

# Minerals in Volcanic Ash 1: Primary Minerals and Volcanic Glass

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## Abstract

Volcanic ash is fragments of magma, and consists of minerals and volcanic glass. These materials in the ash can provide important information on the nature of the magma, because chemical compositions of magma usually show distinct features in each volcano, and because assemblages and compositions of minerals reflect their host melt. Using assemblages and chemical compositions of minerals and glass chemistry, it may be possible to correlate volcanic ash distributed over a wide area. In addition, we may identify the source volcano of the ash. We show several examples of correlating volcanic ash and determining source volcanoes. Moreover, it is possible to discuss magmatic and eruption processes recorded in volcanic ash. We also show several examples of discussing eruption sequences and magma mixing processes using analysis of volcanic ash.

**Key words:** eruption process, magma, minerals, volcanic ash, volcanic glass

## 1. Introduction

In explosive eruptions, magma is fragmented by rapid exsolution of dissolved volatile components to produce pyroclastic materials. Fine-grained portions of these materials are called volcanic ash, and are distributed over a wide area far from the source volcano according to the dominant wind direction above the volcano. Magma is usually composed of silicate melt and crystallized minerals (called phenocryst). Thus, volcanic ash consists of minerals and volcanic glass. The glass is quenched melt of magma during an eruption, and the minerals are phenocrysts suspended in the melt. Many petrological and geochemical studies of volcanoes all over the world have revealed that chemical compositions of magma can be distinguished among volcanoes. This has been used in classifying regional magma types (e.g. LeBas, 1988). In addition, comparing magmas of adjacent volcanoes, the magma of each volcano could be distinguished from that of the neighboring volcano (e.g., Sakuyama, 1983). Thus, volcanic ash can be found to correspond to magma of a source volcano, and analysis of minerals and volcanic glass in the ash can provide information on magma from the source volcano.

In this article, we describe minerals and glass in volcanic ash, and review their scientific applications. We mention variations of magma types and representative phenocrystic minerals in magma. We also introduce methods of analyzing minerals and glass in the ash. We present several examples of correlation of volcanic ash over a wide area. In conclusion, we show several examples of research using minerals and glass in volcanic ash.

## 2. Magma Types and Volcanic Ash

### 2.1 Magma types and melt chemistry

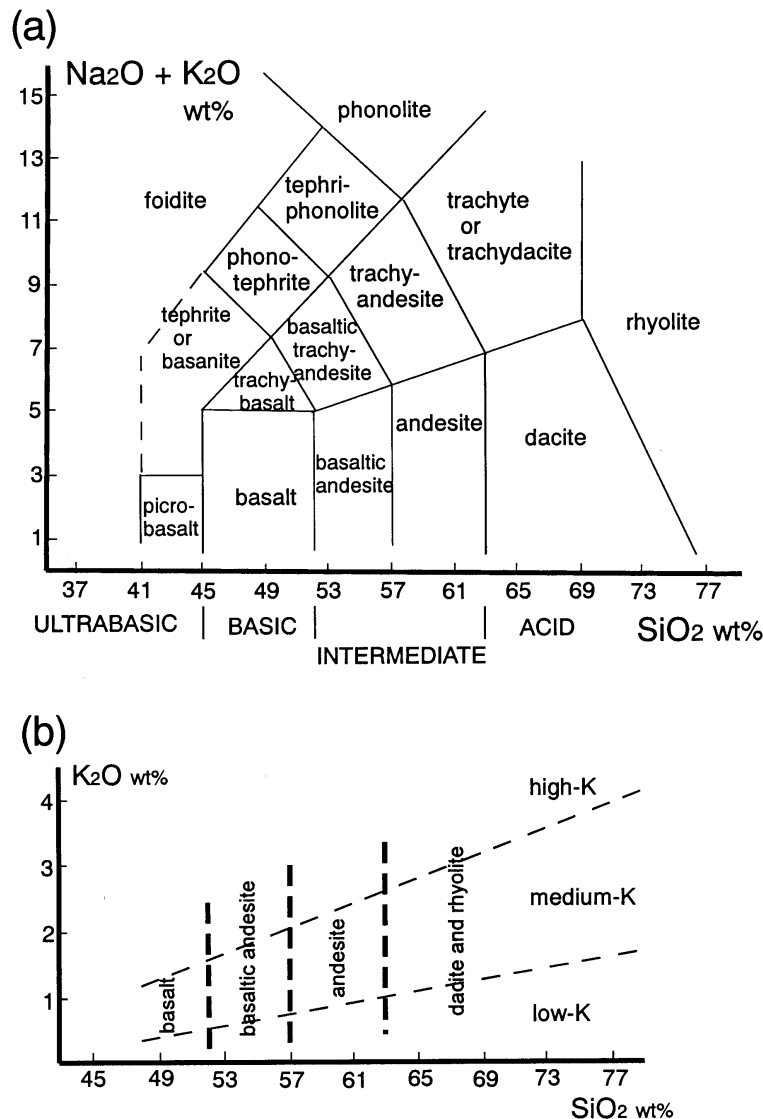
Magma is produced by partial melting of materials from the earth's crust and mantle, and is usually a mixture of melt and mineral crystal. In many cases, the minerals crystallize in the magma during the ascent to the surface due to cooling of the magma. Chemical compositions of magma vary according to both chemical compositions and mineral assemblage of source materials. Also, magma varies in terms of conditions of melting, such as degree of melting, pressure, volatile components, etc. Integrated geochemical and petrological studies have revealed that there exist variations in magma types corresponding to regional tectonic settings. These variations have

been classified into rock types in terms of  $\text{SiO}_2$  – total alkali and  $\text{K}_2\text{O}$  diagrams (Fig. 1).

Considering magmatic processes forming compositional variations, there exist two types of mechanisms for compositional variations of magmas; variations in primary magmas and variations due to differentiation of a primary magma. In Figure 1, the former is variations in alkali and  $\text{K}_2\text{O}$  content at similar  $\text{SiO}_2$  content. These variations are mainly derived from diversity of primary magmas. On the other hand, the latter variations are produced by differentiation processes for a primary magma during ascent. The latter processes are complex, including crystallization-differentiation, contamination of crustal materials, magma mixing processes, etc. Once a primary magma is segregated from its source, its chemical compositions will change due to differentiation processes. These processes usually modify the primary magma toward felsic compositions, as in Fig. 1.

Many explosive eruptions have been caused by felsic magma, and have produced widespread volcanic ash. Thus, in the case of non-alkaline rocks, magma types from explosive eruptions are usually dacite and rhyolite. Explosive eruptions by more mafic magma often produce tephra. In the case of Japan (Fig. 2), for example, the Fuji, Iwate and Izu-Oshima volcanoes have produced basaltic tephra. However, these basaltic tephra are not as widely distributed compared with those of the same scale (magmatic volume) of explosive eruption of felsic magma.

The above description of magmatic compositions is based on whole-rock chemistry of eruptive products (rocks), which include melt plus minerals (phenocrysts). Thus, in order to determine melt compositions during eruption, we have to subtract the compositions of minerals from the whole-rock compositions. Table 1 shows examples of chemical compositions of magmatic melt (volcanic glass) found in the Tyatya volcano (Fig. 2). In many cases, melt



**Fig. 1** (a) Chemical classification and nomenclature of volcanic rocks using the total alkali versus silica diagram (Le Maitre, 1989).  
 (b) Division of basalts, basaltic andesites, andesites, dacites and rhyolites into low-K, medium-K and high-K types (Le Maitre, 1989).

compositions are less silicic than those of the whole-rock composition. For example, although the eruptive products of historic eruptions of the Hokkaido-Komagatake volcano (Fig. 2) are andesitic ( $\text{SiO}_2=60\%$ ), their melt compositions are rhyolitic (Table 1) (Kozu, 1934).

## 2.2 Minerals in magma

Rock-forming minerals crystallizing from magma are mainly silicate minerals. These silicate minerals can be divided into colored and colorless minerals. The colored minerals contain considerable amounts of transition metal ions, such as iron. On the other hand,

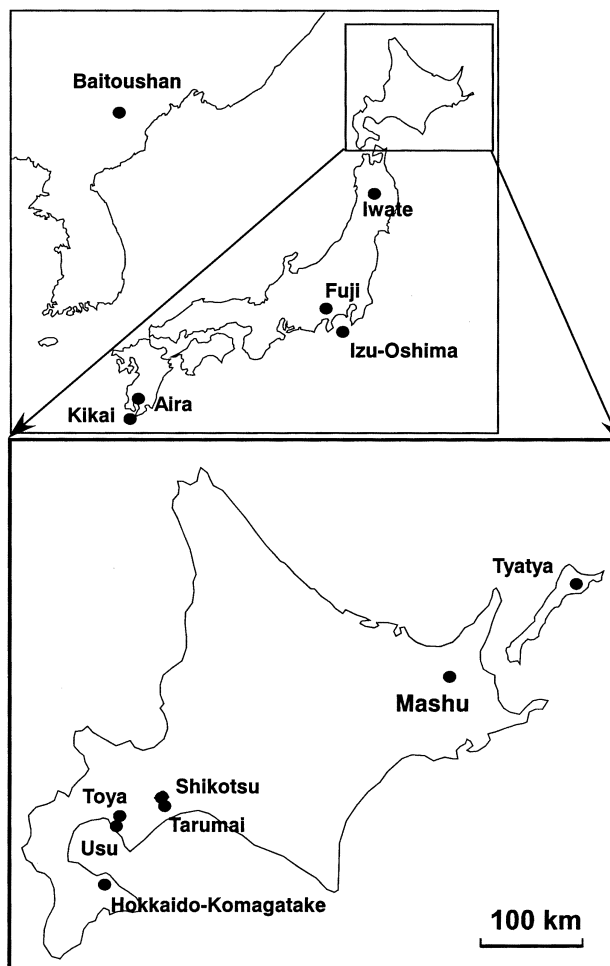


Fig. 2 Index map showing volcanoes in the text.

**Table 1** Chemical compositions of volcanic glass of tephra found in the Tyatya volcano.

Sample	Ty-136	Ty-134	Ty-42	Ty-133	Ty-138	Ty-170
Analysis No.	136-1	134-9	42-5	133-6	138-1	170-6
Tephra	-	Ko-c1	Ko-c2	Ta-a	Ma-b	B-Tm
Source	Tyatya	Koma.	Koma.	Tarumai	Mashu	Baito.
Age	?	1856 AD	1669 AD	1739 AD	ca. 1 ka	ca. 969 AD
(wt%)						
SiO <sub>2</sub>	53.07	75.16	77.08	76.88	73.91	72.15
TiO <sub>2</sub>	1.55	0.44	0.33	0.23	0.66	0.21
Al <sub>2</sub> O <sub>3</sub>	13.40	11.85	11.90	12.03	12.72	8.92
total FeO	12.68	1.94	1.75	1.77	3.03	3.73
MnO	0.23	0.08	0.01	0.08	0.08	0.00
MgO	4.53	0.36	0.38	0.29	0.64	0.01
CaO	9.07	2.16	1.89	1.83	3.33	0.23
Na <sub>2</sub> O	2.79	3.25	3.44	3.57	4.27	5.00
K <sub>2</sub> O	0.89	1.79	1.75	2.32	0.72	4.70
Total	98.19	97.02	98.52	98.98	99.36	94.95

(Abbreviations: Koma., Hokkaido-Komagatake; Baito., Baitoushan)

the colorless minerals do not contain transition metal ions as a major constituent. Besides the silicates minerals, Fe-Ti oxide minerals are also contained in

almost all magmas. Table 2 summarizes major rock-forming minerals occurring in volcanic ash. Major colored minerals in widespread tephra are

**Table 2** Representative rock-forming minerals in volcanic ash.

Group	minerals	major end-member	Chemical formula*	Solid solution	Remarks
Feldspar group	Plagioclase	Anorthite (An)	$\text{CaAl}_2\text{Si}_2\text{O}_8$	between An and Ab	
		Albite (Ab)	$\text{NaAlSi}_3\text{O}_8$		
	Alkali feldpar	potassium feldspar	$\text{KAlSi}_3\text{O}_8$	between potassium feldspar and Ab	Sanidine is common
Silica minerals	Quartz		$\text{SiO}_2$		
Olivine group	Olivine	Forstelite (Fo)	$\text{Mg}_2\text{SiO}_4$	between Fo and Fa	
		Fayalite (Fa)	$\text{Fe}^{2+}_2\text{SiO}_4$		
Pyroxene group	Orthopyroxene	Enstatite (En)	$\text{MgSiO}_3$	between En and Fs	
		Ferrosilite (Fs)	$\text{Fe}^{2+}\text{SiO}_3$		
	Clinopyroxene	Wollastonite	$\text{CaSiO}_3$	among En, Fs and Wo (Wo<50 mole%)	Augite is common
Amphibole group	Hornblende	Actinolite (Act)	$\text{Ca}_2(\text{Mg}, \text{Fe}^{2+})_5\text{Si}_8\text{O}_{22}(\text{OH})_2$	among Act, Ed, Prg and Ts	AlIV>0.8
		Edenite (Ed)	$\text{NaCa}_2(\text{Mg}, \text{Fe}^{2+})_5\text{AlSi}_7\text{O}_{22}(\text{OH})_2$		
		Pargasite (Prg)	$\text{NaCa}_2(\text{Mg}, \text{Fe}^{2+})_4\text{Al}_3\text{Si}_6\text{O}_{22}(\text{OH})_2$		
		Tschermakite (Ts)	$\text{Ca}_2(\text{Mg}, \text{Fe}^{2+})_3\text{Al}_4\text{Si}_6\text{O}_{22}(\text{OH})_2$		
	Cummingtonite		$(\text{Mg}, \text{Fe}^{2+})_7\text{Si}_8\text{O}_{22}(\text{OH})_2$		
Mica group	Biotite	Annite (Ann)	$\text{K}_2\text{Fe}^{2+}_6\text{Al}_2\text{Si}_6\text{O}_{20}(\text{OH})_4$	among Ann, Sdp, Phl and Est	Relatively Mg-poor
		Siderophyllite (Sdp)	$\text{K}_2\text{Fe}^{2+}_5\text{Al}_4\text{Si}_5\text{O}_{20}(\text{OH})_4$		
		Phlogopite (Phl)	$\text{K}_2\text{Mg}_6\text{Al}_2\text{Si}_6\text{O}_{20}(\text{OH})_4$		
		Eastonite (Est)	$\text{K}_2\text{Mg}^{2+}_5\text{Al}_4\text{Si}_5\text{O}_{20}(\text{OH})_4$		
Spinel group	Ti-magnetite	Magnetite (Mag)	$\text{Fe}^{2+}\text{Fe}^{3+}_2\text{O}_4$	between Mag and Ulv	
		Ulvospinel (Ulv)	$\text{Fe}^{2+}_2\text{TiO}_4$		
	Ilmenite		$\text{Fe}^{2+}\text{TiO}_3$	include $\text{Fe}^{3+}_2\text{O}_3$ component	

\* major elements, and trace elements are not included.

pyroxene, amphibole and mica groups. In addition, olivine is often recognized in tephra. Major colorless ones are the feldspar group and quartz. In alkaline magma, alkali feldspar is often present. Major Fe-Ti oxide minerals are Ti-magnetite and ilmenite (Table 2). Examples of mineral compositions are also shown in Table 3.

Even if minerals have the same crystal structure and are named as the same mineral, chemical com-

positions of these minerals vary. This is because many rock-forming minerals are a solid solution, which can exchange ions in the crystal structure of various ratios (Table 3). For example, olivine has two end-member components, forsterite ( $\text{Mg}_2\text{SiO}_4$ ) and fayalite ( $\text{Fe}_2\text{SiO}_4$ ). Between both end-members,  $\text{Fe}^{2+}$  and  $\text{Mg}^{2+}$  ions can be exchanged with each other in various proportions. In the case of a solid solution, minerals are usually described by the mole ratio of an

**Table 3** Mineral compositions and numbers of ions of representative silicate rock-forming minerals

Source Mineral (wt%)	Toya Clinopyroxene	Toya Orthopyroxene	Toya Hornblende	Tarumai Olivine	Toya Plagioclase	Toya Plagioclase
$\text{SiO}_2$	52.74	53.32	48.21	37.77	66.78	48.83
$\text{TiO}_2$	0.20	0.16	1.60	0.03	nd	nd
$\text{Al}_2\text{O}_3$	1.29	0.70	7.11	0.02	20.81	32.29
$\text{Cr}_2\text{O}_3$	0.00	0.01	0.00	0.00	nd	nd
FeO	9.56	21.94	13.54	23.87	0.10	0.57
MnO	0.60	1.19	0.62	0.41	nd	nd
MgO	13.86	21.78	14.45	37.05	0.00	0.01
CaO	20.93	0.97	10.99	0.15	2.32	16.44
NiO	nd	nd	nd	0.02	nd	nd
$\text{Na}_2\text{O}$	0.32	0.00	1.36	0.02	10.09	2.21
$\text{K}_2\text{O}$	nd	nd	0.08	nd	0.54	0.01
total	99.50	100.07	97.95	99.32	100.64	100.36
Si	1.978	1.987	7.020	0.998	2.919	2.232
Ti	0.006	0.004	0.175	0.001	----	----
Al	0.057	0.031	1.220	0.001	1.072	1.740
Cr	0.000	0.000	0.000	0.000	----	----
Fe	0.300	0.684	1.651	0.528	0.004	0.022
Mn	0.019	0.038	0.076	0.009	----	----
Mg	0.775	1.210	3.138	1.460	0.000	0.001
Ca	0.841	0.039	1.715	0.004	0.108	0.805
Ni	----	----	----	0.000	----	----
Na	0.023	0.000	0.383	0.001	0.855	0.196
K	----	----	0.014	----	0.030	0.001
total	3.999	3.993	15.393	3.002	4.988	4.996
Number of O	6	6	23	4	8	8
Fo				73.4		
Mg/(Mg+Fe)	72.1	63.9	65.5			
Wo	43.9	2.0				
En	40.5	62.6				
Fs	15.7	35.4				
Or					3.0	0.1
An					10.9	80.4
Ab					86.1	19.5

Abbreviations; Fo, forstelite mole%; Wo, wollastonite mole%; En, enstatite mole%; Fs, ferrosilite mole%; Or, orthoclase ( $\text{KAlSi}_3\text{O}_8$ ); An, anorthite; Ab, albite. See table 2

end-member; e.g., the forsterite (Fo) mole % in olivine (Table 3).

### 3. Analytical Methods

Constituents of volcanic ash are small in size, and can be identified by using a microscope or polarized microscope. To identify volcanic glass and minerals, refraction indexes have been widely used (e.g., Machida and Arai, 1990). However, the index may also be affected by trace elements in the glass and minerals. Thus, it has been widely accepted that direct measurement of glass and mineral compositions is essential for research of volcanic ashes. Chemical compositions of volcanic glass and minerals are determined by EPMA (electron probe micro analyzer), which determine chemical compositions of small areas or spots (~several  $\mu\text{m}$  in diameter) using an electron-beam. On the basis of the X-ray dispersion method, the EPMA is divided into two types, wave length (WDS) and energy dispersive spectrometry (EDS). The former type can determine trace elements (~several hundreds ppm), because it utilizes a strong electron beam. However, such a strong beam may damage the sample, especially glass and hydrous minerals. In contrast, the latter type can be applied to glass and hydrous minerals without serious damage, because it does the analysis with a weak electron beam. However, detection limits of analyzed elements by EDS are higher than those of WDS. Considering its ability to get high detection limits, the WDS type is used widely now. In the case of analysis of glass and hydrous minerals by the WDS system, defocused and/or scanned electron beams have been applied to avoid sample damage.

Analytical methods have also been developed especially for volcanic glass focusing on trace elements, such as rare earth elements. In this case, several hundred mg of concentrated glass is treated for ICP-AES. Although major element analysis of glass by EPMA must be enough to correlate ashes, if we try to discuss magma genesis by using volcanic ash, further analysis of glass and minerals, such as by ICP-Mass with a laser ablation system, may be essential.

### 4. Application of Glass Chemistry in Volcanic Ash Studies

In this section, we overview several examples of research using chemical compositions of volcanic glass in ash. The primary purpose of using volcanic glass is to correlate volcanic ash, and to identify the source volcano of the volcanic ash. Another example shows that volcanic ash also contains a record of magmatic processes during eruption.

#### 4.1 Correlation and source volcano of volcanic ash

The pioneering and most successful research of volcanic glass is correlation of widespread tephra of giant eruptions forming calderas in southern Kyushu. Machida and Arai (1976) identified Aira-Tn tephra (AT) over a wide area of the Japanese islands. They correlated these tephras using a refractive index of volcanic glass and minerals. Moreover, by using the index in addition to stratigraphic investigation, they revealed that the ash is derived from a 20-25 ka eruption of the Aira caldera (Fig. 2). In addition, Machida and Arai (1978) also recognized Kikai-Akahoya tephra (K-Ah) from the Kikai caldera in southern Kyushu (Fig. 2), on the basis of correlation by the refractive index of volcanic glass and minerals. This tephra has been dated as 6.3 ka (Machida & Arai, 1990). Since then, many major volcanic ash layers in the Japanese islands have been correlated. In addition, the source volcanoes of these layers have also been identified by tephrochronological and petrological studies of these layers. These results are reviewed by Machida and Arai (1992).

Since the 1980s, in addition to measurement of refractive index, chemical compositions of volcanic glass determined by EPMA have been adopted for correlation of volcanic ash. For example, Tokui (1984) correlated volcanic ash distributed over eastern Hokkaido to AD 1739 ash of the Tarumai volcano (Ta-a) in southwestern Hokkaido. These ashes had been correlated as distinct ashes originating from different volcanoes. In addition, Tokui (1984) and Okumura (1980) summarized many tephras in eastern Hokkaido, some of which were derived from large eruptions of volcanoes in southwestern Hokkaido during the 17-19 centuries. In southwestern Hokkaido, it has been widely accepted that three volcanoes, Hokkaido-Komagatake, Usu and Tarumai volcanoes, erupted sequentially from AD 1640 to 1667. Thus, it might be hard to identify each ash in distal areas, because there exists thin soil between each ash. However, using chemical compositions of volcanic ash, distal ash from the three volcanoes can be identified, for example, in the  $\text{TiO}_2\text{-K}_2\text{O}$  diagram (Fig. 3).

Distal volcanic ash can also reveal the eruption history of a volcano. Katsui *et al.* (1989) summarized the eruption history of the Hokkaido-Komagatake volcano. However, on the basis of field observations at proximal sites, Hayakawa (1991) suggested that the so-called AD 1694 ash of the volcano was the product not of a distinct eruption but of a later phase of the 1640 eruption, and pointed out that the occurrence of the 1694 eruption might be doubtful. Furukawa *et al.* (1995) also investigated volcanic ash at distal areas, and indicated that there exists distinct ash of the AD 1667 Tarumai ash between two ash layers, both of which have volcanic glass with chemical compositions derived from Hokkaido-Komagatake. The

upper layer is covered by another ash of the 1739 Tarumai eruption. Thus, according to stratigraphy of distal ash layers, it can be concluded that the Hokkaido-Komagatake volcano erupted just before AD 1667, and between 1667 and 1739. Thus, it has been proven that the Hokkaido-Komagatake volcano did erupt in 1694, and that the so-called 1694 ash of Hokkaido-Komagatake volcano is not a product of a later phase of the 1640 eruption.

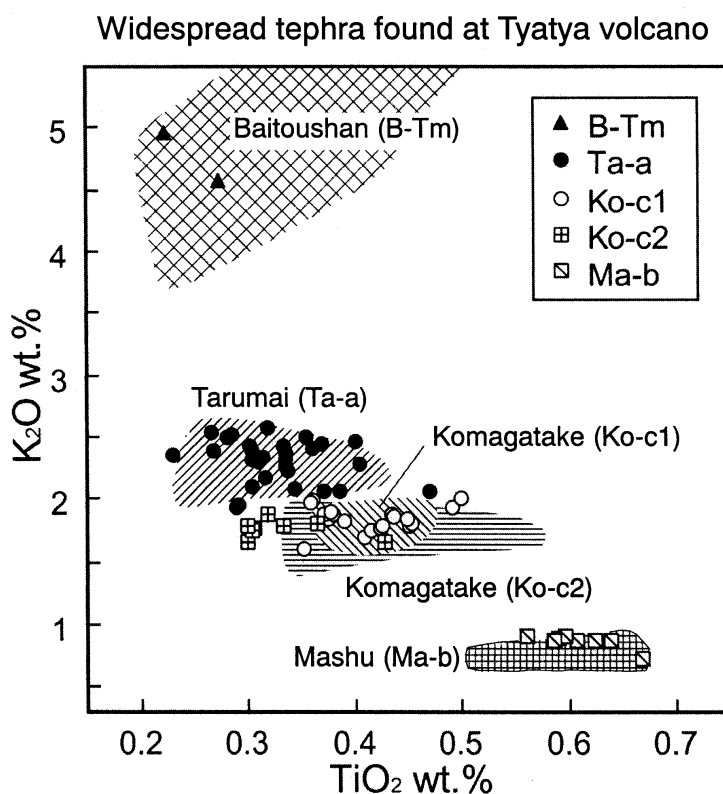
If the source volcano of ash and its age can be identified, the ash becomes a possible time marker to construct a stratigraphy for the area. Nakagawa *et al.* (2002) investigated geological studies of the Tyatya volcano, southern Kuril Islands, and constructed a stratigraphic relationship among the eruptive products of the volcano. They also found several widespread ash layers among these eruptive products. Using chemical compositions of the volcanic glass of these ashes, the source volcano and eruption age were determined (Fig. 3). They identified five widespread ash layers of volcanoes far from the Tyatya volcano, the 1694 and 1856 eruptions of Hokkaido-Komagatake, the 1739 of Tarumai, and eruption around 1 ka of the Mashu and Baitoushan (at the boundary of North Korea and China) volcanoes (Fig. 2). Based on the presence of these ash layers, they discussed the eruption history and mode of eruption of the Tyatya volcano.

#### 4.2 Magma variations and eruption processes

In the case of correlation of volcanic ash, average chemical compositions of volcanic glasses have been used in many cases. However, there exist possible compositional variations in glass chemistry beyond analytical error. In this section, we introduce our ongoing research of the Baitoushan volcano to show that glass chemistry of ash can provide important information for understanding of eruption processes.

Baitoushan volcano is located at boundary between China and North Korea (Fig. 2), and is a large shield volcano with a summit caldera. Recent eruptions have occurred at the summit caldera, and discharged large amounts of felsic magma. The last large eruption occurred around the 10th century and produced widespread tephra covering northern Japan (B-Tm tephra; Machida and Arai, 1984). Chemical compositions of glasses of the B-Tm tephra have been determined by many authors. According to these data, the glass of the tephra shows wide compositional variations, for example in the  $\text{SiO}_2$ - $\text{K}_2\text{O}$  diagram. However, these variations have not been emphasized yet.

We investigated the 10th century eruption of the Baitoushan volcano both in distal and proximal areas. In the proximal area, the eruption can be divided into phase 1 and phase 2. In phase 1, a large plinian eruption occurred to produce pumice fall deposits, which are trachytic. Although there might exist a consider-



**Fig. 3**  $\text{TiO}_2$ - $\text{K}_2\text{O}$  diagram for identification of volcanic ash layers in Hokkaido (shaded area). Shaded areas are after Furukawa *et al.* (1997) and Nakagawa *et al.* (2002). Chemical compositions of volcanic glass found at the Tyatya volcano are also shown.

able break between the two phases, subsequent large eruptions (phase 2) occurred to produce a plinian fall and pyroclastic flow, which are more mafic. We also collect distal ash fall in Hokkaido 1,000 km east of the volcano, where the thickness of the ash is about 1-2 cm. We divided the ash into three layers, lower, middle and upper, and collected each part carefully. Chemical compositions of both proximal and distal ashes are plotted in Fig. 4. Our analytical results for the ash are the same as previously reported variations in B-Tm tephra (Machida and Arai, 1992). In addition, compositional differences in the ash also exist among the three parts. Taking the mineral effects in the proximal deposits into consideration, compositional variations in proximal deposits are similar to those in distal deposits. Moreover, the compositional difference of the proximal deposits between the two phases can be also recognized in distal ash from lower to upper parts. Thus, we could conclude that the previously reported compositional variations in glass from B-Tm tephra are not due to analytical error but possible variations in melt

compositions. The variations in the 10<sup>th</sup> century eruptive products may reflect variations of magma types in the magma chamber(s) just before the eruption. Although detailed magmatic processes during the 10<sup>th</sup> century eruption will be submitted to another journal, we would like to emphasize that compositional variations in the glass of volcanic ash can provide an important basis for discussion of eruption processes.

## 5. Application of Mineral Chemistry in Volcanic ash

### 5.1 Correlation of tephra

The presence of rare minerals in volcanic ash may be useful for correlating and identifying the ash. For example, volcanic ash from the Toya volcano (Fig. 2), northern Japan, is characterized by the presence of albite (Na-rich plagioclase: An~10), eulite (Fe-rich orthopyroxene: En~25) and cummingtonite (mineral of the amphibole group). These minerals and their chemical compositions are not common in other

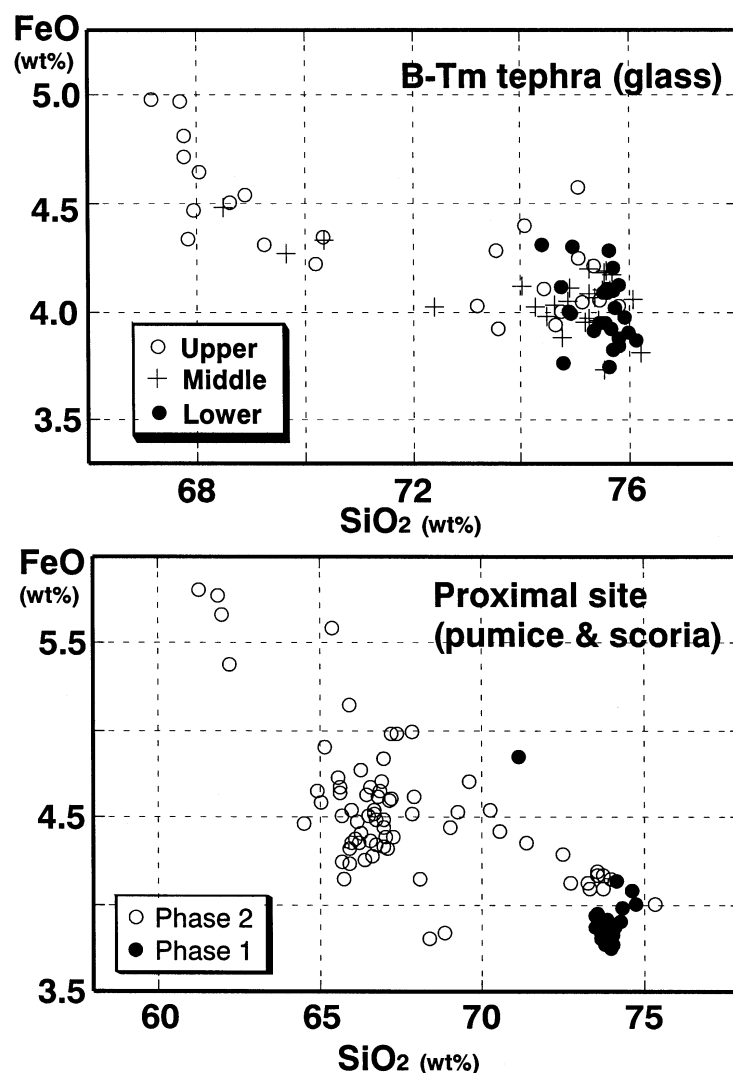


Fig. 4 SiO<sub>2</sub> versus FeO diagrams for volcanic glass of B-Tm tephra and whole-rock compositions of pumice clasts from the Baitoushan volcano. Symbols are shown in the text.



volcanic ashes in Japan during the late Quaternary (Machida and Arai, 1992). B-Tm ash from the Baitoushan volcano is also characterized by the presence K-feldspar. K-feldspar is not present in many ashes of Japan during the late Quaternary. This is because the magma which produced B-Tm ash was strongly alkaline. Such alkaline-rock series are characteristic of volcanism on the continent, and have not occurred in many volcanoes of the Japanese Islands. Therefore, the presence of such minerals must be strong evidence for identifying Toya and B-Tm ash.

Even if the same minerals are contained in the ash, mineral chemistry might be also useful for identifying each ash. This is because chemical compositions of minerals strongly depend on melt compositions and/or magmatic temperatures. For example, the Fe/Mg ratios of olivine and orthopyroxene reflect the ratios in the magma. Thus, if melts of two volcanoes have similar Fe/Mg ratios, and if the melts can be distinguished by other elements, the Fe/Mg ratios of these minerals must be similar. Thus, although mineral chemistry might be useful for identifying ash, it would not be easier than using glass chemistry.

Even if major elements in minerals are similar, trace elements are often available to identify the ash.

Using a Mn/Mg – Al diagram, Tomiya (1995) suggested that the Ti-magnetite of each historical eruption of the Usu volcano from 1640 to 1977 shows distinct compositional variations in the diagram, and that eruptive materials can identify eruption age by using the diagram. On the basis of systematic compositional variations in T-magnetite, Tomiya *et al.* (2002) indicated that the initial eruption of a series of eruptions of the Usu volcano during 2000 was caused by new magma, which was distinct from any other historic magmas.

## 5.2 Implications for study of magma genesis

Besides identification of ash, mineral chemistry could provide important information on magma genesis, because the assemblage and chemistry of minerals depend on magma compositions and crystallization conditions (temperature, pressure, etc.). As mentioned before, Toya tephra contain minerals with unique compositions. For example, although albite plagioclase is most dominant in Toya ash, more calcic plagioclase is often recognized in the ash. These calcic and albitic plagioclases could not coexist in equilibrium. Figure 5 shows histograms of plagioclase from three pumices in the same pyroclastic flow.

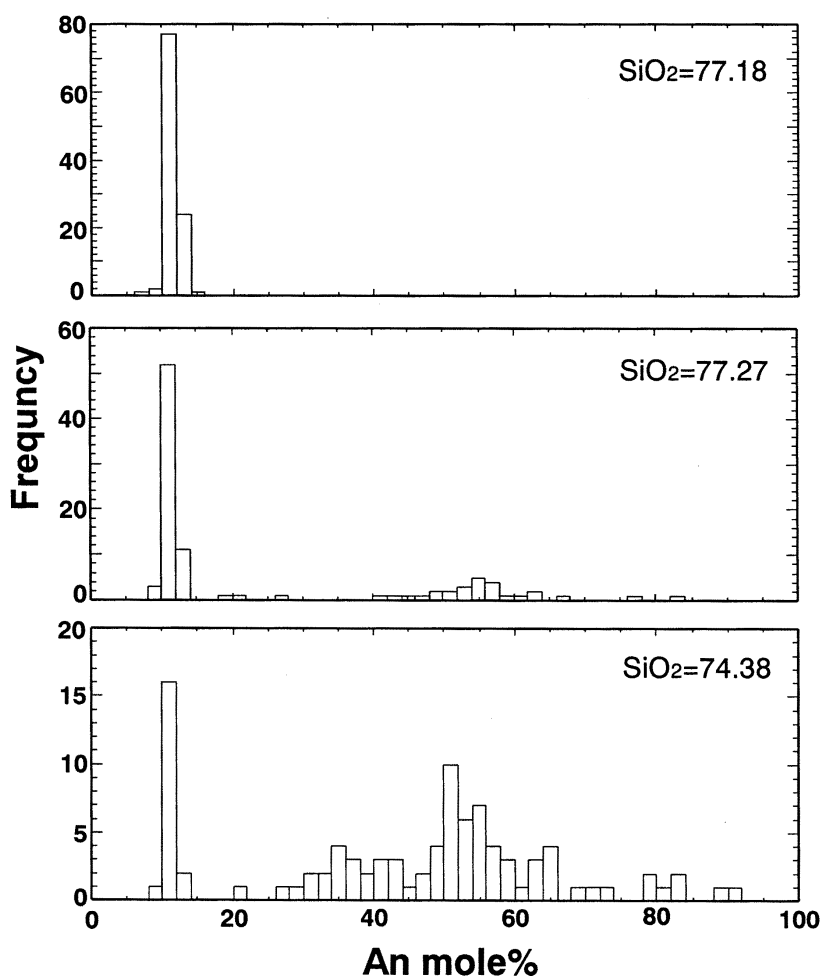


Fig. 5 Histograms for plagioclase phenocrysts from three pumice clasts of a Toya pyroclastic flow. An mole %;  $100 \cdot \text{Ca} / (\text{Ca} + \text{Na} + \text{K})$

According to whole-rock chemistry of these pumices, the compositional distributions of the plagioclase differ. More felsic pumice contains albite plagioclase only, whereas chemical compositions of plagioclase in more mafic pumices range from An ( $100 \cdot \text{Ca}/(\text{Ca} + \text{Na} + \text{K})$ )  $\sim 90$  to  $\sim 9$ . Such wide variations could not be achieved by crystallization from a single magma. This strongly suggests that mixing between two magmas with different chemistries and temperatures occurred during the Toya eruptions.

Equilibrium magmatic temperature can be calculated using mineral chemistry. In this section, we show an example from the 1739 Tarumai eruption (Fig. 2). The eruptive materials contained both Ti-magnetite and ilmenite. Compositional variations of Mn/Mg ratios are wide in Ti-magnetite, whereas they are narrow in ilmenite (Fig. 6). Equilibrium relationships between both minerals can be checked by the relationship of the Mn/Mg ratio of the minerals (Bacon and Harshmann, 1994). Ilmenite can coexist with type 1 Ti-magnetite at low Mn/Mg ratios, whereas other types of Ti-magnetite cannot coexist with these ilmenites (Fig. 7). In summary, there exist more than two types of Ti-magnetite in the 1739

Tarumai eruptive materials. The Ti-magnetite and ilmenite in equilibrium indicate a magmatic temperature of  $\sim 900^\circ\text{C}$  whereas the other Ti-magnetites with higher Mn/Mg ratios must be derived from another magma having a much higher magmatic temperature. This temperature cannot be calculated, because there is no ilmenite coexisting the Ti-magnetite in equilibrium. Thus, on the basis of the compositional relationship between Ti-magnetite and ilmenite, it can be concluded that the eruptive materials of the 1739 Tarumai eruption are products of mixing, and that the magmatic temperature of one of end-member magma with a lower temperature was about  $900^\circ\text{C}$ .

## 6. Summary

Volcanic ash is fragments of magma, and consists of glass and minerals. Thus, both glass and minerals can provide information on the magma. Chemical compositions of these glasses and minerals have been determined not only to correlate ashes from different areas but also to identify their source volcanoes. In addition to these purposes, melt and minerals can also provide a record of magmatic and eruption processes

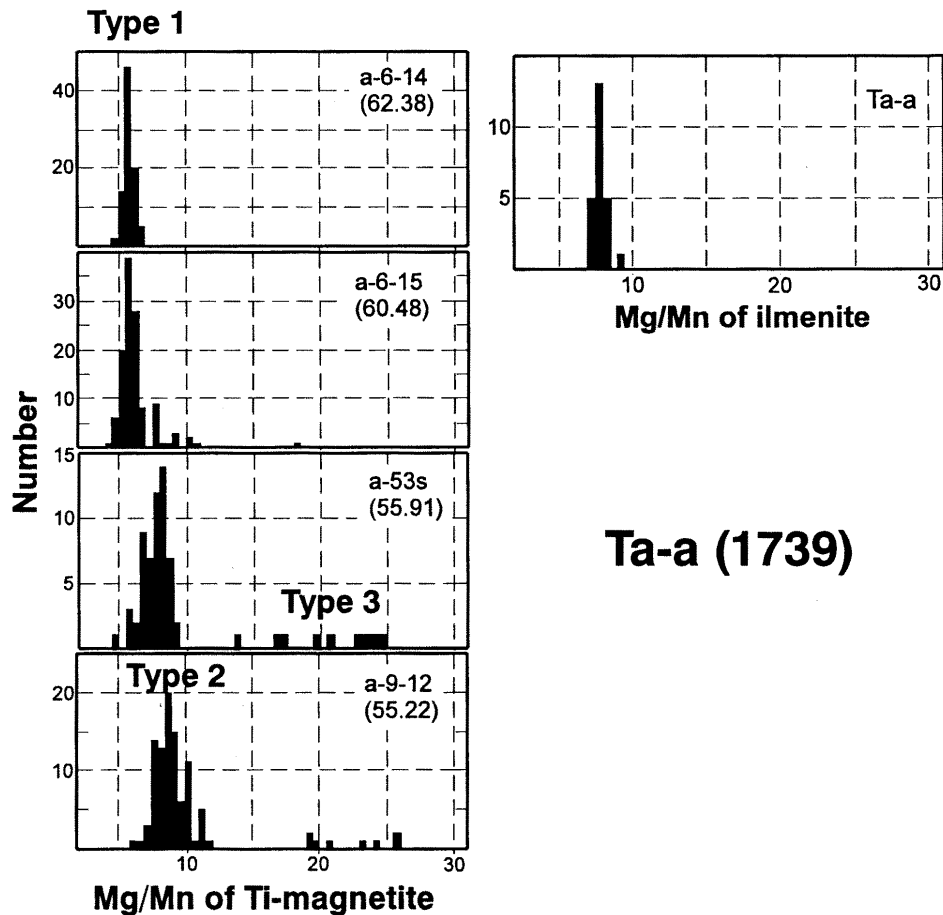


Fig. 6 Histograms of Mg/Mn ratio of Ti-magnetite and ilmenite phenocrysts of pumice of the AD 1739 eruption of the Tarumai volcano. In the case of Ti-magnetite, each histogram corresponds to each pumice. The histogram of ilmenite includes minerals in four pumices.

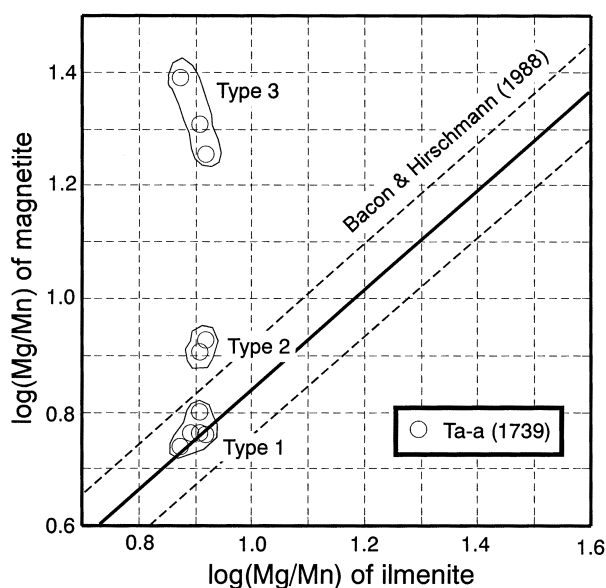


Fig. 7 Mg/Mn ratios between Ti-magnetite and ilmenite. If both minerals are in equilibrium, the ratios of the minerals are plotted near the solid line in the figure.

just before and/or during eruption. Thus it should be noted that petrological and geochemical studies of glass and minerals in volcanic ash must be developed, in addition to tephrochronological study.

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