formed by refreezing of melt water
(**——**)	Crust layer
(——)	Layer boundary
(------)	Obscure layer boundary

Boundary of annual snow layers

⟶	Likely
? →	Doubtful

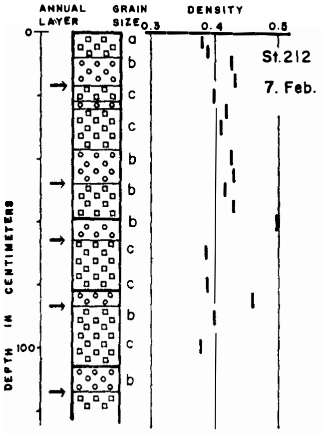
Symbols for grain sizes

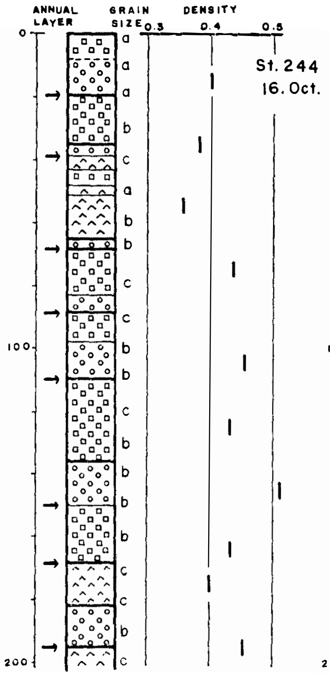
a	< 0.5 mm in diameter
b	0.5–1.0 mm
c	1.0–2.0 mm
d	2.0–3.0 mm
$\underline{\text{d}}$	> 3.0 mm

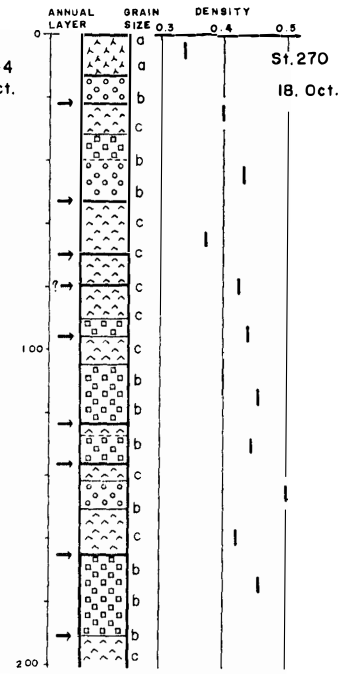


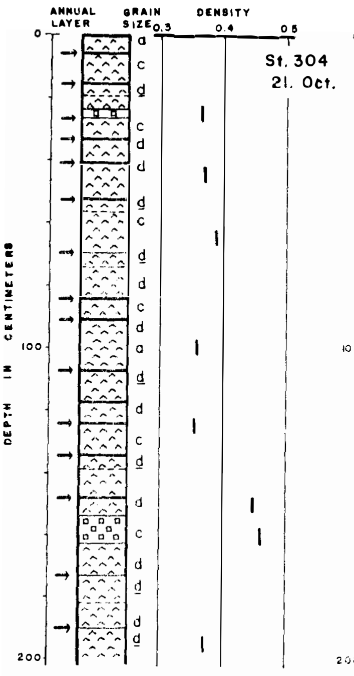
ANNUAL LAYER
GRAIN SIZE
DENSITY
0.3
0.4
0.5
DEPTH IN CENTIMETERS
100
200
St. 31
14. Feb.
St. 70
12. Feb.
St. 90
11. Feb.
St. 122
10. Feb.
St.140
9. Feb.
St.170
8. Feb.

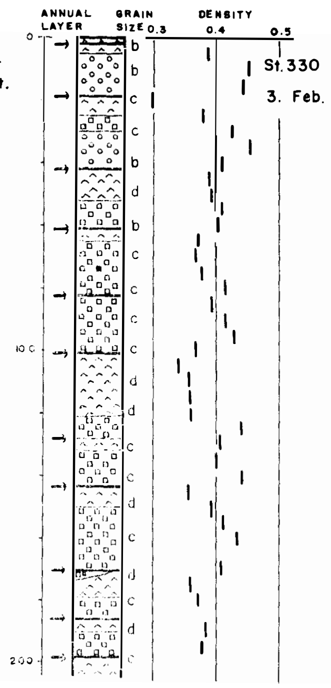
A–I–1

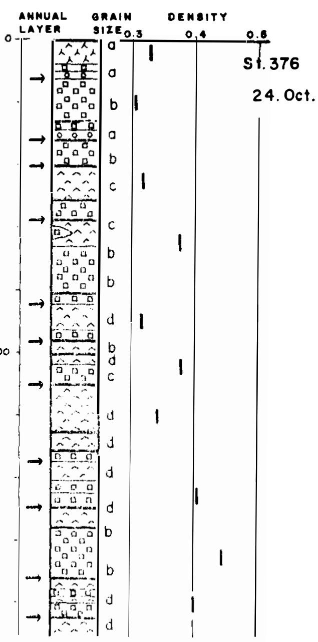

ANNUAL LAYER
GRAIN SIZE
DENSITY
0.3
0.4
0.5
St.212
7. Feb.
DEPTH IN CENTIMETERS
0
100

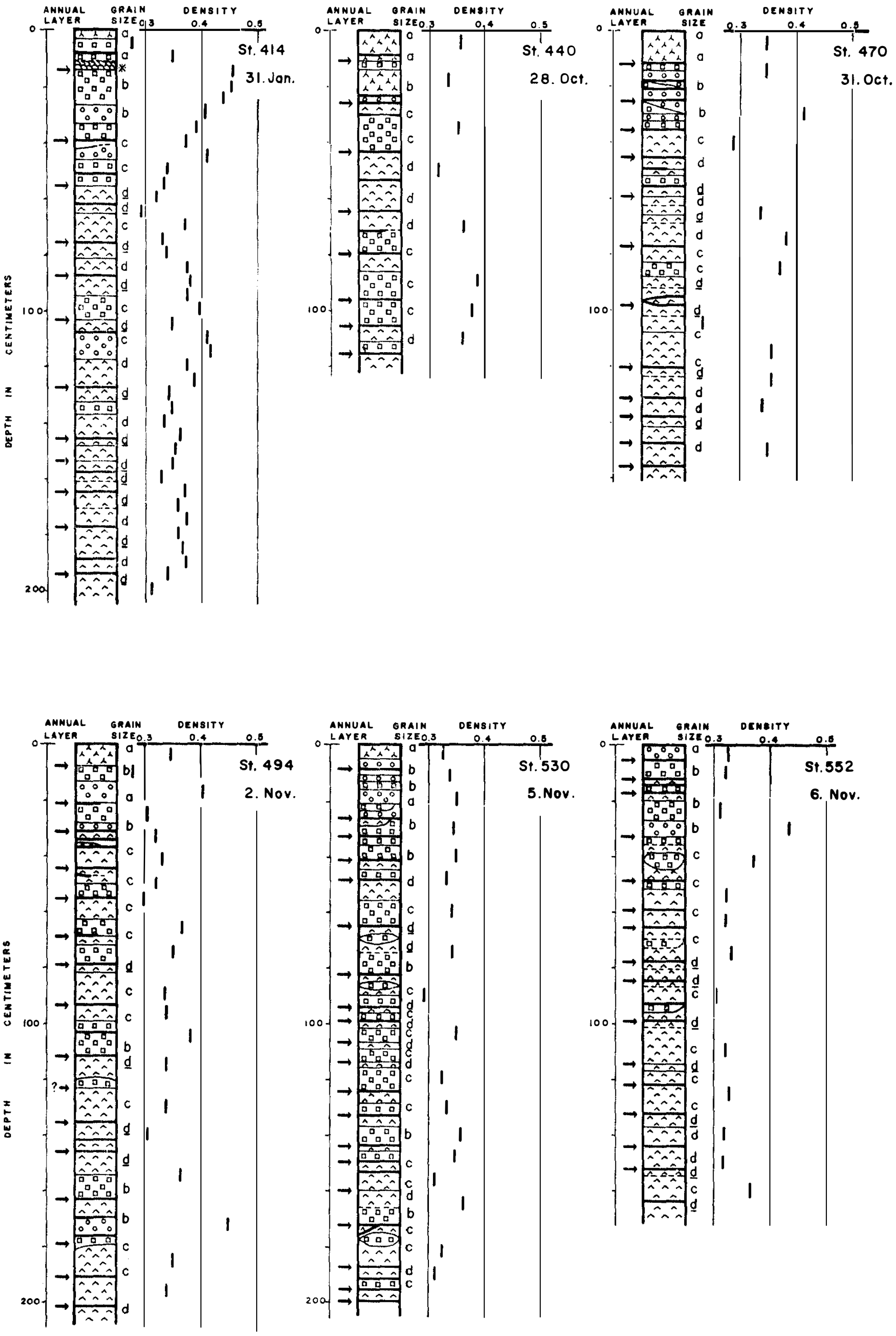

ANNUAL LAYER
GRAIN SIZE
DENSITY
0.3
0.4
0.5
St. 244
16. Oct.
0
100
200

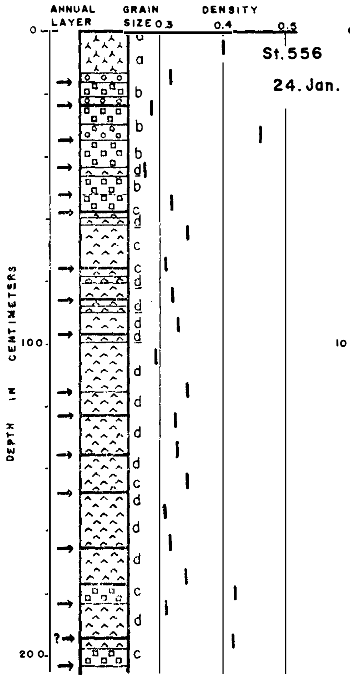

ANNUAL LAYER
GRAIN SIZE
DENSITY
0.3
0.4
0.5
St. 270
18. Oct.
0
100
200

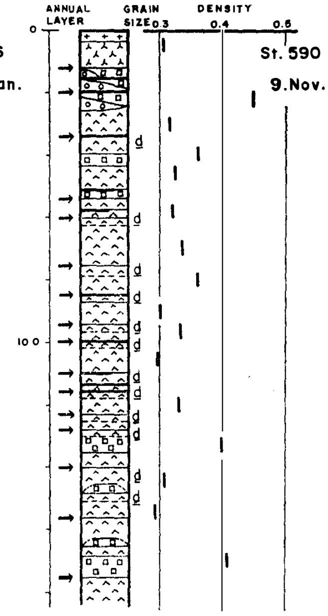

ANNUAL LAYER
GRAIN SIZE
DENSITY
0.3
0.4
0.5
St. 304
21. Oct.
DEPTH IN CENTIMETERS
0
100
200

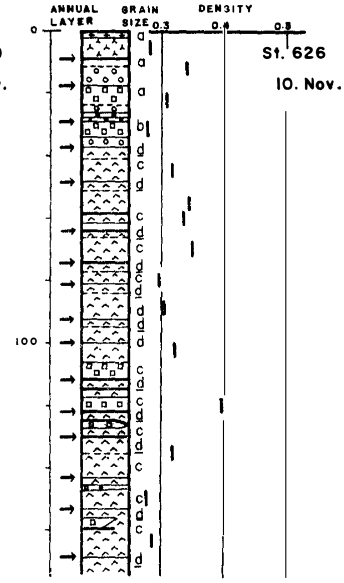

ANNUAL LAYER
GRAIN SIZE
DENSITY
0.3
0.4
0.5
St. 330
3. Feb.
0
100
200

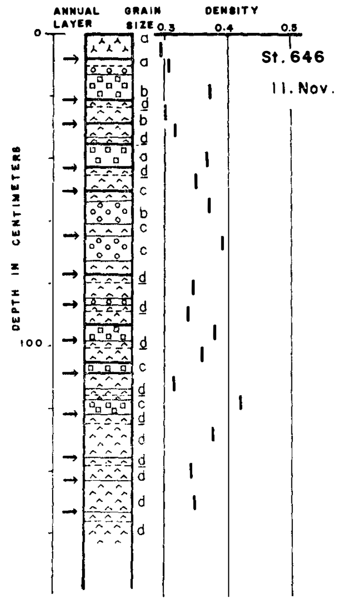

ANNUAL LAYER
GRAIN SIZE
DENSITY
0.3
0.4
0.5
St. 376
24. Oct.
0
100

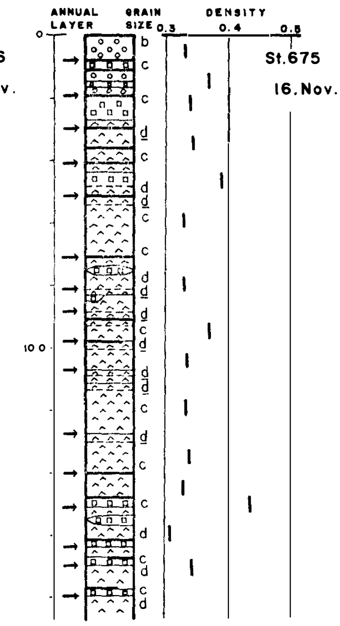

ANNUAL LAYER
GRAIN SIZE
DENSITY
0.3
0.4
0.5
DEPTH IN CENTIMETERS
St. 414
31. Jan.
St. 440
28. Oct.
St. 470
31. Oct.
St. 494
2. Nov.
St. 530
5. Nov.
St. 552
6. Nov.

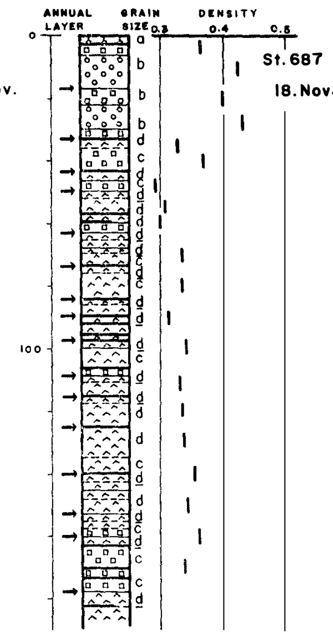

ANNUAL LAYER
GRAIN SIZE
DENSITY
0.3
0.4
0.5
St.556
24. Jan.
DEPTH IN CENTIMETERS
0
100
200

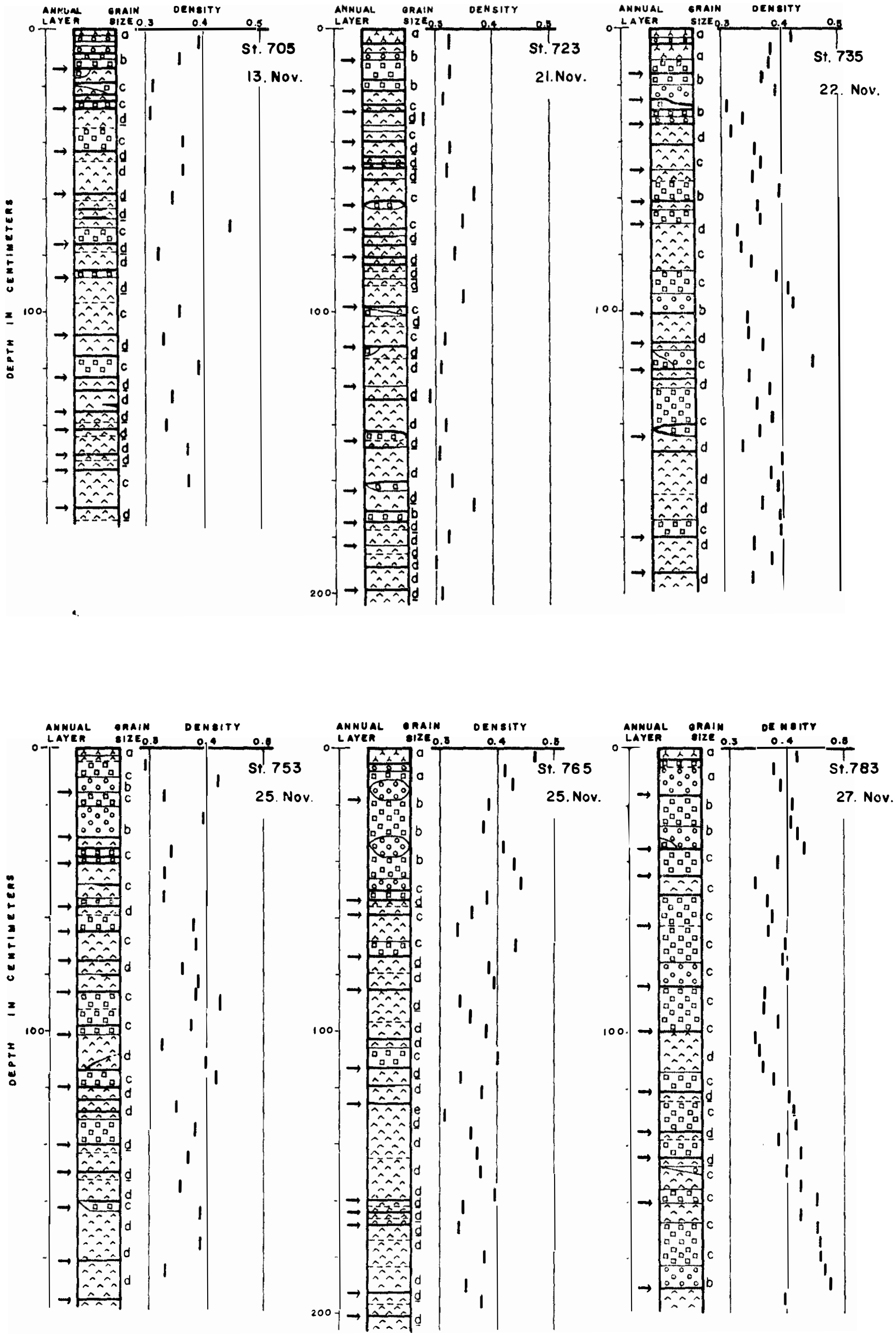

ANNUAL LAYER
GRAIN SIZE
DENSITY
0.3
0.4
0.5
St.590
9.Nov.
0
100


ANNUAL LAYER
GRAIN SIZE
DENSITY
0.3
0.4
0.5
St.626
10. Nov.
0
100

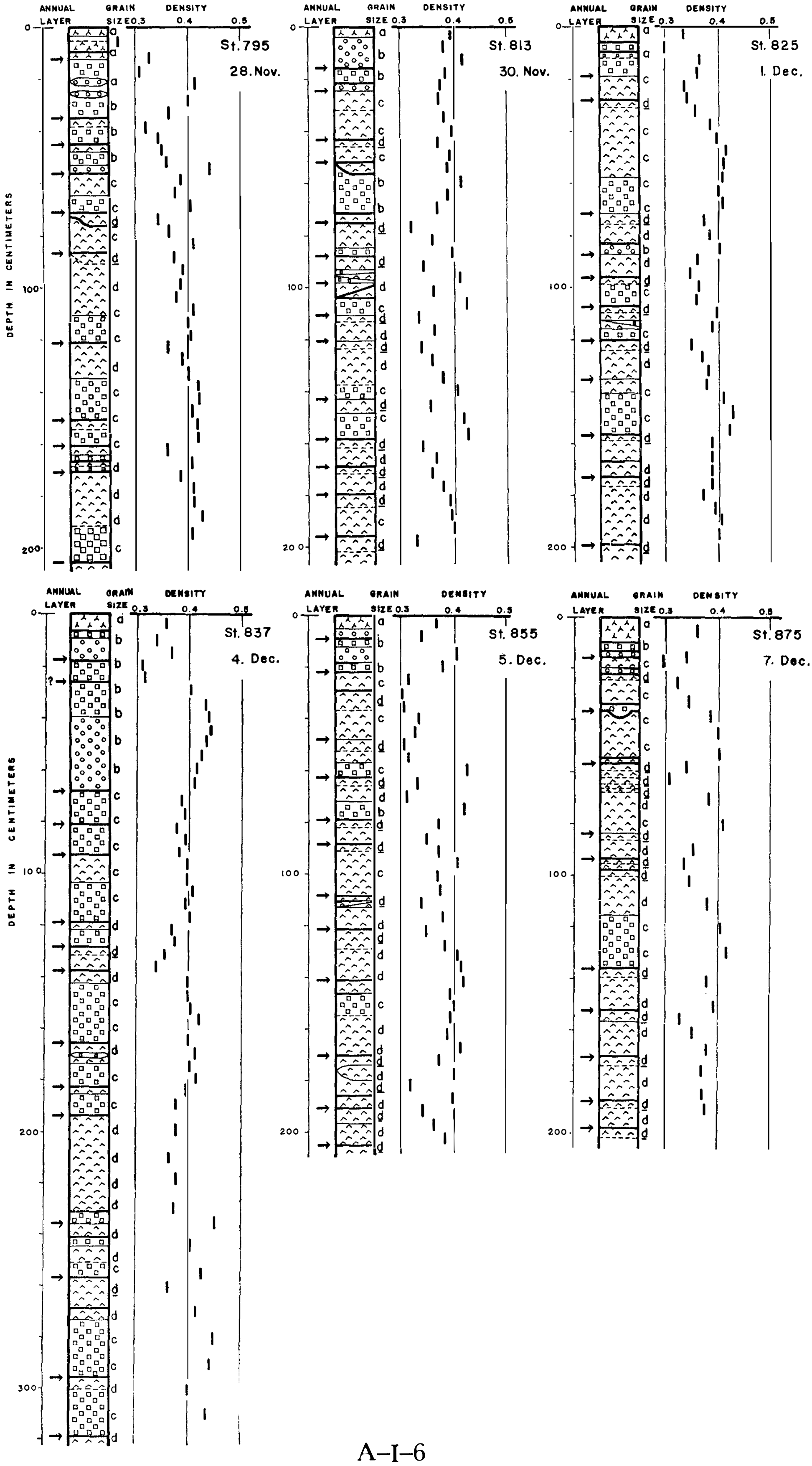

ANNUAL LAYER
GRAIN SIZE
DENSITY
0.3
0.4
0.5
St.646
11. Nov.
DEPTH IN CENTIMETERS
0
100

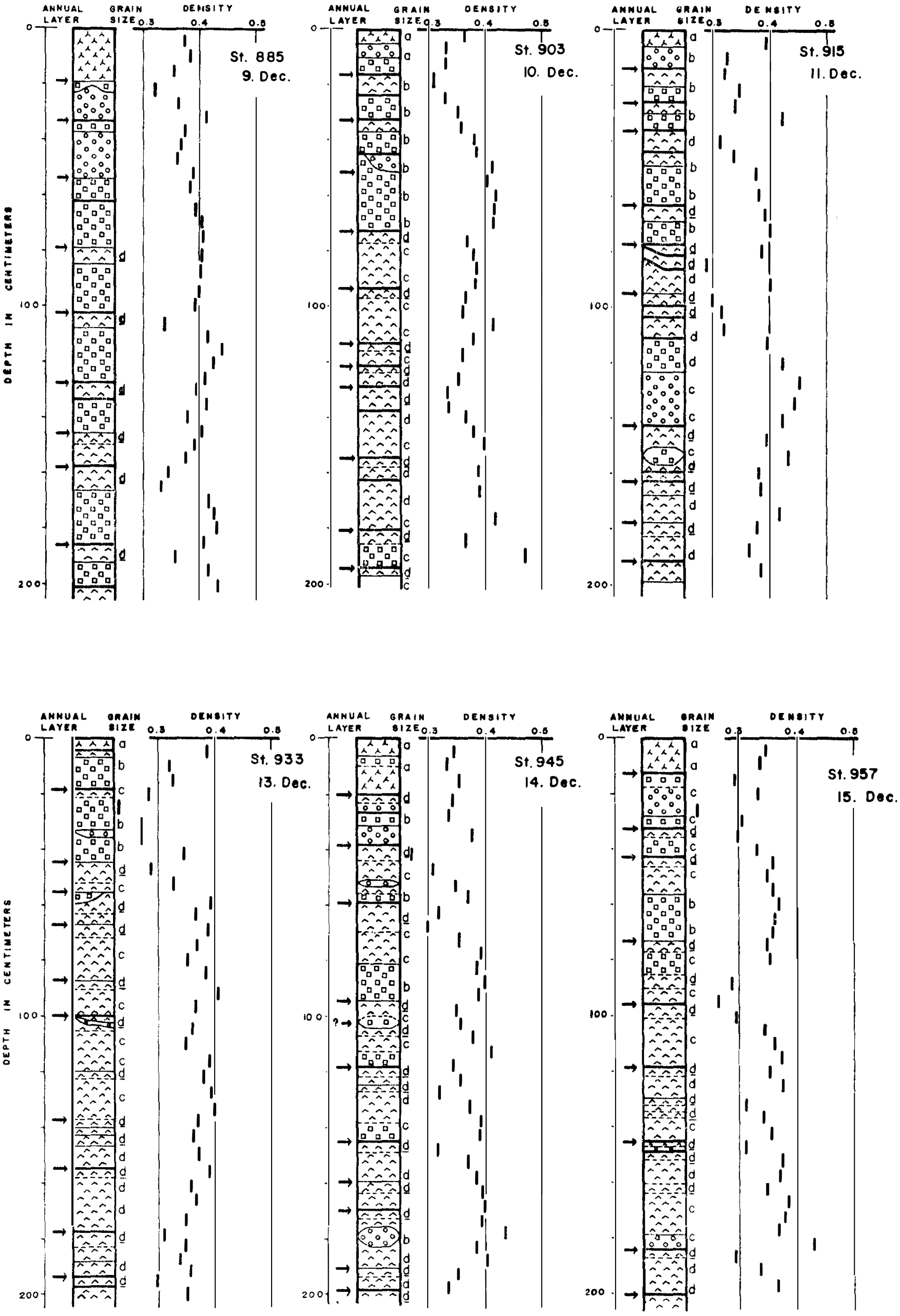

ANNUAL LAYER
GRAIN SIZE
DENSITY
0.3
0.4
0.5
St.675
16.Nov.
0
100

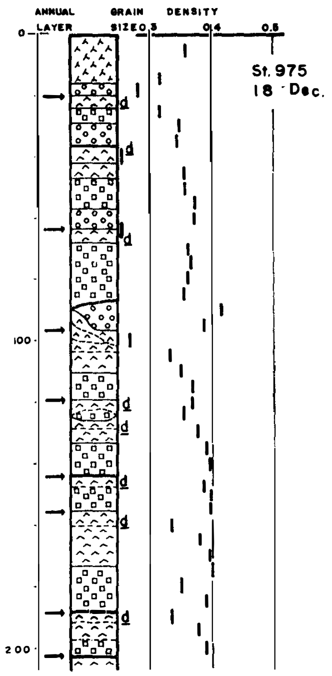

ANNUAL LAYER
GRAIN SIZE
DENSITY
0.3
0.4
0.5
St.687
18.Nov.
0
100


ANNUAL LAYER
GRAIN SIZE
DENSITY
0.3
0.4
0.5
DEPTH IN CENTIMETERS
0
100
200
St. 705
13. Nov.
St. 723
21. Nov.
St. 735
22. Nov.
St. 753
25. Nov.
St. 765
25. Nov.
St. 783
27. Nov.

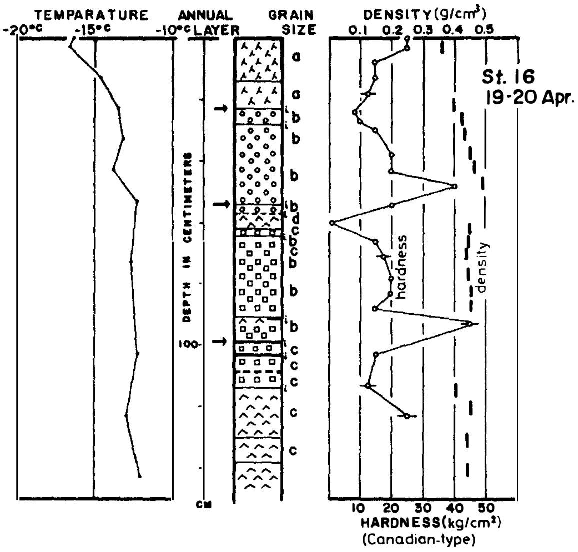
A–I–5


ANNUAL LAYER
GRAIN SIZE
DENSITY
DEPTH IN CENTIMETERS
St. 795 28. Nov.
St. 813 30. Nov.
St. 825 1. Dec.
St. 837 4. Dec.
St. 855 5. Dec.
St. 875 7. Dec.


ANNUAL LAYER
GRAIN SIZE
DENSITY
0.3
0.4
0.5
DEPTH IN CENTIMETERS
0
100
200
St. 885
9. Dec.
St. 903
10. Dec.
St. 915
11. Dec.
St. 933
13. Dec.
St. 945
14. Dec.
St. 957
15. Dec.



ANNUAL LAYER
GRAIN SIZE
DENSITY
0.3
0.4
0.5
0
100
200
St. 975
18 Dec.



TEMPARATURE
-20°C
-15°C
-10°C
ANNUAL LAYER
GRAIN SIZE
DEPTH IN CENTIMETERS
100
CM
DENSITY(g/cm³)
0.1
0.2
0.3
0.4
0.5
St. 16
19-20 Apr.
hardness
density
10
20
30
40
50
HARDNESS(kg/cm²)
(Canadian-type)

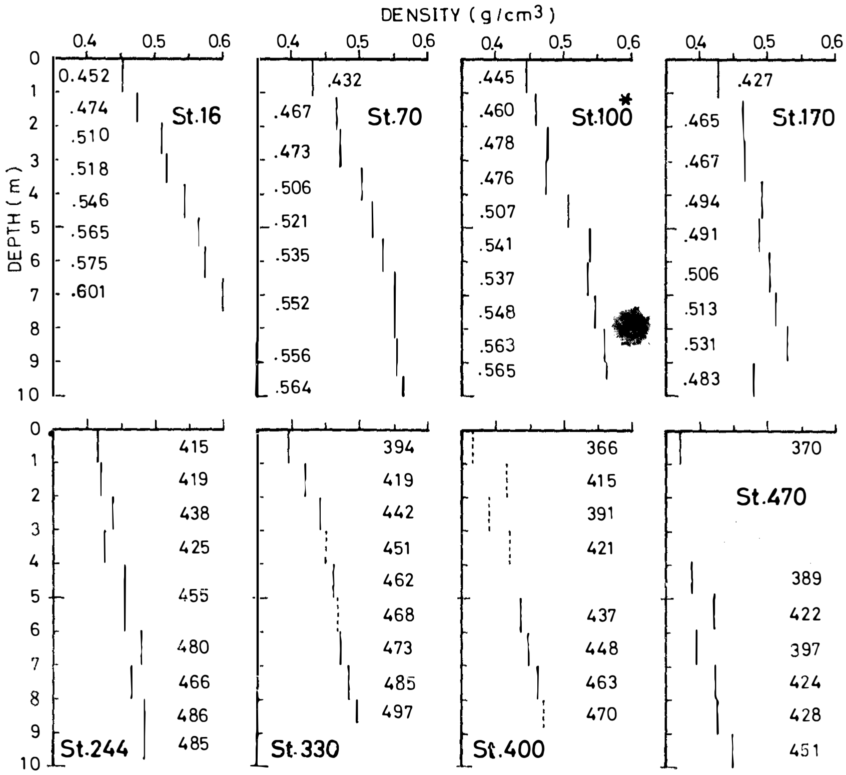
A–I–8

APPENDIX II—Density-Depth Curves from the Surface to a Depth of 10 m

Snow densities were measured using snow cores picked up in a good shape.

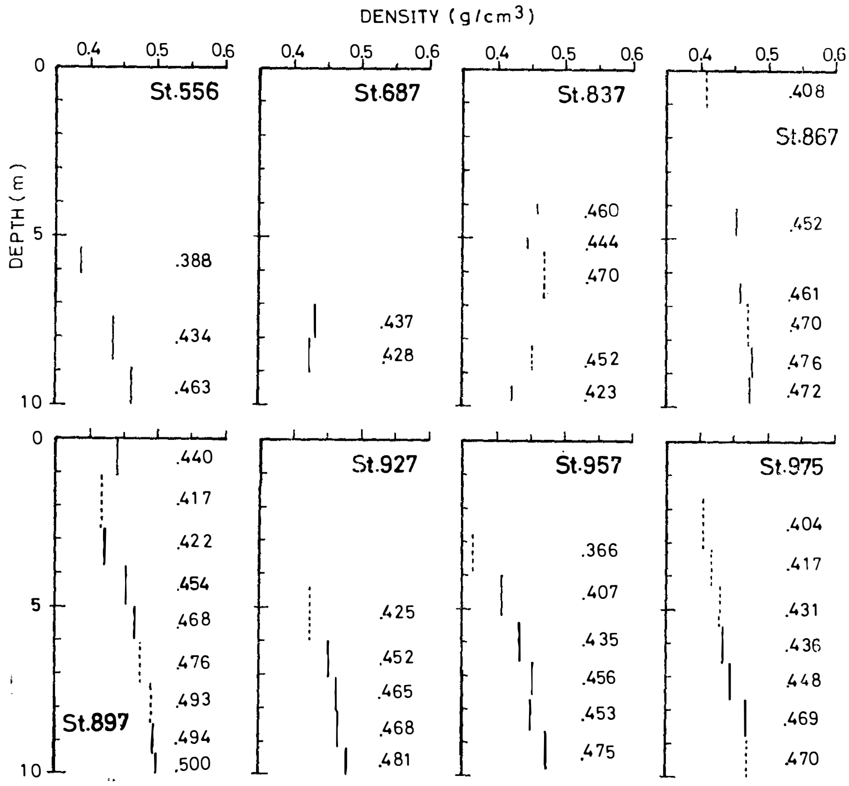
Collection rate of core samples is expressed by the ratio in percentage of the total length of snow cores piked up to the depth of a hole.

—— > 75%
------ 75–50%
< 50%



* after NARUSE *et al.* (1972)

A–II–1



A–II–2