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Scientific Note

MAJOR ELEMENT ANALYSIS OF FINE TEPHRAS FOUND IN AN ICE CORE FROM DOME FUJI STATION, ANTARCTICA

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Abstract: Fine tephras from 25 visible tephra layers, which were found in an ice core from Dome Fuji Station in Dronning Maud Land in East Antarctica, were prepared for electron microprobe analyses. Major element compositions of the tephras in three layers at depths of 573, 1361 and 2202 m were determined by electron microprobe. The tephras in the 573 and 2202-m layers were andesite and dacite, respectively. These tephras were considered to be originated from Visokoi and Candlemas Islands in the South Sandwich Islands, respectively, on the basis of their chemical similarity to analyzed rocks from these sources. The 1361-m tephra having trachyte composition was considered to be originated from Mt. Takahe in Marie Byrd Land. These tephra layers may serve as key beds of Antarctic ice cores.

1. Introduction

Far-traveled atmospheric aerosols of volcanic, terrestrial, marine and artificial origins deposit on polar ice sheets through wet or dry processes. Ice cores obtained from the polar ice sheets, therefore, preserve records of past volcanic activities, climatic and environmental changes. Visible volcanic ash (tephra) layers have been observed in ice cores from Dome C (KYLE *et al.*, 1981), Byrd (GOW and WILLIAMSON, 1971; KYLE and JEZEK, 1978; KYLE *et al.*, 1981; PALAIS, 1985) and Vostok (KYLE *et al.*, 1984; PALAIS *et al.*, 1989a, b, 1990; BASILE, 1997) in Antarctica. These layers have the potential to provide key beds for correlating, and possibly in some cases, dating Antarctic ice cores.

Compositional features of tephras make it possible to infer their source regions or volcanoes. The ice core from Byrd Station contained 25 distinct tephra layers (KYLE *et al.*, 1981; PALAIS, 1985). Most of them, deposited onto the ice sheet surface between *ca.* 19 and *ca.* 27-ka B.P., were considered to have originated from Mt. Takahe, which is about 450 km away from the coring site, in Marie Byrd Land. About 30 tephra layers were observed in the ice core obtained at Vostok Station (BASILE, 1997). The tephras in most layers were considered to have originated from volcanoes in Antarctica, sub-Antarctica and the South Andes in South America (KYLE *et al.*, 1984; PALAIS *et al.*, 1987, 1989a, b, 1990; BASILE, 1997).

A 2503-m deep ice core from Dome Fuji Station (77° 19′01″S, 39° 42′12″E, 3810 m a.s.l.; Fig. 1), which is located at the summit of the inland plateau in Dronning Maud Land, East Antarctica, contains 25 visible tephra layers (FUJII *et al.*, 1999). The ice core was obtained by the 32nd to 38th Japanese Antarctic Research Expeditions in 1991

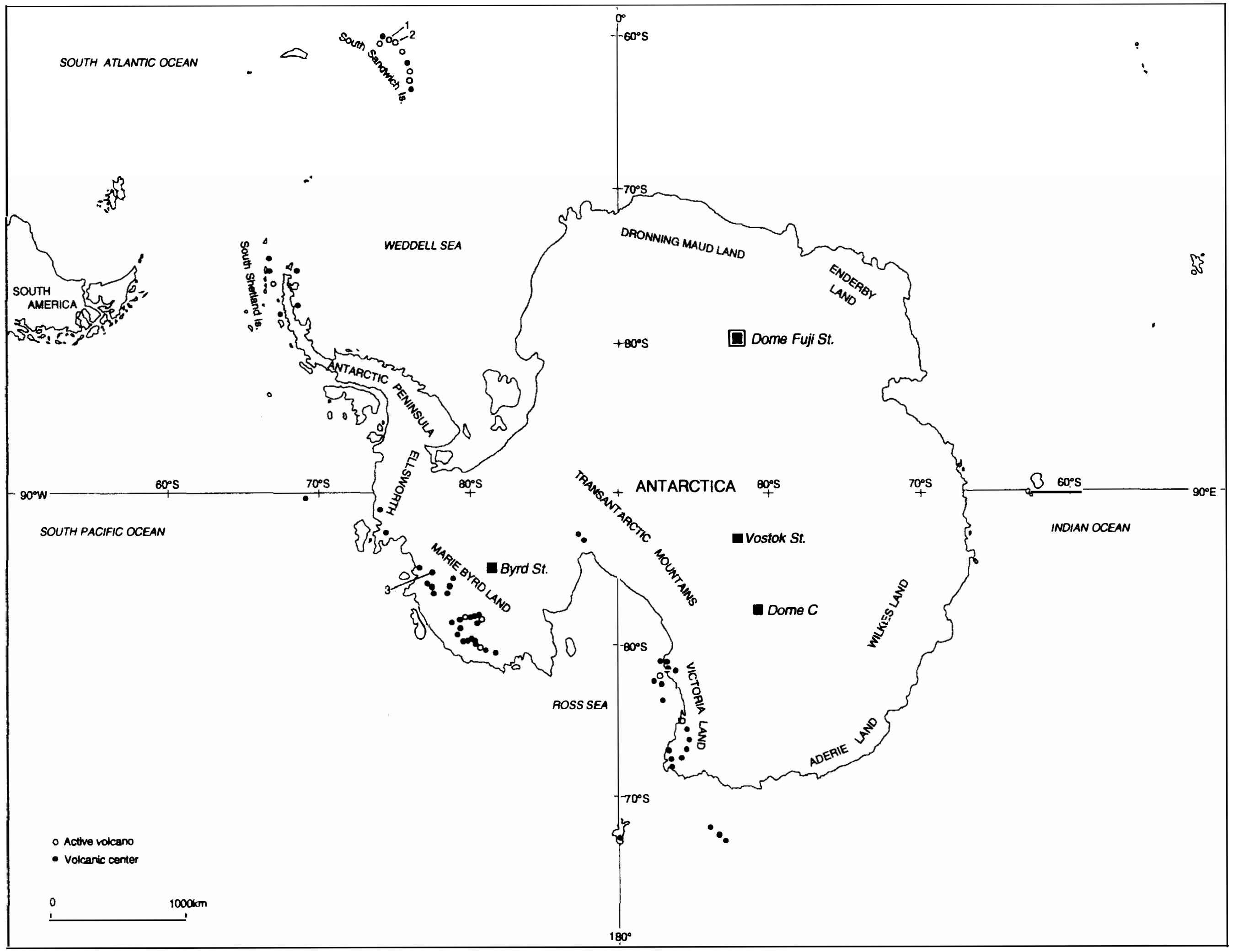

Fig. 1. Location of Dome Fuji Station and other deep ice-coring sites in Antarctica. The late Cenozoic volcanoes and active volcanoes are also indicated by solid and open circles, respectively (1: Visokoi Island; 2: Candlemas Island; 3: Mount Takahe).

to 1997. The core was cut into three pieces along the direction of a core axis in the ratio of 60, 25 and 15% of the core section (A-, B- and C-core, respectively; DOME-F DEEP CORING GROUP, 1998).

We first describe sample preparation of tephra in ice cores for electron microprobe analyses. We examine grain size, texture and major element composition of volcanic glass found in three layers at depths of 573, 1361 and 2202 m, which are enough thick to obtain considerable volcanic glass. On the basis of these results, we make preliminary estimate of their source volcanoes.

2. Samples and Sample Preparation

The depth, thickness of the layer, an inclination angle of the layer to direction of a core axis and layer color in a low-temperature room of $-20°C$ using the B-core of the 25 visible tephra layers were logged.

Small ice samples of about 200–300 mg were taken out of the 573, 1361 and 2202-m tephra layers in the C-core with a small chisel for tephra analyses. Each sample was then rinsed, in order to eliminate contamination of outer the part, with ultra-pure water at 0°C in a class-1000 clean room, and stored in each Teflon bottle. The samples were melted in a refrigerator at 5°C.

A $4 \mu l$ water sample was dropped twice on a slide glass placed on a hot plate with a micro-pipette and then dried in a class-100 clean-bench in the clean room. The dried sample was covered with a few drops of Petropoxy Resin #154 (Palouse Petro Products) by a sharp-pointed stainless stick. The resin solidified on the hot plate at a temperature of ~130°C in 3 hours in the clean-bench.

The slide glass containing the tephra sample was carefully polished with alumina powder (5, 2.5 and $1.5 \mu m$ in grain size) and then with diamond or alumina paste (1.0 and $0.25 \mu m$ in grain size) until the tephra section was exposed. After microscopic observation of the tephra, the surface of the slide glass was coated with a conducting carbonaceous surface layer to provide a path for the electron beam current and prevent electrical charging by vacuum evaporation.

Grain size and texture were examined and microphotographs were taken using a scanning electron microscope (SEM; JEOL-JSM5200).

3. Analytical Procedure

Major element analyses of the tephra were performed using a wavelength-dispersive electron microprobe analyzer (EPMA; JEOL-JXA8800) by the ZAF correction method (DUNCUMB and REED, 1968). The tephras were analyzed with an accelerating voltage of 15 keV and an electron-beam current of 12 nA. The electron-beam diameter was set at larger than $5 \mu m$ to minimize migration of sodium during the analyses of glassy 1361 and 2202-m tephras. The 573-m tephra which was devitrified was, however, analyzed with a broad electron-beam (10–15 μm) in order to obtain an average chemical composition of groundmass without microphenocrysts.

The accuracy and reproducibility of the analyses were checked by duplicate analyses of reference glasses which were made of natural rock powder samples (JB-1,

Table 1. Test analyses of reference glasses[a].

	JB-1a			JB-3			JA-1			JA-2			JR-1		
	R.V.[b]	Ave.[c]	1σ[d]	R.V.	Ave.	1σ	R.V.	Ave.	1σ	R.V.	Ave.	1σ	R.V.	Ave.	1σ
Oxide, wt%															
SiO_2	53.68	54.01	0.41	51.47	51.80	0.27	65.02	65.63	0.34	58.14	58.49	0.20	76.59	77.41	0.44
TiO_2	1.31	1.31	0.05	1.45	1.44	0.03	0.86	0.82	0.03	0.68	0.66	0.03	0.11	0.10	0.04
Al_2O_3	14.80	14.58	0.26	17.37	17.09	0.04	15.47	14.97	0.36	15.88	15.94	0.41	13.02	12.90	0.08
FeO*[e]	8.27	7.85	0.06	10.84	10.28	0.13	6.41	5.83	0.18	5.81	5.44	0.04	0.82	0.81	0.03
MnO	0.15	0.15	0.01	0.18	0.18	0.02	0.16	0.17	0.03	0.11	0.12	0.01	0.10	0.11	0.02
MgO	8.02	8.01	0.06	5.24	5.40	0.19	1.60	1.68	0.08	7.83	7.42	0.12	0.12	0.11	0.02
CaO	9.54	9.70	0.11	9.89	10.23	0.05	5.79	6.08	0.10	6.48	6.64	0.07	0.68	0.76	0.02
Na_2O	2.80	2.96	0.07	2.76	2.81	0.10	3.90	4.00	0.15	3.20	3.44	0.21	4.08	3.51	0.12
K_2O	1.43	1.44	0.03	0.79	0.78	0.02	0.78	0.82	0.03	1.87	1.86	0.07	4.48	4.29	0.11
Total	100.00	100.00		100.00	100.00		100.00	100.00		100.00	100.00		100.00	100.00	
n[f]		7			7			6			9			14	

[a] Reference glasses made of natural rock powder samples (JB-1a, alkali basalt; JB-3, high-alumina basalt; JA-1, dacite; JA-2, andesite; JR-1, rhyolite; Geological Survey of Japan reference samples, "Igneous rock series"; IMAI *et al.*, 1995).

[b] Recommended value (IMAI *et al.*, 1995) normalized by 100%.

[c] Average of analyses normalized by 100%.

[d] One standard deviation (1σ) of analyses.

[e] All iron calculated as FeO.

[f] Number of analyses.

alkali basalt; JB-3, high-alumina basalt; JA-1, dacite; JA-2, andesite; JR-1, rhyolite; Geological Survey of Japan reference samples, "Igneous rock series"; IMAI *et al.,* 1995) whose compositions have been precisely determined. Table 1 summarizes the error statistics of our electron microprobe analyses and the recommended values (IMAI *et al.,* 1995). Agreement between the results and the recommended values was satisfactory.

4. Results and Discussion

The tephra layers at depths of 573, 1361 and 2202 m in the Dome Fuji core were estimated to have been deposited in 18, 72 and 196 ka B.P., respectively (FUJII *et al.,* 1999) on the basis of annual layer thickness which was estimated by a linear relationship between $\delta^{18}O$ and annual accumulation rate using a simple steady state ice flow model (DANSGAARD and JOHNSEN, 1969; WATANABE *et al.,* 1999). Three layers are actually 8 mm thick. Initial thicknesses of these layers at their formation are calculated by the ice flow model (NYE, 1963) to be about 10, 18 and 68 mm, respectively (FUJII *et al.,* 1999). The durations of the tephra fallout were calculated to be about 0.5, 0.7 and 2.3 years, respectively, from the thickness and estimated annual accumulation rate (FUJII *et al.,* 1999). The long duration implies that the fine tephras were intermittently ejected and/ or became suspended in the stratosphere. We ascertained the proper colors of these tephra layers with the standard soil color charts (OYAMA and TAKEHARA, 1988). The 573-m layer looks dull yellow (2.5Y, 6/3) and the others look light gray (2.5Y, 8/2; FUJII *et al.,* 1999).

Scanning electron microphotographs of tephras from these layers, whose average sizes range from 20 to 50 μm, are shown in Fig. 2. The tephra grains a few tens of μm in size are thought to have been transported in the troposphere and stratosphere from source volcanoes in and around Antarctica. The 573-m tephra is commonly blocky and poor in vesicularity (Fig. 2a). It shows pilotaxitic texture. It is composed of euhedral microphenocryst and subhedral microlite, which are commonly plagioclase, clinopyroxene and magnetite, with a minor quantity of interstitial glass. The 1367-m tephra is blocky, glassy and moderately vesiculated (Fig. 2b). The 2202-m tephra is glassy and moderately vesiculated (Fig. 2c).

Mean chemical compositions of the tephras and comparative compositions of rocks from possible sources are shown in Table 2 (BAKER, 1978; TOMBLIN, 1979; PALAIS, 1985). They are plotted on a variation diagram of total alkalis (Na_2O+K_2O) and silica, which are considered to be the most important chemical parameters for classification of igneous rocks (COX *et al.,* 1979; Fig. 3). This indicates that the 1361-m tephra was rich in alkaline components and the others poor in alkaline components. Compositions of the 573 and 2202-m tephras (andesitic and dacitic, poor in K_2O, respectively) are typical of subduction volcanism. Their compositions approximately correspond to the compositions of aphyric basaltic andesite from Visokoi Island in the South Sandwich Islands (BAKER, 1978) and aphyric dacitic lava from the northern part of Candlemas Island in the South Sandwich Islands (BAKER, 1978; TOMBLIN, 1979; Table 2), respectively. This suggests that the 573 and 2202-m tephras were ejected at the times of major eruptions of Visokoi Island and Candlemas Island in the South Sandwich Islands, respectively. The 1361-m tephra, which is peralkaline trachyte, is similar in composi-

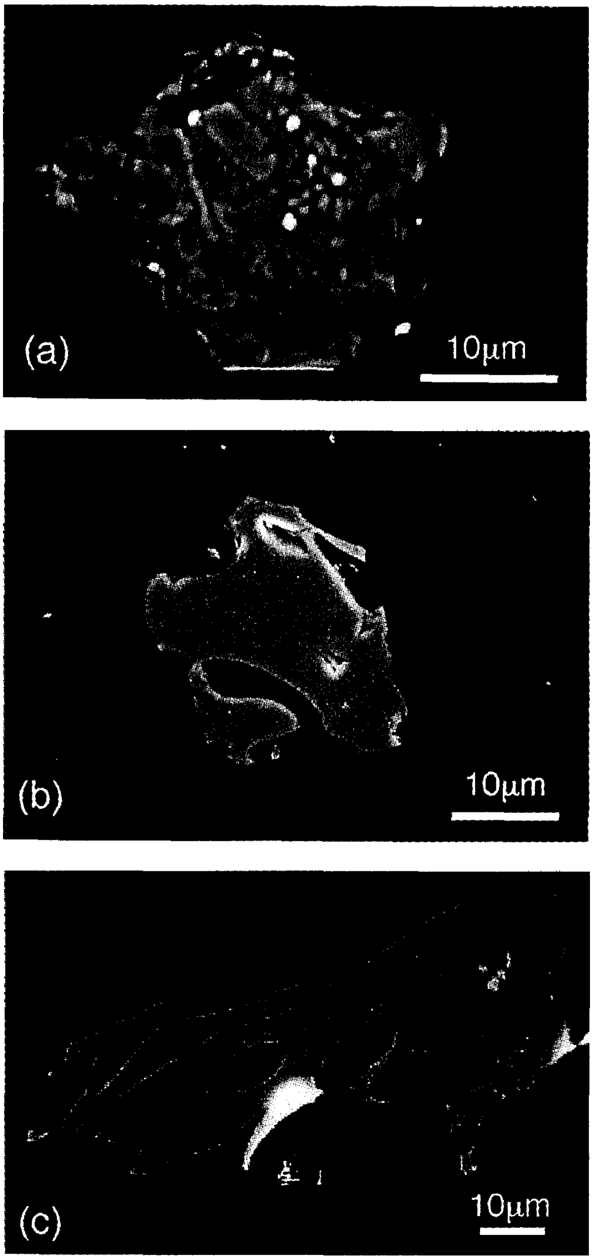

Fig. 2. Scanning electron microscopic (SEM) photographs of tephras in the layers at depths of (a) 573 m, (b) 1361 m and (c) 2202 m in an ice core from Dome Fuji Station.

tion to a tephra from a volcano in Marie Byrd Land (probably, Mt. Takahe; PALAIS, 1985; Table 2). Mount Takahe, which is one of the youngest volcanoes in Marie Byrd Land, is a likely candidate for the source volcano which produced the tephra.

Tephras, whose source is considered to be the South Sandwich Islands, have been found in ice cores from Mizuho (*ca.* 6 ka B.P.; HIGASHI and FUJII, 1994) and Vostok (*ca.* 3.2, 35, 140, 160, 170 and 200 ka B.P.; PALAIS *et al.*, 1987, 1989a; BASILE, 1997) Stations; and in bare ice areas near the Yamato (KATSUSHIMA *et al.*, 1984; NISHIO *et al.*, 1984) and

Table 2. Major element analyses of tephras found in an ice core from Dome Fuji Station and corresponding analyses of possible sources.

Sample	1 Dome F core 573 m depth	2 Dome F core 1361 m depth	3 Dome F core 2202 m depth	4 Visokoi Is. S.S.I.[a]	5 Mt. Takahe M.B.L.[b]	6 Candlemas Is. S.S.I.[a]
Oxide, wt%						
SiO_2	55.25 (0.54)[c]	61.53 (0.31)	64.78 (0.52)	54.00	61.22	64.40
TiO_2	1.12 (0.15)	0.53 (0.05)	0.79 (0.04)	1.31	0.61	0.15
Al_2O_3	13.92 (0.65)	14.47 (0.36)	14.52 (0.20)	14.84	15.16	14.40
FeO*[d]	13.11 (1.39)	7.84 (0.15)	7.19 (0.15)	11.80	7.07	7.22
MnO	0.24 (0.05)	0.32 (0.01)	0.19 (0.03)	0.22	0.29	0.15
MgO	4.18 (0.48)	0.07 (0.04)	1.64 (0.12)	4.17	0.12	1.84
CaO	8.04 (0.40)	1.42 (0.24)	5.07 (0.14)	8.86	1.30	5.28
Na_2O	2.31 (0.31)	9.23 (0.88)	4.63 (0.16)	2.82	7.97	3.79
K_2O	0.22 (0.04)	4.88 (0.06)	0.82 (0.04)	0.60	4.80	0.45
Total	98.39	100.28	99.62	98.62	98.54	97.68
n[e]	4	4	4	—	—	—

[a]South Sandwich Islands.
[b]Marie Byrd Land.
[c]One standard deviation (1σ) of analyses.
[d]All iron calculated as FeO.
[e]Number of analyses.
1–3: Tephras from in the 573, 1361 and 2202-m layers in the Dome Fuji ice core.
4: Aphyric basaltic andesite from Shamrock Hill, Visokoi Island in South Sandwich Islands (BAKER, 1978).
5: Peralkaline trachyte from Mt. Takahe in Marie Byrd Land (KYLE *et al.*, 1981).
6: Aphyric dacite from Candlemas Island in South Sandwich Islands (BAKER, 1978; TOMBLIN, 1979).

Sør Rondane (NARAOKA *et al.*, 1991) Mountains in Dronning Maud Land. Tephras from volcanoes in Marie Byrd Land have also been found in the Byrd (*ca.* 3, 19, 20, 23, 27 ka; KYLE and JEZEK, 1978; KYLE *et al.*, 1981, 1984; PALAIS, 1985; BASILE, 1997), Dome C (*ca.* 25 ka; KYLE *et al.*, 1981) and Vostok (*ca.* 140 ka; BASILE, 1997) ice cores. The 573, 1361 and 2202-m tephra layers do not correspond to those tephra layers in the Vostok, Byrd and Dome C cores judging from the $\delta^{18}O$ profile or the ice core ages (FUJII *et al.*, 1999).

The tephras have been released to the atmosphere at times of major volcanic eruptions in the South Sandwich Islands and Marie Byrd Land, and widely spread onto the surface of the inland plateau of the east Antarctic ice sheet, several thousand kilometers away from the source regions. The tropospheric transport paths of the tephras are controlled by air masses which flow into the inland plateau with low pressure disturbances (ALT *et al.*, 1959; MOSELEY-THOMPSON and THOMPSON, 1982; PALAIS *et al.*, 1987). The tephras which were injected to the stratosphere are transported over the Antarctic ice sheet and fall onto the ice sheet surface by subsidence.

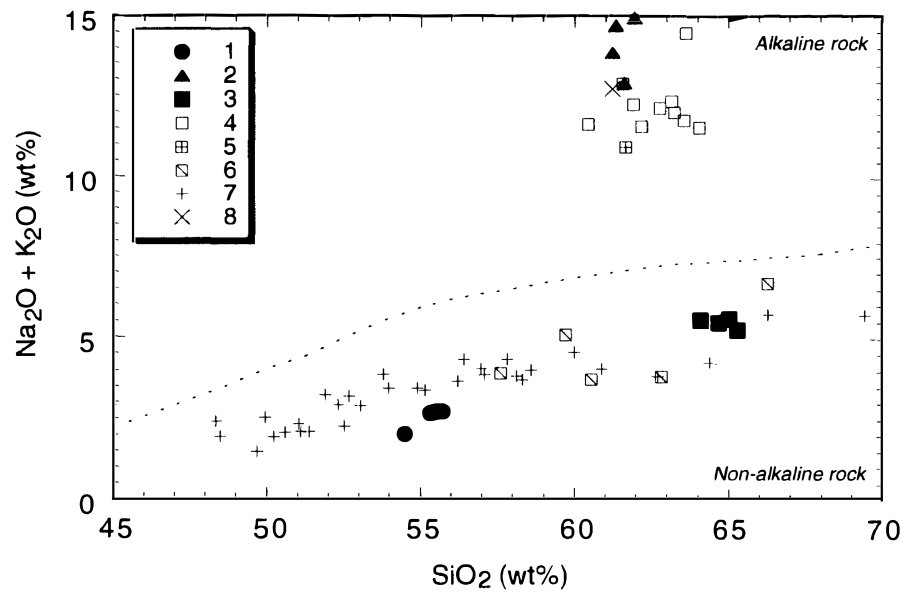

Fig. 3. SiO_2 vs. Na_2O+K_2O diagram of tephras found in an ice core from Dome Fuji Station and other deep ice-coring sites. Compositions of the Cenozoic volcanic rocks are also plotted for comparison (BAKER, 1978; KYLE et al., 1981). Broke line shows a boundary between alkaline and non-alkaline rock fields (MIYASHIRO, 1978).
Symbols: 1–3: 573, 1361 and 2202-m tephras in an ice core from Dome Fuji Station; 4–6: Tephras found in an ice core from Byrd Station (KYLE et al., 1981; PALAIS, 1985), Dome C (KYLE et al., 1981) and Vostok Station (KYLE et al., 1984; PALAIS et al., 1987, 1989a,b, 1990); 7–8: The Cenozoic volcanic rocks from the South Sandwich Islands (BAKER, 1978) and Marie Byrd Land (Mt. Takahe; KYLE et al., 1981).

5. Conclusions

We prepared samples for EPMA analyses of fine tephras in visible tephra layers found in ice cores using small amounts ($8 \mu l$) of water sample. We made preliminary estimates of the source volcanoes of tephras in three specific tephra layers at depths of 573, 1361 and 2202 m in an ice core from Dome Fuji Station in East Antarctica on the basis of their major chemical compositions. The 573 and 2202-m tephras and the 1361 -m tephra are considered to have originated from volcanoes in the South Sandwich Islands and Marie Byrd Land, respectively. These tephra layers have the potential to serve as stratigraphic markers for correlating Antarctic ice cores. Moreover, if ages of the tephras are determined by K-Ar or other methods, the layers containing them may become time markers of Antarctic ice cores which provide absolute ages.

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