TEMPERATURE PROFILE IN THE BARE ICE AREA NEAR THE YAMATO MOUNTAINS, ANTARCTICA

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***Abstract*:** The temperature profile of the ice sheet in the bare ice area (Meteorite Ice Field) near the Yamato Mountains (72°S, 36°E) was calculated on the basis of the heat conduction theory under the steady state condition. The effect of the geothermal heat flux, the vertical velocity of ice mass and the ice thickness on the temperature profile was examined. The analysis of the profile in the past stages of the ice sheet fluctuation showed that before the Fukushima ice stage (about 10^4 years B.P.) the upward velocity and the ablation rate were approximately zero or the downward motion of ice mass and accumulation might have occurred. This result is completely different from the present state (upward velocity 5 cm/year and ablation rate 5 cm/year), which suggests that most of the Yamato meteorites collected in 1969–1975 were exposed on the surface of the area after the Fukushima stage.

1. Introduction

In 1969, the field party of the Japanese Antarctic Research Expedition (JARE) discovered and collected 9 pieces of meteorite in a bare ice area around the Yamato Mountains (YOSHIDA *et al.*, 1971; KUSUNOKI, 1975). In 1973 and 1974, the JARE field party collected about 660 pieces of meteorite in the same area (SHIRAISHI *et al.*, 1976; YANAI, 1978). Then the party collected another 300 pieces of meteorite from the same area in 1975 (MATSUMOTO, 1978).

The bare ice areas occupy about 3250 km^2 including the ice-free rocky areas of about 50 km^2 in the region bounded by the square of about 125 km $\times$ 70 km. NAGATA (1978) investigated a mechanism of concentration of meteorites in such a limited area. He concluded that a large amount of meteorites falling over the Antarctic interior during a long time have been transported by the ice flow which resulted in a horizontal convergence near the Yamato Mountains and the upwell of ice motion in the bare ice area due to the bedrock topography. The transported pieces of meteorites have been concentrated on the surface of the area because of the ablation effect in the bare ice area.

As was indicated by the ice flow investigations in laboratories and in field, the flow velocity of ice depends sensitively upon the ice temperature (for example, PATERSON, 1969). Therefore, in order to develop Nagata's theory and to study the concentration of meteorites quantitatively, it is necessary to consider the thermal conditions of the ice sheet in the bare ice area.

ROBIN (1955) indicated that the vertical profile of ice temperature varied with not only air temperature, ice accumulation and ice velocity but also with ice thickness.

For the steady state condition of ice sheet, Robin's theory gives a reasonable account of the temperature profile. At present, the ice sheet in the bare ice area near the Yamato Mountains is in the equilibrium state (NARUSE, 1978).

Contradictorily, the ice sheet, which extends in the region of about 100 km to 250 km eastward from the Meteorite Ice Field in the Mizuho Plateau, is thinning by 70 cm/year (NARUSE, 1978).

Three stages of the ice sheet fluctuation were reported based on the geomorphological study of the Yamato Mountains (about 72°S, 36°E) (YOSHIDA, 1977).

Though we have no measurement of the profile of ice temperature and we could not compare our results of calculation of temperature profile with observed ones, it is necessary to calculate the ice temperature profiles in the past, as well as at present, with different thickness of ice sheet and to consider the thermal conditions of the ice sheet in the Meteorite Ice Field.

2. Calculation of Temperature Profile

2.1. Equation of heat conduction

The temperature profiles in the ice sheet have been calculated by several investigators (for example, BUDD, 1969) using heat conduction models on the assumption of a steady state. The temperature profiles calculated using such a steady state condition are approximately consistent with the temperature profiles measured in deep boreholes drilled through the ice sheet at Camp Century in Greenland and at Byrd Station in the Antarctic (for example WEERTMAN, 1968; RADOK *et al.*, 1970). For example, the base temperature observed at Camp Century is only about 3°C higher than the calculated temperature (PHILBERTH and FEDERER, 1971). Therefore, as an approximate calculation of the ice temperature profiles in the bare ice area near the Yamato Mountains, it is reasonable to use such a steady state condition of heat conduction.

For the steady state condition, it is assumed that the surface and the bottom of the ice sheet are approximately parallel and flat, and the flow lines are parallel, and x is the horizontal coordinate in the direction of flow, z is the height above the bedrock, u and w are corresponding velocities, the temperature T at any fixed point within the ice sheet is given by

$$\kappa\frac{\partial^2 T}{\partial z^2}-u\frac{\partial T}{\partial x}-w\frac{\partial T}{\partial z}+Q_Z=0 \qquad (1)$$

where κ is the thermal diffusivity of the ice, and Q_Z is the heat caused by internal friction at height z.

In order to solve eq. (1), it is necessary to introduce more simplifications and approximations as follows.

1) For the steady state condition the vertical velocity at the top of the column (w_s) is the same as the mean rate of accumulation of ice ($\dot{b}$) and also the vertical strain rate is constant throughout the column, *i.e.*

$$\dot{\varepsilon}=\frac{\partial w}{\partial z}=-\frac{\dot{b}}{h} \tag{2}$$

where h is the ice thickness, $\dot{b}$ the accumulation rate (+) or ablation rate (−) and $w_s=\dot{b}$ at the surface of the ice sheet.

2) Let the surface temperature vary along the surface at a constant rate, that is to say $\partial T_s/\partial x=\alpha\lambda$, where T_s is the surface temperature, α the surface slope and $\lambda=\partial T_s/\partial z$. Under these conditions we may expect the advection rate to be constant throughout the column, namely

$$u\frac{\partial T_s}{\partial x}=u\alpha\lambda. \tag{3}$$

3) We modify the heat of friction Q_z as being distributed throughout the medium according to the values of stress and strain rate at all depths to the additional heating of the friction concentrated at the base, namely, we consider a sliding slab of ice with velocity u.

Hence, with the above-mentioned approximations and modifications, our equations under steady state conditions now become

$$\kappa\frac{\partial^2 T}{\partial z^2}+\frac{\dot{b}}{h}z\frac{\partial T}{\partial z}=u\alpha\lambda \tag{4}$$

with the boundary conditions

$$z=h,\ T=T_s;\ z=0,\ \frac{\partial T}{\partial z}=\gamma_G+\frac{\tau_b u}{JK} \tag{5}$$

where γ_G is the geothermal heat flux, J the mechanical equivalent for heat, K the ice conductivity and τ_b the basal shear stress.

2.2. *Flow and fluctuations of ice sheet in the bare ice area*

In order to check the validity of eq. (4) in the calculation of the temperature profiles in the bare ice area around the Yamato Mountains and the ice sheet in the Mizuho Plateau, and to consider the reliability of the results of the calculation, the features of ice flow and the fluctuation of the ice sheet are summarized as follows.

2.2.1. Ice flow

As seen in Figs. 1 and 2 the ice flow velocity is of small values, less than 2 m/year, and the ice flow direction is northwestward in the vicinity of the Yamato Mountains (NARUSE, 1975). The bedrock surface is not horizontally flat but complicated. The small velocity of ice flow is due to the effect of sub-ice mountains and nunataks existing in the downstream area of bare ice as illustrated in Fig. 1 and also these sub-ice mountains and nunataks give rise to an upward velocity of the ice sheet flow. As seen in Fig. 2, the upward velocity in the Meteorite Ice Field near the Yamato Mountains was observed by the triangulation survey and was in the range from 2 to 8 cm/year (NARUSE, 1975). On the other hand, the annual rate of the ablation in the bare ice area amounts to 2–7 cm by the measurements of snow stakes (YOKOYAMA, 1975), which is approximately equal to the annual upward velocity. Thus the bare ice area in the vicinity of the Yamato Mountains is in equilibrium at the present time.

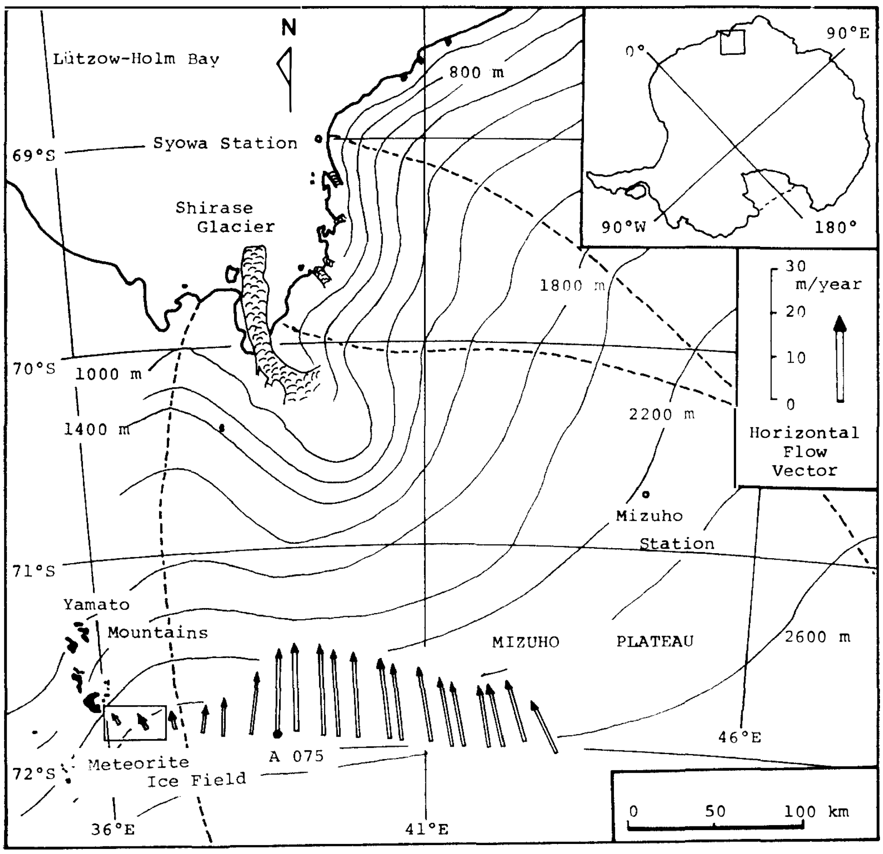

Fig. 1. Location of the bare ice area around the Yamato Mountains (Meteorite Ice Field) and the Mizuho Plateau.

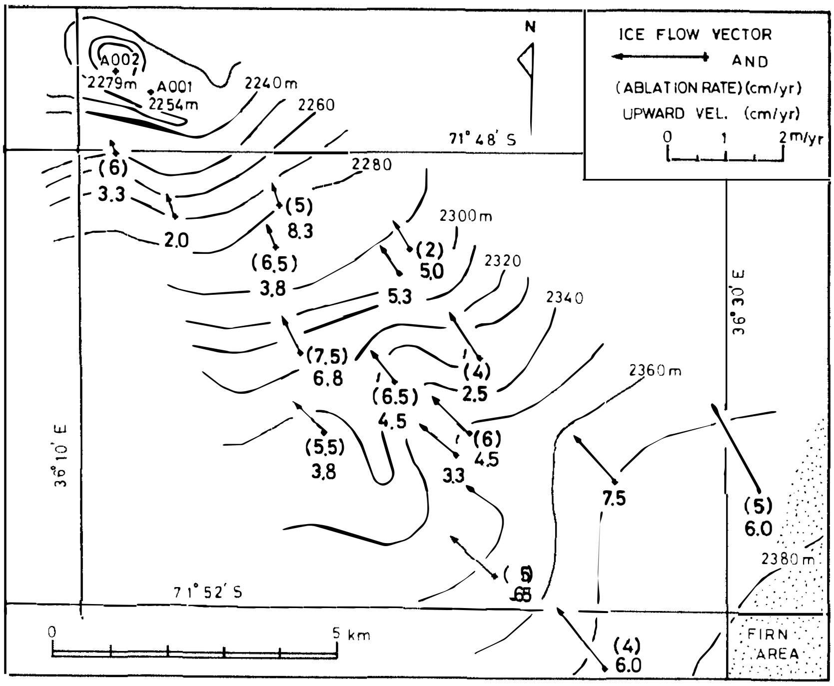

Fig. 2. Surface ice flow vectors, ablation rate and upward vectors in the Meteorite Ice Field near the Yamato Mountains (After NARUSE, *1975).*

2.2.2. Fluctuation of the ice sheet

The three stages of the ice sheet fluctuation, namely, the Yamato stage of about 5×10^6 years B.P. (about 700 m higher than the present ice surface level), the Fukushima stage of 10^4 years B.P. (about 400 m higher than the present ice surface level), and the present Meteorite Glacial Stage named by YOSHIDA are reported based on the geomorphological study in the Yamato Mountains (YOSHIDA and MAE, 1978). Though there is no direct evidence, it was proposed by YOSHIDA and MAE (1978) that the ages of the Yamato and Fukushima stages in the Antarctic glacial history are 5×10^6 years B.P. and 10^4 years B.P., respectively. For the calculation of ice temperature, it is necessary to know how long such equilibrium states and non-equilibrium states of the ice sheet are maintained.

The ice sheet in the Mizuho Plateau which is apart about 100 km to 250 km eastward from the bare ice area is thinning at the present time. The triangulation surveys have shown the observed rate of change of the ice thickness by excluding the effect of the firn densification amounts to 70 cm/year (NARUSE, 1978). MAE (1977), and MAE and NARUSE (1978) considered that the thinning is caused by the basal sliding due to the rise of ice temperature at the base to the melting point and the thinning might have occurred within 10^3 years. On the other hand, the thinning of ice sheet in the bare ice area during a period between the stable stages is not caused by the basal sliding but by the decrease of ice accumulation due to the climatic change and the thinning rate may be very small compared with that of the ice sheet in the Mizuho Plateau. If we assume that a period of thinning between the Fukushima stage and the present stage is 10^4 years, the thinning rate is about 4 cm/year. During a period between the Fukushima and Yamato stages the thinning rate is about 1×10^{-2} cm/year. This leads to the conclusion that the ice sheet in the bare ice area has been approximately in the equilibrium state since the Yamato stage.

2.3. *Results of calculation*

The change of ice temperature can propagate throughout the ice in 10^4 years in the bare ice area so that even during a period between the Fukushima and the present stages the temperature profile can be calculated approximately using eqs. (4) and (5).

The measurements of the surface temperature, T_s, of the bare ice area was not made, but the temperature can be estimated to be -30°C using the relationship between the 10 m firn temperature and the surface elevation in the Mizuho Plateau (SATOW, 1978).

The annual rate of the ablation ranges from 2 to 7 cm/year, averaging 5.4 cm/year. The ice flow velocity is less than 2 m/year and the effect of flow on the temperature profile is so little as to be neglected.

In the previous section we assumed that the flow lines are parallel and the heat generation is concentrated at the base. These assumptions are different from the real state of ice flow in the bare ice area, but a negligibly small effect of ice flow on the temperature profile means that the difference does not influence the

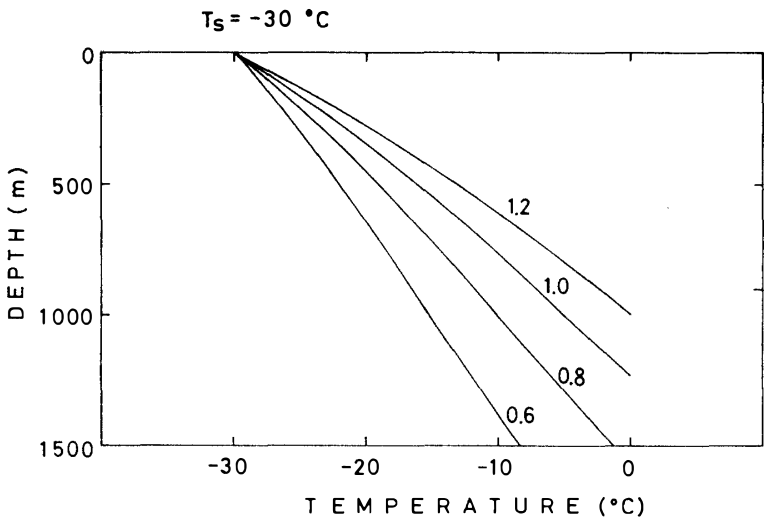

Fig. 3. Steady state temperature profiles in the Meteorite Ice Field for different values of geothermal heat flux (unit: μcal·cm^{-2}·s^{-1}). The ice thickness is 1500 m, the ablation rate 5 cm/year, the ice flow velocity 2 m/year and the surface temperature -30°C.

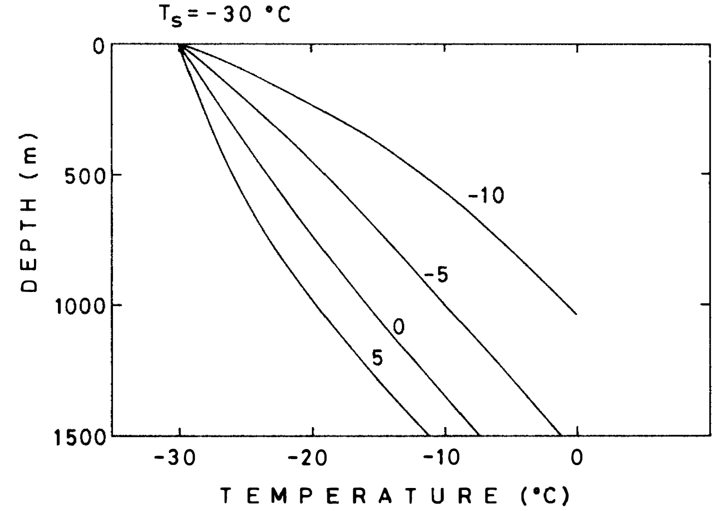

Fig. 4. Steady state temperature profiles in the Meteorite Ice Field for different ablation rate (—) and accumulation rate (+) (unit: cm/year). The geothermal heat flux is 0.8 μcal·cm^{-2}·s^{-1}, the ice flow velocity 2 m/year and the surface temperature −30°C.

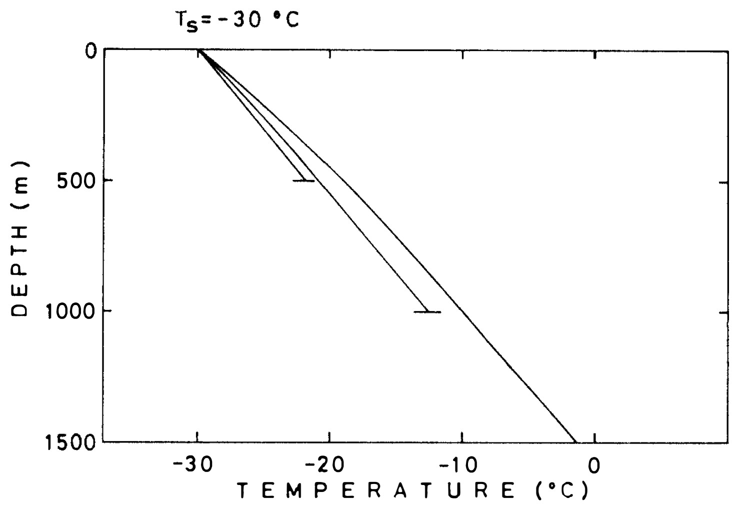

Fig. 5. Steady state temperature profiles in the Meteorite Ice Field for different ice thicknesses. The geothermal heat flux is 0.8 μcal·cm^{-2}·s^{-1}, the ablation rate 5 cm/year, the ice flow velocity 2 m/year and the surface temperature −30°C.

results of calculation on the temperature profile.

Substituting the values of various parameters of eqs. (4) and (5), we obtain the temperature profiles as shown in Figs. 3, 4 and 5. Figs. 3, 4 and 5 show the effect of the geothermal heat flux, vertical velocity of ice mass and ice thickness on the temperature profile, respectively. It is seen from these figures that the upward motion of ice mass produces a large positive temperature gradient at the upper part of the ice sheet.

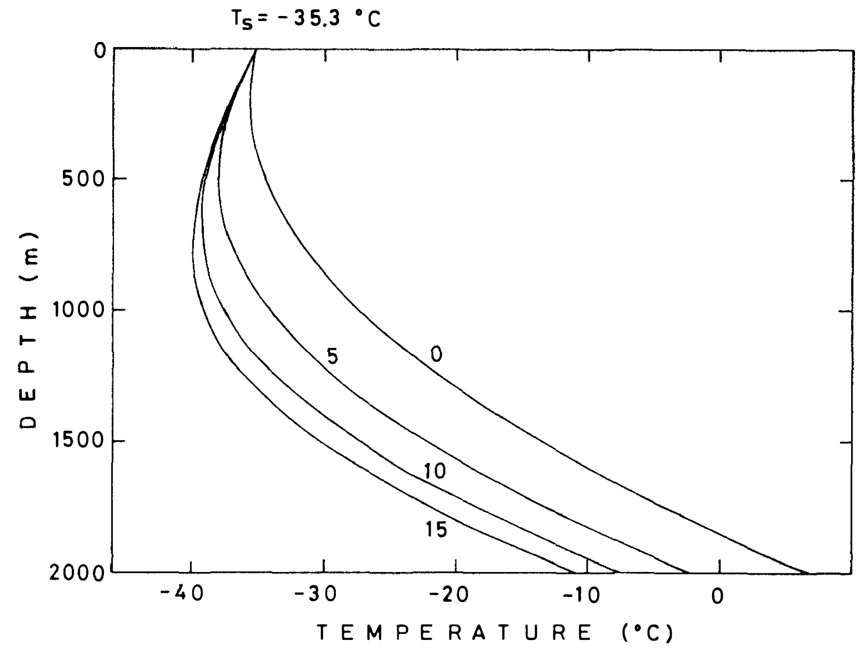

Fig. 6. Steady state temperature profiles in the accumulation area at A075 (71°55.3′S, 39°25.8′E) in the Mizuho Plateau for a different accumulation rate (unit: cm/year). The geothermal heat flux is 1.0 μcal·cm^{-2}·s^{-1}, the ice flow velocity 20 m/year and the surface temperature −35.3°C.

As shown in Fig. 3, the temperature profile depends upon the geothermal heat flux, γ_G. Since the base of the ice sheet in the bare ice area is frozen (MAE, 1977; MAE and NARUSE, 1978), the expected temperature profile is that γ_G is equal to or less than 0.8 μcal·cm^{-2}·s^{-1}.

On the other hand, the base of the Mizuho Plateau is wet (MAE, 1977; MAE and NARUSE, 1978) so that it is clear from Fig. 6 that γ_G is nearly equal to 1.0 μcal·cm^{-2}·s^{-1} because the accumulation rate is about 5 cm/year. Though BUDD *et al.* (1971) took the value of 1.2 μcal·cm^{-2}·s^{-1} for East Antarctica, LEE (1970) summarized the values of measured geothermal heat flux, and their mean value in the Precambrian shield area is 1.0 μcal·cm^{-2}·s^{-1} (East Antarctica is a typical Precambrian shield). Therefore, we can conclude that 1.0 μcal·cm^{-2}·s^{-1} is a true value of γ_G in the bare ice area.

The calculation of the temperature profile in the bare ice area is based on the assumption that the bed surface is horizontally flat and therefore it is likely that the discrepancy between calculated and true values of γ_G might be caused by the inclination (about 1/10) of the bed surface. Though the true value of γ_G is 1.0 μcal·cm^{-2}·s^{-1}, for the present calculation of temperature profile, γ_G of 0.8 μcal·cm^{-2}·s^{-1} may be reasonable because the base in the Mizuho Plateau is wet so that the base temperature in the bare ice area is not much below the pressure melting point.

Fig. 4 shows the effect of various ablation rate (—) and accumulation rate (+) on the temperature profile. From eq. (4) on the basis of the steady state condition, the ablation rate corresponds to the upward velocity of ice mass. The large upward velocity tends to increase the positive temperature gradient at the upper part of the ice sheet and the temperature difference between the surface and the base of the ice sheet. Since the average annual rate of ablation in the bare ice area is 5.4 cm/year, the expected temperature profile is the value of ablation of −5 cm/year.

Fig. 5 gives the effect of varying the ice thickness. For thin ice thickness, the temperature difference between the surface and the base of the ice sheet is small. Hence, as the ice thickness is less than 1500 m, the base of the ice sheet in the bare ice area is frozen.

In order to make clear the characteristic features of the temperature profile in the bare ice area, it is necessary to compare with the temperature profile in the accumulation area at A075 (71°55.3′S, 39°25.8′E), about 100 km east of the Meteorite Ice Field in the Mizuho Plateau. Unfortunately, the temperature profile was not measured, but the basic values of the parameters except the geothermal heat flux in eqs. (4) and (5) were observed at A075 (Naruse, 1978). Then, we can calculate the temperature profile using the basic values, such as the ice thickness 2000 m, the surface temperature −35.3°C, the horizontal velocity of ice flow 20 m/year, the accumulation rate between 5 and 10 cm/year, and the geothermal heat flux assumed to be 1.0 $\mu cal \cdot cm^{-2} \cdot s^{-1}$. The analysis of the ice temperature in the bore hole down to about 150 m at Mizuho Station (70°41.9′S, 44°19.9′E) indicates that the thinning in the Mizuho Plateau occurred about $2\text{–}3 \times 10^2$ years ago. Since the propagation time of the temperature change throughout the ice mass is about $10^4\text{–}10^5$ years in the Mizuho Plateau, the thinning effect on the calculation of ice temperature is so small that it is reasonable to use eqs. (4) and (5) for the calculation in the Mizuho Plateau.

The result of the calculation of temperature profile is shown in Fig. 6. The profile is completely different from that in the bare ice area shown in Figs. 3, 4 and 5. The difference is caused by the downward motion of ice mass in the Mizuho Plateau which is a common phenomenon in the accumulation area. And also the temperature profile in the accumulation area shows a negative temperature gradient extending to depths of several hundred meters. This negative gradient results from the horizontal advection term $u\alpha\lambda$ in eq. (4). Since the base of the ice sheet in the Mizuho Plateau is wet, the reasonable profile is expected to be the accumulation rate of 5 cm/year.

Now we concern our examination with the past temperature profiles in the bare ice area where the ice thickness at the present time is about 1500 m.

As shown in Fig. 7, the temperature profile at the Fukushima stage is

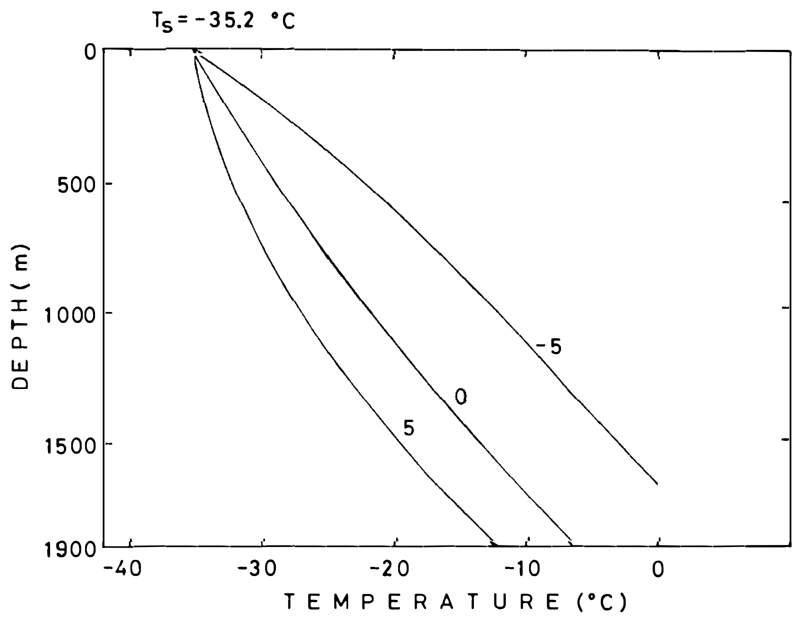

Fig. 7. Temperature profiles at the Fukushima stage on the basis of the steady state in the Meteorite Ice Field for different ablation rate (—) and accumulation rate (+) (unit: cm/year). The geothermal heat flux is 0.8 μcal·cm^{-2}·s^{-1}, the ice flow velocity 2 m/year and the surface temperature −35.2°C. The ice thickness of 1900 m is expected at the Fukushima stage of 10^4 years B.P.

calculated for γ_G=0.8 μcal·cm^{-2}·s^{-1} and the surface temperature of −35.2°C using the relationship of 1.3°C/100 m between the 10 m firn temperature and the surface elevation in the Mizuho Plateau (SATOW, 1978). At the stage the base was frozen just as at the present time because even the base at the Mizuho Plateau became wet within 10^3 years in the past (MAE, 1977; MAE and NARUSE, 1978). Therefore, it is considered from Fig. 7 that at the Fukushima stage the upward velocity of ice mass may be approximately zero or the downward motion may occur. Since at the Fukushima stage the ice sheet was in equilibrium, it leads to the conclusion that the ablation rate was approximately zero or even the accumulation took place.

As shown in Fig. 8 which represents the temperature profile in the present bare ice area at the Yamato stage, we can conclude that the upward motion at the Yamato stage is zero or the downward motion may occur as well as at the Fukushima stage. This situation is the same as during a period between the Fukushima and Yamato stages because the thinning rate is very slight.

Therefore, it is considered that before the Fukushima stage, the upward motion of ice mass was zero or the downward motion might have occurred, and during a period between the Fukushima and the present stages, the upward velocity increased with the thinning of the ice sheet, reaching the present value.

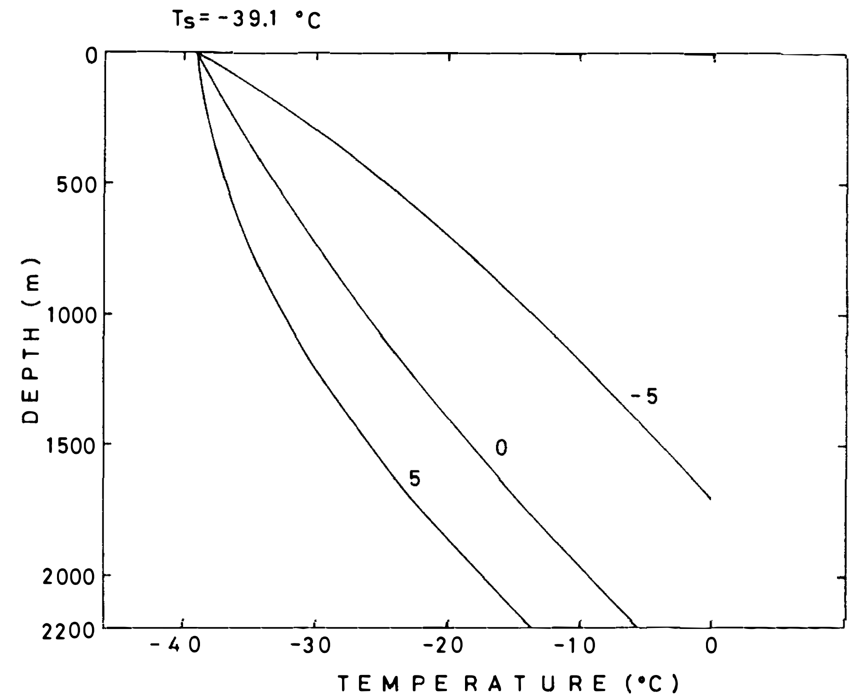

Fig. 8. Temperature profiles at the Yamato stage on the basis of the steady state in the Meteorite Ice Field for different ablation rate (—) and accumulation rate (+) (unit: cm/year). The geothermal heat flux is 0.8 $\mu cal \cdot cm^{-2} \cdot s^{-1}$, the ice flow velocity 2 m/year and the surface temperature —39.1°C. The ice thickness of 2200 m is expected at the Yamato stage of 5×10^6 years B.P.

3. Discussion on the Exposure of Yamato Meteorites

In order to examine the results of the calculation shown in the previous section, the measurement of profile of ice temperature should be carried out over a wide area, especially along the flow line. The present temperature profile computation, though incomplete, suggests that the upward velocity of ice mass and the ablation rate were approximately zero or the vertical motion of ice mass preferred the downward to the upward and therefore accumulation might have occurred in the present bare ice area before the Fukushima stage of the ice sheet fluctuation. If this is true, most of the meteorites collected in the bare ice area might be exposed after the Fukushima stage. The precise ages of the Yamato and Fukushima stages are not known yet and the determination of them is one of the most important problems to be solved in future for determining the age of exposure of meteorite on the ice surface.

During a period between the Yamato stage and the present, the thickness of the ice decreased. In such a case, the steady state approximation is not adequate for the precise calculation of ice temperature. In the case of an unsteady state, the calculation is complicated because the temperature profile may be influenced by the ice flow, especially the vertical motion of ice mass, and because as the thickness of the ice sheet decreases, the effect of bedrock topography on the ice flow increases.

After the Fukushima stage the exposure rate of meteorite depends upon not only the flow of ice mass but also the ablation rate. Therefore, it is very important to investigate quantitatively the past and present ablation phenomena near the Yamato Mountains.

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(*Received October 19, 1978*)