Tephrochronological data for correlation of distal air-fall tephra from Ilopango Caldera in the central highlands of El Salvador, Central America

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1. Introduction

Ilopango Caldera is a large caldera (8 x 11 km) located in the eastern neighbor of Metropolitan Area of San Salvador City (MASS), the capital of Republic of El Salvador (Fig. 1). The latest huge eruption of Ilopango Caldera occurred in the 4^{th} to 6^{th} century (Dull et al., 2001; Dull, et al., 2010; Kitamura, 2010) producing the emplacement of pyroclastic flow up to 40 km from the caldera and the broad distribution of volcanic ash in all over the territory of El Salvador. The tephra, called "TBJ", is recognized as the most important time marker by archeologists in Central America.

On the other hand, three tephras, called TB2, TB3 and TB4, produced by the eruptions of Ilopango Caldera before the TBJ eruption were also reported previously. However, their dispersal areas in land and their stratigraphic relationship with other local volcanic events or topographic surface remains unknown without the proximal area of the origin. For example, around Santa Ana Volcano near Chalchuapa City, which located ca. 80 km from Ilopango, some vitric white ash layers that show distal facies similar to the TBJ tephra (Kitamura, 2009), but their origins remain unknown.

In order to identify tephra in distal area, mineralogical and chemical properties of tephra are important, because tephra changes its geological properties from proximal to distal area. For instance, it is general that the grain size and the thickness of tephra becomes finer and thinner, respectively, from proximal to distal area. The same tephra shows different properties, such as the coarse thick pumice layer in proximal area and the thinly bedded, or discontinuous, vitric fine ash layer in distal area.

This study aims at clarifying mineralogical and chemical properties of the tephras from Ilopango Caldera before the TBJ eruption as the basis for the identification of the distal fine ash layers, and correlating the vitric fine ash layers interlayered in the succession of Santa Ana volcanic deposit near Chalchuapa City in the western part of El Salvador, C. A.

2. Previous studies

(1) Tephras from Ilopango Caldera prior to the TBJ tephra

CEL (1992) reported three light colored pumiceous tephras under the TBJ tephra, named TB2, TB3 and TB4, from the upper to the lower. In the CEL report, the TB2 tephra is introduced as a pumice-fall deposit covered by paleosol under the TBJ tephra. The roughly estimated age of the TB2 tephra by K-Ar dating is presented to be ~7,000 B. C. The TB3 tephra is described as a pumiceous ash-fall deposit with accretionary lappilli, presumably associated with phreatomagmatic activity.

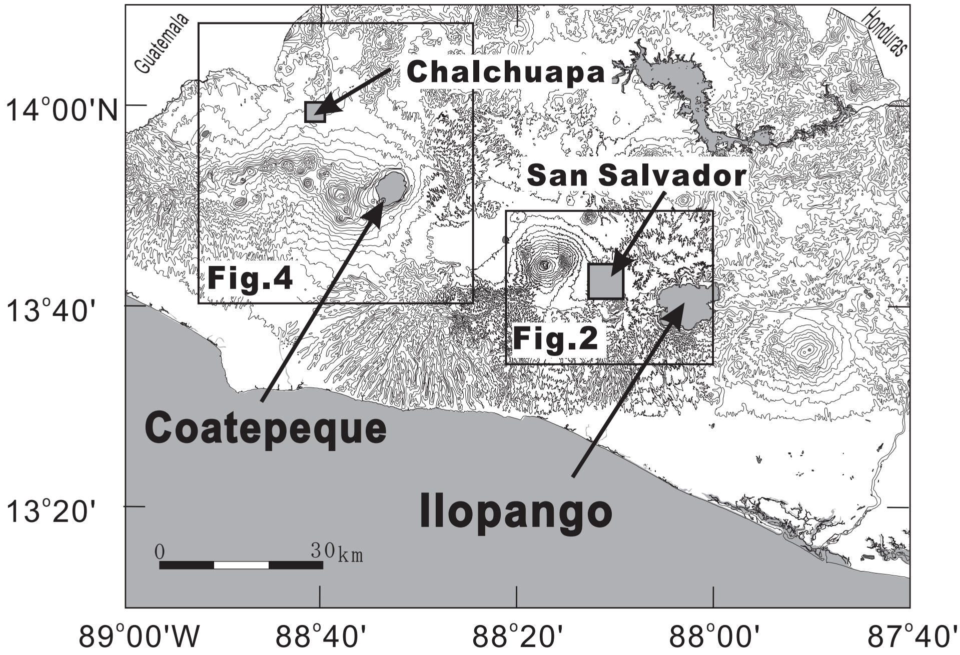

Fig. 1 General map of study area

The contour interval is 100m. Quadrangles with solid line indicate the study areas shown in fig. 2 and fig. 4.

The TB4 tephra is observed as a prominent pumice lapilli around the Ilopango Caldera including the MASS. The TB4 tephra was also discovered in marine core at the Pacific sea floor, and it is assumed to cover 7 x 10^4 km^2 and its volume is calculated to be 36.3 km^3 (Kutterolf, et al., 2008). The depositional date is estimated as ~36 ka from the stratigraphy in marine core. Although the marine core data indicates the presumable thickness of the TB4 tephra around Chalchuapa City as more than 10 cm, it has never been reported there in previous studies.

(2) Tephras with distal facies in the area around Chalchuapa city.

Around Chalchuapa City, two fine-grained vitric ash layers, La Periquera ash and El Refugio ash are described as probable distal ash-fall tephra from remote origin in the pyroclastic sequence of the scoria and pumice layers from Santa Ana volcanic complex and volcanoes in Cuyanausul Range (Kitamura, 2009).

La Periquera ash is preserved in the sequence of the Canelo scoria group as a discontinous lamina composed of light-colored, fine-grained volcanic ash. El Refugio ash, observed almost at the top of the sequence of the Manzano scoria group underlying the Canelo scoria group, is thinly-bedded, fine-grained ash-fall deposit, which does not contain accretionary lappilli. The former has been found out in only one location, the latter can be observed broader around Chalchuapa City.

Depositonal dates of La Periquera ash and El Refugio ash are estimated to be 10 ka and 30-45 ka, respectively, by extrapolation and interpolation from the thickness of paleosol and age-known horizon (Kitamura, 2009).

3. Methods of study

Pumice and volcanic ash are sampled from the TB2, the TB3 and the TB4 in the proximal area, at an outcrop in the MASS previously described by Hernández (2004) and two exposures in the margin of the MASS. The distal ashes are sampled at outcrops reported in Kitamura (2009), around Chalchuapa City, in the pyroclastic succession.

Volcanic glass and minerals were isolated from vitric ash deposit or crushed pumice by supersonic washing and sieving. Mineral assemblage was investigated by microscopic observation with polarized microscope. Chemical composition of volcanic glass was analyzed quantitatively with a wave-length-dispersive electron microprobe (JEOL JXA-8800RL) in the Department of Earth and Environmental Science, Hirosaki University. For analyses, 30 glass shards of each sample were randomly selected. Beam currents of 3 x 10^{-9} A and beam diameters of 10 μm were used at an accelerating voltage of 15 kV. Oxide percentage were renormalized to 100% and averaged with calculating standard deviation from 14 to 38 analyses, after removal of obvious anomalous results.

4. Sampling sites and levels

(1) Proximal area

There was an outcrop, P1, beside the road at the south of the MASS to the Comalapa Internacional Airport (Fig. 2), although it has been covered by cement for recent ten years. A

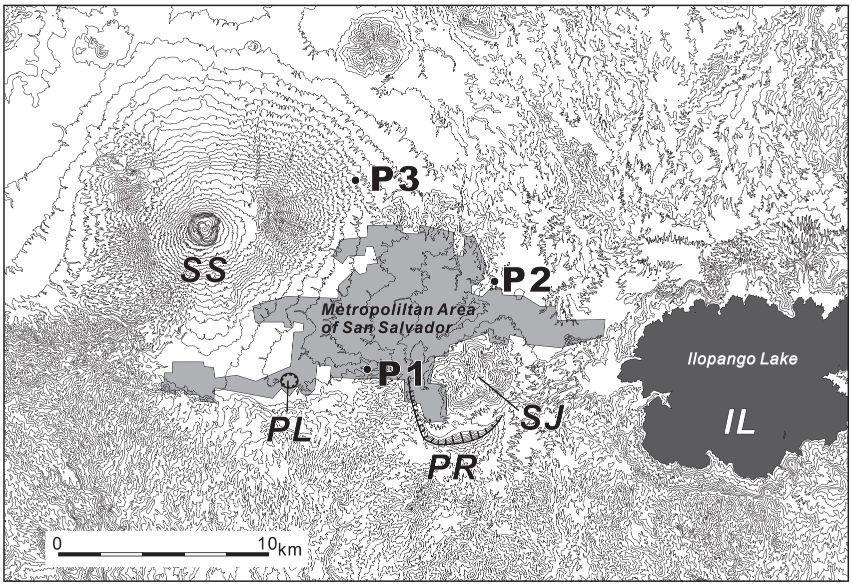

Fig. 2　Location of the sampling site in proximal area.

Solid circle with the symbol (P1, P2 and P3) shows the location of sampling site and the site code. IL: Ilopango Caldera, PL: Plan de Laguna Maar, PR: Planes de Renderos Caldera, SS: San Salvador Volcano, SJ: San Jacinto Domes.

pyroclastic flow deposit was exposed at the base of the outcrop. Above the layer, from the lower to the upper, the TB4 tephra, the G1 tephra which originates from San Salvador Volcano (Boquerón), the TB3 tephra, the TB2 tephra, and the TBJ tephra were observed (Fig.3; CEL, 1992; Hernández, 2004). Samples were collected from these layers at the field survey in 2003. Unfortunately, it was not enough for the observation of facies, textures or depositional structure of these tephras at the tall outcrop, neither for the measurement of their thickness, because of the time limit for the survey.

Other outcrop, P2, is located beside the highway bypassing through the north margin of MASS (Fig. 2), along the small path down to the valley. The TBJ tephra was observed at the top, while the TB2, the TB3 and the TB4 tephras are overlain by the TBJ tephra (Fig. 3). The TB2 tephra is composed of coarse pumice, the size of which is 2 to 3 cm at average maximum, accompanied with fine ash unit at the base of the deposit. The TB3 tephra is fine ash containing small amount of coarse pumice beneath the TB2 tephra. The TB4 tephra is distinct coarse pumice-fall deposit, and is beneath the G1 tephra overlain by the TB3 tephra. A pyroclastic flow deposit also exists under the TB4 tephra here.

At the outcrop, P3, in the north of MASS, beside the road to the highway, the TB2 and the TB4 tephras are exposed (Figs. 2 and 3). Here, the TB2 tephra is composed of small pumice of several millimeters in size, while the TB4 tephra is composed of coarser pumice of several millimeters to centimeters in size. In the outcrop, there is the TBJ teprha at the top and several scoria layers from Boquerón are intercalated among the pumice layers.

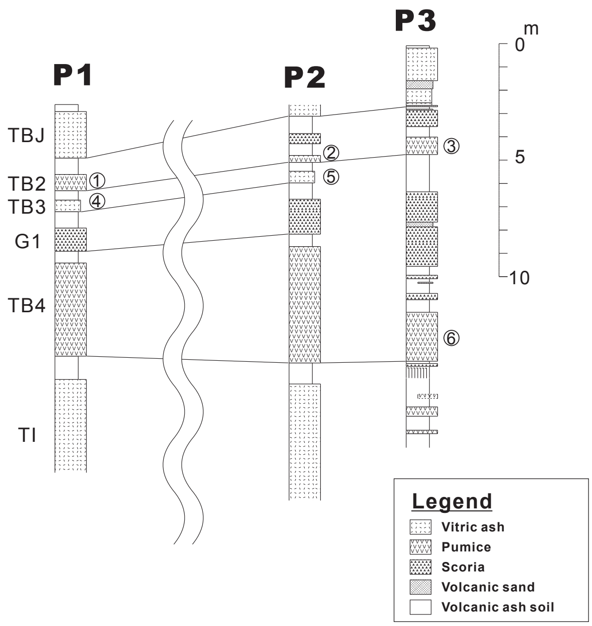

Fig. 3 Tephra stratigraphy in the sampling sites

Number with circle shows sampling level and sample code. The scaleless column P1 shows only the stratigraphic relationship of tephras, and height of box showing the tephra layer does not mean the precise thickness of tephras. The height of box in columns with scale, P2 and P3, is associated with the thickness measured at the outcrop.

（2）Distal area in the western El Salvador

At an outcrop, D1, beside the road up to a farm on the hilltop from the road to Sonsonate City from Santa Ana City, many scoria layers named Canelo Scoria Group in Kitamura (2009) originating from Santa Ana Volcano and Los Naranjos Volcano are exposed (Fig. 4). A white vitric ash named "La Periquera" tephra (Kitamura, 2009) is observed at the outcrop in volcanic ash soil intercalated between distinct scoria layers (Fig. 5). The layer is discontinuous and the thickness is less than 5 cm.

Other outcrop, D2, located on the side of the road from Santa Ana City to Sonsonate City bears many scoria layers intercalating a pumice layer and a 7-cm-thick white vitric ash layer (Figs. 4 and 5). The former pumice is called Juayua 1, the latter vitic ash, El Refugio ash (Kitamura, 2009). Both layers are commonly observed around the Cuyanausul Range. While the origin of the Juayua 1 is assumed to be close and to the west because the pumice is thicker and coarser to the west, the origin of the El Refugio ash may be far because it is fine ash and shows almost the same thickness in the area. The El Refugio ash are also exposed in other outcrop, D3, near the El Refugio town (Fig. 4). It is observed alone as the 17-cm-thick white fine ash intercalated by paleosol, which is sandy clay brown volcanic ash soil produced from volcanic material by weathering.

5. Mineral assemblage of tephra and Chemical composition of volcanic glass

Mineral assemblage and chemical composition of volcanic glass of the tephra samples described above are shown in tables 1 and 2. The results of chemical analyses of the tephras are also shown

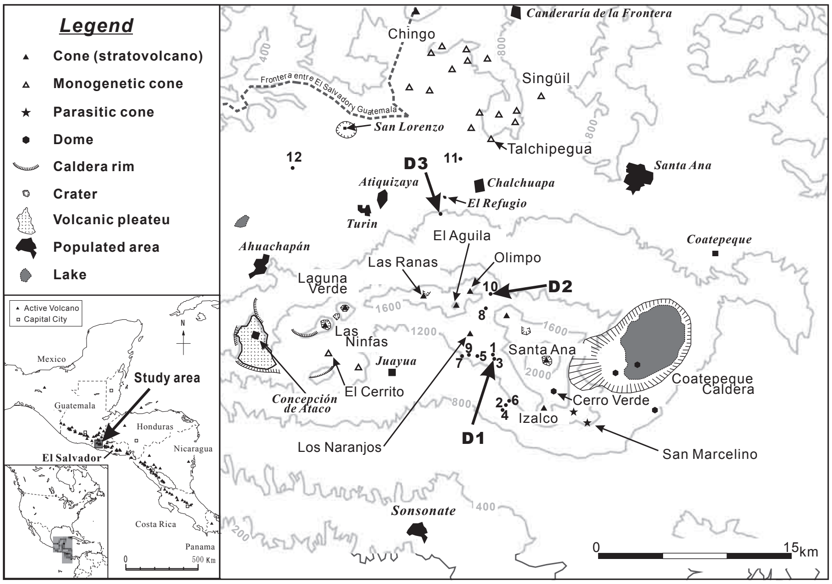

Fig. 4　Location of the sampling site in distal area

Sampling sites in this study are added to a map in Kitamura (2009). Solid circle indicated by arrow with symbol (D1, D2 and D3) shows the location of sampling site. The contour interval is 400 m.

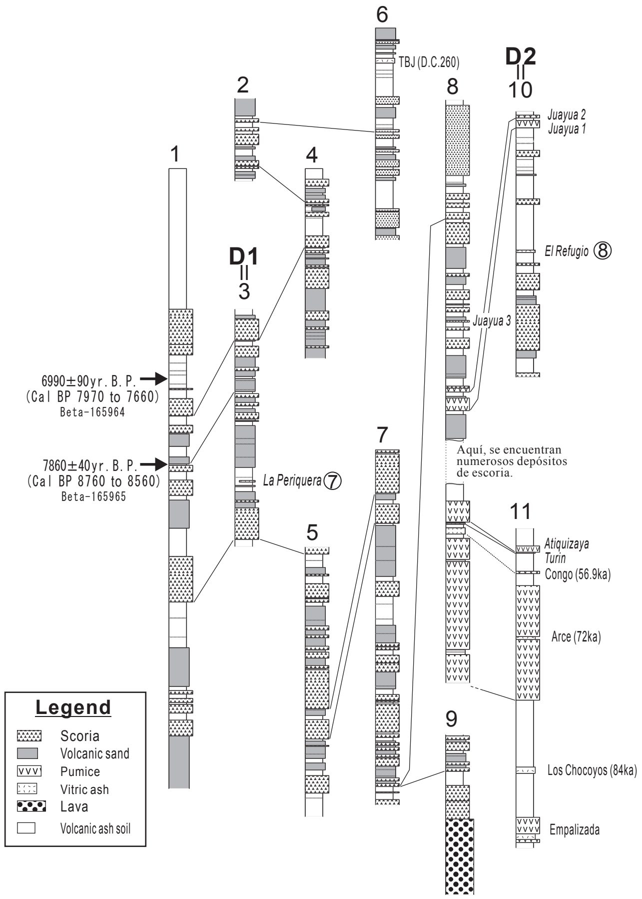

Fig. 5 Tephra stratigraphy in the sampling sites

Sampling sites and sampling levels in this study are added to a figure of columnar sections in Kitamura (2009). The number with circle shows sampling level and sample code.

Table 1 Mineral assemblage and chemical composition of volcanic glass of the proximal tephras

Tephra	Sample No.	Mineral assemblage		SiO_2 (%)	TiO_2 (%)	Al_2O_3 (%)	FeO (%)	MnO (%)	MgO (%)	CaO (%)	K_2O (%)	Na_2O (%)	Total (%)
TB2	1	opx, ho	Average	76.4	0.2	13.0	1.3	0.1	0.2	1.4	2.9	4.4	100.0
			Std. dev.	0.7	0.1	0.4	0.2	0.1	0.1	0.2	0.2	0.2	(20)
	2	opx, ho; mt	Average	76.3	0.3	13.0	1.4	0.1	0.3	1.5	2.9	4.1	100.0
			Std. dev.	1.2	0.1	0.6	0.3	0.1	0.1	0.3	0.3	0.6	(26)
	3	opx, ho; mt	Average	76.5	0.2	13.0	1.2	0.1	0.2	1.4	2.9	4.5	100.0
			Std. dev.	0.3	0.0	0.3	0.1	0.1	0.1	0.1	0.1	0.2	(14)
TB3	4	opx > ho	Average	77.2	0.2	12.8	1.1	0.1	0.2	1.3	3.0	4.2	100.0
			Std. dev.	0.5	0.1	0.2	0.2	0.1	0.1	0.1	0.1	0.3	(27)
	5	opx > ho; mt	Average	76.9	0.2	12.8	1.2	0.1	0.2	1.4	3.0	4.2	100.0
			Std. dev.	0.5	0.1	0.3	0.2	0.0	0.1	0.2	0.1	0.2	(28)
TB4	6	opx > ho; mt	Average	77.2	0.2	12.8	1.1	0.1	0.2	1.1	2.9	4.5	100.0
			Std. dev.	0.3	0.1	0.2	0.1	0.1	0.1	0.1	0.2	0.3	(30)

The number with parentheses indicates quantity of analysis. Oxide percentage was renormalized to 100%. Chemical quantitative analysis was realized with a wave-length-dispersive electron microprobe (JEOL JXA-8800RL) in the Department of Earth and Environmental Science, Hirosaki University under the following conditions: beam current, 3 x 10^{-9} A; beam diameter, 10 μm; accelerating voltage, 15 kV.

in Harker diagrams of fig. 6-1 to -4 and fig. 7. In addition, the chemical data of the TBJ tephra from Kitamura (2016) are also shown in fig. 6-1 for comparison. The chemical comparison of tephras originating from Ilopango Caldera with other tephras from Coatepeque Caldera is performed in Harker diagrams (Fig. 8).

(1) Mineral assemblage

All samples commonly include orthopyroxene and hornblende, and intend to be more abundant in the former than the latter, so that there is not so different in mineral assemblage among the TB2, the TB3, the TB4 tephras, the La Periquera and the El Refugio ashes (Tables 1 and 2). Only the difference among the samples is that the proximal samples contain magnetite while the distal samples almost lack it.

(2) Chemical composition of volcanic glass

Chemical composition of volcanic glass of the samples in this study show mostly homogeneous, chemical plots are concentrated in the Harker diagrams, so that it is easy to distinguish them from the TBJ tephra, because chemical composition of the most of volcanic glass from the TBJ tephra are mostly homogenous but it contains heterogenous component. Most of chemical plots of the TBJ tephra are concentrated in a zone but some plots are dispersed obviously on a trend in Harker diagrams (Fig. 6-1).

On the other hand, it is not so easy to distinguish the three tephras in this study from one another because chemical composition of volcanic glass of the samples are also similar to one another (Tables 1 and 2). However, looking in detail, some small differences are presumable to be indicated.

Mean values of the CaO content of the TB2 and the TB3 tephras are slightly higher than that of the TB4 tephra, and the mean value of SiO_2 of the TB2 pumice is slightly lower than those of the others while the value of SiO_2 of the TB2 and the TB3 tephra is rather dispersive (Table 1). The volcanic glass of the La Periquera ash-fall deposit shows slightly higher CaO value and slightly lower and more dispersive SiO_2 value. The El Refugio ash-fall deposit indicates lower CaO value and higher and more concentrated SiO_2 value (Table 2).

In the Harker diagrams (fig. 6-1 to -4), these trends are also recognizable in different form.

As mentioned above, the most of chemical composition plots of the TBJ tephra are mostly concentrated in a zone but other plots are dispersed along a trend line in the Harker diagrams of SiO_2 against Al_2O_3, CaO, K_2O and Na_2O. The chemical plots of the TB2 are more concentrated than that of the TBJ tephra, but the concentrated area is moved slightly to lower SiO_2 and higher

Table 2 Mineral assemblage and chemical composition of volcanic glass of the distal tephras

Tephra	Sample No.	Mineral assemblage		SiO_2 (%)	TiO_2 (%)	Al_2O_3 (%)	FeO (%)	MnO (%)	MgO (%)	CaO (%)	K2O (%)	Na_2O (%)	Total (%)
La Periquera	7	opx > ho	Average	76.5	0.2	13.0	1.3	0.1	0.3	1.4	2.9	4.4	100.0
			Std. dev.	0.9	0.1	0.7	0.2	0.0	0.1	0.3	0.4	0.2	(38)
El Refugio	8	opx > ho	Average	77.0	0.1	12.7	1.1	0.1	0.2	1.1	3.0	4.7	100.0
			Std. dev.	0.3	0.1	0.2	0.2	0.1	0.1	0.1	0.1	0.2	(29)
	9	opx > ho	Average	77.2	0.2	13.0	1.2	0.1	0.2	1.1	3.0	4.1	100.0
			Std. dev.	0.4	0.1	0.3	0.2	0.1	0.0	0.1	0.2	0.2	(15)

Table structure and analytical conditions are the same as in table 1.

CaO values, partly overlapping the TBJ concentrated plots area, in Harker diagrams (Fig. 6-1). Additionally, the TB2 chemical plots are assumed to include small amounts of dispersive component (about 5% of the total quantity), the plots of which seems to be distributed on the dispersive trend zone of the TBJ tephra.

The chemical plots of the TB3 and the TB4 tephras are concentrated in Harker diagrams,

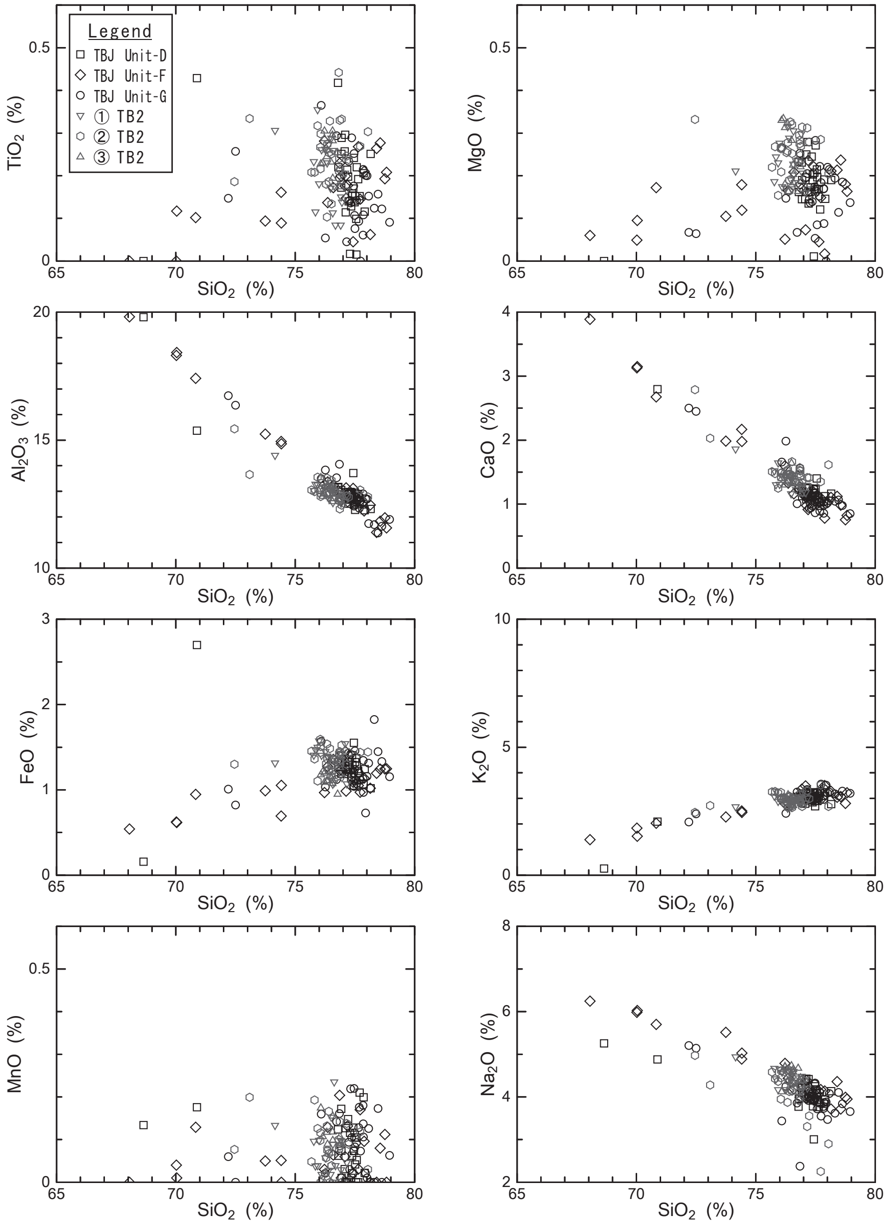

Fig. 6-1 Chemical composition of volcanic glass from tephras in proximal area (the TB2 and the TBJ tephras)
See text and table 1 for analytical conditions.

without dispersive components (Fig. 6-2), and their plot areas are mostly coincide with the concentrated area of the TBJ tephra. Their plot areas overlap each other, but the plot area of the TB3 tephra is slightly broader than that of the TB4 tephra in Harker diagrams, especially plots in the diagrams of SiO_2 against CaO. The chemical composition of the TB4 tephra is the most concentrated, that is, the most homogenous of the four tephras from Ilopango Caldera.

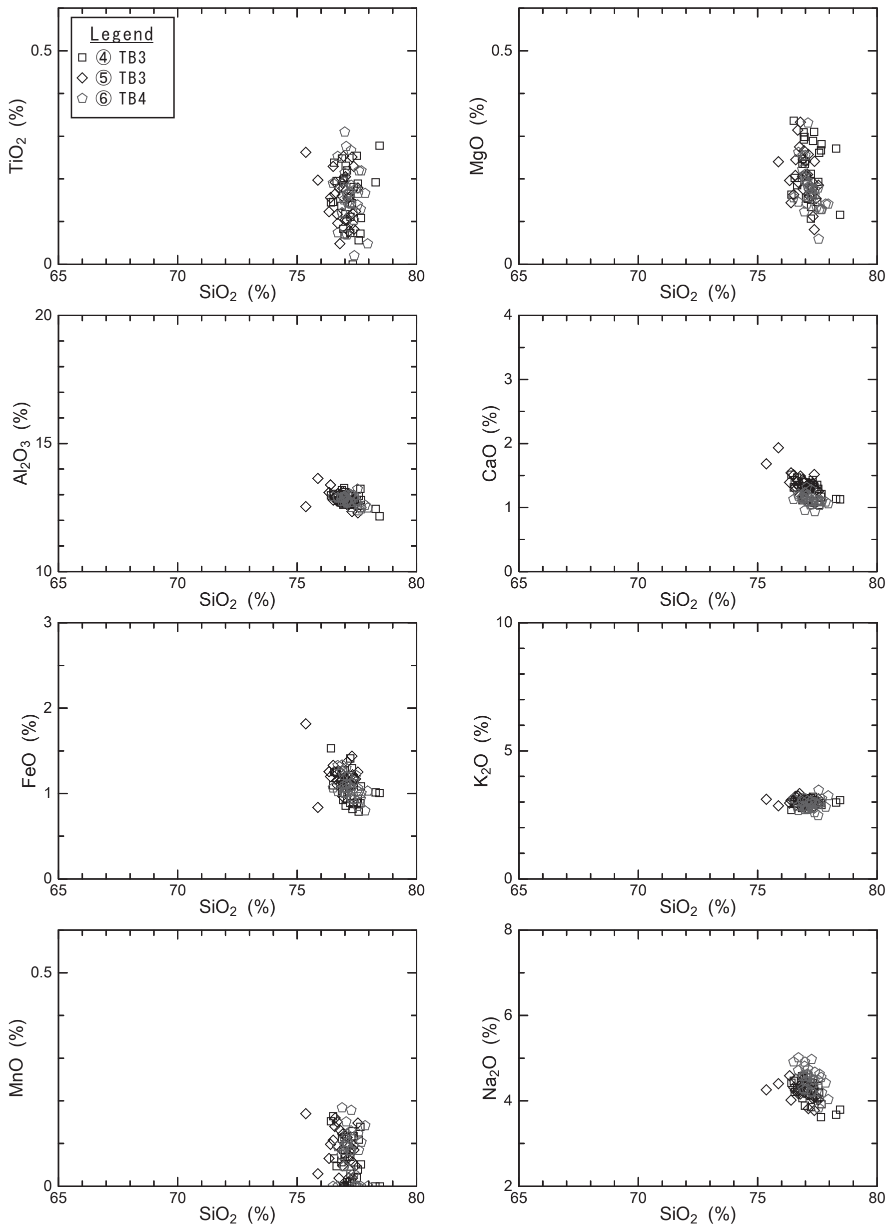

Fig. 6-2　Chemical composition of volcanic glass from tephras in proximal area (the TB3 and the TB4 tephras)
See text and table 1 for analytical conditions.

Comparing the TB2 tephra with the TB4 tephra, it can be indicated that not only CaO content but also FeO content is rather abundant in the TB2 thephra than in the TB4 tephra (Fig. 7).

The chemical plots of the La Periquera ash is mostly concentrated but contain about 5% dispersal component. The plot area coincides well with that of the TB2 tephra, also shows the trend of lower SiO_2, higher CaO, and higher FeO (Fig. 6-3 and 7). The plots of the El Refugio ash is well

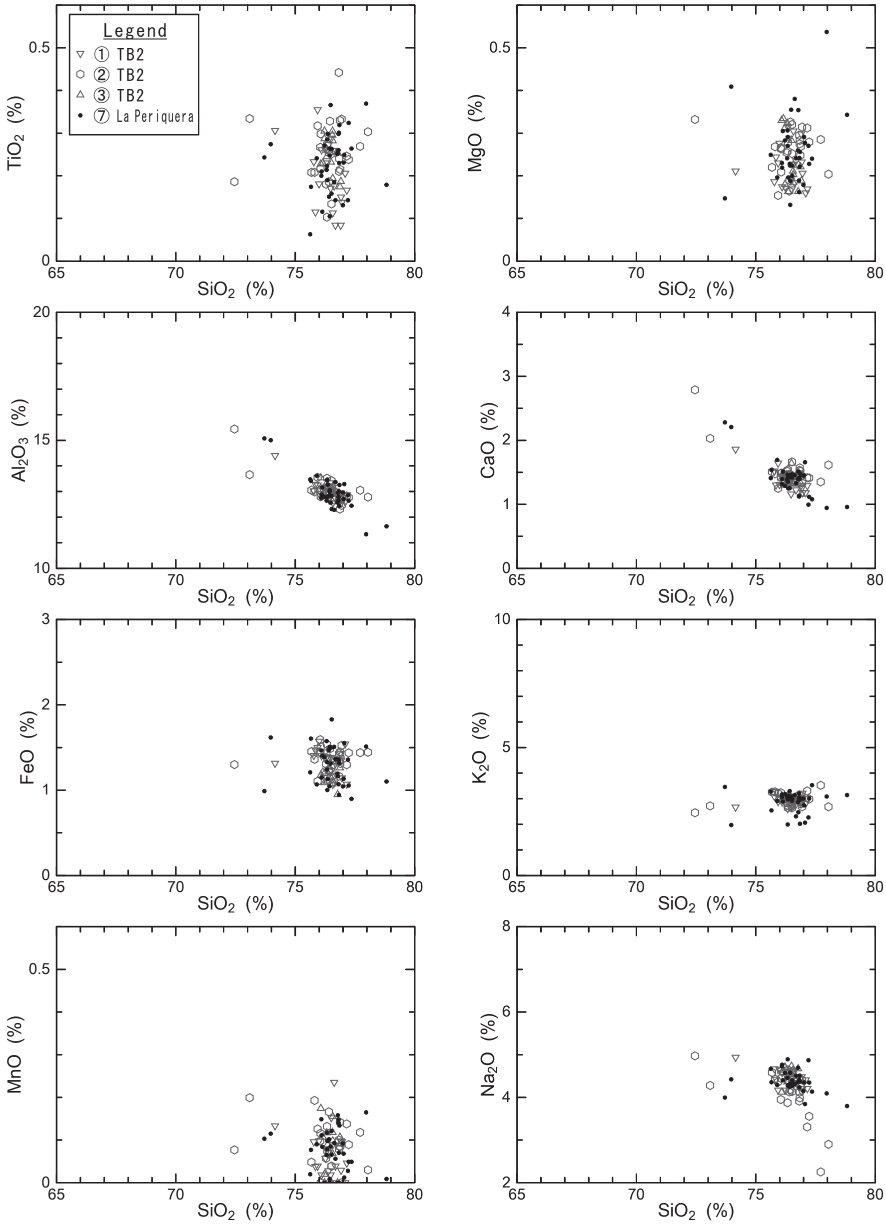

Fig. 6-3 Chemical composition of volcanic glass from the La Periquera ash-fall deposit, with the repeated data of the TB2 tephra for comparison
See text and table 1 for analytical conditions.

concentrated, without dispersive component, and its plot area is consistent with that of the TB4 tephra (Fig. 6-4).

Chemical composition of volcanic glass from Ilopango Caldera is different from that of volcanic glass from Coatepeque Caldera which is located closer to the sampling sites, D1 to D3, than Ilopango caldera, so that it is not necessary to be anxious for misidentification (Fig. 8).

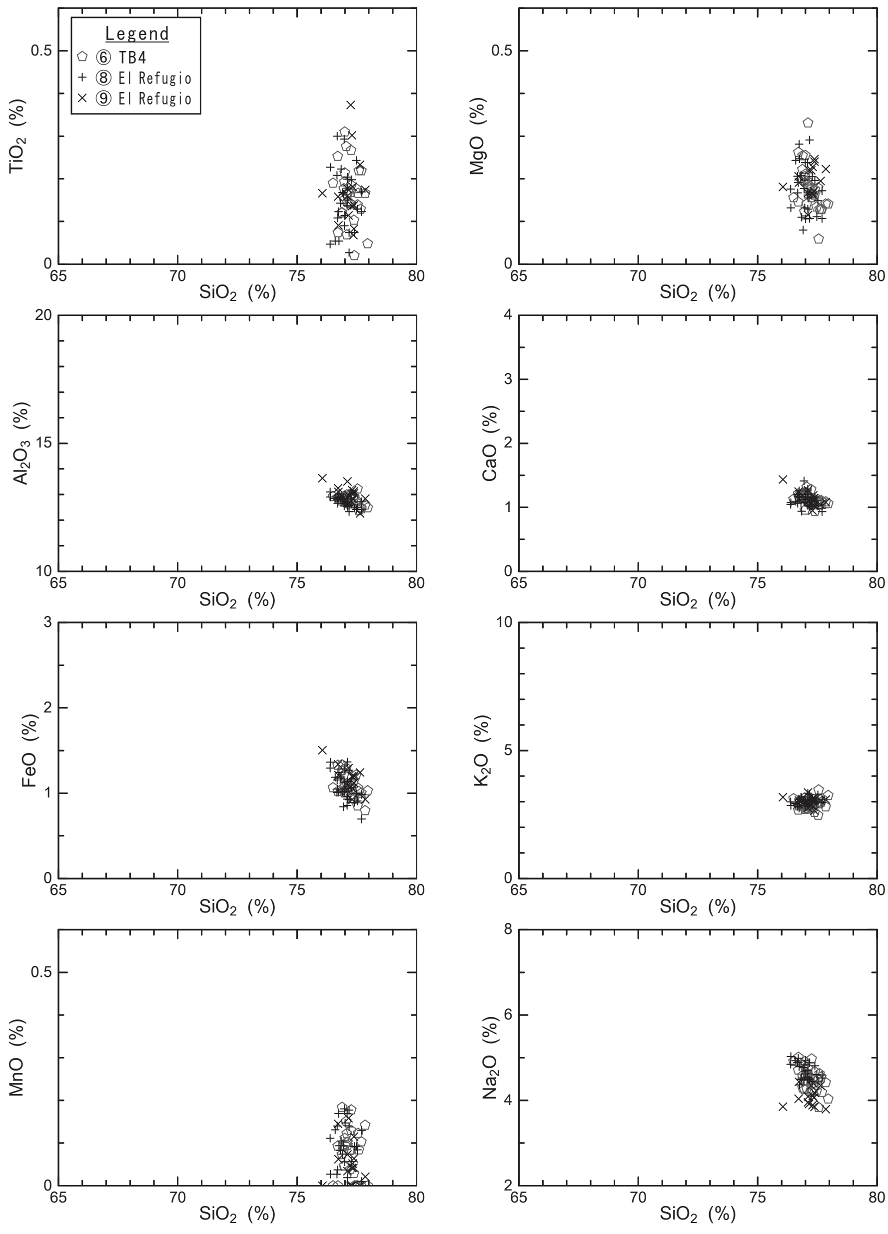

Fig. 6-4　Chemical composition of volcanic glass from the El Refugio ash-fall deposit, with the repeated data of the TB4 tephra for comparison
See text and table 1 for analytical conditions.

6. Correlation between proximal and distal tephras

The TB2, the TB3 and the TB4 tephras is demonstrated to be distinguishable from the TBJ tephra and other pumice or white ash which originates in the Coatepeque Caldera by the chemical composition of volcanic glass. On the other hand, although it is not easy to identify the three tephras individually by chemical composition and/or the mineral assemblage without the geological data such as stratigraphic position and depositional structure, they are identifiable by small difference among the three in the chemical composition of volcanic glass.

The La Periquera ash and the El Refugio ash are similar to the TB2, the TB3 and the TB4 tephras in the mineral assemblage and the chemical composition of volcanic glass. Therefore, the former each tephra around Chalchuapa can be correlated with the either of the latter three tephras. The tendency of lower SiO_2 and higher CaO and slightly higher iron oxide in the La Periquera ash suggest the probable correlation to the TB2 tephra although the posiblity of correlation to the TB3 tephra should remain. On the other hand, the tendency of higher SiO_2 and lower CaO and slightly lower iron oxide in the El Refugio ash suggest the probable correlation to the TB4 tephra.

These correlation is not inconsistent with the stratigraphic relationship between the TB2 and the TB4 tephras and their individual volumes. The smaller presumable volume of the TB2 tephra coincide with the feature of La Periquera ash, which is thinly deposited as less-than-5-cm-thick discontinuos layer and has been found out in one location. The presumable volume of the TB3 tephra smaller than the TB2 suggests that the La Periquera ash could be more probable to be correlated to the TB2 tephra. On the other hand, larger plinian eruption producing the TB4 pumice-fall deposit is probable enough to emplace the El Refugio ash, which is the several- to more-than-20-cm-thick fine

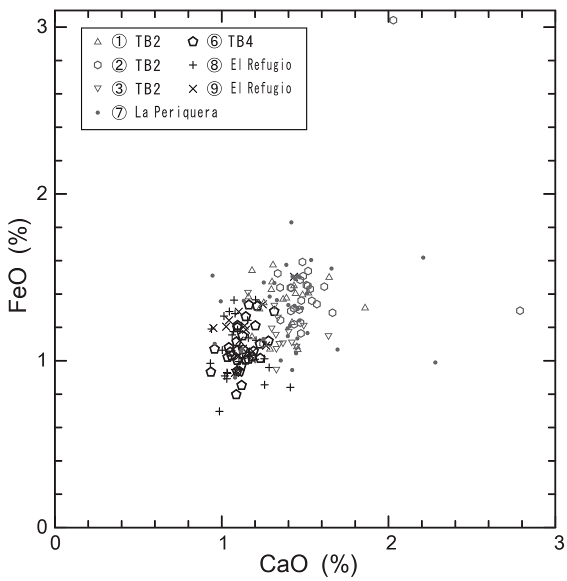

Fig. 7 Chemical comparison among the tephras in the scatter diagram of CaO against FeO
See text and table 1 for analytical conditions.

ash observed commonly around Chaluchapa City.

The K-Ar age of the TB2 tephra as ~7,000 B. C. and the estimated date as 10 ka from the tephra stratigraphy are similar. The depositional age of the TB4 tephra proposed from marine core data as ~36 ka is not contradictory to the estimated date as 30–45 ka from the tephra stratigraphy in the area around Chalchuapa City.

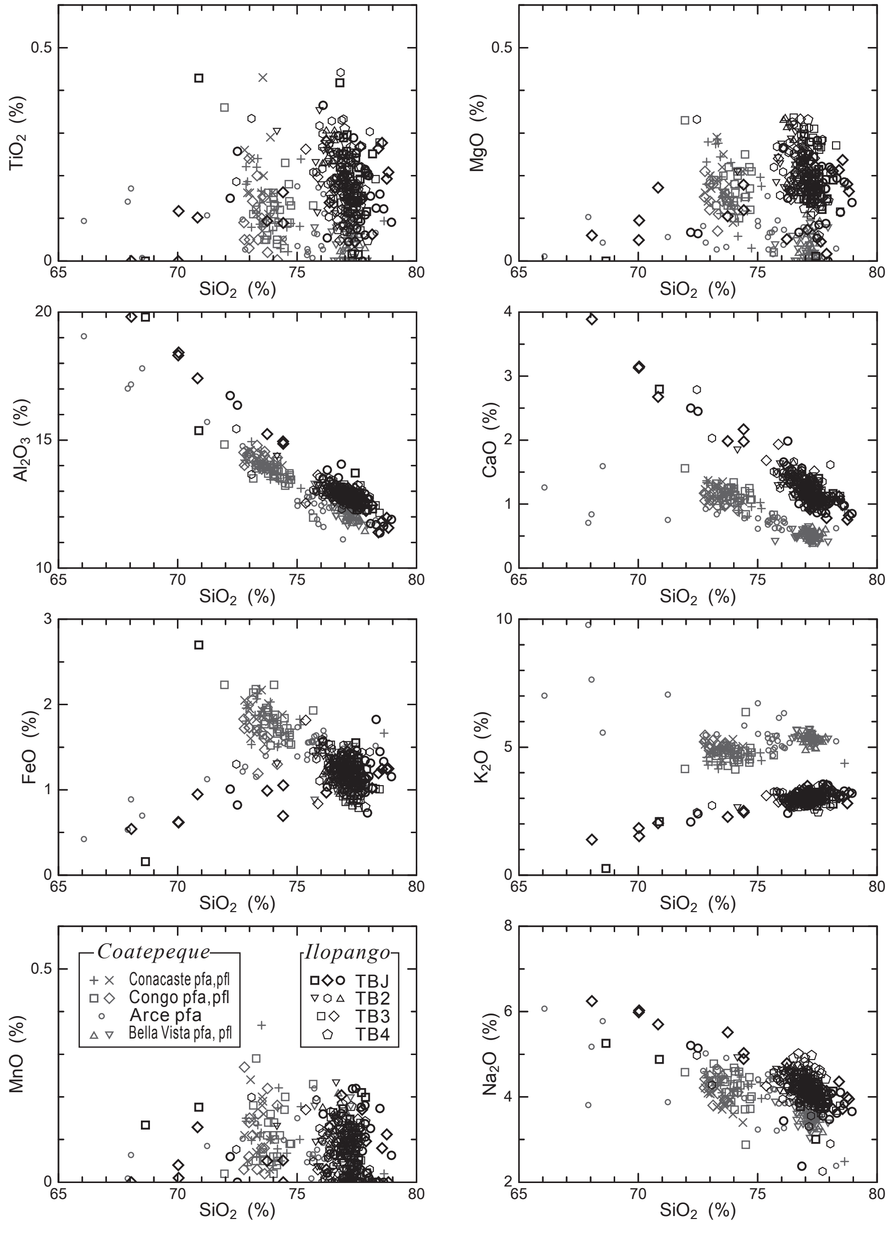

Fig. 8　Chemical composition of volcanic glass from Coatepeque Caldera and Ilpango Caldera

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