COMPOSITION OF DIRT LAYERS 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 of tephra were found on the bare ice surface in the Meteorite Ice Field near the Yamato Mountains, Queen Maud Land, and in the bare ice area near the Allan Hills, Victoria Land. Their age is unknown but supposed to be several to several tens of thousands of years. Their constituent fragments are well-sorted and composed mainly of volcanic glass shards with minor amounts of crystal fragments.

Glass shards of tephra from the Yamato Mountains region have a composition of tholeiitic andesite which is low alkali and high iron but not so enriched in titanium, and the associated crystal fragments consist of calcic plagioclase, subcalcic clinopyroxene, orthopyroxene and magnetite. Such character of island arc tholeiite of the tephra indicates its source to be some volcano in the South Sandwich Islands.

On the other hand, the tephra from the Allan Hills region is composed of glass shards with trachybasaltic composition and crystal fragments of titanaugite, calcic plagioclase, kaersutite, olivine, rhönite and titanomagnetite. Some young volcano of the McMurdo Volcanic Group is suggested to be a possible source of the tephra.

1. Introduction

Dirt layers are exposed in the Meteorite Ice Field near the Yamato Mountains in Queen Maud Land and in the bare ice area near the Allan Hills in Victoria Land. The two regions are as much as 3000 km apart (Fig. 1). During the 1978–79 field season, some specimens from the dirt layers in the Allan Hills region have been collected by the third U.S.-Japan joint party for meteorite search (NISHIO and ANNEXSTAD, 1979). Then, some of the dirt layers from the Yamato Mountains region have been sampled by the inland traverse party of the 23rd Japanese Antarctic Research Expedition (JARE-23) in 1982–83. The dirt layers can be observed on the surface of bare ice and their occurrences resemble each other in both regions. The layers are several centimeters to over ten centimeters in thickness, and gently dip upstream.

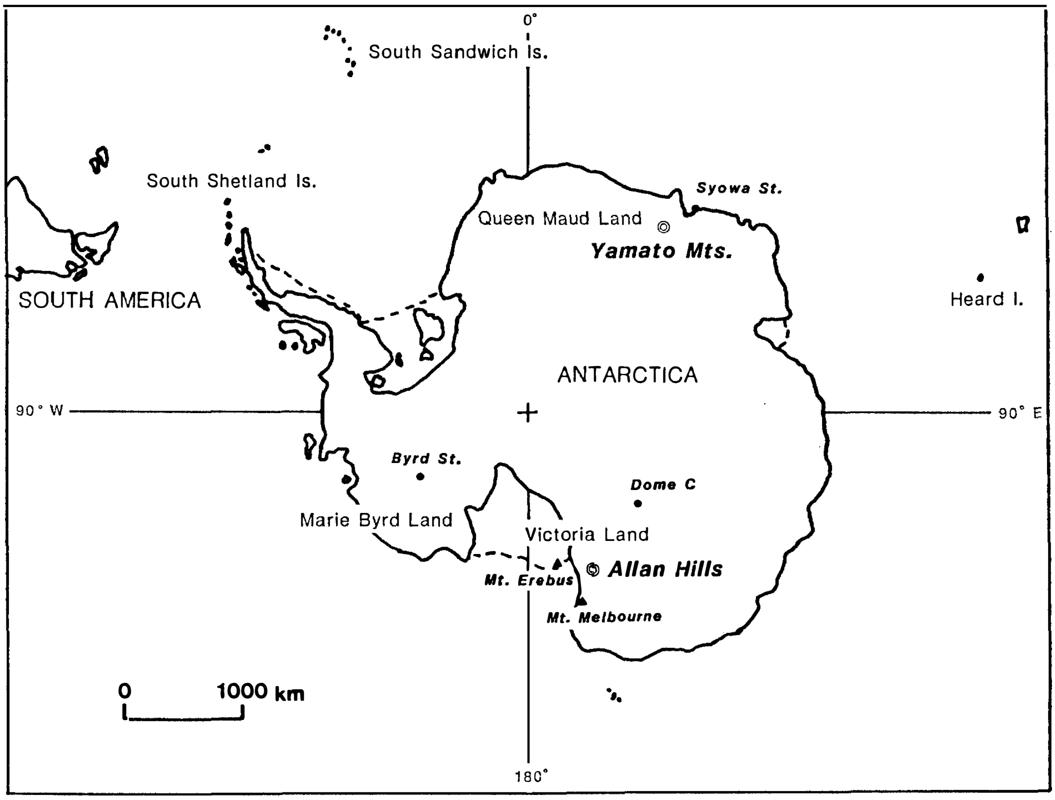

Fig. 1. Location map of the dirt layers.

Their absolute age has not been determined, but the age of the surrounding ice is estimated to be several to several tens of thousands of years (NARUSE and HASHIMOTO, 1982; NISHIO *et al.*, 1982). Because of darkness of the layers contrasting to the white surface of bare ice, their extensions are easily recognized on aerial photographs. The authors have observed their occurrence in the field. Petrographical investigations revealed that they are tephra layers, and that their constituent volcanic ashes are markedly different in composition between the two regions.

Tephra layers in ice sheets have been reported from Antarctica. KEYS *et al.* (1977) described the modes of occurrence and compositions of some tephra layers on the surface of the Skelton Névé and Kempe Glacier, South Victoria Land. They also compiled other tephra layers in Antarctica reported by them. GOW and WILLIAMSON (1971) and KYLE and JEZEK (1978) reported tephra layers from ice cores at Byrd Station, Marie Byrd Land, and studied their source on the basis of chemical composition of glass shards. Similar tephra layers were also observed in the Dome C ice core, which are believed to have derived from the same source as those of the Byrd Station ice core (KYLE *et al.*, 1981).

On the other hand, in Queen Maud Land tephra layers have never been reported. This paper gives the first description of the tephra layers found in this region. The modes of occurrence and grain size analyses of the tephra layers from the Yamato Mountains and the Allan Hills regions were described in detail by NISHIO *et al.* (1984). In the present paper, the petrography and results of chemical analyses by EPMA of the constituent materials of tephra layers from both regions are given with special emphasis on the glass shards. The petrochemical features of the volcanic ashes from both regions are compared, and their source areas are discussed.

2. Petrography of Tephra

2.1. Yamato Mountains region

The dirt layer in the bare ice of the Meteorite Ice Field near the Yamato Mountains contains abundant fine fragments which are well-sorted and composed predominantly of glass shards, with minor quantities of crystal fragments such as plagioclase, clinopyroxene, orthopyroxene and opaque minerals. Glass shards are obviously volcanic glass. Most of the crystal fragments carry adherent glass, indicating that they are of volcanic origin. The fragments which are identified as volcanic ash under the microscope exceed 95% of total fragments (Table 1).

Table 1. Model compositions of fragmental material in dirt layers.

Locality	Yamato	Allan
Glass shards	85.5	72.7
Crystal fragments		
Plagioclase	9.7(7.0)*	6.9(4.6)
Clinopyroxene	3.3(2.4)	10.1(5.5)
Orthopyroxene	1.2(0.9)	—
Olivine	—	4.1(2.1)
Amphibole	—	3.9(1.0)
Others	0.3	2.2
Glass shards + crystals with adherent glass /total fragmental material	95.8	85.9

* Figures in parentheses indicate modal composition of crystal fragments with adherent glass.

Glass shards, generally 20–40 μm in size, are mainly colorless to light brown and rarely dark brown. They are characteristically angular and highly vesicular, and include crystallites and rarely microlites (Figs. 2 and 4).

Crystal fragments occur with or without adherent glass. Orthopyroxene and clinopyroxene are generally slender prismatic and 10–70 μm in length. Orthopyroxene shows faint pleochroism of light yellowish green, whereas clinopyroxene is light yellowish green free from pleochroism. Plagioclase is colorless and subhedral to anhedral. Magnetite occurs as euhedral crystal in some glass shards.

2.2. Allan Hills region

The dirt layer in the bare ice area near the Allan Hills also includes abundant fine fragments which are well-sorted and composed mainly of glass shards and subordinate amounts of crystal fragments (Table 1). Therefore, most of them are also identified as volcanic ash. However, the deposits are slightly larger in size and have more abundant crystal fragments than those of the Yamato Mountains region.

Glass shards, 30–200 μm in size, are pale brown to cloudy dark brown and

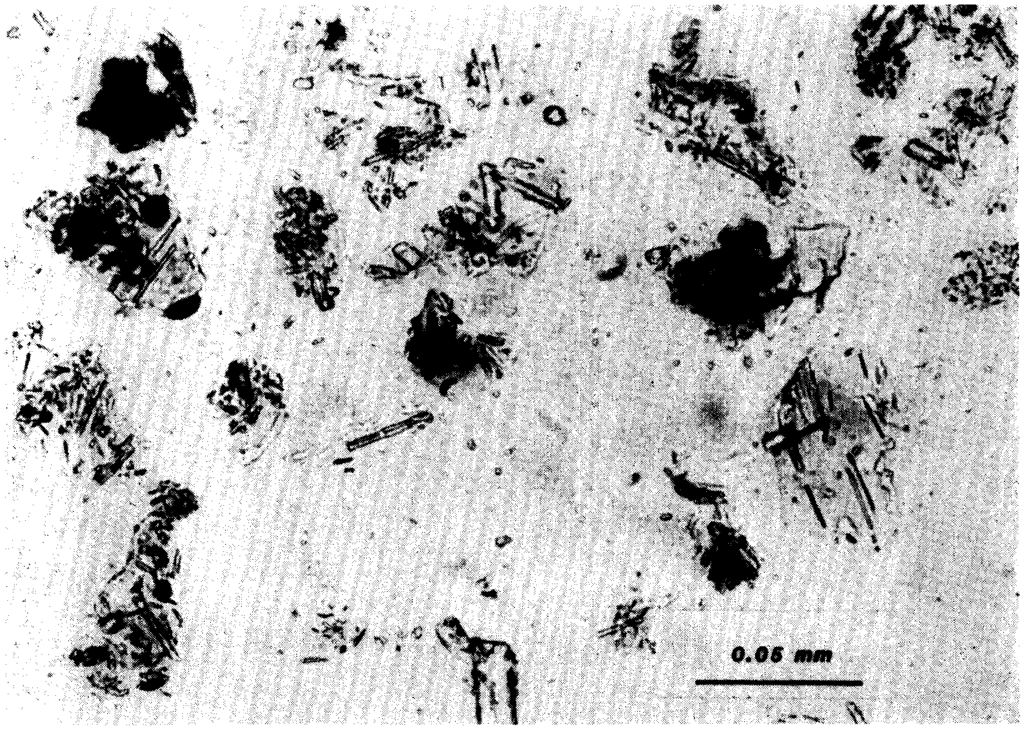

Fig. 2. Photomicrograph of the volcanic ash from the dirt layer in the Yamato Mountains region. Note abundant colorless volcanic glass shards containing crystallites and/or microlites.

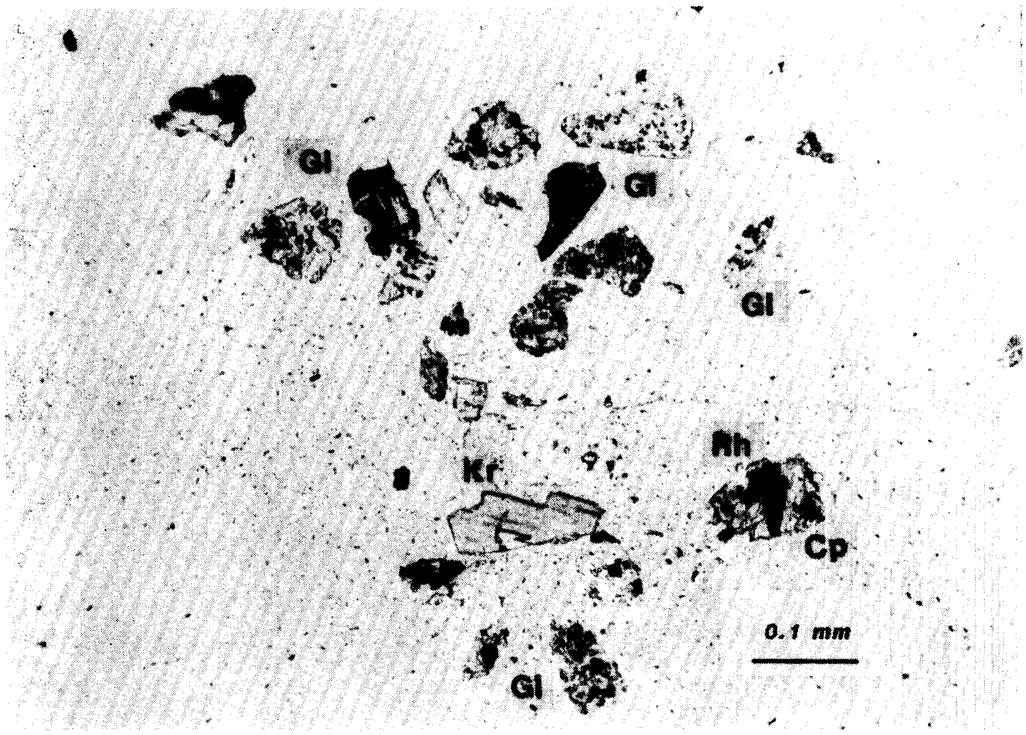

Fig. 3. Photomicrograph of the volcanic ash from the Allan Hills region. Volcanic glass shards (Gl), clinopyroxene (Cp), kaersutite (Kr), and rhönite (Rh) are observed.

(a)

(b)

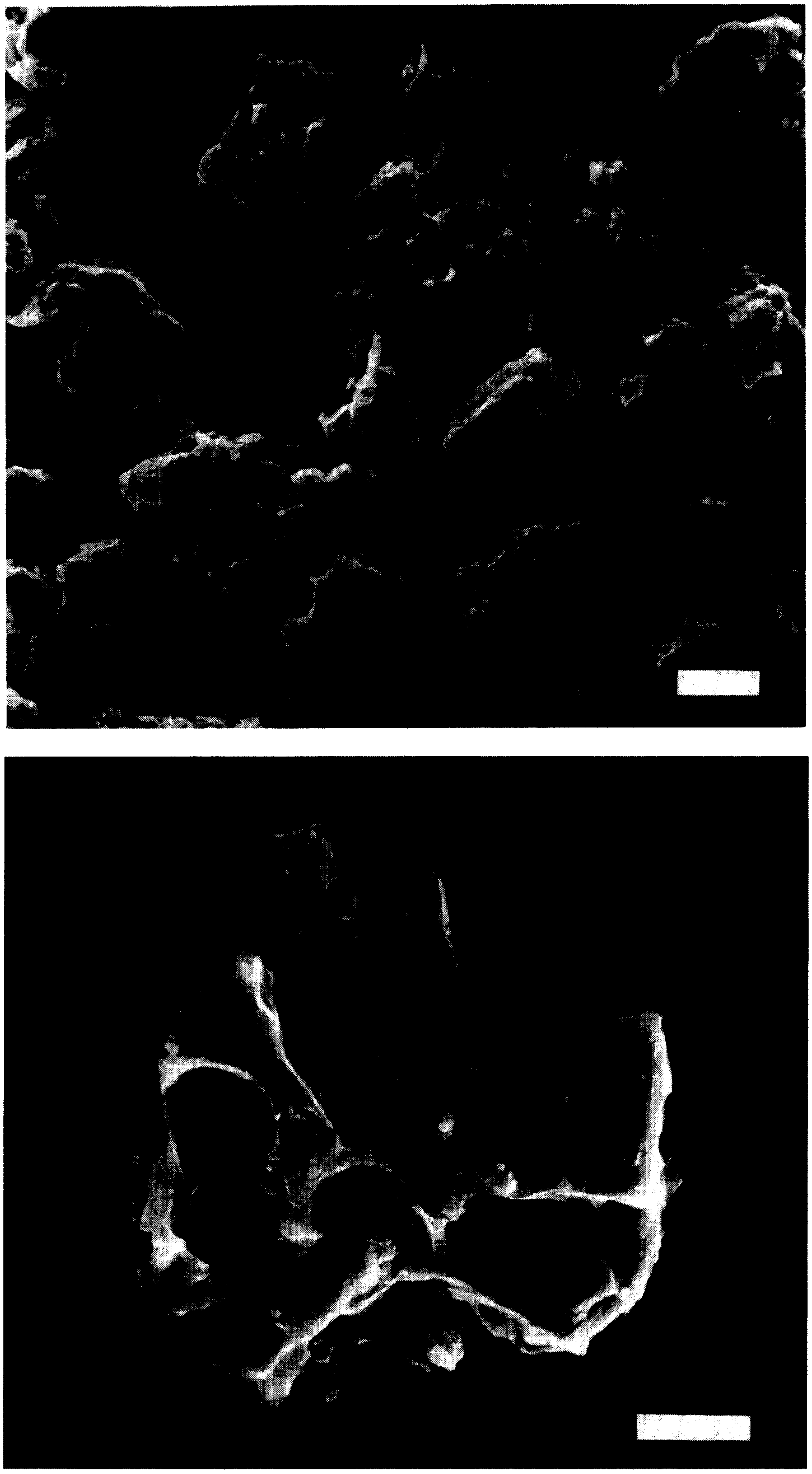

Fig. 4. Scanning electron microphotographs of the volcanic ash from the dirt layer in the Yamato Mountains region. (a): Highly vesicular glass shards and two crystal fragments at center right. The scale is 20 μm. (b): A highly vesicular glass shard. The scale is 10 μm.

(a)

(b)

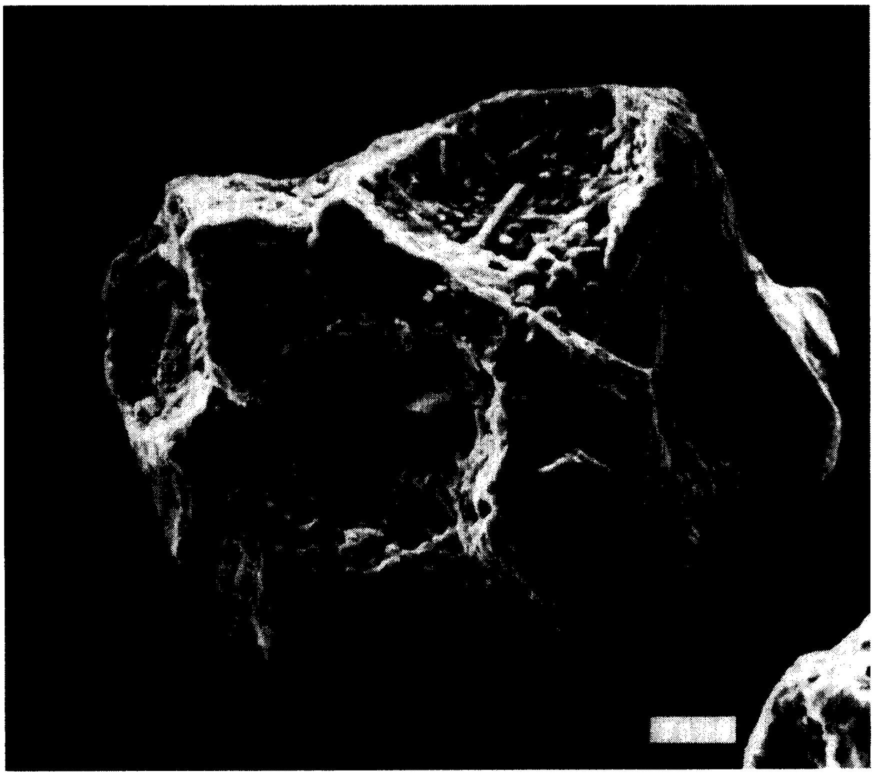

Fig. 5. Scanning electron microphotographs of the volcanic glass shards from the dirt layer in the Allan Hills region. (a): A poorly vesicular glass shard with smooth surface. The scale is 50 μm. (b): A rectangular, poorly vesicular glass shard with a large amount of crystallites. The scale is 20 μm.

include microlites and crystallites. They are generally poor in vesicularity, and their vesicle walls and surfaces are relatively smooth. Some of the glass shards contain a large amount of microlite and crystallite, and show rough-walled and rectangular or polygonal shapes (Figs. 3 and 5).

Plagioclase, titanaugite, olivine, kaersutite, rhönite and titanomagnetite are observed under the microscope. Titanaugite is euhedral to subhedral, and shows faint pleochroism of light purplish brown. Small grains of olivine occur in some glass shards as microlites, which alter into iddingsite with intense pleochroism, reddish brown to pale orange. Kaersutite is commonly isolated, relatively coarse grained, and euhedral to subhedral, and shows distinct pleochroism, brown to light brown. Rhönite occurs with titanaugite and shows strong pleochroism, dark brown to light brown.

3. Chemical Composition

Major element compositions of the glass shards and the crystal fragments composing each of the dirt layers from the Yamato Mountains and the Allan Hills regions were analyzed by the electron probe microanalyzer (JEOL-733) at the National Institute of Polar Research. Both samples are named tentatively the Yamato ash and the Allan ash, respectively.

3.1. Glass shards

Chemical compositions of glass shards in tephra layers may indicate the nature of the rock suite, because they correspond to the liquid compositions of the source magma. Table 2 lists the average chemical composition of the glass shards in both ashes. The compositions of glass shards in the Yamato ash are relatively uniform, whereas those in the Allan ash are more or less dispersed.

As shown in the Na_2O+K_2O *vs.* SiO_2 diagram (Fig. 6), the glass shards of the Yamato ash fall in the non-alkaline field, whereas those of the Allan ash in the alkaline field. Selected analyses of the Cenozoic volcanic rocks from Antarctica are also plotted in this diagram. They are classified into two volcanic provinces: (1) the alkaline province of Marie Byrd Land and Victoria Land, and (2) the non-alkaline province of the South Shetland Islands (high-alumina basalt series rich in Na_2O) and the South Sandwich Islands (low-alkali tholeiite series) (KATSUI, 1972; GONZÁLEZ-FERRÁN and VERGARA, 1972; GONZÁLEZ-FERRÁN, 1982). Subantarctic islands such as Heard Island comprise alkaline rocks.

Volcanic rocks of the South Sandwich Islands are characterized by iron enrichment in the middle stage of differentiation of the tholeiitic series. As shown in Na_2O+K_2O–total FeO–MgO diagram (Fig. 7), the glass shards of the Yamato ash are plotted within the field of the South Sandwich Islands. The glass shards of the Yamato ash have low TiO_2 content and are not markedly enriched in total FeO (Fig. 8). Accordingly, it is concluded that the glass shards of the Yamato ash have the distinctive feature of island arc tholeiite defined by JAKEŠ and GILL (1970). These features are similar to those of the rocks from the South Sandwich Islands. According to BAKER (1976), these volcanic islands are dominated by basalt and basaltic andesite of

Table 2. Average chemical analyses of volcanic glass shards in the Yamato and the Allan ashes, and comparative analyses of volcanic rocks from Bellingshausen and Ross Islands.

Locality	Yamato ash	Allan ash	B. I.	R. I.
	n=14 (σ_n)	n=12 (σ_n)		
SiO_2	57.92 (0.71)	44.23 (2.25)	56.98	44.6
TiO_2	1.00 (0.09)	3.76 (0.47)	0.91	3.46
Al_2O_3	13.98 (0.82)	16.29 (1.37)	16.14	16.9
Cr_2O_3	0.01 (0.01)	0.01 (0.01)	—	—
FeO*	11.03 (0.44)	10.19 (0.78)	10.59	10.7
MnO	0.23 (0.07)	0.22 (0.06)	0.18	0.22
MgO	2.81 (0.37)	4.06 (1.02)	2.80	3.78
CaO	7.57 (0.25)	9.91 (2.37)	8.32	9.44
Na_2O	2.71 (0.25)	4.29 (0.86)	3.44	5.37
K_2O	0.39 (0.06)	2.95 (0.50)	0.60	2.01
P_2O_5	0.12 (0.07)	1.57 (0.24)	0.12	1.39
NiO	0.05 (0.05)	0.03 (0.03)	—	—
Others	—	—	0.16	0.44
Total	97.82	97.51	100.24	98.3
C. I. P. W. norm**				
Q	16.15	—	9.21	—
or	2.29	17.44	3.55	11.88
ab	22.95	10.97	29.11	15.80
an	24.83	16.48	26.83	16.07
ne	—	13.72	—	16.06
di	10.12	18.52	11.59	18.03
hy	17.30	—	15.89	—
ol	—	7.75	—	8.34
mt	2.12	1.95	2.03	2.05
cm	0.01	0.01	—	—
il	1.90	7.15	1.73	6.57
ap	0.28	3.64	0.28	3.22
Total	97.95	97.63	100.22	98.02

* FeO=total Fe as FeO.
** For norm calculations, Fe_2O_3 standardized at $0.15 \times$FeO*.
B. I.: Basaltic andesite from Bellingshausen Island (BAKER, 1978).
R. I.: Trachybasalt from Ross Island (GOLDICH *et al.*, 1975).
n: Number of individual analyses. σ: Standard deviation.

island arc tholeiite composition. Among the South Sandwich Islands, Bellingshausen Island has probably developed in very recent times (BAKER, 1978). The composition of the less porphyritic basaltic andesite from this island is similar to that of the glass shards of the Yamato ash (Table 2).

On the other hand, the glass shards of the Allan ash have the features of the alkaline rock series. Cenozoic alkaline volcanic rocks are widely scattered throughout Marie Byrd Land and Victoria Land. It is unlikely that their compositions show consistent areal variation. Therefore, only a representative rock, a trachybasalt from Ross Island (GOLDICH *et al.*, 1975) which has similar composition to the glass shards of the Allan ash, is presented in Table 2 for comparison.

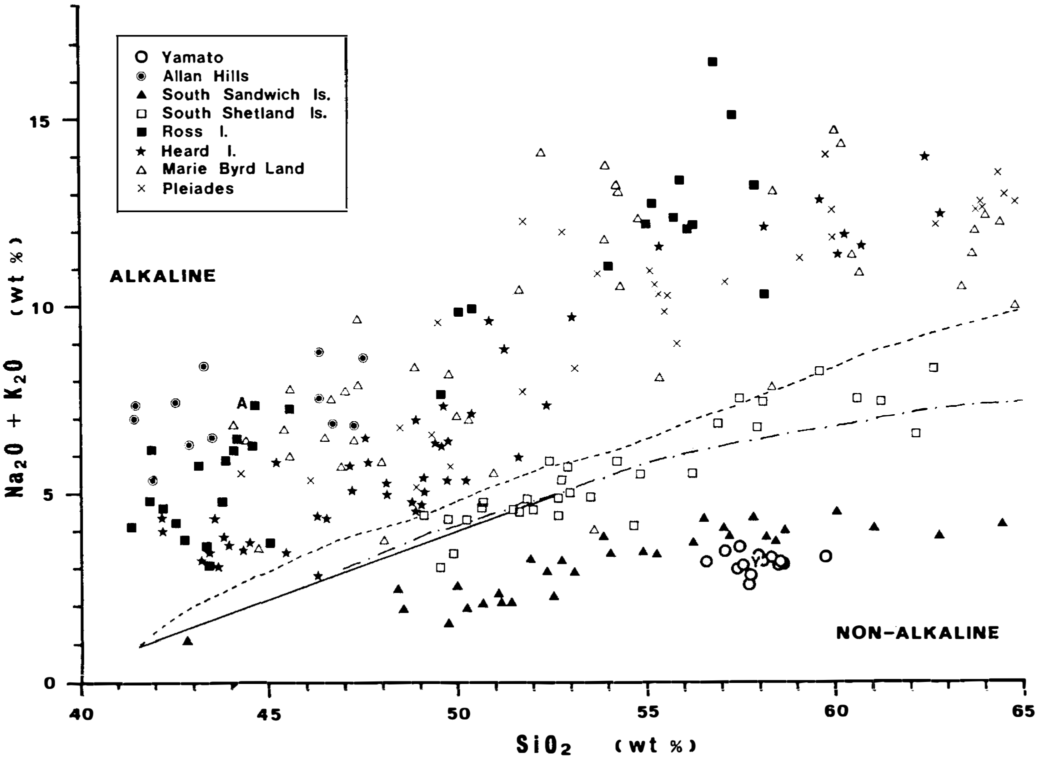

Fig. 6. *SiO_2–Na_2O+K_2O diagram of analyzed glass shards in the Yamato and the Allan ashes (Y: average composition of glass shards in the Yamato ash. A: average composition of those in the Allan ash). Shown for comparison are compositions of the Cenozoic volcanic rocks from the South Sandwich Islands (BAKER, 1978), the South Shetland Islands (GONZÁLEZ-FERRÁN and KATSUI, 1970; WEAVER et al., 1982), Ross Island (GOLDICH et al., 1975), Pleiades (KYLE, 1982), Marie Byrd Land (GONZÁLEZ-FERRÁN and VERGARA, 1972), and Heard Island (STEPHENSON, 1972). The boundaries between alkaline and non-alkaline fields are shown by solid (MACDONALD and KATSURA, 1964), chain (MIYASHIRO, 1973) and broken lines (GONZÁLEZ-FERRÁN, 1982).*

3.2. Crystal fragments

Pyroxene occurs in both ashes, and their analyses are shown in Fig. 9. Subcalcic augite in the Yamato ash has similar composition to that of the South Sandwich Islands (BAKER, 1978). On the other hand, titanaugite, which is characteristic in alkaline rocks is found in the Allan ash. In the Allan ash, kaersutite (titanium-rich amphibole) and rhönite are observed (Table 3). Occurrence of rhönite in basanite has been reported from the McMurdo Volcanic Group (KYLE and PRICE, 1975). Table 4 presents compositions of the mineral fragments in the Yamato and the Allan ashes. For comparison, those of the basaltic andesite from Bellingshausen Island and the trachybasalt from Ross Island are also listed in Table 4.

4. Discussion

4.1. Nature of the dirt layers

As a result of microscopic investigations, the constituent fragments of the dirt

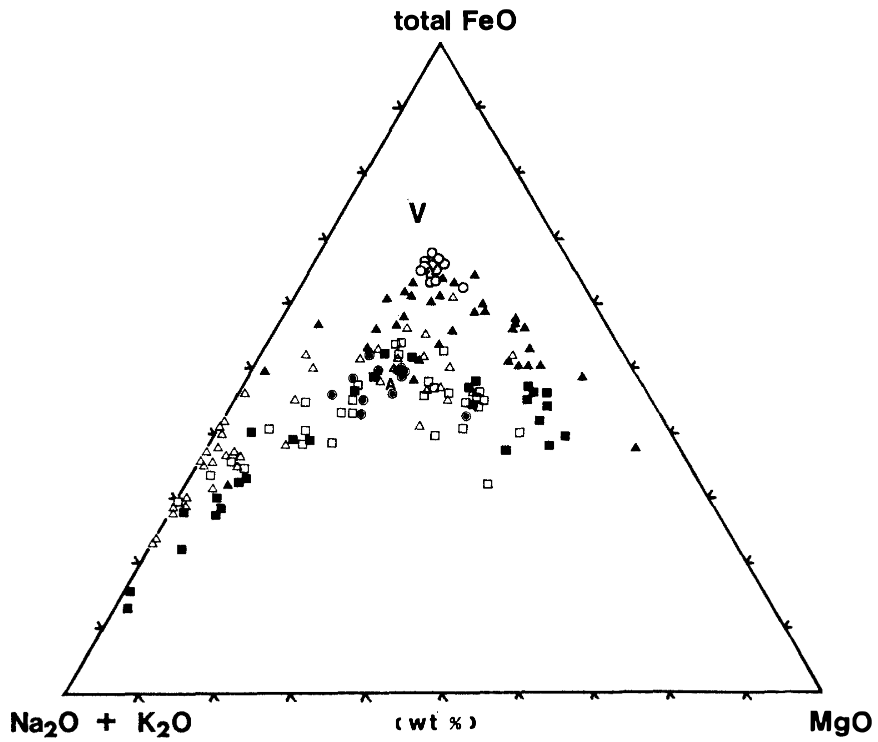

Fig. 7. Na_2O+K_2O–total FeO–MgO diagram of analyzed glass shards in the Yamato and the Allan ashes. Shown for comparison are compositions of the Cenozoic volcanic rocks from Antarctica. Legends and references are the same in Fig. 6.

layers exposed in the Yamato Mountains and the Allan Hills regions are well-sorted and composed mainly of volcanic glass shards. The chemical compositions of the glass shards are relatively uniform in each layer, but differ markedly between the two dirt layers. The mineral assemblages and chemical compositions of the crystal fragments in both layers are compatible with the compositions of the respective glass shards. No foreign fragments derived from the basement rocks can be observed. Therefore, it is suggested that each of the dirt layers represents a single fall unit of tephra which precipitated on the surface of the ice sheet.

4.2. Tephra source

Major element chemistry of the glass shards and composition of the mineral fragments in the dirt layers indicate that the Yamato ash has characteristics of the island arc tholeiite series, whereas the Allan ash has those of the alkaline rock series. These compositional features make it possible to infer their source regions in reference to the Quaternary petrographic province in and around Antarctica. As described earlier, the Yamato ash is correlated with basaltic andesite from the South Sandwich Islands. Basaltic andesite of the low-alkali tholeiite of island arc type has not been reported around Antarctica except for the South Sandwich Islands. Therefore, it is inferred that the Yamato ash has been derived from some volcano of the South Sandwich Islands which are about 3000 km away from the Yamato Mountains region. Although the flying distance of volcanic ash depends on both eruptive cloud height and wind velocity, small ash particles of a few tens of μm in size may be transported in the air

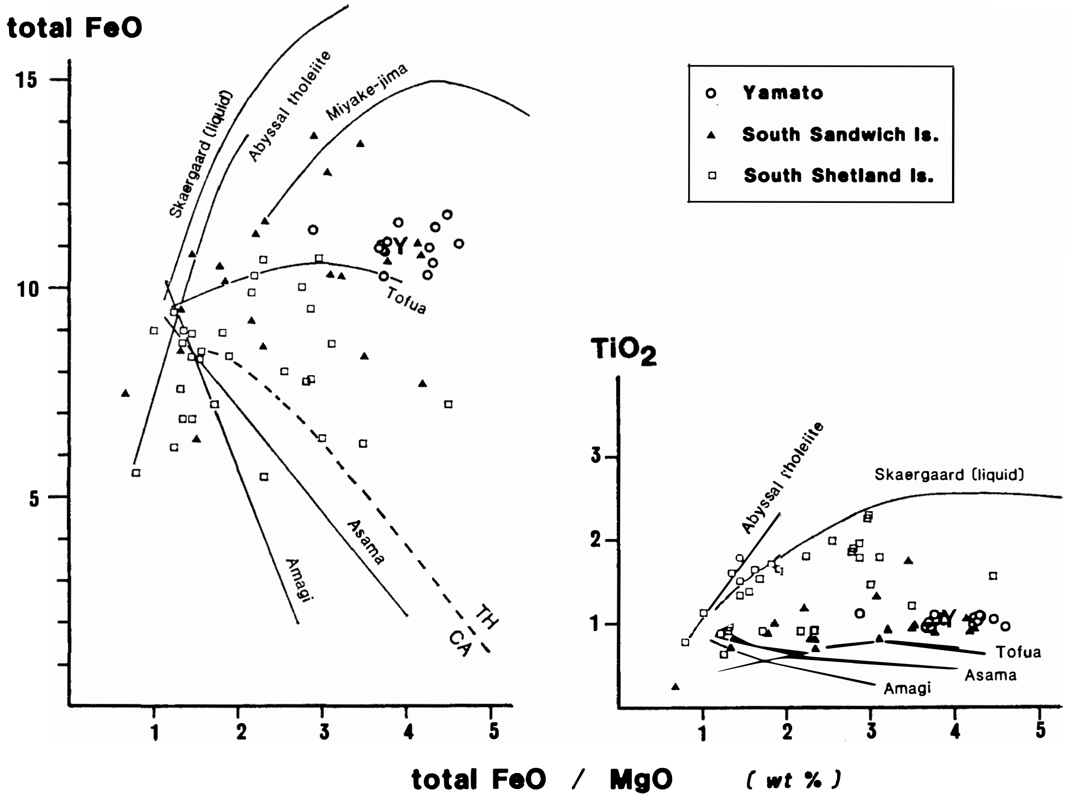

Fig. 8. Plots of total FeO and TiO_2 vs. total FeO/MgO ratio for glass shards in the Yamato ash (Y: average composition). Shown for comparison are compositions of the volcanic rocks from the South Sandwich Islands (BAKER, 1978) and the South Shetland Islands (GONZÁLEZ-FERRÁN and KATSUI, 1970; WEAVER et al., 1982). Solid lines: the trends of some volcanic suites, and broken line: the boundary between tholeiitic (TH) and calc-alkalic series (CA) (MIYASHIRO, 1973).

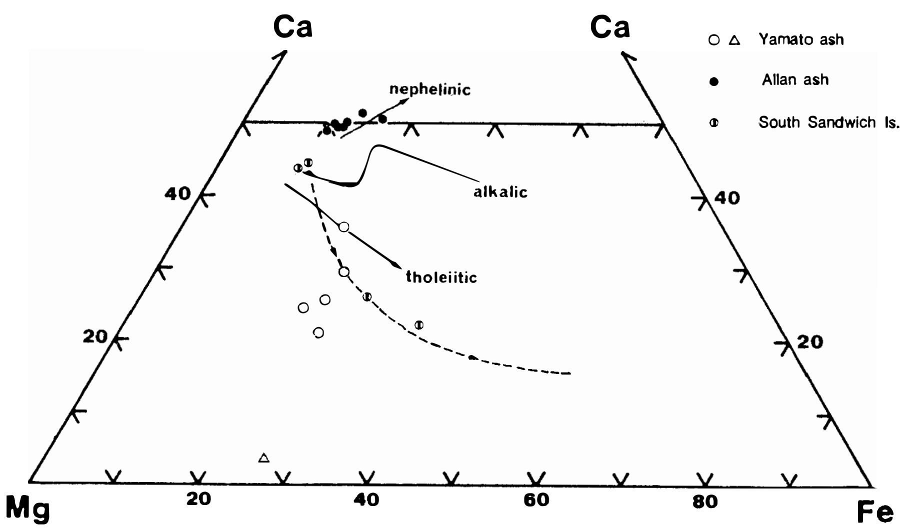

Fig. 9. Plot of analyzed pyroxenes in the Yamato and the Allan ashes. Shown for comparison are the compositions and differentiation trend (broken line) of clinopyroxene from the South Sandwich Islands (BAKER, 1978), and the trends (solid lines) of clinopyroxenes from three rock types in Hawaii (FODOR et al., 1975).

Table 3. Chemical analyses of crystal fragments in the Allan ash.

	Titanaugite	Kaersutite	Rhönite
SiO_2	45.10	38.59	23.75
TiO_2	3.99	5.43	12.00
Al_2O_3	7.22	14.14	16.72
Cr_2O_3	.01	.00	.00
FeO*	7.20	11.19	20.67
MnO	.11	.14	.27
MgO	12.71	12.10	12.67
CaO	22.94	11.58	11.24
Na_2O	.46	2.40	1.11
K_2O	.02	1.85	.00
Total	99.76	97.42	98.43
	O=6	O=23	O=20
Si	1.701	5.771	3.284
Al	.321	2.493	2.725
Ti	.113	.610	1.249
Cr	.000	.000	.000
Fe	.227	1.400	2.390
Mn	.004	.017	.031
Mg	.715	2.697	2.612
Ca	.927	1.855	1.666
Na	.033	.696	.297
K	.001	.353	.000

Table 4. Crystal fragments in the Yamato and the Allan ashes and constituent minerals in volcanic rocks from Bellingshausen and Ross Islands.

	Yamato ash	Basaltic andesite* (Bellingshausen Island)
Plagioclase	An 59–79	An 65–85
Clinopyroxene	Augite–Subcalcic augite	Augite–Subcalcic augite
Orthopyroxene	Bronzite–Hypersthene	Bronzite–Hypersthene
Opaque mineral	Magnetite	Magnetite
	Allan ash	**Trachybasalt** (Ross Island)**
Plagioclase	An 59–70	Labradorite
Clinopyroxene	Titanaugite	Titaniferous augite
Amphibole	Kaersutite	Kaersutite
Others	Olivine, Rhönite, Titanomagnetite	Olivine, Apatite, Opaque mineral

* BAKER (1978), ** GOLDICH *et al.* (1975).

for such a distance (FISHER, 1964; NISHIO *et al.*, 1984). Accordingly, the Yamato ash is considered to have derived from the South Sandwich Islands. This is the first finding of tholeiitic tephra in ice sheets of Antarctica.

On the other hand, alkaline tephras have been described in several other areas of Antarctica. The tephras found in the Byrd Station ice core and the Dome C ice core were considered to be derived from Mt. Takahe in Marie Byrd Land as evidenced by their chemical similarity (KYLE and JEZEK, 1978; KYLE *et al.*, 1981). An example of tephra exposed on the surface of bare ice was reported from the Skelton Névé and Kempe Glacier, South Victoria Land (KEYS *et al.*, 1977). According to them, their grain size composition, age and other features indicate that the tephra layers were supplied from some volcano in the Royal Society Range–Koettlitz Glacier area.

Quaternary alkalic volcanic rocks are widely distributed throughout Marie Byrd Land and Victoria Land including the McMurdo Sound region. The chemical feature of each volcano is, however, not enough to be realized. Therefore, at present, it is difficult to specify which volcano yielded the Allan ash. According to the K-Ar ages given by ARMSTRONG (1978), the rocks of the Pleiades and Mt. Merbourne, North Victoria Land, are younger than those of other volcanoes of the McMurdo Volcanic Group (KYLE and COLE, 1974) except for Mt. Erebus. The ages of these young volcanic centers may not be so different from that of the ice sheet which encloses the Allan ash. The coarse grain size of the Allan ash compared with the Yamato ash may indicate the source volcano to be not so distant as that of the latter (NISHIO *et al.*, 1984). Accordingly, the Allan ash may have been supplied from some young volcano of the McMurdo Volcanic Group, though further studies are needed before the source volcano is specified.

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