# DIRT LAYERS AND ATMOSPHERIC TRANSPORTATION OF VOLCANIC GLASS IN THE BARE ICE AREAS NEAR THE YAMATO MOUNTAINS IN QUEEN MAUD LAND AND THE ALLAN HILLS IN VICTORIA LAND, ANTARCTICA

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***Abstract:*** Dirt layers containing volcanic ash fragments were found on the bare ice surface in the Meteorite Ice Field near the Yamato Mountains, Queen Maud Land, and near the Allan Hills, Victoria Land. The grain size analysis of volcanic ash fragments shows that the mean grain size in the Allan Hills region is larger than that in the Yamato Mountains region. This fact indicates that the volcanic sources of the dirt layer in the Yamato Mountains region is farther away than that for the Allan Hills.

Based upon the equations describing the transport of volcanic ash fragments, the distance of atmospheric transportation can be predicted by the grain size distribution, and, furthermore, the tephra sources are estimated. The age of ice-containing tephra is also discussed.

## 1. Introduction

In the Meteorite Ice Field near the Yamato Mountains in Queen Maud Land and in the Allan Hills bare ice area in Victoria Land, Antarctica, many prominent dirt layers occur up-glacier from nunataks. On both bare ice areas a large number of meteorites have been discovered and collected (YANAI, 1981). To elucidate the mechanism of accumulation of a large number of meteorites, studies of the ice flow in both bare ice areas were carried out and the occurrences of dirt bands were also described (NISHIO and ANNEXSTAD, 1979). Though the dirt layers dip up-glacier, little is known of their geometry. It was suggested that the dirt layers are probably windblown dust or perhaps even tephra layers.

During the two austral summers in 1978–79 and 1979–1980, ice samples containing the dirt layer in the Allan Hills bare ice aera were collected by the joint U.S.-Japan meteorite search team (NISHIO and ANNEXSTAD, 1980). In the Meteorite Ice Field near the Yamato Mountains, the dirt layers were found and specimens of them were collected by the glaciological survey party of the 23rd Japanese Antarctic Research Expedition in 1982–1983.

Based upon the petrographical study, it is indicated that all samples of dirt layers collected contain abundant volcanic ash fragments. This fact shows that most of the dirt layers in the bare ice area are tephra layers. Tephra in glacier ice offers a great potential as marker levels for stratigraphic studies and should be useful in providing isochronous planes in the ice sheet.

Many tephra layers have also been found in the ice cores and at the ice surface of glaciers in Antarctica. GOW (1963) presented the first report on tephra layers in ice cores of the Ross Ice Shelf drilled at Little America V. In the deep ice core to a depth of 2164 m at Byrd Station, Marie Byrd Land (Fig. 1), 25 distinct tephra layers and an estimated 2000 dust bands are preserved (GOW and WILLIAMSON, 1971) and their volcanic source for the six tephra layers are studied on the basis of chemical composition of glass shards (KYLE and JEZEK, 1978; KYLE *et al.*, 1981). Large volcanic glass shards were reported by KYLE *et al.* (1981) at 726 m depth in the Dome C ice core, which have compositions similar to those analyzed in the Byrd Station ice core and the same source in Marie Byrd Land. Volcanic glass shards were also reported by KING and WAGSTAFF (1980) from the 101-m firn core at South Pole Station. Furthermore, a 5-cm thick dust band at a depth of 100.8 m in the Vostok Station ice core has been identified as tephra (KYLE *et al.*, 1982). In addition to the known occurrences of tephra layers in Antarctic ice cores, KEYS *et al.* (1977) described the occurrence and compositions of some tephra layers in the ice surface of several glaciers in South Victoria Land.

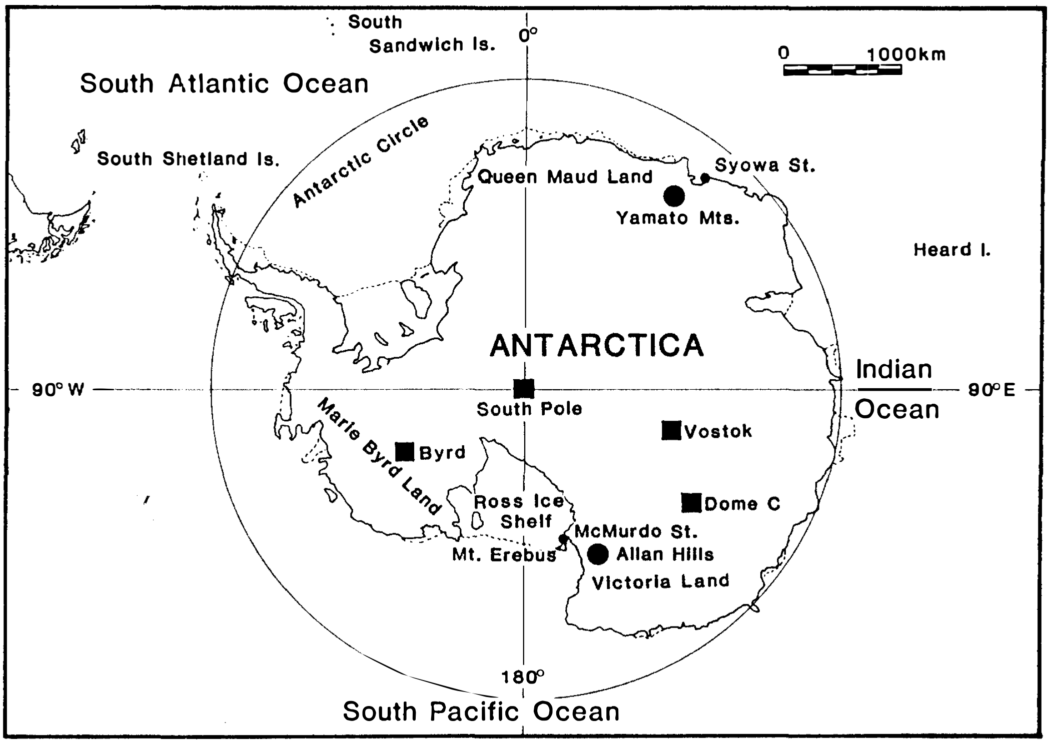


*Fig. 1. Map of Antarctica showing the location of the Yamato Mountains and the Allan Hills (large solid circle) and indicating sites of four ice cores (solid square) known to contain tephra layers.*

It is very important to study tephra layers found in both bare ice surface of the Yamato Mountains and the Allan Hills because tephra layers offer stratigraphic makers in the ice sheet in correlation between widely spaced ice cores and, if tephra is datable volcanic ash, the tephra layers are isochronous planes in the ice sheet.

The petrography and the results of chemical analyses obtained by EPMA of the constituent materials of each tephra layer in both regions were described by KATSUSHIMA *et al.* (1984) with special emphasis on the glass shards. In the present paper we describe the occurrence and grain size analyses of dirt layers found in the bare ice areas near the Yamato Mountains and the Allan Hills. We also describe the atmospheric transportation of volcanic glass based on the grain size distribution and estimate their source area. Furthermore, the ages of ice in both regions are estimated and discussed.

## 2. Occurrence and Description of Dirt Layers

Englacial dirt layers outcropping on the bare ice surface can be observed easily when there is no snow deposited but may be missed where dirt in the ice is in low concentration. Since albedo decreases locally on the surface of a dirt layer, the ice within the dirt layer ablates faster than the surrounding ice to form narrow shallow troughs (Fig. 2). Individual dirt layers showed great differences in length, width, composition of materials and their concentration. Two types of layers are distinguished by the difference in color tone. The darkest layer is very dark brown to black with high concentration of materials generally containing pale brown, dirty fragments and devitrified glass shards. The other type of pale brown layer is characterized by low concentration of materials generally containing colorless, pale brown fragments and clear glass shards. The thickness of the dirt layers varies from a few centimeters to up to about 15 cm. As shown in Fig. 3, the layers dip steeply up-glacier. The dirt

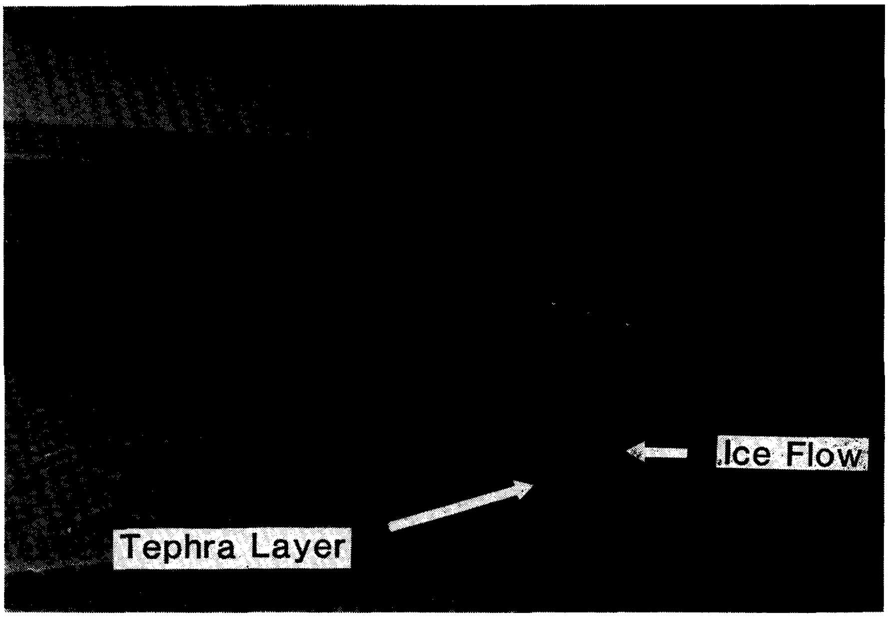


*Fig. 2. Tephra layers on the bare ice surface in the Allan Hills. Ice flows from right to left.*

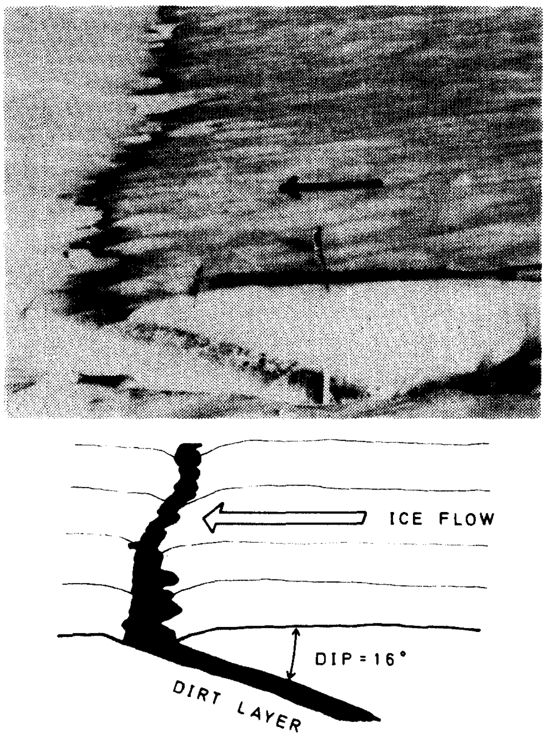


*Fig. 3. Darkest layer of tephra on the bare ice surface in the Allan Hills which dip up-glacier. The ice in this layer of 8 cm in thickness was sampled at site 4 in Fig. 5.*

layers generally have a sharp dirt-ice boundary in the bottom of dirt layer, whereas in the upper part of the layer it is diffuse.

Comments on occurrence of dirt layers in both areas studied are given below.

### 2.1. *Meteorite Ice Field*

Three of the dirt ice samples were collected at different dirt layers in the Meteorite Ice Field near the Yamato Mountains during the triangulation chain surveying to measure the glacial movement as shown in Fig. 4. The ice flow near the Motoi Nunatak was estimated from the southeast to the northwest at a velocity of 0.5–1 $m \cdot yr^{-1}$ (NARUSE, 1978). Glacial movement in the bare ice area where dirt layers were collected is probably directed from southeast to northwest at a velocity of less than several meters per year. Each dirt layer is about 1 m in width and several centimeters in thickness and gently dip up-glacier. In Fig. 4, both dirt layers of K-26(1) and K-26(2) apart 1.3 km are perhaps identical though this was not checked.

### 2.2. *Allan Hills bare ice field*

Eight dirt layers containing tephra were found in the bare ice area east of the Allan Hills as shown in Fig. 5. Dirt layer 4 was followed for approximately 6 km, and was covered with snow in places. As shown in Fig. 3, this layer 8 cm in thickness dips steeply by 16 degrees up-glacier, and the darkest one contains pale brown and devitrified glass shards. Dirt layers 2, 3 and 5 are approximately parallel to layer 4, the closest being 100 m from layer 3.

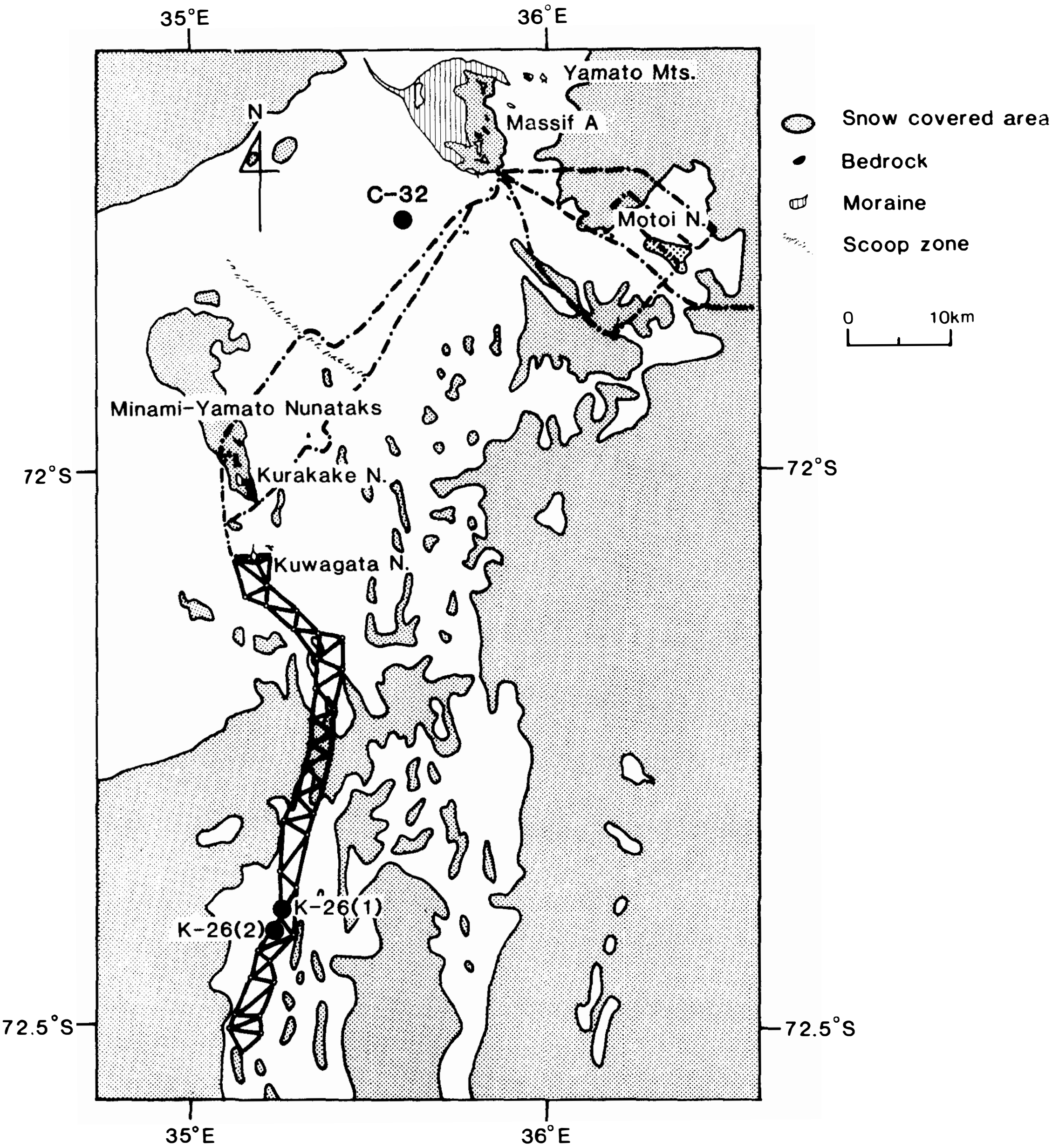


*Fig. 4. Map of southern part of the Meteorite Ice Field near the Yamato Mountains. Solid circles show the sampling site of dirt ice in the dirt layer, and sample names are given as C-32, K-26 (1) and K-26 (2). Solid line indicates the triangulation chain installed on the Kuwagata Nunatak as datum points and extended about 50 km southward. Dotted-dash line shows the traverse route for glaciological study.*

The horizontal velocity of the bare ice was less than $2.5\,\mathrm{m \cdot yr^{-1}}$ and the velocity vector principally points northeast which is perpendicular to the contour lines (NISHIO and ANNEXSTAD, 1980). As can be seen in Fig. 5, most of the dirt layers are oriented perpendicular to the glacier flow, but at places they are parallel to the glacier flow. The most remarkable layer 4 shows a U-shpae surface configuration, thrusted by the upward glacial flow.

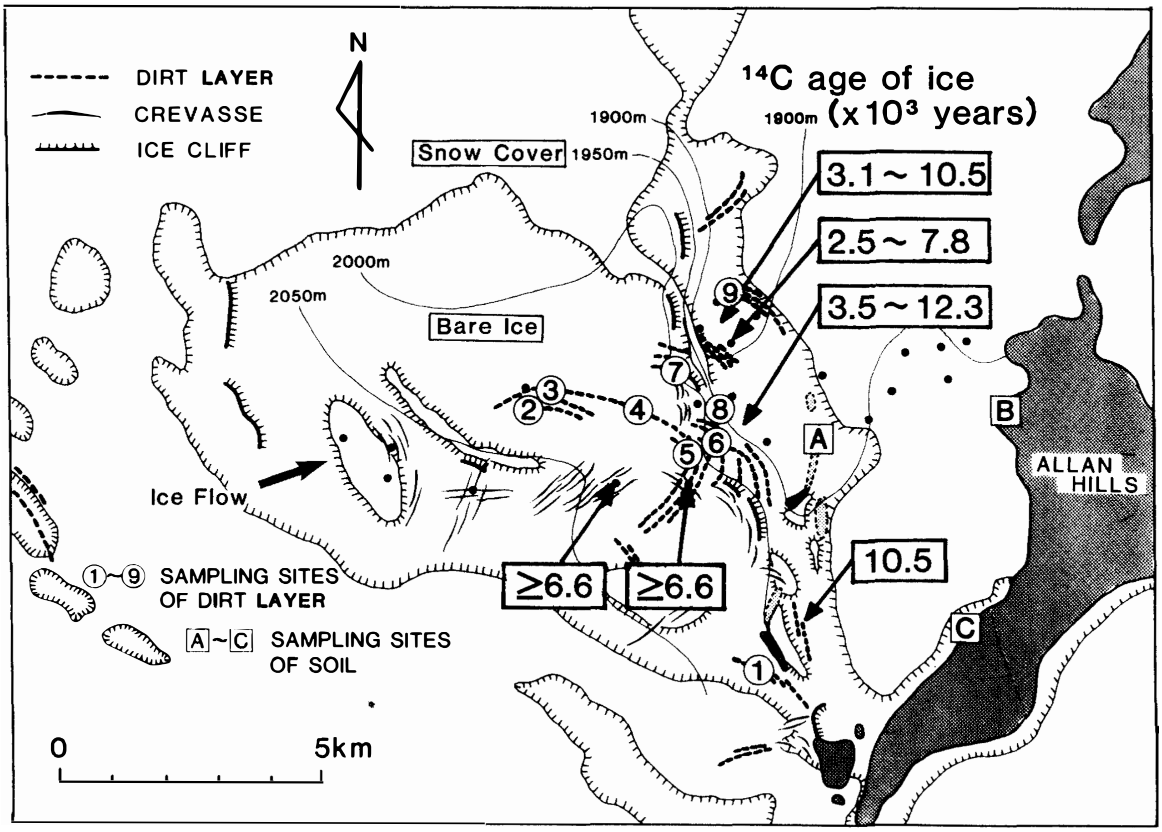


*Fig. 5. Surface morphology and dirt layer distribution in the Allan Hills bare ice field. The open circles with number show the location of samples. The $^{14}$C age of ice (FIREMAN and NORRIS, 1982) is also indicated by arrows. The unit of age is $10^3$ years.*

## 3. Structure of the Ice

Thin sections of ice-containing tephra were prepared and photographed through crossed polaroids. Figure 6 shows the vertical thin section of dirt layer the same as the layer in Fig. 3. The ice from the surface to 2 cm in depth contains tephra and crystal size is finer than that in the rest of the vertical thin section. The finer crystal size in the layer is probably attributable to restricted growth of the crystals in the dirt-rich ice. Almost all fabric diagrams of the ice specimens without tephra exhibit double maxima of $c$-axis orientation (NISHIO *et al.*, 1982). However, the ice specimens containing tephra indicate the single maximum and the direction of principal $c$-axes is nearly perpendicular to the dirt layer. Therefore, it may be inferred that shearing deformation has occurred paralles to the dirt layer.

## 4. Grain Size of Volcanic Ash Fragments

The grain size distribution of these tephra layers has been determined by scanning electron microphotographs, in which the cross-sectional area of the irregular shape of volcanic ash fragments is estimated by the area of the circle and then the grain size is given as particle diameter, the same as the area of circle shape. The grain size distri-

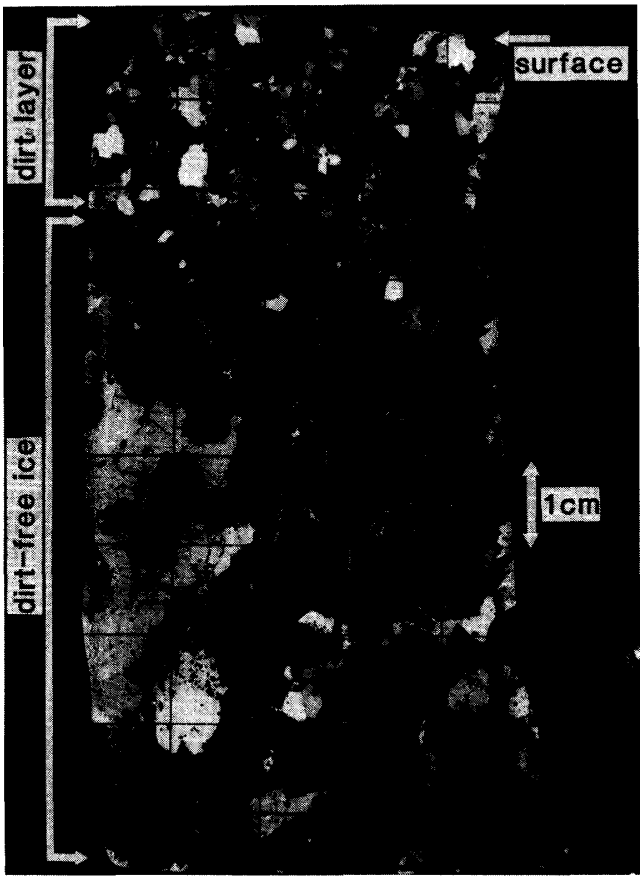


*Fig. 6. Vertical thin section of ice of dirt layer 4 in the Allan Hills, photographed through crossed polaroids.*

bution is given as histograms in Fig. 7 for three tephra layers in the Meteorite Ice Field and eight, designated ALH, in the Allan Hills bare ice area Grain size is shown on a logarithmic scale in units of phi and $\mu$m.

All the tephra layers show normal grain size distribution. The samples in the Allan Hills beside ALH-8 have a strong indication of unimodality with median grain size of 125–65$\mu$m, whereas ALH-8 shows broadly normal distribution with median grain size of 20$\mu$m. The samples in the Meteorite Ice Field also have a strong normal distribution with median grain size of 50–35$\mu$m. The nature of the distribution is probably a function of the distance from volcanic source and the eruption size. CAREY and SIGURDSSON (1982) and CORNELL *et al.* (1983) show that generally the mean grain size of deposited volcanic ash decreases with increasing distance from volcanic source. And also, the grain size distribution near the eruption center is bimodal, whereas distal samples are unimodal in grain size from analyses of ash-layers in deep-sea cores and ashfall deposited by eruption of Mount St. Helens. The larger grain of ash is due probably to the shorter distance transportation. As can be seen in Fig. 7, the mean grain sizes in the Allan Hills are larger than those in the Meteorite Ice Field. Therefore, it is suggested that the volcanic sources of tephra layer in the Meteorite Ice Field are farther than those in the Allan Hills.

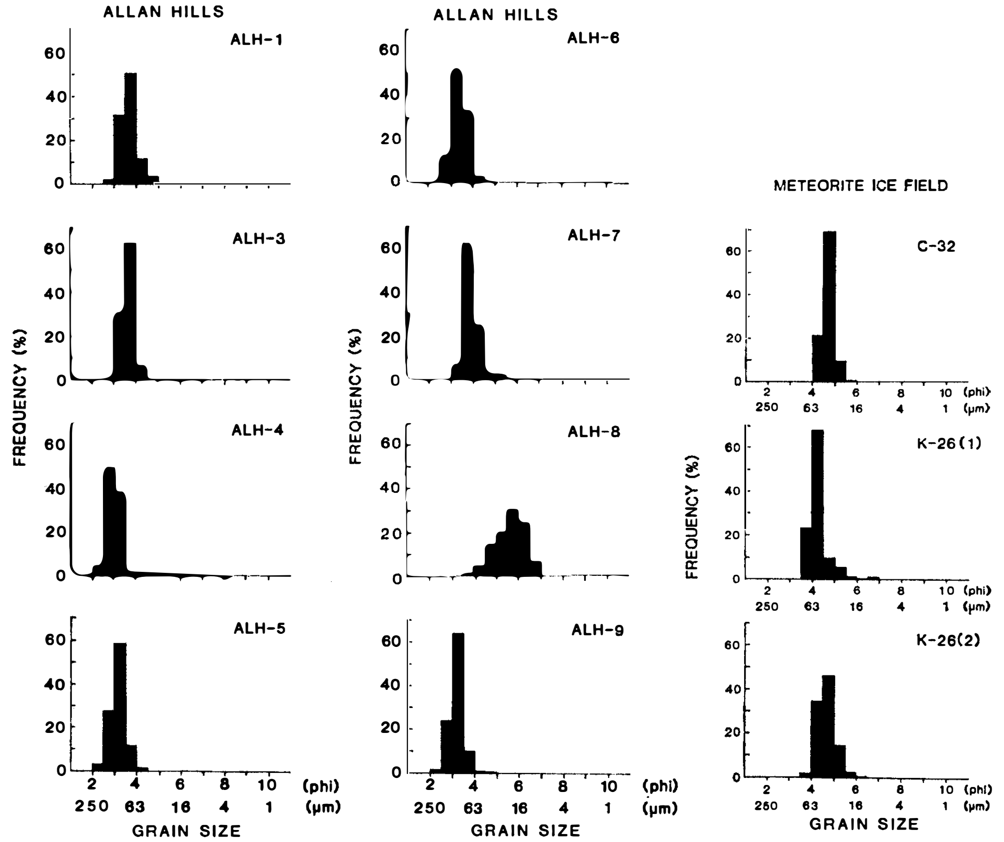


*Fig. 7. Histograms of grain size distribution for three tephra layers in the Meteorite Ice Field and eight, designated ALH, in the Allan Hills bare ice area. The per cent of particles of each grain size interval was computed assuming a circular cross-section for the particles. Note that the size is logarithmic, in units of phi and μm.*

## 5. Atmospheric Transportation of Volcanic Glass

We have constructed a simple method of atmospheric transportation of volcanic ash fragments composed of more than 80% volcanic glass shards in dirt layers to estimate volcanic source from the grain size analyses. SHAW *et al.* (1974) developed equations describing the transport of ash particles in terms of mean horizontal wind speed, lateral expansion of the eruption plume, settling velocities of the particles, and height of the eruption column.

The general equation for the horizontal distance traveled by a particle of size $r$ starting at height $H$ are given by

$$X(r, H)=\sum_{z=H}^{0} [u(z)\cdot T(r, z)]\Delta z, \tag{1}$$

where $u(z)$ is the zonal mean wind in the layer of thickness $\Delta z$ (here taken at 1-km increments) at height $z$ and $T(r, z)$ is the fall time through the layer by Stokes' law.

The fall time of particle $r$ in the altitude increment $\Delta z$ ($=1$ km) is given as

$$T(r)=\Delta z/V(r). \tag{2}$$

Here, $V(r)$ is the terminal settling velocity of particle $r$ as follows.

$$V(r)=\frac{2\rho g}{9\eta}r^2, \tag{3}$$

where $g$ is acceleration due to gravity, $\eta$ the viscosity of air and $\rho$ the apparent density of volcanic glass ($=2\,g/cm^3$).

We assume the eruptive cloud height base and top at 1 and 30 km, respectively. In order to develop the model it is necessary to use a wind profile. The vertical wind profile used is shown in Fig. 8. These data are the monthly zonal averaged wind in the Southern Hemisphere around 60°S for July in winter and January in summer (BENGTSSON *et al.*, 1982). The hatched area shows the standard deviation of vertical wind profile. It can be seen in Fig. 8 that the wind profile shows a strong westerly wind in austral winter, whereas in summer it shows a weak westerly wind in the troposphere and easterly wind in the stratosphere. We also have used the standard deviation of vertical profile in order to examine the sensitivity of the model to wind variability.

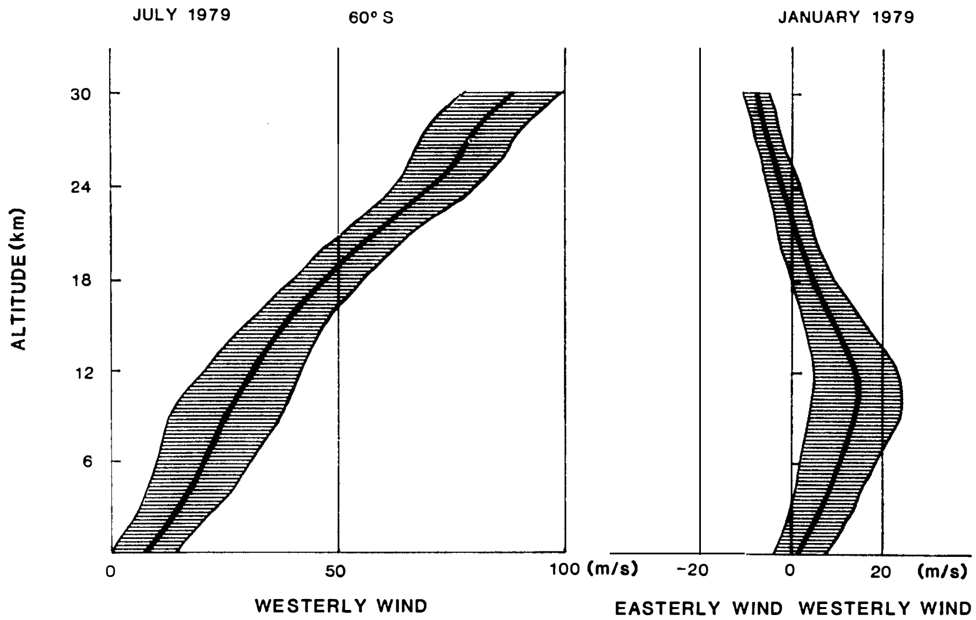


*Fig. 8. Vertical profile of zonally averaged wind in the Southern Hemisphere around 60°S in January and July 1979. The hatched area shows standard deviation of wind profile.*

The result is given in Fig. 9, in which particle size is plotted against distance from the source for a family of curves representing the height of eruptive cloud. From this graph it is possible to predict, for example, that the 16-$\mu$m particle of volcanic glass from the height of eruptive cloud of 5 km will be deposited closer to the source than 4000 km as to the zonal mean wind in winter. However, in the standard deviation of vertical wind profile, we determine that the nearest deposit is 1500 km and the furthest is 6000 km. Conversely, the variability of distance due to alternation of wind velocities for the higher eruptive cloud becomes small, for example, 125-$\mu$m particles will be deposited closer than 1000 km to 1500 km, as can be seen in Fig. 9.

Figures 10 and 11 have been derived from the source data used to generate the

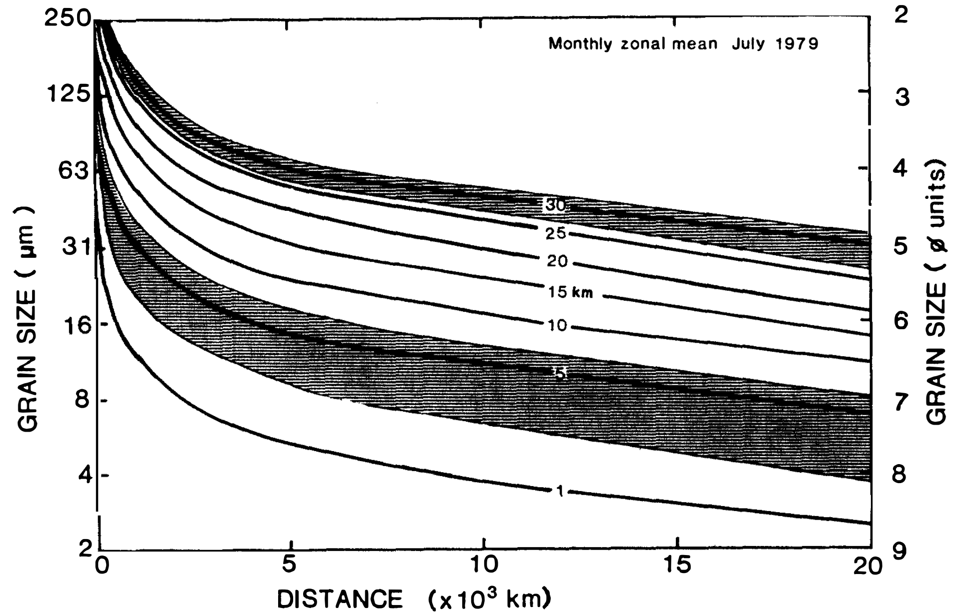


*Fig. 9. Distance in which volcanic glass travels before deposition by grain size in microns (left-hand scale) or $\phi$ units (right-hand scale) as a function of the height at which volcanic glass leaves the eruptive cloud. Heights range from 1 to 30 km. Hatched area show the standard deviation of vertical wind profile as seen in Fig. 8.*

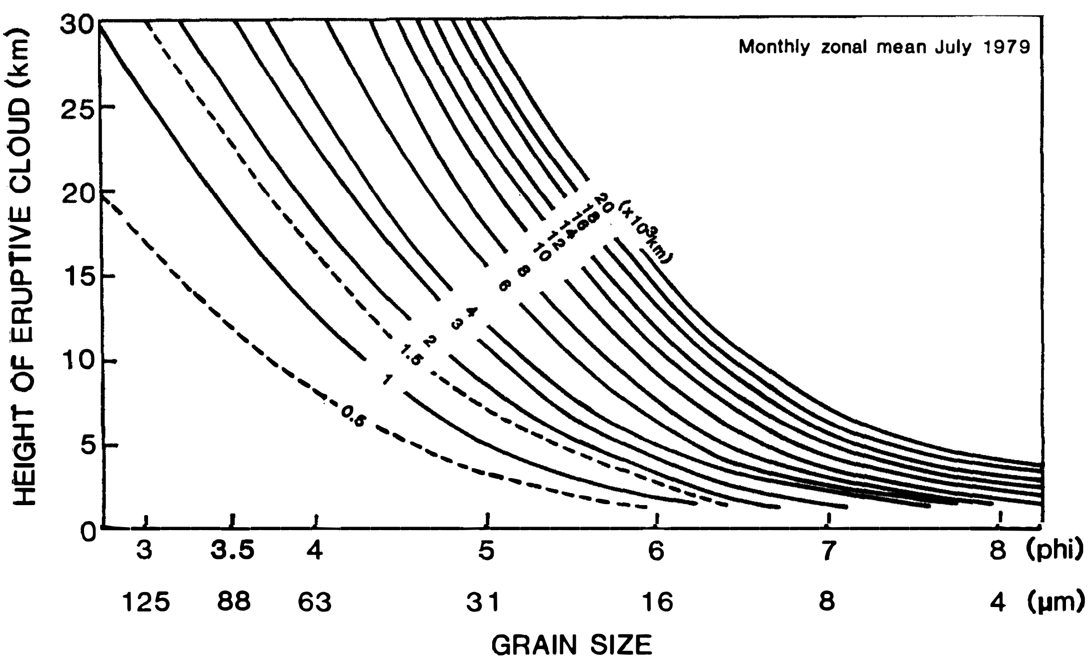


*Fig. 10. Distances of atmospheric transportation of volcanic glass in kilometers between 500 and 20000 km as a function of the height of eruptive cloud for various grain sizes in winter.*

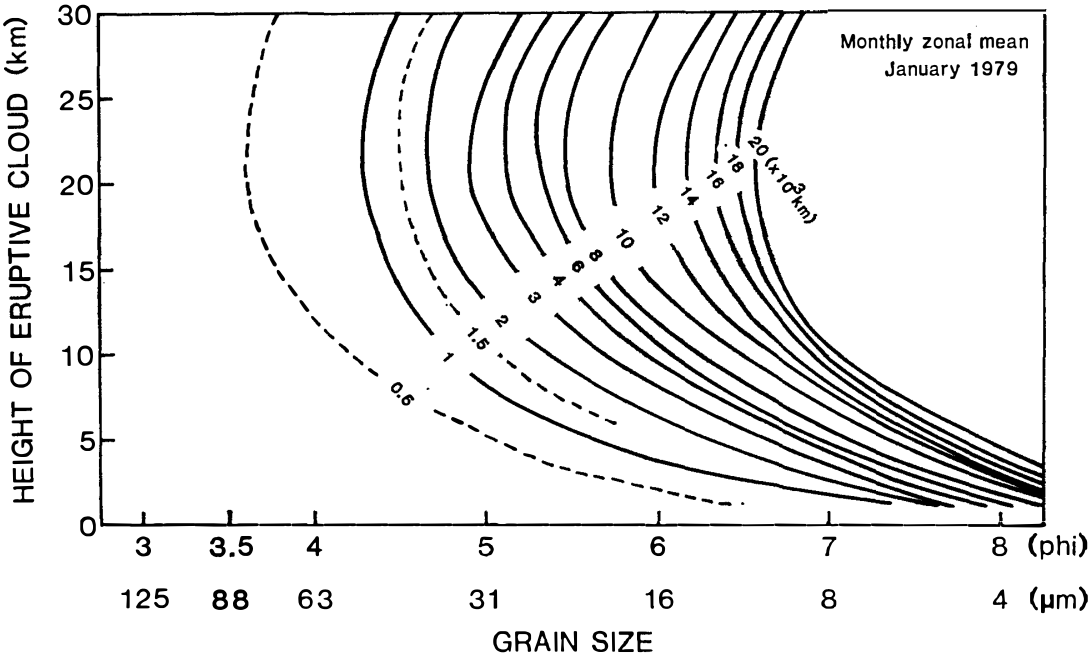


*Fig. 11. Distances of atmospheric transportation of volcanic glass in kilometers between 500 and 20000 km as a function of the height of eruptive cloud for various grain sizes in summer.*

relationship shown in Fig. 9, and show the distances of atmospheric transportation of volcanic glass as a function of the cloud height for various particle sizes. These figures can be utilized as it is in the following example. Assuming that the distance traveled by the 88-$\mu$m fraction is determined to be 3000 km, it can be seen in Fig. 10 that this corresponds to the height of eruptive cloud of 30 km in winter, whereas no 88-$\mu$m fraction travels 3000-km distance in summer, as shown in Fig. 11. Thus, the explosivity of a volcano may be estimated from the height of eruptive cloud by knowing the grain size distribution of tephra and the estimated location of the volcano based on analysis of chemical composition of tephra.

## 6. Estimated Age of Ice and Tephra Layers

### *6.1. Allan Hills ice*

$^{14}C$ ages of ice collected in the Allan Hills bare ice field were measured by FIREMAN and NORRIS (1982) as shown in Fig. 5. $^{14}C$ ages of six ice samples are in the range of 2500–12300 years before the present. But it must be considered in age estimates of near-surface Allan Hills ice that the cosmic ray spallation of oxygen in the near-surface ice can produce more $^{14}C$ than the radiocarbon in the $CO_2$ of the trapped gas. Therefore, the measured age of ice may indicate a younger value than the actual age of ice.

Furthermore, NISHIIZUMI *et al.* (1983) show that, though the absolute ages of ice dated by the $^{10}Be/^{36}Cl$ ratio cannot be determined, the age of the Yamato Mountains ice is probably younger than that of Allan Hills ice. The younger age of the Yamato Mountains ice is consistent with the fact of the terrestrial ages of Yamato meteorites which are younger than those of Allan Hills meteorites.

As mentioned above, at present the age of ice due to the $^{10}Be/^{36}Cl$ ratio is older than that of $^{14}C$ measurements. In order to determine the age of ice, the ice samples for $^{14}C$ measurements are needed at the greater depth of 60 m (FIREMAN and NORRIS, 1982) and measurements with improved precision of $^{10}Be/^{36}Cl$ dating of ice will be required for further progress.

On the other hand, NISHIO *et al.* (1982) suggests that the age of the bare ice at a depth of 8 m ice core is estimated to be approximately $2\times10^4$ yr on the basis of fabric characteristics and grain size growth rate of depositional ice using accumulation and uplift rates of the ice in a marginal catchment area near the Allan Hills. Thus, if the grain growth rate of the bare ice is assumed to be deduced from Byrd and Dome C ice cores (GOW and WILLIAMSON, 1976; DUVAL and LORIUS, 1980), it implies that we are observing ice in the Allan Hills formed by precipitation during the last ice age.

### 6.2. *Yamato Mountains ice*

$^{36}Cl$ content was measured in only one ice sample, which implies that the age of ice in the Meteorite Ice Field is less than one $^{36}Cl$ half-life ($3\times10^5$ yr) (NISHIIZUMI *et al.*, 1979).

The terrestrial ages of the four Yamato meteorites are determined in the range of 3000–22000 yr (NISHIIZUMI, private communication) and hence the age of ice is probably estimated to be the same order.

Furthermore, NARUSE and HASHIMOTO (1982) made the numerical computation of internal flow lines, *i.e.* particle paths, and the age of ice in the ice sheet upstream of the Motoi Nunatak in the Yamato Mountains and the estimated age ranges from one to several thousand years.

As mentioned in the previous subsection, the age of the Allan Hills bare ice is estimated to be approximately $2\times10^4$ yr and, therefore, the estimated age of the Yamato Mountains ice ranging from one to several thousand years is consistent with the fact that the age of the Yamato Mountains ice is probably younger than that of the Allan Hills ice.

And also tephra layers in the Yamato Mountains ice are probably younger than those in the Allan Hills ice.

## 7. Conclusions and Discussion

Based upon the petrographical study under the microscope, the constituent fragments of the dirt layers exposed in the Meteorite Ice Field near the Yamato Mountains and in the Allan Hills bare ice field are composed of more than 80% volcanic glass shards. KATSUSHIMA *et al.* (1984) note the major element chemistry of the glass shards and composition of the mineral fragments in the dirt layers of the Yamato Moutains region have been characteristic of the island arc tholeiite series, whereas those of the Allan Hills have been characterized by the alkaline rock series. Therefore, it is inferred that the tephras in the Yamato Mountains have been derived from some volcano of the South Sandwich Islands, which are about 3000 km away from the Yamato Mountains region.

As shown in Fig. 7, the median grain size in the Yamato Mountains region is smaller than that in the Allan Hills region. It is suggested that, since the decrease in median diameter probably indicates a greater distance of the eruptive centers from the areas of deposition, the volcanic sources of the tephra layer in the Yamato Mountains is farther than those in the Allan Hills.

According to the grain size distribution, the maximum distance of atmospheric transportation of tephra is probably restricted to the maximum grain size in the dirt layer. In the Yamato Mountains region, tephra samples C-32, K-26(1) and K-26(2) have the maximum grain size of 61, 91 and 67 $\mu$m in diameter. Consequently, the 91-$\mu$m particles from an eruptive cloud 30 km high will be deposited closer to the source than 3000 km as shown in Fig. 9.

As the vertical wind distribution is used in winter as shown in Fig. 10, the 91-$\mu$m particles starting at an eruptive cloud 30 km high will be transported a distance of 3000 km. However, in summer as shown in Fig. 11, no 91-$\mu$m particle from any cloud will be transported a distance of 3000 km.

Therefore, it is inferred that the volcanic ash fragments in the Yamato Mountains region could be derived from some volcano of the South Sandwich Islands from an eruptive cloud height of more than 30 km in winter.

On the other hand, six dirt layers in the Allan Hills region contain the maximum grain size ranging from 126 to 200 $\mu$m in diameter. As can be seen in Fig. 9, these large grains will travel a distance of less than 1500 km. In consequence, it is inferred that tephra sources of dirt layers contained these large grain sizes should be located at some volcano in Victoria Land, McMurdo Volcanic Group such as Mt. Erebus, and perhaps in Marie Byrd Land. The other two dirt layers contain maximum grain sizes ranging between 83 and 123 $\mu$m. These grains will be transported a distance of 2000–3000 km in winter, and these tephras could be also from the similar eruptions as mentioned above, although there is no distinct evidence.

## Acknowledgments

The authors wish to thank members of the 23rd Japanese Antarctic Research Expedition, led by Prof. T. HOSHIAI, National Institute of Polar Research. We also thank Dr. K. NISHIIZUMI for providing the terrestrial age of Yamato meteorites. Prof. G. WAKAHAMA, the Institute of Low Temperature Science, Hokkaido University and Prof. Y. YOSHIDA, National Institute of Polar Research kindly read and commented on a draft of this paper.

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*(Received August 13, 1984; Revised manuscript received September 14, 1984)*