A POSSIBLE MECHANISM OF CONCENTRATION OF METEORITES WITHIN THE METEORITE ICE FIELD IN ANTARCTICA

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Abstract: 991 pieces of meteorites of various kinds have been collected from a bare ice field (now named the "Meteorite Ice Field") near the Yamato Mountains (about 72°S, 36°E) in Antarctica. Among these meteorites, 2 are irons and 1 is a stony-iron, while all the others are chondrites or achondrites, in which 5 pieces of carbonaceous chondrite are included. The differential mass distribution spectrum of these stony meteorites is represented by $N(m) \propto m^{-5/3}$,which is in agreement with the theoretically expected result for small asteroidal bodies based on the fragmentation model theory.

An interpretation that all the meteorites are due to one or several meteorite showers can be rejected because their meteoritic characteristics are broadly dispersed. The most plausible interpretation is such that a large number of meteorites falling over the Antarctic interior during a long period of time have been transported by the ice sheet movements which result in a horizontal convergence and an upwell of ice flow owing to the bedrock topography. Another necessary condition is the exposure of meteorites on the blue ice surface caused by the ablation effect. Semi-quantitative examinations of each process involved seem to justify the above-mentioned hypothesis. Results of the examinations are as follows:

(a) The estimated gravity separation effect of meteorite in ice is negligibly small so that all Yamato meteorites should have been transported by the ice sheet flow.

(b) The velocity distribution along the streamlines of ice flow estimated on the basis of a new theory of an ice sheet profile gives rise to an estimate of the longest time interval from a meteorite fall to its exposure as 10^5 years.

(c) The bedrock topography comprising the Yamato Mountains and the sub-ice Vernadski Mountains is very likely to cause a horizontal convergence and an upwell of the ice sheet flow in the vicinity of the Yamato Mountains, where triangulation surveys have shown an actual example of the horizontal convergence and the observed upwell velocity ranging from 2 to 8 cm/year.

(d) Continuous ablation of the ice sheet surface can result in an accumulation of meteorites on the bare ice surface. The annual ablation rate there amounts to 2–7 cm/year.

It seems that these conditions are favorable for an accumulation of meteorites which have fallen in the accumulation area on the northern slope of the Fuji Divide.

A U.S.–Japan cooperative program of Antarctic search for meteorites in West Antarctica, planned on the basis of this hypothetical mechanism, has led to a collection of 11 meteorites from two bare ice areas among theoretically predicted ones.

1. Introduction

In December 1969, the field party of the Japanese Antarctic Research Expedition for the geological and geomorphological surveys of the Yamato Mountains in East Antarctica found and collected, by accident, nine pieces of meteorite within a small blue ice area (between 71°48′S and 71°52′S in latitude and between 36°10′E and 36°30′E in longitude) at the southeastern foot of the Yamato Mountains. Eight of these meteorites are chondrites and one is an achondrite. Four large pieces (heavier than 60 gm in weight) among these stony meteorites have been chemically, petrographically, mineralogically and physically analyzed in some detail (NAGATA, *ed.*, 1975).

Accordingly, the field party for the same geological survey in 1973 made some effort to find meteorites in the same blue ice area, collecting twelve new pieces of meteorite. These also are all stony meteorites including one achondrite.

Encouraged by these findings of meteorites in a very limited area of blue ice in East Antarctica, the field party sent out to the same area in 1974 made special effort to find and collect meteorites as many as possible. Thus, the 1974 field party has collected 663 pieces of meteorite (YANAI, 1975, 1978). Except one piece of stony-iron meteorite (pallasite), all samples collected are stony meteorites, either chondrites or achondrites. Because a large number of meteorite pieces were found within a limited small area at this time, the appearance behaviors *in situ* of these Yamato meteorites could be statistically characterized to a certain extent. Their appearance behaviors *in situ* are as follows: (a) With two exceptional cases, all meteorites pieces were lying on the blue ice surface; one exceptional small meteorite was lying on the surface of a hard snow layer and the other was buried in the blue ice at a depth of about 10 cm. (b) The majority of collected meteorite pieces are almost entirely covered with the fusion crust, but there are also groups of meteorite pieces which look like fragments of a single meteorite.

The field party in 1975 could collect 307 pieces of meteorite from a little wider area of blue ice in the neighborhood of the Yamato Mountains (MATSUMOTO, 1978). More than a half of the 1975 collection of the Yamato meteorites have the shape of fragments and some of them were concentrated very closely to one another. However, there are also a number of meteorite pieces which are almost entirely covered with the fusion crust. It was guessed in the field by the field workers, M. MATSUMOTO and others, that the minimum possible number of original unbroken meteorites would be 104 pieces. Among 307 meteorite pieces of the 1975 collection, 2 are irons and all the others are chondrites or achondrites.

Summarizing the results of these field works to find and collect meteorites, we may conclude first that the total 991 pieces of meteorites were found in blue ice zones or in the snow area very close to the edge of a blue ice zone (one exceptional case) in the neighborhood of the Yamato Mountains (see Fig. 1). There is only one case that a stony meteorite was found buried in the blue ice at a 10 cm depth. Its discovery was made by mere chance. In the present method

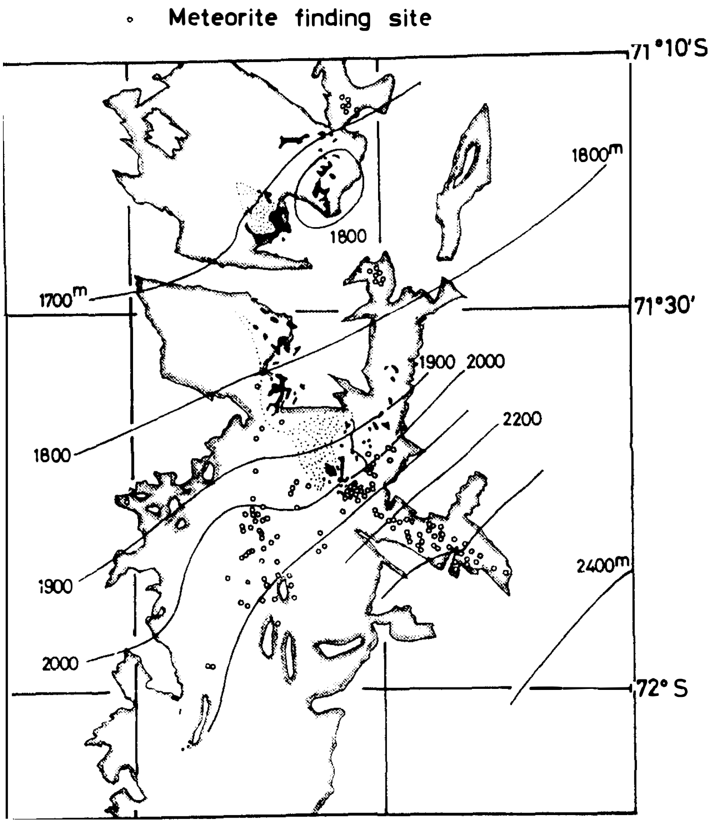

Fig. 1. Locations of comparatively large Yamato meteorites found in the Meteorite Ice Field.

of survey by driving snow vehicles, meteorite pieces are detected only when they lay on the blue ice surface. As the buried meteorite was located very close to a meteorite exposed on the blue ice surface, it was discovered quite accidentally by a member who walked to pick up the latter. This experience may suggest that a number of meteorites might still be buried under the blue ice surface. Thus, the blue ice area surrounding the Yamato Mountains has been especially named the "Meteorite Ice Field".

The second conclusion is that, among 991 pieces of collected Yamato meteorites, there were only two irons and one stony-iron. Among 778 meteorite falls identified up to date, for comparison, irons and stony-irons are 43 and 12 respectively (HEY, 1966). Namely, irons and stony-irons occupy 5.5% and 1.6% respectively of the total meteorite falls. Compared with these percentages, the abundance of irons and stony-irons in the Yamato meteorite assemblage is significantly small. However, it is possible that the apparent total number of the Yamato meteorites may include products of some meteorite showers and fragments of meteorites broken on the ice surface when they hit the surface. Judging from the field work results in 1974 and 1975, the total number of original meteorites could be reduced to about 1/3 of the apparent total number as the possible minimum figure. Then, the percentages of abundance of irons and stony-irons in the Yamato meteorites can be estimated as 0.6% and 0.3% respectively, which are still considerably smaller than those in the world collection of meteorite falls.

In regard to the Yamato meteorite collection, two questions may be specifically raised. The first question is the cause of the concentration of so many pieces of meteorite on the surface of a limited small area of blue ice at a particular locality in Antarctica. The second question is the reason of the smaller percentages of irons and stony-irons in the Yamato meteorite collection than those in the world collection of meteorite falls.

A simple hypothesis that a single or several meteorite showers might have resulted in the large accumulation of meteorite pieces is hardly acceptable, because almost all kinds of meteorites have been identified in the Yamato meteorite collection. As already described, two irons and one stony-iron were found together with 988 pieces of stony meteorites in the Meteorite Ice Field. 56 pieces of the stony meteorite weighing heavier than 100 gm have been identified to date. The result is represented by a classification of these stony meteorites into 1 enstatite chondrite, 29 olivine-bronzite chondrites, 14 olivine-hypersthene chondrites, 2 amphoterites, 1 carbonaceous chondrite and 9 achondrites. Furthermore the metamorphic types of the olivine-bronzite and olivine-hypersthene chondrites range in H_3–H_6 and L_3–L_6 respectively. If each group of stony meteorites having nearly the same meteoritic characteristics is attributed to each different meteorite shower, we may have to assume at least ten meteorite showers within such a limited area as illustrated in Fig. 1.

Another factor which should be taken into consideration in this connection will be the distribution of chemically classified types of the 56 identified Yamato stony meteorites, given in Table 1 together with that of the world stony meteorites registered in the "Catalogue of Meteorites" (HEY, 1966). In Table 1, the percentage of each chemically classified type among the total stony meteorites is

Table 1. Classification of Yamato stony meteorites heavier than 100 gm in comparison with that of registered world stony meteorites.

Total	Enstatite-ch.	Olivine-bronzite ch.	Olivine-hyper-sthene ch.	Amphote-rites	Olivine-pigionite-ch.	Carbo-naceous ch.	Achon-drite
	(Yamato meteorites, mass>100 gm)						
56 (100%)	1 (1.8)	29 (51.8)	14 (25.0)	2 (3.6)	0 (0.0)	1 (1.8)	9 (16.1)
	(Registered stony meteorites in Catalogue of Meteorities)						
Falls: 663 (100%)	11 (1.7)	225 (33.9)	273 (41.2)	39 (5.9)	15 (2.3)	41 (6.2)	59 (8.9)
Finds: 463 (100%)	6 (1.3)	188 (40.6)	231 (49.9)	10 (2.2)	0 (0.0)	18 (3.9)	10 (2.2)
Total: 1126 (100%)	17 (1.5)	413 (36.7)	504 (44.8)	49 (4.4)	15 (1.3)	59 (5.2)	69 (6.1)

given in parentheses. As shown in this table, the relative ratios of abundances of chemical types in the 56 Yamato stony meteorites are not essentially different from those in the registered world stony meteorites, if the fact that the total number of the Yamato stony meteorites concerned is about one-twelfth of that of the world stony meteorite falls is taken into account. This result may suggest that a partial assemblage of the Yamato meteorite collection (selected by a criterion for their masses heavier than 100 gm) could be considered as a partial assemblage of the world individual stony meteorites identified to date. In other words, it might be unnatural to assume that the Yamato stony meteorites are products of a few showers of meteorites having respectively different chemical (mineralogical) compositions.

As already reported (NAGATA *et al.*, 1976), the most plausible mechanism to result in a concentration of a large number of meteorites of various different kinds within a small limited area of the blue ice surface of the great Antarctic ice sheet would be hypothesized as follows: (a) A large number of meteorites of various kinds falling on the surface of Antarctic interior ice sheet (10^7 km^2 in the order of magnitude) during a long period of time (10^5–10^7 years) have been transported by the ice flow through the ice sheet towards the sea coast; (b) influenced by the bedrock topography such as the Yamato Mountains and the neighboring sub-ice mountain ranges, the ice flow carrying the meteorite pieces forms a horizontal convergence to result in stagnant areas and an upwell motion due to some barriers in front like mountains; (c) the meteorite pieces transported to the surface of the ablation zone of ice sheet have remained on the surface while the ice mass itself is continuously disappearing by the ablation effect. In brief, it seems very likely that the unusually high accumulation of meteorites within the Meteorite Ice Field could be interpreted as a result of integrations of the meteorite falls over a wide Antarctic interior with the ordinary rate over the earth's surface with respect to both area and time.

Quantitative examinations of the hypothesis can be made on the basis of complete data of the Yamato meteorites in regard to both their meteoritic characteristics and their distribution pattern in the Meteorite Ice Field. However, it will take an extremely long time to complete the identifications of all pieces of the Yamato meteorite collection. Up to the present time, the distribution pattern *in situ* of the Yamato meteorites so far collected has been reasonably clarified and the identifications of larger pieces (heavier than 100 gm in weight) of the Yamato stony meteorites as well as the Yamato iron and stony-iron meteorites have been substantially accomplished. On the basis of these interim data, semi-quantitative examinations of each process involved in the dynamic model hypothesis for the Yamato meteorite accumulation are tried in the present work. The examined points are (i) the differential frequency spectrum of mass distribution of the Yamato stony meteorite collection, which may be related to the original mass distribution of meteorite falls and any possible screening effect that may occur during the transportation process; (ii) the gravity separation effect for meteorites in the plastic ice sheet, which may result in the gravity separation of meteorite pieces depending on their densities and sizes; (iii) the velocity distribution of ice flow along the streamlines within the Antarctic ice sheet, which may directly control the transportation of meteorite pieces from the accumulation zone to the ablation zone; (iv) effects of conspicuous topography of the bedrock surface upon the ice flow, which may cause the horizontal convergence of ice flow to result in horizontal stagnant points and an upwell of ice flow; and (v) the ablation rate of the ice sheet surface in the ablation area where the surface ice mass continuously disappears due to the ablation effect but the transported meteorite pieces themselves can remain.

2. Mass Distribution of the Yamato Stony Meteorites

Among 988 pieces of the Yamato stony meteorites, the largest one (Yamato-75102) weighs about 11.0 kg, whereas the smallest pieces are only 0.1 gm in weight. A histogram of the frequency distribution of mass (m) of these 988 stony meteorites with respect to log m is illustrated in Fig. 2, where the occurrence frequency $N(\log m)$ is normalized by $\sum N(\log m)=N_0$. In a range of $m \geq 20$ gm in Fig. 2, $N(\log m)/N_0$ is statistically well represented by

$$\log (N(\log m)/N_0)=a-\frac{2}{3}\log m. \tag{1}$$

However, since the frequency spectrum represented by eq. (1) is given for $N(\log m)d(\log m)$, the mass-frequency spectrum $N(m)dm$ for $m \geq 20$ gm should be given by

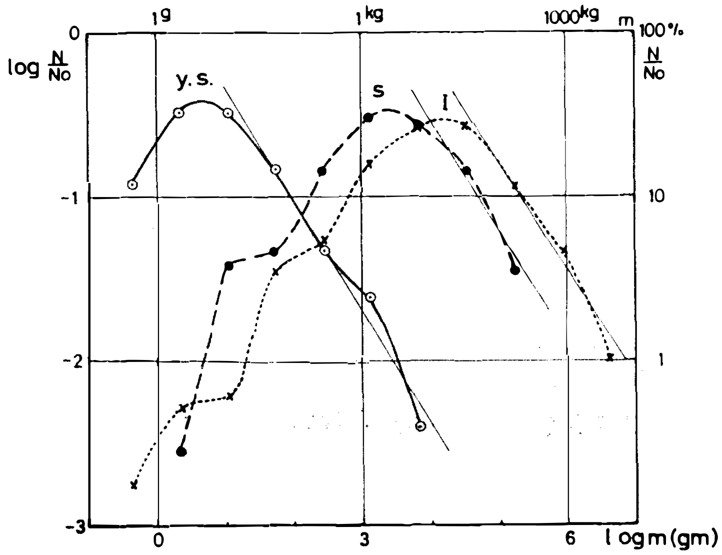

Fig. 2. Differential occurrence frequency spectrum of mass(m) of Yamato stony meteorites (Y.S.) in comparison with that of the world recognized stony meteorites (S) and iron meteorites (I).

$$N(m)=Am^{-5/3}\,. \tag{2}$$

A similar statistical examination is made for the known initial weights of stony meteorites which have hitherto been reported (HEY, 1966). As shown in Fig. 2, the frequency spectrum of mass distribution for $m \geq 10$ kg can be represented by eq. (1) or eq. (2) in this case ($N_0=1064$) also. For comparison, a similar statistical result is given for iron meteorites too ($N_0=565$). Again, eq. (1) or eq. (2) can approximately stand for the iron meteorites of $m \geq 50$ kg.

The maximum value of N takes place for about $m=5$ gm in the Yamato stony meteorite collection and about $m=3$ kg in the world stony meteorite collection, and $N(m)$ decreases with a decrease in m below the critical maximum value. Empirically, the whole frequency spectrum of $N(\log m)/N_0$ illustrated in Fig. 2 can be approximated by

$$\frac{N\,(\log m)}{N_0}=Am^{-2/3}[1-\exp(-m/m_c)]^{\alpha} \tag{3}$$

The critical mass value, m_c, and α are numerically given as $m_c \simeq 5$ gm, $\alpha \simeq 1.7$ for the Yamato stony meteorites and as $m_c \simeq 2.5$ kg, $\alpha \simeq 1.35$ for the world stony meteorites. A decrease of N with a decrease of m below a critical value represented by the factor, $[1-\exp(-m/m_c)]^{\alpha}$, may be mostly due to an effect of increasing difficulty in finding smaller meteorite pieces depending on the circumstances. In the Meteorite Ice Field near the Yamato Mountains, the critical value m_c is only 5 gm. This would suggest naturally that it is not difficult to find stony meteorites heavier than 5 gm in weight on a flat blue ice surface in the Meteorite Ice Field, but it is difficult to find stony meteorites less than 2.5 kg in weight in the ordinary lands which are generally covered with soils, bushes, trees, etc. The factor represented by $[1-\exp(-m/m_c)]^{\alpha}$ in eq. (3) may therefore be provisionally named the masking effect factor.

On the other hand, there should be a lower limit for the mass of meteorites which can reach the earth's surface, because any falling meteorite is burnt up to emit the thermal radiation and to result in a formation of the fusion crust on entry into the earth's atmosphere. The Yamato stony meteorites which have been collected from the least disturbed area on earth may represent the least disturbed characteristic of the mass frequency spectrum of stony meteorites which have fallen on the earth's surface. It may then be concluded that the frequency spectrum of mass distribution of stony meteorite falls, larger than 5 gm in weight, can be represented by eq. (2), namely $N(m)=Am^{-5/3}$. By taking into consideration further the mass-frequency spectrum of the world stony meteorites, heavier than 2.5 kg in weight, we may expect that the law of $N(m) \propto m^{-5/3}$ generally holds for a range of 5 gm–400 kg in weight of the stony meteorites.

A simple model of fragmentation of small solid bodies mutually colliding in the interplanetary space (*e.g.* ALFVEN and ARRHENIUS, 1976) leads to a conclusion that the steady state (time-independent) frequency spectrum of fragment masses (m) is theoretically given by

$$N(m)=X_0 m^{-5/3}\,, \tag{4}$$

which is identical to eq. (2). It is assumed in the theoretical derivation of eq. (4) that each body splits into n smaller bodies of equal mass whenever it collides with another body, where the cross section for the collision is proportional to $m^{2/3}$. In the steady state of $N(m)$ for the bodies of mass between m and $m+dm$, the loss of bodies of m in mass by the collision must be compensated with a product of new bodies of mass m by the collision of a larger body, namely,

$$N(m)m^{2/3}\,dm=N(nm)(nm)^{2/3}\,ndm\,.$$

Putting $N(m)=X_0 m^{-\gamma}$, we then get

$$m^{-\gamma+2/3}=(nm)^{-\gamma+2/3}n\,,$$

which can be satisfied only by putting $\gamma=5/3$. In the present particular case, however, an effect of fragmentation of falling meteorite bodies by their collision with the ice sheet surface also must be taken into account. Let us assume then that a portion ($\alpha<1$) of all falling meteorite bodies split into n' smaller bodies of equal mass when they hit the ice sheet surface, where the collision cross section is independent of m and should be unity. The gain of number ($\Delta N(m)$) of the body of mass between m and $m+dm$ on this assumption is expressed by

$$\Delta N(m)=\alpha\{-N(m)+n'N(n'm)\}=-\alpha X_0 m^{-5/3}(1-n'^{-2/3})\,.$$

Hence, the mass frequency spectrum ($N(m)^*$) of meteorite bodies after the collision with the ice sheet surface is given by

$$N^*(m)=X_0[1-\alpha(2-n'^{-2/3})]m^{-5/3}=X_0^*(n')m^{-5/3}\,. \tag{5}$$

Since the revised coefficient $X^*(n')$ is dependent only on α and n' and α and n' could be considered constant, the modified spectrum of mass frequency distribution of the Yamato stony meteorites can still be expressed by the $m^{-5/3}$ law as expressed by eq. (5).

The observed fact that the mass frequency spectrum of the Yamato stony meteorites, heavier than 5 gm in weight, holds well the theoretical result derived from the fragmentation model theory may indicate that all the stony meteorite pieces larger than 5 gm, which fell over a large area of the Antarctic ice sheet surface, have been transported to the Meteorite Ice Field without any considerable screening effect dependent on the meteorite mass. Nothing can be said from the present data about a possibility of the screening effect for the small pieces of stony meteorites less than 5 gm in weight. It would be reasonable, however, to generally assume that a possible screening effect for the Yamato stony meteorites during the transportation through the ice sheet is not serious.

3. Sinking Speed of a Meteorite Piece in the Ice Sheet —The Gravity Separation Effect—

It has been pointed out by GLEN (1955) and others that the single-crystalline or polycrystalline ice generally makes a plastic flow by the creeping mechanism under the effect of mechanical stress. Namely, the strain rate ($\dot{\varepsilon}$) of ice caused by stress (σ) is expressed by

$$\dot{\varepsilon}=K\sigma^n \qquad (n \gtrsim 2)\,, \tag{6}$$

where K is sensitively dependent on temperature in such a way as

$$K=K_0 \exp(-Q/kT)\,. \tag{7}$$

In his original work, GLEN empirically gave $n=4.2$ and $K=0.148\text{yr}^{-1}\cdot\text{bar}^{-4.2}$ for the polycrystalline ice of $-10°\text{C}$ in temperature. However, a number of later experimental studies (*e.g.* WEERTMAN, 1973) have shown that n ranges between 2 and 4, the median value being about 3, and Q around $-10°\text{C}$ in temperature ranges between 10 and 20 kcal·mole^{-1}, the median value being 14 kcal·mole^{-1}. The experimentally measured values of $\dot{\varepsilon}$ at $-10°\text{C}$ in temperature are about 10^{-9} sec^{-1} for $\sigma=1$ bar and about 10^{-6} sec^{-1} for $\sigma=10$ bars for polycrystalline ice so that K at $-10°\text{C}$ is estimated to be $K(-10°\text{C})\simeq 10^{-9}$ sec^{-1} (bar)$^{-3}$ or $K(-10°\text{C})\simeq 3\times 10^{-2}$ yr^{-1} (bar)$^{-3}$. Putting $Q\simeq 14$ kcal·mole^{-1} into eq. (7), the K value at $-20°\text{C}$ is estimated to be about one third of that at $-10°\text{C}$.

The present problem is concerned with a sinking speed of a meteorite piece under the effect of gravity through the ice sheet which has such a plastic characteristic as summarized above. For an example of the simplest possible case, the speed (U) of steady sinking of a rigid sphere of a in radius and ρ in density in a viscous fluid of ρ_0 in density is given by the Stoke's law

$$U=\frac{2}{9}\frac{\rho-\rho_0}{\mu}ga^2, \tag{8}$$

where μ and g denote respectively the coefficient of viscosity and the gravity accerelation. In the case of a perfectly viscous fluid, the strain-rate stress relation is represented by

$$\dot{\varepsilon}=\sigma/\mu\,, \tag{9}$$

which is identical to the case of $n=1$ in eq. (6). In the present case, a similar problem of the sinking speed of a rigid sphere through the plastic medium represented by

$$\dot{\varepsilon}=K\sigma^3 \tag{6$'$}$$

may stand for a model for a meteorite piece sinking through the ice sheet. It may be difficult to exactly solve such a mathematical problem, but the dimension analysis method can help to evaluate the order of magnitude of the steady sinking speed of a rigid sphere of a in radius through the plastic medium represented by eq. (6′). Let us start first with the case of a perfect viscous medium represented by eq. (9). Denoting the steady sinking speed by U, the creeping strain-rate may be expressed in terms of the average horizontal gradient of downward velocity of the circumsphere medium as given by

$$\dot{\varepsilon}=\alpha\frac{U}{a}, \tag{10}$$

where α denotes a dimensionless numerical factor. On the other hand, the load of the rigid sphere should give rise to a stress distribution within the ice medium beneath the lower spherical surface. Then, the stress (σ) may be represented in terms of the average pressure affecting the lower semi-surface of the sphere as expressed by

$$\sigma=\frac{(4\pi/3)a^3(\rho-\rho_0)g}{2\pi a^2}\beta=\frac{2}{3}a(\rho-\rho_0)g\beta, \tag{11}$$

where β represents a dimensionless numerical factor. Putting eqs. (10) and (11) into eq. (9), we get

$$U=\frac{2\beta}{3\alpha}\frac{(\rho-\rho_0)}{\mu}ga^2. \tag{12}$$

If we put

$$\beta/\alpha=\frac{1}{3}, \tag{13}$$

eq. (12) becomes identical to eq. (8). The agreement of physical characteristics of expression of U between eqs. (12) and (8) may justify the present approach with the aid of dimension analysis method.

Now, putting eqs. (10) and (11) into eq. (6′), we can get

$$U=\frac{8}{27}K\frac{\beta^3}{\alpha}(\rho-\rho_0)^3g^3a^4. \tag{14}$$

or putting eq. (13) into eq. (14),

$$U=\frac{8}{81}K\beta^2(\rho-\rho_0)^3g^3a^4. \tag{15}$$

As for the numerical values of ρ of meteorites and ρ_0 of ice, we may be able to adopt $\rho=3.4$ for the stony meteorites, $\rho=7.0$ for the iron meteorites and $\rho_0=0.85$ for the average ice sheet. As already discussed, the K values can be estimated as

$$K(-10°\mathrm{C})=3\times10^{-2}\,\mathrm{yr}^{-1}(\mathrm{bar})^{-3}=3\times10^{-21}\,\mathrm{yr}^{-1}\,(\mathrm{erg/cm}^2)^{-3}$$

and

$$K(-20°\mathrm{C})=1\times10^{-2}\,\mathrm{yr}^{-1}(\mathrm{bar})^{-3}=1\times10^{-21}\,\mathrm{yr}^{-1}\,(\mathrm{erg/cm}^2)^{-3}.$$

Then, eq. (15) can give the numerical estimates of U in unit of β^2 (cm/year) for various sizes of a for both the stony and iron meteorites as given in Table 2. Since U depends on the dimensionless numerical factor β, an approximate magni-

Table 2. Steady sinking speed (U) of a spherical meteorite of a in radius through ice.

a	0.4	1	2	4	10	20	40 (cm)
Stony meteorite (ρ=3.4)							
$T=-10°C$	1.2×10^{-13}	4.6×10^{-12}	7.4×10^{-11}	1.2×10^{-9}	4.6×10^{-8}	7.4×10^{-7}	1.2×10^{-5}
$T=-20°C$	3.9×10^{-14}	1.5×10^{-12}	2.5×10^{-11}	3.9×10^{-10}	1.5×10^{-8}	2.5×10^{-7}	3.9×10^{-5}
Iron meteroites (ρ=7.0)							
$T=-10°C$	1.7×10^{-12}	6.5×10^{-11}	1.0×10^{-9}	1.7×10^{-8}	6.5×10^{-7}	1.0×10^{-5}	1.7×10^{-3}
$T=-20°C$	5.5×10^{-13}	2.2×10^{-11}	3.5×10^{-10}	5.5×10^{-9}	2.2×10^{-7}	3.5×10^{-6}	5.5×10^{-4}

(unit for U: β^2 cm/year)

tude of β will have to be estimated. It may be obvious here that both α and β values are not much different from unity, as indicated in the hydrodynamical treatment in detail for a falling rigid sphere through a viscous fluid (*e.g.* LAMB, 1932). Actually the ratio of β to α is 1/3 as given by eq. (13). It may thus be considered that β will not exceed 10 in its largest possible case. Referring then to Table 2, the largest one (11.0 kg in weight; 9.2 cm in mean radius) of the Yamato stony meteorites should have the sinking speed less than only 4.6×10^{-6} cm/year at $-10°C$ of ice temperature. The actual shape of this stony meteorite (Yamato-75102) is approximately oblate, about 13 cm in the major radius rather than spherical, but no essential difference can be expected by taking this shape into consideration in regard to the order of magnitude of sinking speed.

It may thus be concluded that the estimated value of U for the Yamato stony meteorites can never exceed 5×10^{-6} cm/year. Since the downward component of ice flow velocity within the ice sheet can be estimated at 5–20 cm/year, as discussed in the next section, steady sinking of the Yamato stony meteorites through the ice sheet caused by the gravity separation effect could be ignored in comparison with the downward movement speed of the meteorites together with the surrounding ice. In other words, we can consider that the Yamato stony meteorites are transported by the surrounding ice flow within the ice sheet with a negligibly small mutual displacement.

This situation is not essentially different even for the iron meteorites provided that their mean diameter is less than 80 cm, which corresponds to about 1.9 tons in weight and less than 0.17 cm/year in the sinking speed.

4. Transportation of Meteorites by Ice Flow in the Ice Sheet

The surface topography of the ice sheet in the vicinity of the Yamato Mountains and Fuji Divide is illustrated in Fig. 3 (FUJIWARA *et al.*, 1971). It is observed in the figure that the surface topography of the ice sheet along a line connecting the Fuji Divide and the Yamato Mountains forms a typical ice sheet profile. Results of the snow accumulation measurements with the aid of snow stakes (FUJIWARA and ENDO, 1971) have shown that the annual accumulation

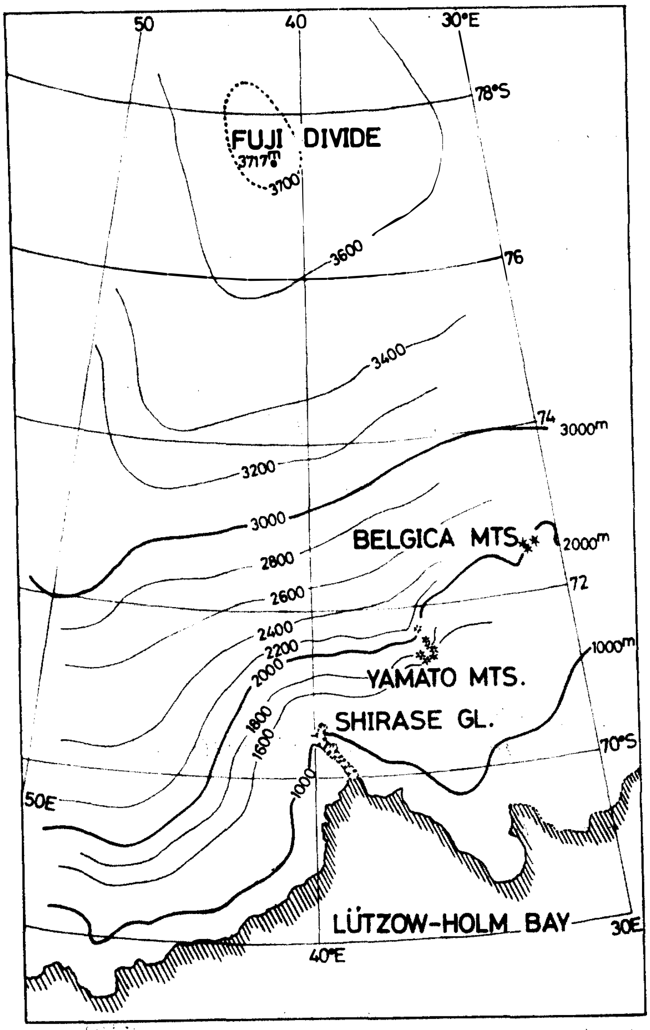

Fig. 3. Ice sheet surface topography in the vicinity of the Yamato Mountains and the Fuji Divide.

rate of snow between 72°S and 76°S in latitude in this area ranges from 5 to 15 cm water/year. It will be obvious that the snow and ice mass in the area concerned is a part of the East Antarctic ice sheet which maintains as approximately steady state owing to the mass balance between the accumulation of snow over the ice sheet surface and the loss of ice and snow at the edges of ice sheet as well as the loss by the ablation effect.

As discussed in the foregoing section, the gravity separation effect of a meteorite in the ice sheet is negligibly small in comparison with the ice flow in the ice sheet. Therefore, a meteorite piece which fell in the accumulation area of the ice sheet surface is to be transported directly by the ice flow to the ablation area surface. In this connection, the ice flow characteristics within an ice sheet will be theoretically discussed in the following. Theoretical ice sheet profiles kinematically derived by NYE (1959) and HAEFELI (1961) are in reasonably good agreement with the observed profiles of ice sheets. Since, however, their theoretical models do not satisfy the mass conservation law in regard to the necessary ice-mass balance between the incoming ice through the accumulation area and the outgoing ice through the ablation area, NAGATA (1977) has proposed a self-consistent ice sheet model, in which the ice mass conservation is exactly satisfied.

In NAGATA's two dimensional model of an ice sheet whose total width and height of the crest point are represented by $2L$ and H respectively, the elevation of ice sheet surface (h) at horizontal distance (x) from the crest point position ($x=0$) is expressed by

$$\frac{x}{L}=\left(1+\frac{m}{m+1}\cdot\frac{h}{H}\right)\left(1-\frac{h}{H}\right)^{m/(m+1)}, \tag{16}$$

where m denotes a constant representing the stress and strain-rate relationship of plastic ice and generally $m=2$–3. When a uniform thickness of ice (b) is continuously added to the ice sheet surface per unit time, the horizontal and vertical velocities (u and w respectively) of ice flow at coordinates (x, z) within the ice sheet are given by

$$\left.\begin{aligned} u&=b\left(\frac{2m+1}{m+1}\right)\cdot\frac{x/H}{1+(h/H)m/(m+1)},\\ w&=-b\frac{z}{h}. \end{aligned}\right\} \tag{17}$$

provided that the bedrock surface beneath the ice sheet ($z=0$) is assumed to be horizontally flat. The corresponding streamlines of ice flow are expressed as

$$\left(\frac{xz}{LH}\right)\left(1+\frac{m}{m+1}\cdot\frac{h}{H}\right)^{-(m+1)/(2m+1)}=\textbf{constant}. \tag{18}$$

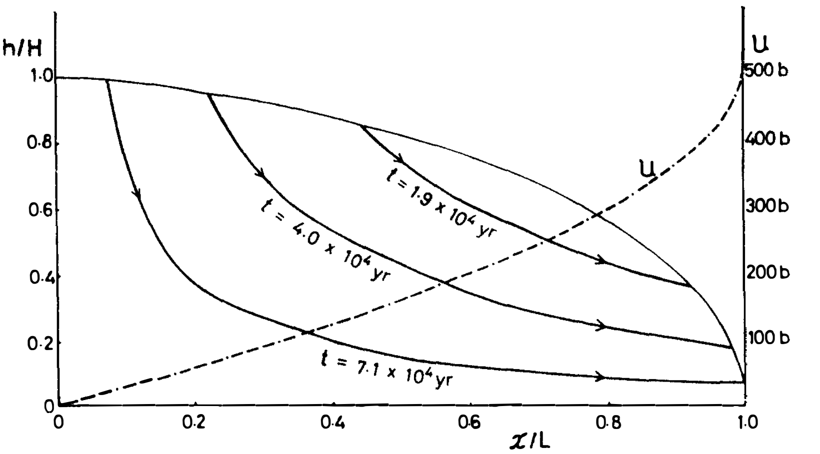

Fig. 4. Theoretical ice sheet profile and streamlines of ice flow within the ice sheet.

In Fig. 4, the ice sheet surface profile given by eq. (16) and three typical streamlines given by eq. (18) are illustrated for the case of $m=2$, together with the dependence of u in unit of b upon x/L. As shown in Fig. 4, all masses of snow accumulating on the accumulation surface which is defined by $x \leq x_e$ flow through the ice sheet interior to the ablation surface defined by $x \geq x_e$, where x_e of the equilibrium point is given by

$$x_e = L\left(\frac{3m+1}{2m+1}\right)\left(\frac{m}{2m+1}\right)^{m/(m+1)} .$$

Hence, any meteorite falling on the accumulation surface should be transported together with the ice flow to the ablation surface. On the ablation surface, the transported ice itself disappears owing to the ablation effect, but the transported meteorites will remain on the ice sheet surface. In this regard, the observed fact that the Yamato meteorites have been found only on the blue ice surface would suggest that the strong ablation effect on the ablation area is an extremely important necessary condition to result in the presence of meteorites on the blue ice surface.

Since the meteorites found on the blue ice surface of the ablation area may have been transported by the ice flow from the accumulation surface where they fell some time ago, the travel time for the meteorites from the point of fall to the point of exposure can be estimated with the aid of eqs. (17) and (18). In the case of the Yamato meteorites, $m=2$, $L=900$ km, $H=3000$ m and $b=10$ cm water/year would be reasonable figures for the parameters, m, L, H and b in eqs. (17) and (18). In Fig. 4, the travel times (t) of meteorites along three streamlines starting from $x=70$ km, 120 km and 400 km thus estimated are given as 7.1×10^4 years, 4.0×10^4 years and 1.9×10^4 years respectively. This result may indicate that the Yamato meteorites found on the blue ice of the ablation area fell in the accumulation area of the snow surface on the northern slope of the Fuji Divide at least 10^4–10^5 years ago, though no estimate could be made at present how long they have been lying on the Meteorite Ice Field since their exposure time.

5. Effects of Bedrock Surface Topography

In the foregoing section, the ice flow within the ice sheet is theoretically examined for the two dimensional model, in which the bedrock surface is assumed to be horizontally flat. The ice sheet in the vicinity of the Yamato Mountains and the Fuji Divide, however, is three dimensionally extended and the bedrock surface is not horizontally flat at all but has a considerably complicated topography. Particularly, the bedrock topography near the Yamato Mountains forms a barrier obstructing the flow of ice sheet as illustrated in Figs. 1 and 3. In a simple model of three-dimensional ice sheet formed on the horizontally flat base (*e.g.* HAEFELI, 1961; NAGATA, 1977), the direction of ice flow is perpendicular to the contours of the ice sheet surface. In fact, the ice sheet surface flows observed between 2,400 m and 2,250 m in the surface elevation in Fig. 1 are approximately perpendicular to the contours (see Fig. 7). It may be clear in Fig. 1, then, that the ice sheet flow coming down towards the Yamato Mountains is prevented by the mountain range which makes a rigid obstacle against the ice flow. Hence, the ice flow coming down towards the Yamato Mountains should be forced to make an upwell movement up to the ice sheet surface at least in the close neighborhood of the mountains. The effect of presence of high bedrock mountains reaching above the ice sheet surface upon the ice sheet flow behaviors has not yet been theoretically examined, though a similar problem for the case of a bedrock mountain range whose height is small compared with the ice sheet thickness was treated by NYE (1959). Hence it can not be theoretically estimated how much part of the coming down ice flow shows up to the ice sheet surface while the other parts take circuitous routes around the mountains. In the present study, therefore, the vertical movement of the ice sheet surface will be experimentally examined in the neighborhood of the Yamato Mountains. In Fig. 3, on the other hand, it looks likely that the ice sheet surface flow west of 43°E meridian line tends to horizontally converge towards the Yamato Mountains area. The total cultivation area for the ice sheet flow converging towards the mountains amounts at least to 2.5×10^5 km^2. The main driving force for such a horizontal convergence could be attributed to the bedrock topography in East Antarctica which forms two large sub-ice mountain ranges between 0° and 60°E in longitude, as illustrated in Fig. 5. As shown in the figure, the Sør-Rondane Sub-Ice Mountains extend nearly parallel to the Antarctic Sea coast and the Yamato Mountains are located near the eastern end of the sub-ice mountains, while the Vernadsky Sub-Ice Mountains extending northwards along 40°E meridian line forms a valley between themselves and the Sør-Rondane Mountains in the bedrock topography. It seems very likely that the Shirase Glacier shown in Fig. 3 is subjected to the ice stream caused by the sub-ice valley. Although, it seems very likely in the sub-ice bedrock topography that the two sub-ice mountains may cause a horizontally converging tendency as well as a pilling-up of the flowing ices on the southern side of the Sør-Rondane Mountains, theoretical estimates of the pilling-up ice masses and the flowing-out ones are still difficult at present. In the present study, therefore, the horizontal convergence (or divergence) of ice sheet surface in the neighborhood of the Yamato Mountains will be observationally examined.

Fig. 6 shows an enlarged part of Fig. 1, where the locations of a large number of meteorites collected in 1969, 1973, 1974 and 1975 are plotted in the blue ice area together with the triangulation point stakes which were specifically set up for the purpose of measuring the movement of ice sheet surface in this area. The base points, A1 and A2, were set up on nunatak surfaces respectively so that both the horizontal and vertical movements of each triangulation point were exactly determined as the relative movements with respect to the fixed bedrock coordinates.

The triangulation survey on the network was first carried out in November-

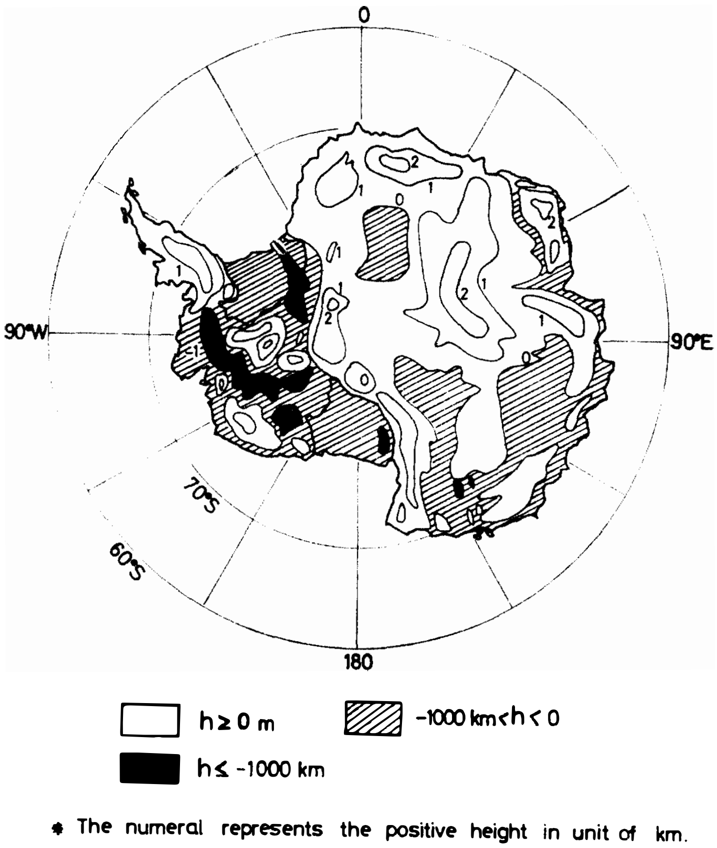

Fig. 5. Bedrock topography of the Antarctic Continent (after Budd, *1971).*

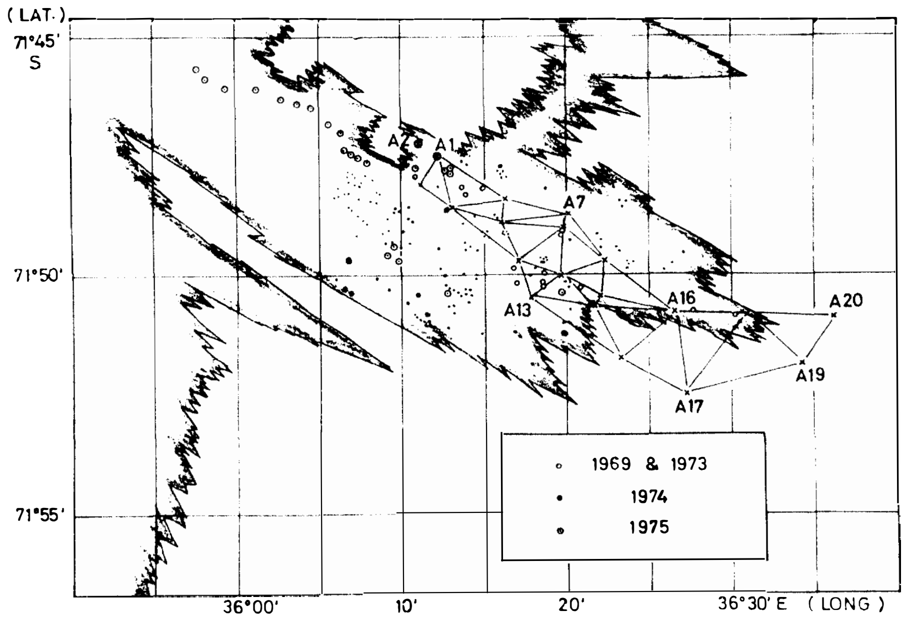

Fig. 6. Distribution of the Yamato meteorites in the southeastern corner of the Meteorite Ice Field, and the triangulation networks for measuring the ice sheet surface movement.

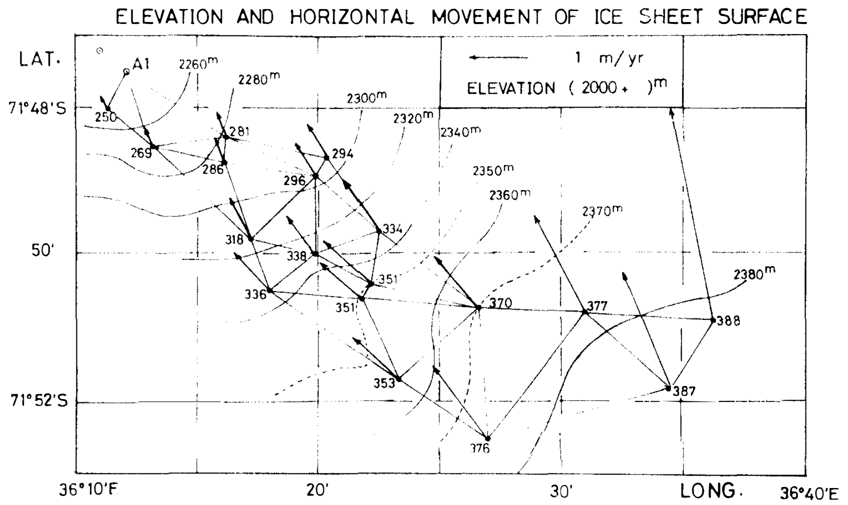

Fig. 7. Horizontal movement and elevation of ice sheet surface near the Yamato Mountains.

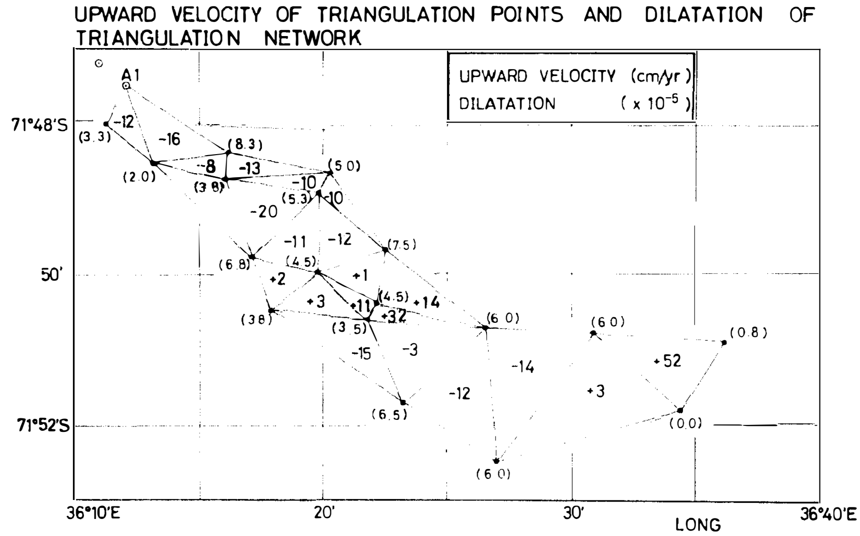

Fig. 8. Upward velocity of the ice sheet surface and dilatation of the triangulation network near the Yamato Mountains.

December 1969 and re-surveyed in December 1973–January 1974 (NARUSE, 1975). The horizontal movement velocities at these triangulation points observed during the four years are shown by vector arrows in Fig. 7, where the elevations of these points also are given together with approximate contours of the ice sheet surface. As illustrated in Fig. 7, the velocity vectors of the horizontal ice flow are, in principle, perpendicular to the contour lines, and the velocity magnitude gradually decreases towards zero with the approach of the ice sheet surface towards the base point on Nunatak (A1). In Fig. 8, the annual rate of vertical movement of each triangulation point is given in parentheses. It can be observed in the figure that all triangulation points except the base point A1 are making

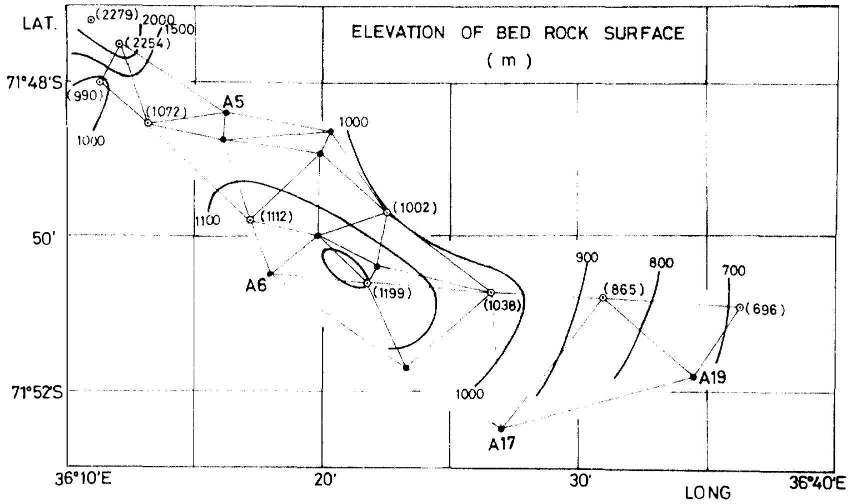

Fig. 9. Elevation of bedrock surface beneath the triangulation network.

upward movements of 0–8 cm/year in velocity, the average upward velocity being 4.6 cm/year. It must be noted that the vertical movement values reported here represent the net vertical movement, the effect of the thickness of net accumulation of snow being eliminated. For comparison, similar surveys carried out during the same period to measure the horizontal and vertical movements of the ice sheet surface along an approximately east-west survey route of about 72°S in latitude and between 38°E and 43°E in longitude in Mizuho Plateau have shown that the approximately northward horizontal flow velocity amounted to 15–20 m/year, while the vertical movement was downwards and its average speed was about 1 m/year (NARUSE, 1975). It seems that the flow pattern of ice sheet surface in this area of 72°S in latitude and 38°–43°E in longitude represents reasonably well the general flow pattern of ice sheet surface which is theoretically discussed in Section 4. Namely, the inclination of ice flow vector ($\simeq -1/20$) is in approximate agreement with the inclination of ice sheet surface itself ($\sim -1/20$) in the area concerned. It may be concluded then that the ice sheet surface flow pattern shown in Figs. 7 and 8 is much anomalous, strongly suggesting an upward and horizontally convergent movement of ice sheet surface in the Meteorite Ice Field. In order to numerically estimate the magnitude of horizontal convergence in the Meteorite Ice Field area, the horizontal dilatation of each triangle area cornered by the triangulation points have been computed. As shown by the result of computations in Fig. 8, the dilatation values in most triangle areas shows negative values (*i.e.* horizontal convergence). A narrow band comprising six small triangle areas having positive dilatation values (*i.e.* horizontal divergence) reflects the effect of a sub-ice bedrock mountain, shown in Fig. 9.

It seems thus that all the observed results in regard to the three-dimensional movements of ice sheet surface in the neighborhood of the Yamato Mountains are in favor of the hypothesis that the ice mass accumulating in a wide area (about 2.5×10^5 km^2) on the NNW slope of the Fuji Divide flows down through the ice sheet to a comparatively limited area near the Yamato Mountains and is forced to come up to the ice sheet surface owing to the sharp bedrock mountain topography.

6. Ablation of Blue Ice Surface to Expose Meteorite Pieces

As mentioned in Introduction, all Yamato meteorite pieces were found on the blue ice surface in the Meteorite Ice Field, with one exceptional case of a stony meteorite which was buried in the blue ice at about 10 cm in depth. The blue ice areas occur only in the ablation area of ice sheet, where the compressed dense glacier ice rises from the interior up to the surface of ice sheet. It has been actually observed that the blue ice in the Meteorite Ice Field is moving upwards with an annual velocity of about 5 cm/year. Another necessary condition for forming a blue ice surface area in the ablation area of an ice sheet is of course that the ablation rate is large enough to continuously remove the accumulating snow. The measurements of the accumulation of snow or the ablation of blue ice were made by the snow stake method during the same period as that for measuring the horizontal and vertical movements of ice sheet surface at the triangulation points shown in Fig. 6 (YOKOYAMA, 1975). The observational results are illustrated in Fig. 10, where the annual ablation rate (−) or the accumulation rate (+) at each point is given in unit of cm/year. (Remarks: At the two points with no value of accumulation or ablation rate in Fig. 10, the snow stakes were damaged during the four years). It is seen in the figure that, at all measured points, the ablation rate amounts to 2–7 cm/year, whereas the accumulation rate is positive at some points in the snow covered area. The average annual rate of ablation at 10 points within the blue-ice area amounts to 5.4 cm/year.

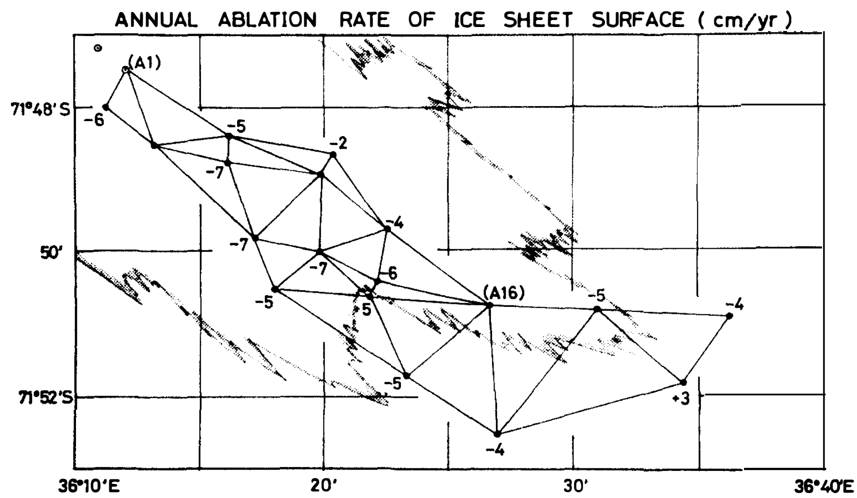

Fig. 10. Annual ablation rate of ice sheet surface over the triangulation network area near the Yamato Mountains (cm/year).

The accumulation rate (A) given in Fig. 10 represents an annual change rate of the ice sheet surface referred to the base point of the bottom end of a snow stake which is about 2 m deep from the surface, whence the observed value of A should be the sum of the local snow accumulation rate (b) and the local net ablation rate for both the accumulating snow and the coming-out blue ice (a). Owing to the local pattern of prevailing wind system, actual values of b and a may be considerably different at different points. Over the blue ice surface area, therefore, the ablation effect must be considered to be large enough to completely remove the accumulating snow and further scrape out the surface of the upwelling blue ice. The observed average value (-5.4 cm/year) of annual ablation rate in the blue ice area is approximately cancelling the average value of the annual upward rate ($+4.6$ cm/year) of blue ice mass over the same area.

From the observed results of the movements and the ablation rate of ice sheet surface in the blue ice area, described in the foregoing and present sections, it may be generally concluded that the blue ice mass is coming upwards from the ice sheet interior with an annual rate of about 5 cm/year and it is continuously scraped out by the ablation effect of about 5 cm/year in annual rate, thus the blue ice surface being maintained in an almost steady state in the blue ice area near the Yamato Mountains. The blue ice flow is continuously carrying a number of meteorites with it to the bare surface, and those meteorites after their long-time travel may remain on the blue ice surface though the ice itself will continue to diminish owing to the ablation effect. This interpretation suggests that the exceptional meteorite piece buried at about 10 cm from the blue ice surface may probably be on its way to come out to the surface.

7. Summary and Concluding Remarks

The differential frequency spectrum of the Yamato stony meteorites (which hold the majority of Yamato meteorites), a possible effect of the gravity separation for meteorite pieces sinking through the plastic ice sheet ice of lower density and the ice flow behaviors within an ice sheet are first examined in the present study. These studies have led to a conclusion that all meteorites falling in the accumulation area of the Antarctic ice sheet will be transported by the ice flow within the ice sheet, without a considerable displacement from the surrounding ice mass, to the ablation area surface. Then, the surface ice flow and the ablation effect of the Antarctic ice sheet in the vicinity of the Meteorite Ice Field near the Yamato Mountains in East Antarctica are practically examined on the basis of the observed glaciological data. These data analysis studies have indicated that the blue ice surface of the Meteorite Ice Field very close to the Yamato Mountains is making an upward and horizontally convergent movement and the blue ice surface is continuously scraped out by the ablation effect, resulting in the exposure of meteorites on the surface. In the case of the Meteorite Ice Field in East Antarctica, it seems very likely further that the ice mass accumulating on a considerably large area on the NNE slope of the Fuji Devide tends to converge towards the Meteorite Ice Field. Summarizing all these results, the most plausible mechanism of accumulating a large number of meteorites ($\sim 10^3$ pieces) within a limited area of blue ice surface ($\sim 4\times 10^3$ km^2) will be such that meteorite pieces falling on a considerably wide surface ($\sim 2.5\times 10^5$ km^2) of the accumulation area of the East Antarctic ice sheet during a long period of time (T) have been convergently transported by the ice sheet flow (1–10^2 m/year in speed) towards the Meteorite Ice Field in the ablation area, where an upwell movement of ice caused by the bedrock topography forming the Yamato Mountains further accelerates the rise of the meteorites to the ice sheet surface (~ 5 cm/year in upward velocity) and the strong ablation effect (~ -5 cm/year) for ice results in the disappearance of ice mass itself, leaving the transported meteorites to remain permanently on the blue ice surface.

In the case of the Yamato meteorites found in the Meteorite Ice Field, the travel time for the meteorite from the points of their fall in the accumulation area to the points of exposure in the ablation area is estimated to be 10^4–10^5 years. It has been believed, on the other hand, that the Antarctic Continent has remained in the present position for the past 10^8 years at least. However, no indicative data are available at present to estimate how long the oldest one of Yamato meteorites has been lying on the present position. Let us assume arbitrarily then that the Yamato meteorite collection is a part of an assemblage of meteorites falling on the estimated accumulation surface of 2.5×10^5 km^2 in area during $T=10^6$ years. According to HAWKINS (1960), the influx rate of meteorite falls on the earth's surface has been estimated to be approximately 4.5×10^{-11} meteorites$\cdot$km^{-2} hr$^{-1} \simeq 4\times 10^{-7}$ meteorites, km^{-2} yr^{-1}. If these figures of the influx rate of meteorites, the area of fallen meteorites converging into the Meteorite Ice Field and the duration of meteorite fall are adopted, the total number of meteorites within the Meteorite Ice Field would amount to as many as 10^5, provided that there has been no loss of meteorites. YANAI (1978a) has estimated that the total number of meteorites including uncollected ones within the Meteorite Ice Field would be about 8×10^3 or less. It could be considered then that the hypothesis for the Yamato meteorite accumulation mechanism discussed above is not unreasonable even if a safety factor with respect to a possible loss of meteorites from the Meteorite Ice Field is taken into consideration.

This hypothesis could be supported by the result of its actual field test in West Antarctica, too. On the basis of this hypothetical interpretation of the Yamato meteorite accumulation, field surveys in search of meteorites on the blue ice surface of the ablation area in Victoria Land of Antarctic ice sheet just on the west side of Transantarctic Mountains were carried out (see YANAI, 1978b). The blue ice areas selected for the meteorite search program in West Antarctica satisfy the necessary conditions concluded in the present hypothesis, such as

(i) blue ice areas in the ablation zone of ice sheet, and

(ii) blue ice areas where the ice sheet flow is prevented by mountains.
The field work searching for meteorites planned on the basis of the present hypothesis was successful in finding 11 pieces of meteorite (9 chondrites, one achondrite and one iron) in the blue ice areas near Mt. Baldr and Allan Nunatak. It seems thus that the present hypothesis for meteorite accumulation mechanism within blue ice areas of Antarctic ice sheet has been reasonably well justified. A remaining question may be concerned with the abundance ratios of iron and stony-iron meteorites among the Yamato meteorite collection. If the observed scarcity of irons and stony-irons in the Yamato meteorite collection is considered statistically significant, there must be a certain mechanism to obstruct the emergence of heavy meteorites onto the blue ice surface. It was once suggested (NAGATA *et al.*, 1976) that the gravity separation effect may prevent the transportation of heavy iron and stony-iron meteorites by the upward ice flow. However, the semi-quantitative examination of this problem summarized in Section 3 of the present paper has shown that the gravity separation effect is considerable only for very large meteorites, such as iron meteorites larger than 2 m in radius or heavier than 200 tons in weight, which may have a sinking speed of about 10 cm/year through the ice sheet of $-10°C$ in temperature. Actually an iron meteorite of 1.51 kg in weight was found on the blue ice surface near Allan Nunatak in Victoria Land in West Antarctica. At the present stage of study, therefore, no definite mechanism for screening heavy iron meteorites could be proposed.

In concluding this paper, it will be worthwhile to announce that more systematic studies on the distribution of the Yamato meteorites within the Meteorite Ice Field and more extensive surveys on the ice sheet flow in its vicinity are being planned for the future on the basis of the results of present analyses.

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