GLACIOLOGICAL ASPECTS AND MASS BUDGET OF THE ICE SHEET IN MIZUHO PLATEAU

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Abstract: Distributions of the glaciological and the meteorological aspects in Mizuho Plateau were plotted against the surface elevation of the ice sheet. Three boundaries common to most of the aspects were found at the elevations of 400–500 m (firn line), 700–1000 m (dry snow line), 1700–2100 m and 3000–3200 m. Glaciological zonation of the ice sheet in Mizuho Plateau was suggested.

An estimation was made on the mass budget of the ice sheet in the Shirase and Sôya drainage basins, Mizuho Plateau. Each mass budget appeared positive during the last several years. Approaches to determine the mass budget of the ice sheet were developed, and problems concerning its studies were pointed out.

1. Introduction

The present aspect of the Antarctic ice sheet—the amount of ice and its morphological feature—is a reflection of the global climatic history, and the existence of the Antarctic ice sheet has played an important role to constitute the global climate today. If a remarkable variation occurred in the aspect of the Antarctic ice sheet, future global climate would change greatly.

A number of researchers have made estimations of the mass budget of the Antarctic ice sheet, especially since the IGY, 1957–1958. Their studies have converged into a conclusion that the Antarctic ice sheet is approximately in an equilibrium state or it is slightly on the increase (BARDIN and SUYETOVA, 1967; LOEWE, 1967), although the individual results scattered in a range of $-0.40 \sim +2.1 \times 10^{12}$ t/year (LOSEV, 1963; BULL, 1971).

The Glaciological Research Program in Mizuho Plateau was projected to investigate the local mass budget of the Antarctic ice sheet in Mizuho Plateau, East Antarctica. Researches were carried out on glaciological, meteorological, geomorphological and geochemical subjects under the Program by the 10th to 15th Japanese Antarctic Research Expeditions (JARE-10 to -15) during the period of 1969–1975. Principal research reports on the subjects under the Program were compiled in this volume.

The authors are to describe in the following sections what they can tell of the ice sheet in Mizuho Plateau from a synthetic standpoint of individual researches under the Program, especially on the glaciological aspects and the mass budget of the ice sheet.

2. Glaciological Aspects of the Ice Sheet in Mizuho Plateau

The glaciological aspects of the ice sheet are basically reflections of meteorological conditions in the terrain of the ice sheet, and their distribution over the ice sheet reveals meteorological conditions in macro-scale. Meanwhile, the existence of the ice sheet and its morphological aspects have a marked effect on the meteorological conditions in the terrain. Therefore, glaciological studies on the ice sheet should be developed in consideration of air-ice interaction.

The glaciological aspects of the ice sheet in Mizuho Plateau are described in this section, from the compiled results of glaciological, meteorological and geochemical researches carried out by JARE-10 to -15 in 1969–1975. Results of the individual researches are summarized in Fig. 1. As seen in the figure, distinct boundaries common to the glaciological, meteorological and geochemical aspects of the ice sheet appeared, apparently as a function of elevation.

2.1. *Region between 0 m and 700–1000 m in elevation (the coastal region)*

In the coastal region lower than 700–1000 m in elevation (dry snow line), glaciological and meteorological aspects are quite unique in comparison with the higher regions, due to its characteristic geographical condition, namely, low elevation, steep slope of the ice sheet surface and coastal location.

In summer, surface melting of the ice sheet takes place in this region. However, the amount and behavior of the meltwater are much different between the upper and the lower domains of this region with a boundary at the elevation of 400–500 m (firn line). In the lower domain, bare ice is exposed throughout the year with superimposed ice at some scattered locations, and snow hardly accumulates because of the steep slope of the bare ice surface and the strong katabatic winds. Active surface melting takes place in summer in this domain, and meltwater

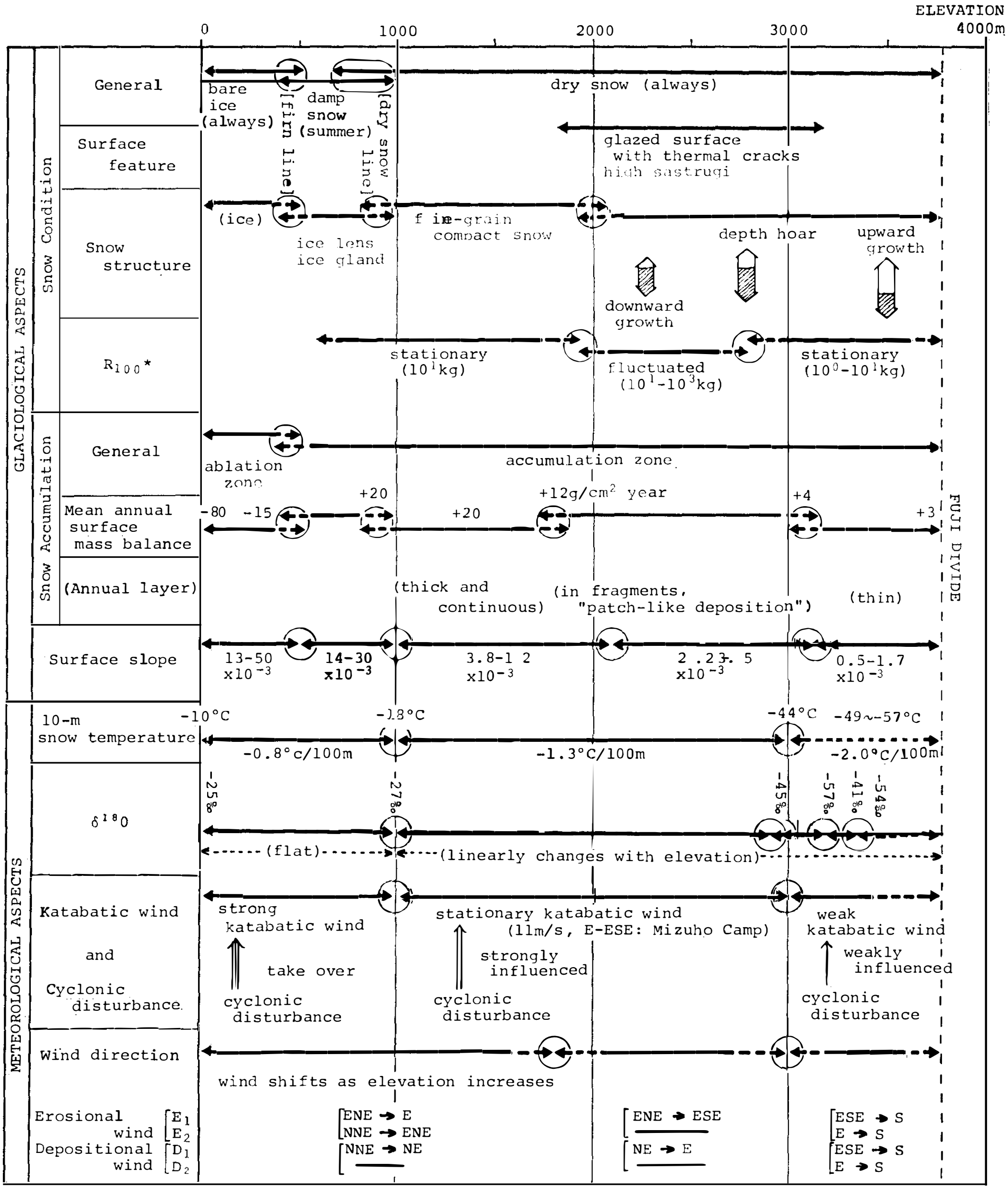

Fig. 1. Distribution of the glaciological and the meteorological aspects over the ice sheet in Mizuho Plateau, 1969–1975. Circle indicates an approximate boundary of a characteristic aspect. R_{100} is Ram profile of snow cover from the surface down to 100 cm in depth. Description of "stationary" or "fluctuated" is concerned with each Ram profile (INOUE et al., 1978; KATO et al., 1978; SATOW, 1978; SHIMIZU et al., 1978; WATANABE, 1978a, 1978b; YAMADA et al., 1978).*

occasionally makes torrents and runs down to the ocean, carving channels of a few square meters in cross-section on the ice sheet surface. This domain constitutes an active ablation zone, even though the annual mean air temperature ranges between −11 and −14°C. In the upper domain, on the other hand, surface melting is moderate in summer, whereby meltwater soaks into snow cover and forms ice lenses and ice glands by a percolation-refreezing process. This domain, which constitutes an accumulation zone, is marked by the surface snow cover which is damp in summer and dry in winter.

Meltwater in the lower domain acts as part of outgoing mass in the mass budget of the ice sheet, while that in the upper domain is retained in the ice sheet and produces no effect on the mass budget. However, the surface melting of the snow cover and the percolation-refreezing process of meltwater give effects on 10-m snow temperature, $\delta^{18}O$ and stratigraphy of the surface snow cover.

2.2. Region between 700–1000 m and 1700–2000 m in elevation

As this region is located above the dry snow line (700–1000 m in elevation), snow melting does not take place even in summer, and snow is dry throughout the year. Although this is a stationary katabatic wind region, cyclonic disturbance takes place when a cyclone passes off the coast, which produces much precipitation in this region. The mean annual balance of snow surface over this area (+20 $g/cm^2 \cdot year$) was highest in Mizuho Plateau in 1969–1975.

The annual snow layers extend horizontally and continuously over the region even with fluctuation of thickness, as a general tendency. Individual unit layers of snow which constitute an annual layer are generally thicker than those in other regions.

The snow cover is predominantly composed of fine-grain compact snow, while depth hoar has grown occasionally in the upper domain of this region.

2.3. Region between 1700–2000 m and 3000–3200 m in elevation

The mean annual balance of snow surface rapidly decreased from +18 g/cm^2 down to +7 g/cm^2, as elevation increased from 1700–1900 m up to 3000–3200 m, in 1969–1975. The ice sheet surface in this region has the minimum slope necessary for the generation of katabatic wind, according to BALL's theory (1960), and actually this is a stationary katabatic wind region.

A small amount of snow deposition and stationary katabatic winds which are sufficiently strong to generate snow drift forming patch-like snow deposits in this region. As the result, horizontal extent of annual layers of snow are limited, and study on the annual layers by means of stratigraphic observations is generally impossible because of the missing of serial annual layers in a pit wall.

Such glaciological and meteorological conditions result in the development of a glazed surface with thermal cracks, high sastrugi up to 50 cm in height and depth hoar, in this region. Depth hoar grows more actively as elevation increases. Alternating stratification of hard depth hoar and fragile depth hoar is characteristic of this region. Although the depth hoar grows downward in most cases, its upward growth is occasionally observed in the upper domain of this region.

2.4. Region higher than 3000–3200 m in elevation (the inland region)

This region is characterized by the distance more than 500 km far from the coast, the extremely gentle slope of the ice sheet surface ranging from 0.5 to 1.7×10^{-3} in inclination, and the high elevation between 3000–3200 and 3750 m. Such geographical and topographical conditions make the climate in this region very stable under low temperature and weak wind, with a very weak effect of a maritime cyclonic disturbance.

The mean annual balance of snow surface is less than $+7 g/cm^2$, the snow surface is gentle, and the stratification of the snow cover is considerablly level. As the unit layer of snow deposition is generally so thin that some annual layers may be missing in a pit wall.

Another characteristic aspect of this region is well-developed depth hoar. Depth hoar grows more actively with a tendency of upward growth as elevation increases. It is so fragile that core sampling of the snow cover by means of an ordinary hand auger is extremely difficult.

From the compiled result of the glaciological, meteorological and geochemical researches in 1969–1975, four characteristic regions common to most of them were found forming zones as a function of elevation, as described above and in Fig. 1. The location of the boundaries given in this paper would be reasonable for a fairly wide extent in Mizuho Plateau. However, as they were deduced only from the data obtained along the traverse routes, they may fluctuate in distance from the routes, according to variation of the local meteorological conditions caused by topography of the ice sheet. More extensive and intensive researches are necessary to bring the zonation of Mizuho Plateau to perfection by figuring out the correct zones and clarifying the mechanism of zone formation.

3. Mass Budget of the Ice Sheet in Mizuho Plateau

Incoming water to the ice sheet surface can be given by precipitation, condensation and snow drifting, while outgoing water therefrom by wind erosion, sublimation and surface melting in the coastal region only when meltwater pours directly into the ocean. An annual accumulation of snow measured by the stake method coincides with the surface mass balance of the snow cover, namely, a value obtained by subtracting the outgo mass from the income mass of water across the snow surface per year at the location of a stake.

From the standpoint of mass budget of the ice sheet, the total income mass of a drainage basin of the ice sheet can be calculated by summing up the surface mass balance per unit area over the extent of the basin, considering its distribution. The total outgo mass is mostly by calving of the coastal ice sheet or outlet

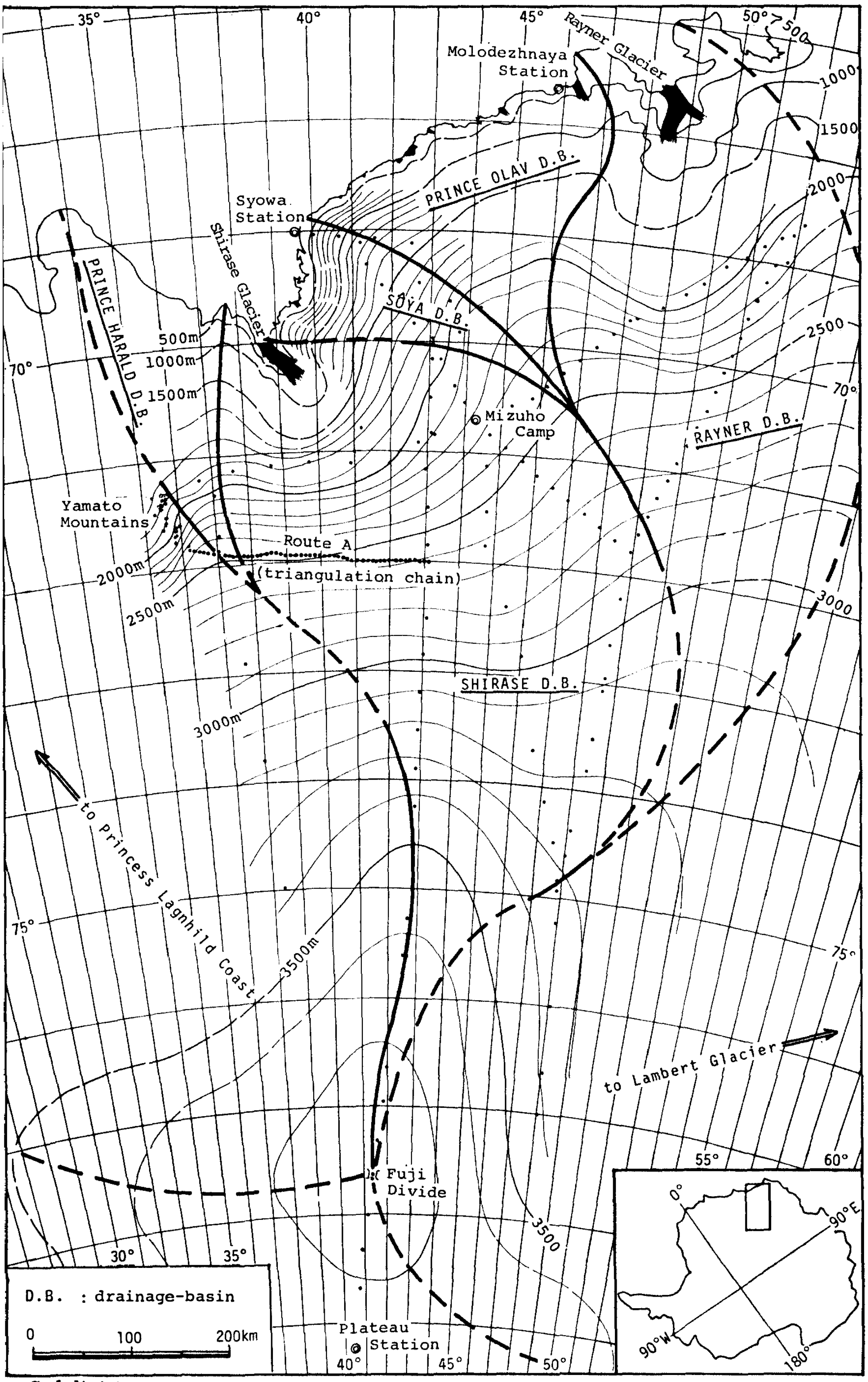

Fig. 2. Subdivisional drainage basins of the ice sheet in Mizuho Plateau (SHIMIZU *et al., 1978*).

glacier: the amount of the surface meltwater of the ice sheet which pours directly into the ocean is counted in the total income mass, and that of bottom meltwater would be negligibly small in comparison with those by calving. An estimation is made of the mass budget of the ice sheet in the subdivisional drainage basins in Mizuho Plateau, and a discussion is made in the following.

Mizuho Plateau was divided into several subdivisional drainage basins on an assumption that ice flows along the general slope of the ice sheet surface, as illustrated in Fig. 2, and mass budget of the Shirase and Sôya drainage basins was estimated.

As for the Shirase drainage basin, a converging type, the following were estimated: it has an extent of 20×10^4 km^2 in area; the stored ice amounted to 32×10^{13} t in weight; the income mass of water amounted to 12.7×10^9 t/year for 1969–1975; the ice discharge through the Shirase Glacier, the outlet glacier of the basin, amounted to 7.4×10^9 t/year for the same period. [A mean value of the maximum and the minimum surface mass balance of 1969–1975 was used as the total income mass (YAMADA and WATANABE, 1978), for this estimation.] Subtracting the outgo mass from the income mass, the mass budget of the ice sheet in this basin was estimated at $+5.3\times10^9$ t/year.

As for the Sôya drainage basin, a diverging type, the following were estimated: it has an extent of 2.2×10^4 km^2 in area; the stored ice amounted to 2.6×10^{13} t; the income mass of water amounted to 3.0×10^9 t/year for 1969–1975; the ice discharge across the Sôya Coast amounted to 1.5×10^9 t/year for the same period. Likewise, the mass budget of the ice sheet in this basin was estimated at $+1.5\times10^9$ t/year.

Three indices indicating dynamic condition of ice mass were defined as i), ii) and iii), by mean of the present amount of stored ice M, the amount of the annual income mass In and outgo mass Out, and the annual mass budget Bgt of the ice mass: where the mass budget is given as $Bgt=In-Out$, the positive sign indicating an increase of ice mass and the negative sign a decrease.

i) Degree of non-equilibrium of an ice mass, $Bgt/(In+Out)$, takes a value in a range of -1 and $+1$. The positive sign indicates an increase of ice mass, while the negative sign a decrease. The absolute value of the index indicates the degree of non-equilibrium of the ice mass, giving zero for a complete equilibrium state, and a larger value for a more non-equilibrium state. The values of -1 and $+1$ of the index give an extreme case respectively, namely, the former indicates that the ice mass has no income mass, and the latter that the one has no outgo mass at all.

ii) Annual change rate of ice mass, Bgt/M (in year^{-1}), takes a positive or negative value: The positive sign indicates an increase of ice mass, and the negative sign a decrease. The absolute value of the index indicates the proportion of the amount of annual change of ice mass to that of the stored ice.

iii) Take over time *M/Out* (in year) is the number of years necessary for the full attainment of mass exchange of the ice in a drainage basin, the smaller the index, the quicker the ice exchange.

The indices of ice mass in the Shirase and Sôya drainage basins were calculated and given in Table 1. One can see in the table, that the ice in the Shirase drainage basin shows a little lower degree of non-equilibrium, a lower annual change rate by 1/3, and a longer time for a 100% mass exchange by three times than those of the Sôya drainage basin.

Table 1. Degree of non-equilibrium, annual change rate and take-over time of the ice mass in the Shirase and Sôya drainage basins, 1969–1975. M, In, Out and Bgt indicate amount of stored ice, annual income mass and outgo mass, and mass budget of the ice sheet, respectively (NAKAWO, 1978; YAMADA and WATANABE, 1978).

Index (unit) \ Drainage basin		Shirase	Sôya
M	(t)	32 $\times 10^{13}$	2.6×10^{13}
In	(t/year)	12.7×10^{9}	3.0×10^{9}
Out	(t/year)	7.4×10^{9}	1.5×10^{9}
Bgt	(t/year)	$+5.3\times 10^{9}$	$+1.5\times 10^{9}$
Degree of non-equilibrium *Bgt/(In+Out)*	—	+0.26	+0.33
Annual changing rate *Bgt/M*	($year^{-1}$)	$+0.2\times 10^{-4}$	$+0.6\times 10^{-4}$
Take over time *M/Out*	(year)	4.3×10^{4}	1.7×10^{4}

It can be said that the Shirase and Sôya drainage basins were increasing ice at the rates of 5.3×10^9 and 1.5×10^9 t/year respectively during the period of 1969–1975.

One should be careful not to misunderstand from these results that these subdivisional drainage basins were increasing the ice mass as a general tendency currently or during a fairly long period in the past. The following are the reasons:

1) The value of the mean annual mass balance at the ice sheet surface which was used for this estimation was obtained from the data only for the last four to seven years out of the period of 1969–1975, and it actually vaired from year to year with a fluctuation, for instance, more than twice as to the maximum value. Moreover, it should be considered that the annual variation of the surface mass balance would have various periods ranging from 10^0 years to more than

10^4 years due to the variation of climatic condition. So, one may obtain a different value of the surface mass balance next year.

On the other hand, the mean annual discharge of ice through an outlet glacier measured even only for several years could be valid for a considerably long term, as the movement of the ice sheet would be fairly steady except for *surging* in comparison with the variation of annual mass balance at the ice sheet surface.

Therefore, a simple subtraction of the outgo mass from the income mass which were obtained during a short limited period is not so meaningful to figure out the general tendency of mass change of a huge ice sheet.

2) The movement of the ice sheet varies as the ice sheet mass changes. Such a behavior of the ice sheet is analogous to that of water in hydrology, namely as regards a relation between the amounts of precipitation and runoff, but the response time of the ice sheet is much longer than that of water. A discussion on the response at the output of a glacier to the variation of the input was theoretically developed by NYE (1960) on the basis of the flow law of ice. Applying NYE's theory to the ice sheet of the Shirase drainage basin, the response time was presumed as 1000–5000 years; namely, the discharge of ice through the Shirase Glacier today is a reflection of the ice mass of the basin in the past of the order of 10^3 years ago.

If so, it can be presumed that the ice sheet in the basin was much smaller in the past of the order of 10^3 years ago than that of today, and that since then the income mass has increased considerably, from the fact that the income mass exceeds the discharge today in a great degree.

The travel time of ice from an upstream region of a drainage basin down to its outlet is longer than the response time. An approximate estimate of 6000 years was obtained of the travel time of ice from Route A which is located about 200 km upstream of the Shirase glacier in a range of 2400–2600 m in elevation down to the outlet of the drainage basin (NARUSE and SHIMIZU, 1978).

3) Strict measurements of the ice sheet flow by means of a triangulation chain set up along Route A indicated a remarkable mass deficit of the order of 60 $g/cm^2 \cdot$ year, which was caused neither by surface melting nor sublimation, but presumably by thinning of the ice sheet (NARUSE, 1978). This fact is apparently at variance with the total positive mass budget, $+5.3 \times 10^9$ t/year in the Shirase drainage basin, described previously. Such a local contradiction in mass budget, however, would really exist over the ice sheet, if the movement of the ice sheet is not stationary.

4. Concluding Remarks

Glaciological zonation of the ice sheet provides a basic requirement for general studies on the ice sheet especially on its mass budget. Moreover, it will contribute greatly to a study on meteorological condition in the terrain concerned, as the glaciological condition of the ice sheet is influenced by the meteorological condition and *vice versa* due to the air-ice interaction.

Although the three boundaries described in Fig. 1 seem to be reasonable in Mizuho Plateau, more extensive and intensive studies are necessary to give the glaciological zones in more detail, and to clarify the mechanism of formation of the zones, in order to develop a study on the mass circulation of water in Antarctica under the influence of the ice sheet.

The following give a summary of problems in studying the mass budget of the ice sheet.

1) Accurate determination of drainage basin

This is of primary importance, as the area and location of a drainage basin of the ice sheet give a direct influence on the estimation of the income mass. The location of a real divide should be determined for accurate demarcation of the drainage basin, together with the amount of stored ice.

2) Estimation of annual mass balance at the ice sheet surface

The most difficult problem for evaluation of mass budget of the ice sheet is a correct estimation of the income mass, namely, accurate value of the total surface mass balance over a vast extent, together with its annual variation. A study on this subject is keenly needed. Deep cores of the ice sheet may tell the history of the surface mass balance.

3) Discharge of ice

Aerophotography is a very useful and effective method to observe the discharge of ice. Annual variation of ice discharge for a long period is easily obtained by this method.

4) Dynamics of the ice sheet

Dynamics of the ice sheet provides one of the most important theoretical basis of studies on the behavior of the ice sheet. A clue may be obtained by a glaciological traverse along a flow line of the ice sheet from the outlet up to the source of a drainage basin.

5) Long-period climatic variation

As the behavior of the ice sheet is strongly affected by climatic condition, its long-period variation is prerequisite for intensive studies of the ice sheet. An analytical study on deep cores of the ice sheet may give the key to its historic information of the order of 10^3 years or older; 10^3 years are of the order of the dynamic response time of the ice sheet of the Shirase drainage basin.

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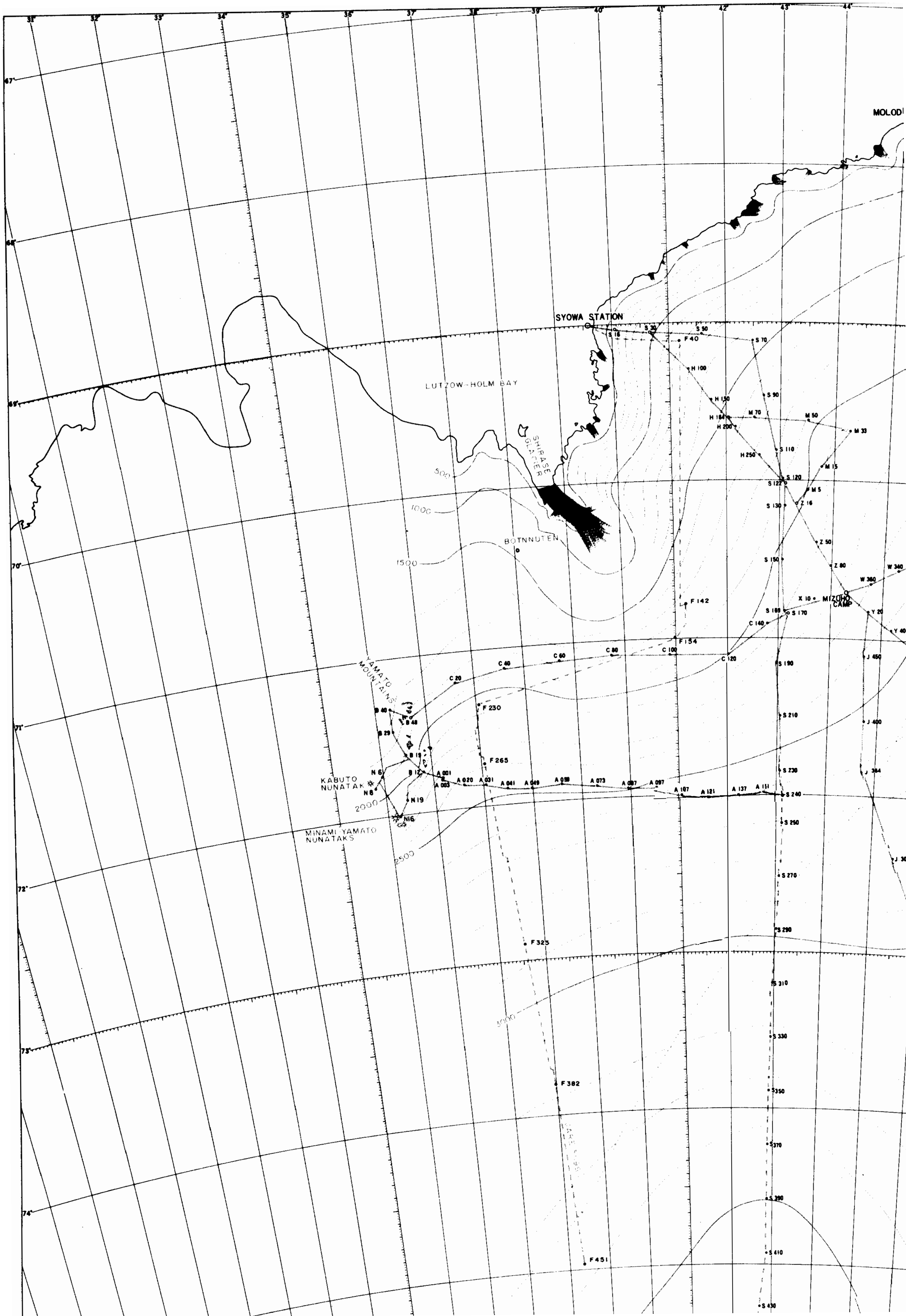

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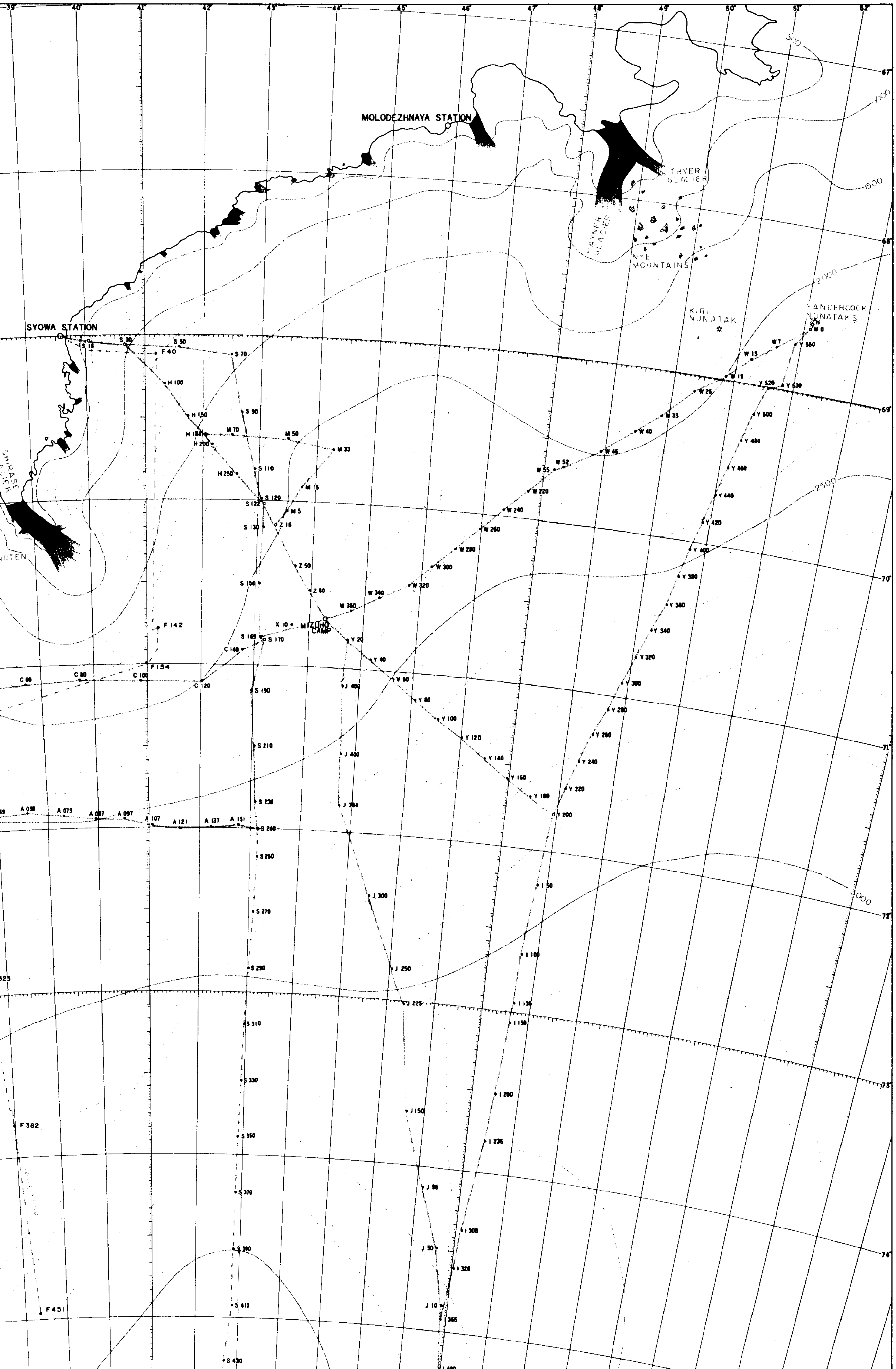

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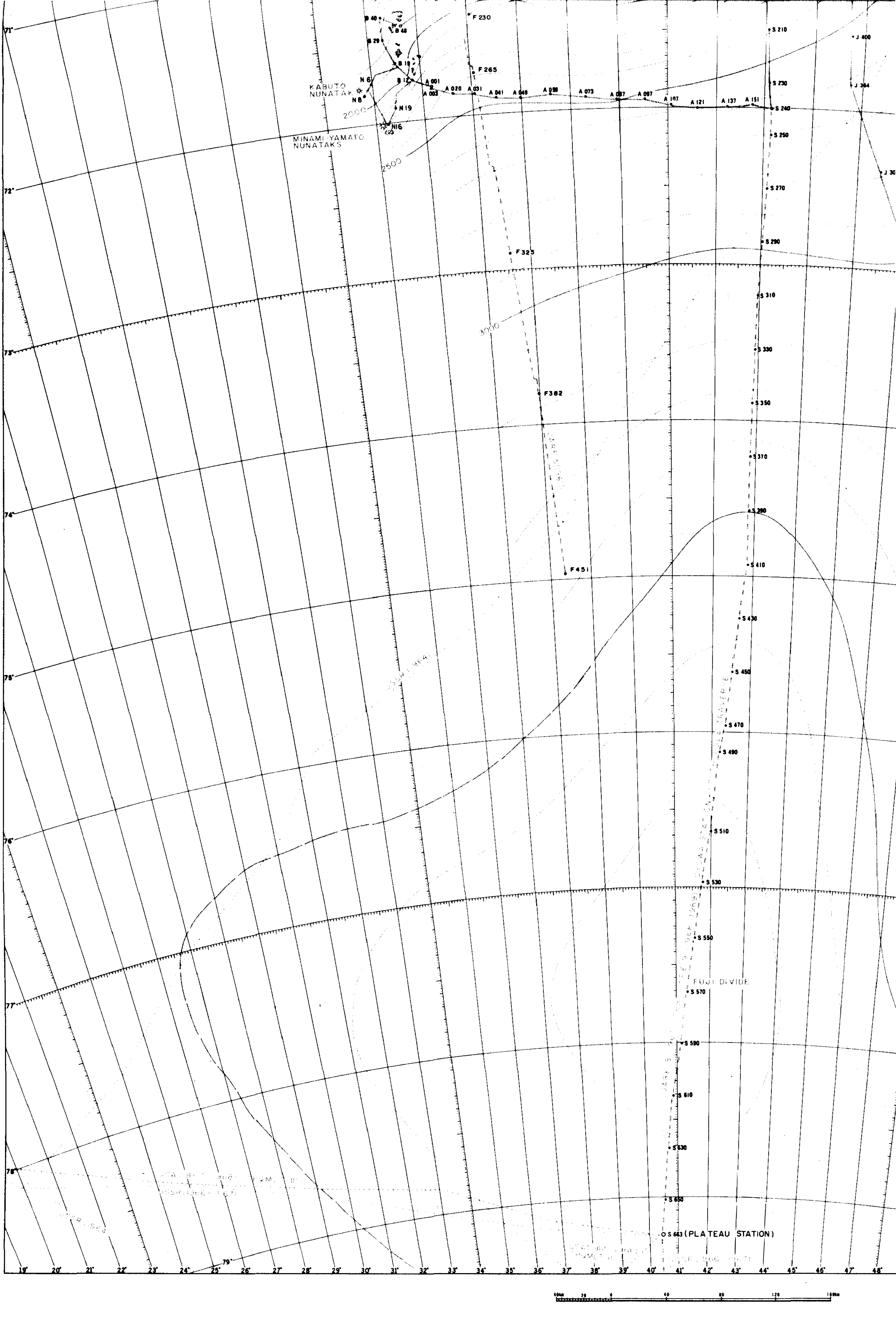

Fig. A. Mizuho Plateau, East Antarctica.

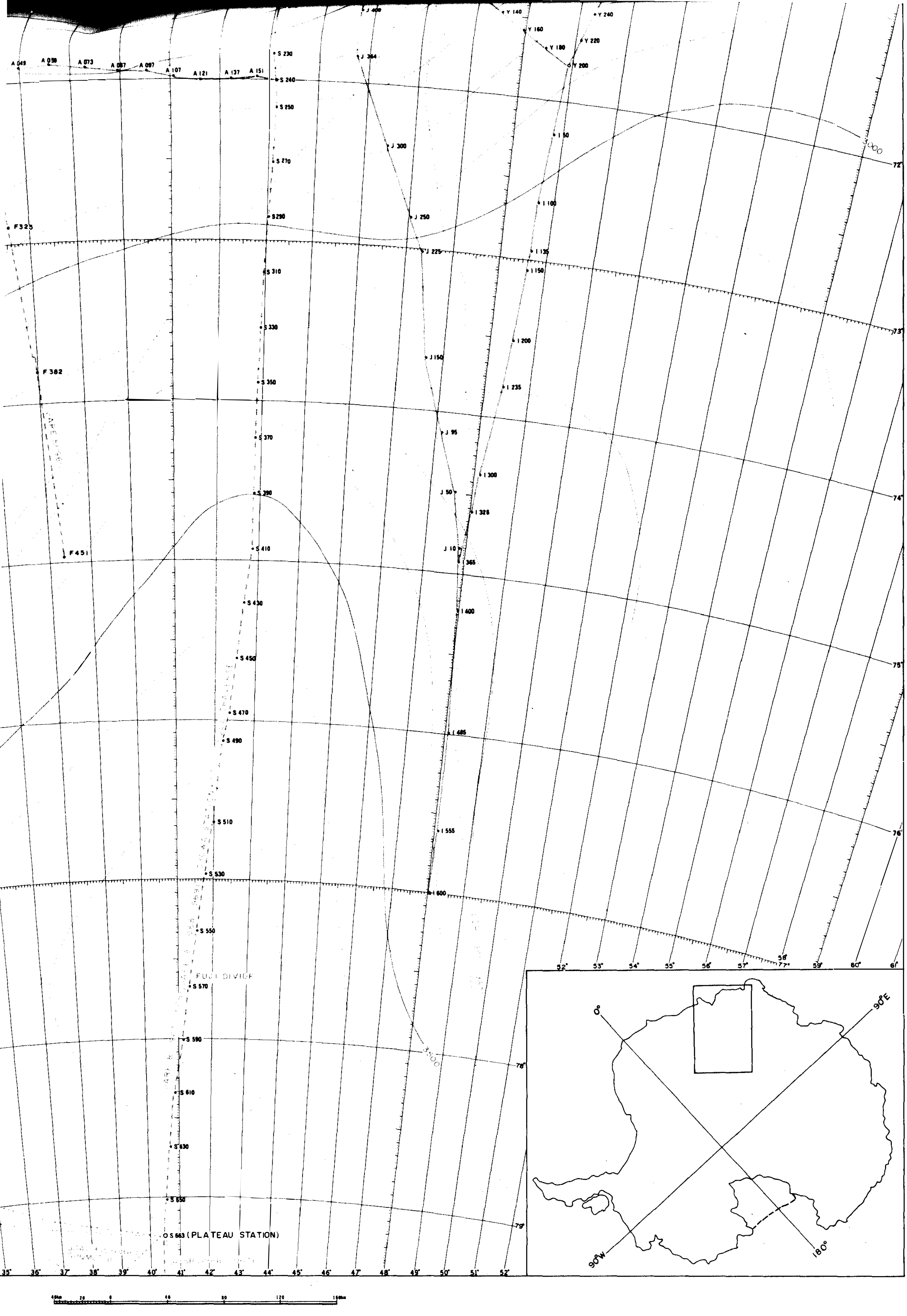

Fig. A. Mizuho Plateau, East Antarctica.