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Tephra Stratigraphy and Eruption History at Bandai Volcano, Northeastern Honshu arc, Japan

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I. Introduction

Bandai volcano, located in the central part of Fukushima Prefecture, Japan, belongs to the Sekiryo volcanic chain of the Tohoku Honshu arc (Fig. 1 : Nakagawa, *at al*., 1988). Bandai volcano is one of the hazardous volcanoes that caused a big debris flow in 1888 by a collapse of the volcanic body. The detailed record of the episode indicates that preceding phreatic eruptions triggered a huge collapse (e.g., Sekiya and Kikuchi, 1889 ; Nakamura, 1978). To know the geological history of a volcano is sometimes valuable in order to predict its future activity. Some volcanoes have a habitual volcanic activity, the so called cyclicity of volcanic activity. The repeated volcano forming and collapse activities of Bandai volcano since ~150ky ago (Chiba *et al*., 1994) is an example of this. This paper discusses the ages, change in mode of eruptions, and formation periods of debris flows at Bandai volcano in geologic time on the basis of tephro- stratigraphic data.

We have been conducting a series of geological survey on the southern flank of Bandai volcano for the purpose of revealing the eruption history of the volcano. The area is underlain by numerous land-laid tephras that are intercalated in the tephric loess sequence (Yoshida and Suzuki, K., 1981 ; Chuman and Yoshida, 1982 ; Tomizuka *et al*., 1985 ; Sato *et al*., 1990 ; Chiba *et al*., 1994 ; Kimura, 1996). Tephric loess, a sort of land-laid deposit consisting of accumulated dust, has been deposited sequentially, and forms a distinctive lithologic unit (e.g., Hayakawa, 1990). The tephric loess sequence records several kinds of geological information. These are tectonic events given as erosion surface(s) in the sequence, volcanic activity deduced from types of intercalated tephras, and ages calculated from the depositional rate of tephric loess (Kimura, 1996).

Chiba *et al*. (1994) have classified the tephric loess into two stratigraphic units. These are the Mineyama and the Hayama Loam Formations, in ascending order. A widely developed erosion surface bounds the two Formations, indicating that an erosion epoch once thoroughly changed the topography of this area. Many layers of tephras from Bandai volcano are intercalated in the tephric loess sequence. The tephras involve plinian pumice falls, vulcanian scoria and ash falls, phreatic eruption ash falls, and pumice flow deposits. A particular tephra sequence exists in the Hayama Loam Formation. Plinian pumice fall(s), which consists of the bottom part, is subsequently followed by a series of thin vulcanian ash falls in a sequence. The repetition of similar sequences is noticeable in the Hayama Loam Formation at least five times. The sequences are interbedded with tephric loess of nonvolcanic origin, indicating that

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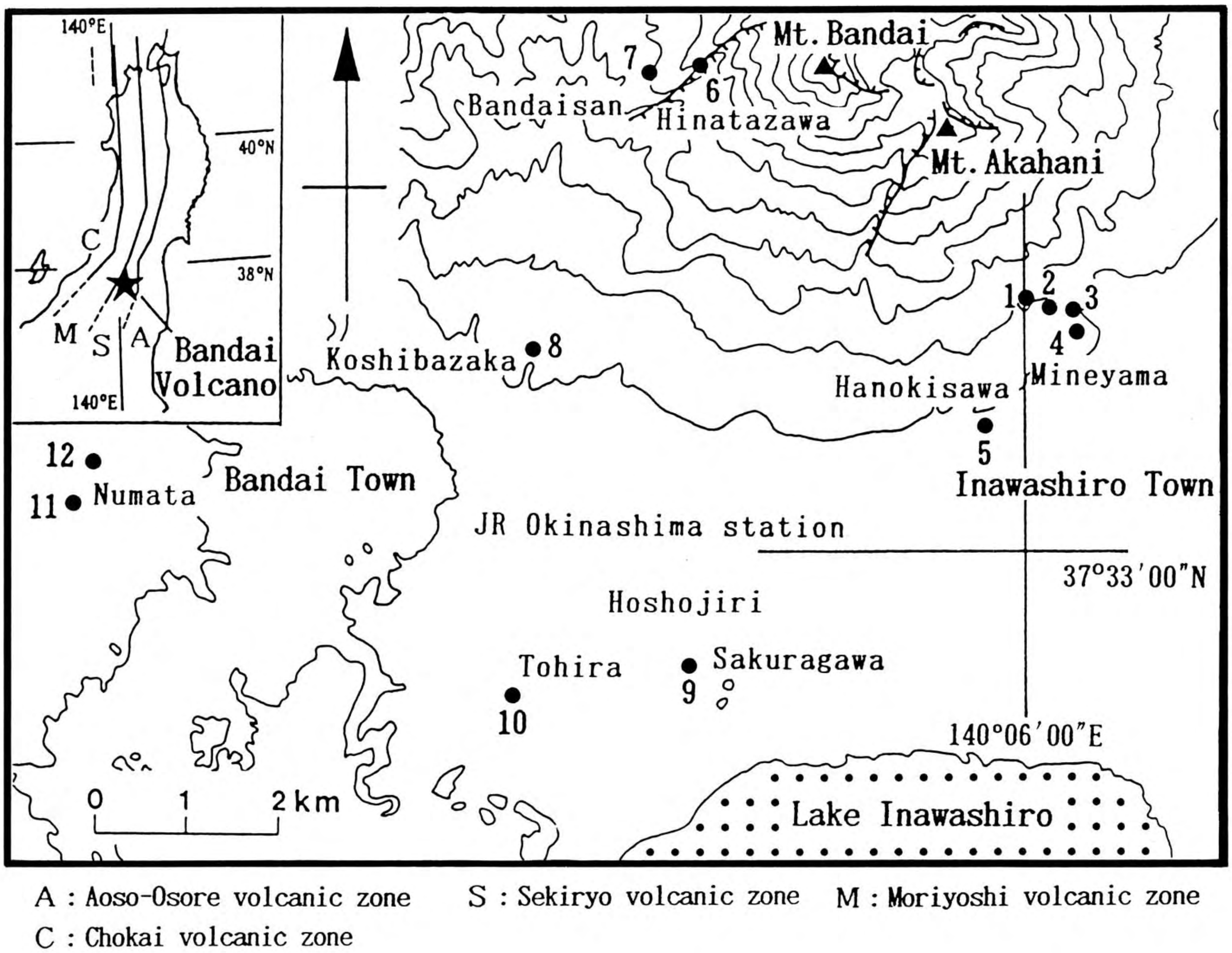

Fig. 1. Locality map of studied area

repose intervals existed in-between these events. This is an evidence that repeated volcanic eruptions occurred in a similar manner (Chiba *et al.*, 1994; Kimura and Chiba, 1994).

A correlation study of tephras from Bandai volcano associated with widespread tephras (Machida and Arai, 1991) has made clear the correlation between the land-laid and sub-aqueous deposits in the area. Cold climate horizons in the sub-aqueous deposits have been found in plant and pollen fossil records (Chuman and Yoshida, 1982; Sohma, 1984). The correlation of cold climate horizons to the $\delta^{18}O$ stratigraphic ages (Imbrie *et al.*, 1988), and the reported radiometric ages of widespread tephras combined to allow dating of seven horizons of tephric loess. Using this age data, we can see that the calculated accumulation rate of the tephric loess was extremely linear. We estimated the accumulation rate to be 18.1mm/ky on average (Kimura, 1996). By application of this depositional rate chronology, The Mineyama Loam Formation can be mainly assigned to the Middle Pleistocene, and the Hayama Loam Formation to the Late Pleistocene to Holocene. The repeated plinian-vulcanian eruptions started to appear from ~165ka, and reoccurred at~80 and ~40ka. Numbers of debris flows which occurred were associated closely with the plinian eruptions at ~80 and ~40ka (Chiba *et al.*, 1994; Kimura and Chiba, 1994). This paper clarifies the characteristics of pumice which is important for stratigraphic correlation, and discusses the rate of deposition of the tephric loess. We also discuss the six phases of volcanic activitiy, and the formation periods of debris flows in conjunction with the volcanic activity of Bandai volcano.

II. Tephric loess and tephras from Bandai volcano

1) Stratigraphy of tephric loess

The land-laid tephric loess in the foothills of Bandai volcano and its vicinity are subdivided into the Mineyama and the Hayama Loam Formations (abbreviate MLF and HLF, hereafter). Figure 2 gives the compiled geologic column of the Formations. A typical nonconformity is observed at numerous locations indicating that topographic changes occurred after deposition of the MLF. This nonconformity is identical throughout the area studied, and therefore, we use it as a basis for stratigraphic division. Within the MLF and HLF, there are 41 distinct tephra layers. Twenty-three of the layers are thick and considered to be from Bandai volcano. These tephras involve fine- to coarse-grained ash layers and pumice or scoria beds which the thicknesses decrease with increasing distance from the volcano center. Such the tephras are of pyroxene andesite affinities. This rock type predominates at Bandai volcano (Chiba, *et al.*, 1994). The remainder of the tephras consist of very fine- to fine-grained volcanic ashes which contain rhyolitic volcanic glass shards and hydrous silicate minerals, e.g., hornblende and biotite. The acid tephra layers are generally uniform in thickness and very well sorted, and therefore, are considered to be from far distant volcanoes outside Bandai. Researchers have idientified the origin volcanoes of the acid tephras. These are Ontake volcano located in central Japan, and Daisen volcano, Aira, and Aso calderas in the Southwestern Japan arc (Machida and Arai, 1991 ; Chiba *et al.*, 1994).

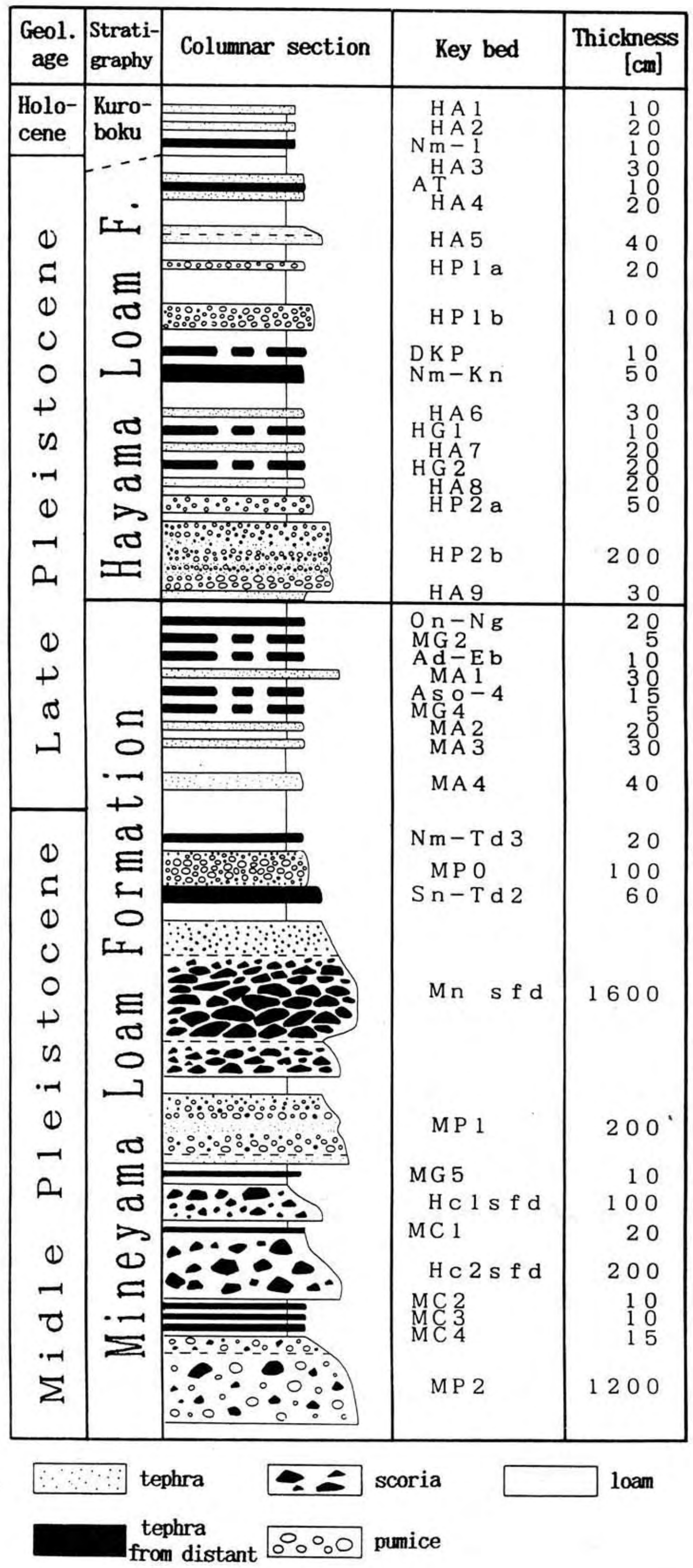

Fig. 2. Represntative columnar section of Mineyama and Hayama Loam Formations

A. Mineyama Loam Formation (MLF)

The MLF is the oldest loam formation among the foothills of Bandai volcano and crops out along the foothills of Mineyama and Hanokisawa. This formation consists of black to reddish scoria, yellow pumice, coarse to fine grained volcanic ash and dark brown tephric loess with a maximum thickness of about 45m. Amongst the tephra layers, the following are considered to be of Bandai volcano origin: MP2 (MP= Mineyama pumice the rest are the same), Hc 2 sfd. (Hc=Hanokisawa; sfd.=scoria flow deposits, the rest are the same), Hc 1 sfd., MP1, Mn sfd. (Mn= Mineyama), MP0, MA4 (MA=Mineyama volcanic ash, the rest are the same), MA3, MA2, MA1. MP0 has been classified as volcanic ash mixed with pumice (MA5) (Chiba *et al.*, 1994). TcP1 (Tsuchiyuzawa pumice) is considered to be a Phase 1 (mentioned later) eruptive product, however, it is not included in Fig. 2 because the relationship with other tephras is not clear. The tephras of distant sources include: MC4 (MC=Mineyama crystalline volcanic ash, the rest are the same), MC3, MC2, MC1, MG5 (MG= Mineyama glassy volcanic ash, the rest are the same). Sn-Td2 (Sunagohare-Todera 2 volcanic ash), Nm-Td3 (Numazawa-Todera 3 volcanic ash), MG4, MG3, Aso-4, MG2, Ad-Eb, and On-Ng. The MC1 to MC4 are correlated with the Apm group of which the source volcano was somewhere in the North Japan Alps (Nishina, 1982; Harayama, 1990; Chiba *et al.*, 1994). The source volcanoes of the glassy tephras have been identified as follows: Aso-4=Aso caldera (Machida et al., 1985), On-Ng=Ontake volcano (Suzuki, T. and Soda, 1994), Ad-Eb=neighboring Adatara volcano (Kimura, 1996).

B. Hayama Loam Formation (HLF)

The HLF is frequently exposed along the southeastern foothills of Mineyama. The Formation consists of yellow pumice, coarse to fine volcanic ash, and brown tephric loess of about 17m thick at maximum. Among the tephras, the followings are thought to be of Bandai volcano origin: HA9 (HA=Hayama volcanic ash, the rest are the same) HP2b (HP=Hayama pumice, the rest are the same), HP2a, HA8, HA7, HA6, HP1b, HP1a, HA5, HA4, HA3, HA2, HA1. The tephras of distant sources include: HG2 (HG= Hayama glassy volcanic ash), HG1, Nm-Kn (Numazawa- Kanayama), DKP, AT, and Nm-1. The distant source volcanoes are considered to be as follows: Nm-Kn and Nm-1=Numazawa volcano in western part of Fukushima Prefecture, DKP=Daisen volcano in the Southwestern Japan arc (Chiba *et al.*, 1994: Suzuki, T. and Soda, 1994), AT=Aira caldera

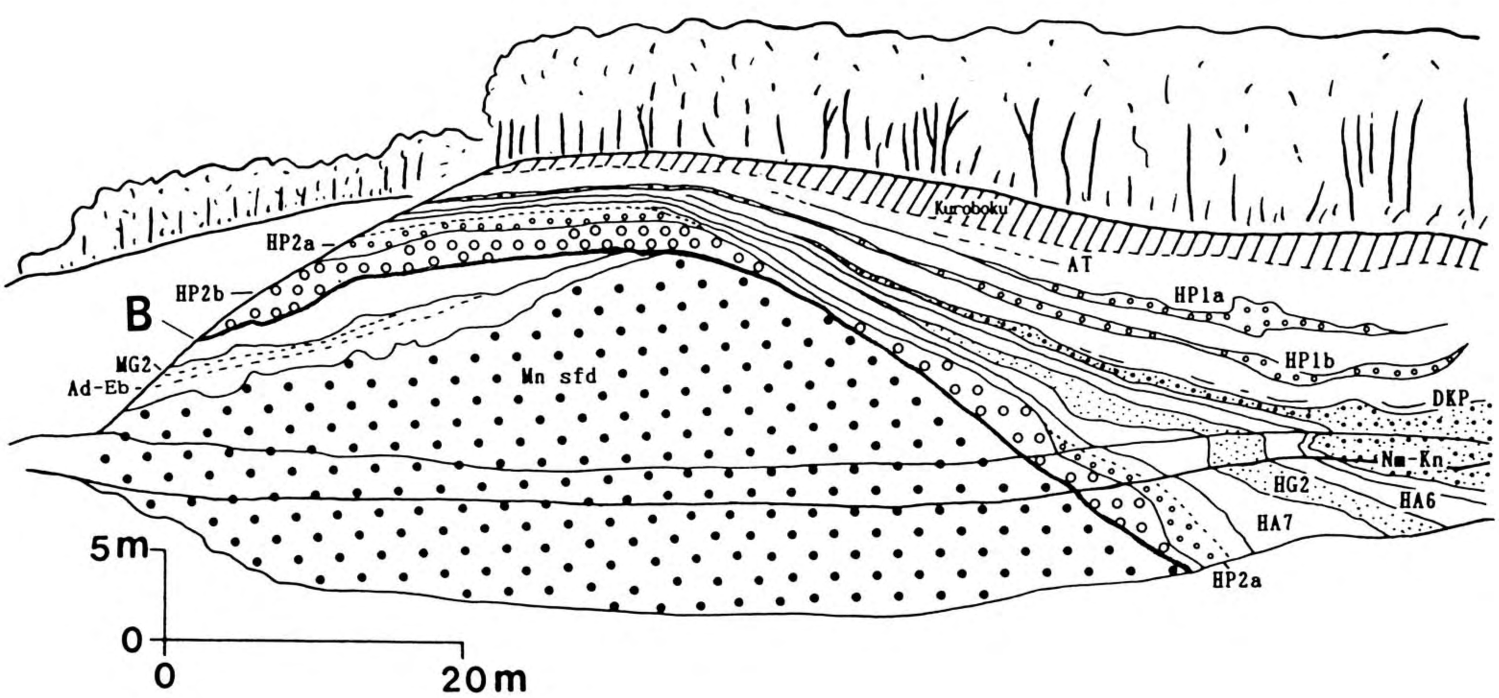

Fig. 3. A sketch showing erosion surface bounding Mineyama and Hayama Loam Formations. B indicates boundary between MLF and HLF.

in Kyushu district (Machida and Arai, 1991). The HLF involves locally two pumice flow deposits and two debris flow deposits. Those are Hinatazawa and Sarashina pumice flow deposits, and Koshibazaka and Okinashima debris flow deposits (Fig. 3). A detailed discussion of about the flow deposits will be given in a later section.

2) Petrographic characteristics of pumice

Among the tephras originating in Bandai volcano, pumice beds are an important tracer for stratigraphic correlation. In order to characterize the pumice beds, chemical compositions of pumice glasses and phenocrystic pyroxenes contained were analyzed. We also determined modal compositions of phenocrystic minerals. The quantitative element analysis was performed by LINK ISIS EDXA with JEOL JSM-8500LV SEM at the Department of Geology, Fukushima University. The analytical method has been reported by Kimura (1994). For modal mineral analysis, over 500 grains of heavy minerals with 2-3ϕ were analyzed and represented as percentages. Table 1 gives both the representative results of glass chemistry and modal composition.

Pumice in the MLF and HLF are both pyroxene andesite. The SiO_2 contents of TcP1, MP2 and MP1 are low compared with the other pumice layers but are rich in FeO*, TiO_2, and P_2O_5. These can be plotted along the general trend of the tholeiitic rock series of Bandai volcano, and the remainder of the pumice has calc-alkaline characteristics (Kimura and Chiba, 1994 ; Kimura *et al.*, 1995). It is possible to differentiate the tholeiite-type and calc-alkaline-type from glass chemistry, but it is not possible to differentiate individual pumice layers. Clinopyroxene pheno-

Table 1 Representative analytical results of glass chemistry, heavy mineral assemblage, and chemical compositions of orthopyroxene contained in pumice crusts

Sp. No.	TcP1	MP2	MP1	MP0	HP2b	HP2a	HP1b	HP1a	Numata (loc. 12)	Numata (loc. 11)	Tohira (loc. 10)	Koshibazaka (loc. 8)
Glass chemistry (wt. % on 100% basis, average of 10 glass shards)												
SiO_2	66.29	nd.	68.30	nd.	77.62	78.03	77.78	77.27	77.70	77.49	77.44	77.44
TiO_2	1.02	nd.	0.94	nd.	0.52	0.50	0.45	0.54	0.43	0.50	0.41	0.44
Al_2O_3	14.35	nd.	14.05	nd.	11.68	11.69	11.74	11.65	11.39	11.61	11.67	11.82
FeO	5.99	nd.	5.14	nd.	2.07	1.81	1.92	2.12	1.86	1.95	1.95	2.07
MnO	0.19	nd.	0.16	nd.	0.10	0.05	0.01	0.13	0.06	0.00	0.05	0.07
MgO	1.79	nd.	1.42	nd.	0.54	0.57	0.51	0.59	0.48	0.47	0.56	0.50
CaO	4.86	nd.	4.19	nd.	1.82	1.67	1.76	1.89	1.74	1.74	1.72	1.88
Na_2O	3.62	nd.	3.57	nd.	3.10	3.21	3.07	3.19	3.32	3.47	3.44	3.21
K_2O	1.74	nd.	1.97	nd.	2.40	2.47	2.38	2.44	2.75	2.46	2.52	2.58
P_2O	0.16	nd.	0.27	nd.	0.16	0.00	0.38	0.18	0.27	0.30	0.24	0.00
Total	100.00	nd.	100.00	nd.	100.01	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Heavy mineral assemblage (grain numbers on 100y basis)												
opx	39.7	20.0	36.5	18.0	21.9	25.2	26.1	29.5	27.8	28.0	27.2	24.6
cpx	39.1	64.6	35.7	35.6	59.4	57.4	63.5	55.5	57.7	62.6	59.2	54.4
io	21.2	15.3	27.8	46.3	18.7	17.4	10.4	15.0	14.6	9.4	13.6	21.0
Total	100.0	99.9	100.0	99.9	100.0	100.0	100.0	100.0	100.1	100.0	100.0	100.0
opx/(cpx+opx)	50.4	23.6	50.6	33.6	26.9	30.5	29.1	34.7	32.5	30.9	31.5	31.1
Chemical composition of opx (mol. %, average of 10 crystals)												
En-rim	62.4	65.97	63.24	58.13	58.25	58.11	58.69	58.18	58.24	57.71	57.79	58.13
Wo-rim	3.6	3.58	3.7	3.07	3.00	3.03	3.10	2.96	3.31	3.04	2.84	3.08
En-core	61.77	65.84	61.76	57.91	58.14	57.81	59.32	58.02	58.28	58.15	58.03	58.39
Wo-core	3.73	3.69	3.69	3.27	3.00	3.01	2.98	2.84	3.13	3.09	2.98	3.07

crysts are commonly found in the tholeiitic pumice. For orthopyroxene composition, tholeiitic pumice is En60-67 and Wo3.0-4.5, while calc-alkaline pumice is En55-61 and Wo2.5-3.7. The calcalkaline pumice is rich in FeO* but low in Wo composition, indicating a lower temperature origin. Kimura *et al.* (1995) have reported the crystallization temperatures of the co-existing pyroxenes as 1020°C-1060°C for tholeiitic pumice and 930°C-1000°C for calcalkaline pumice. Since the compositional variations of orthopyroxene are within 5% of En composition for tholeiite and calcalkaline pumice, even in comparing the En compositions, it is difficult to distinguish the individual pumice layers within the rock series. This similarity in En compositions also shows that the magmatic system beneath Bandai volcano, which differentiated the pumice, have been extremely similar over a long period.

There are some differences in the modal composition of the phenocrystic minerals of the pumice in the HLF. For example, in comparison with HP2b, the orthopyroxene content is 5% higher in the pumice layers above HP2a. The ratio of orthopyroxene and clino-pyroxene is low at the bottom of HP2b compared to the ratios in the upper layers. The magnetite content in HP2a and HP2b is high but in HP1a, it is about 5% lower (see Fig. 4). The orthopyroxene content in the pumice flow deposits within HLF is high, along with Tohira, Numata, and Koshibazaka, and the ratio of opx/cpx is also high. The petrographic characteristics of the pumice flows are similar to that of the three pumice-fall layers which are above HP2a. Moreover, the magnetite content of the pumice in the pumice flow deposits in the Tohira and Numata areas are low, therefore these two can be correlated to the pumice falls of HP1b or HP1a. The pumice flow deposit at Koshibazaka has higher magnetite content, and this can be correlated to the HP2a pumice fall.

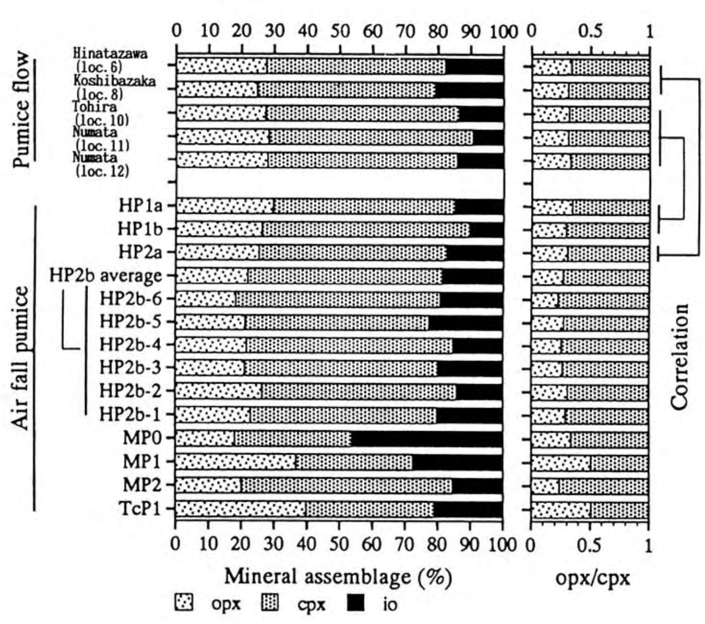

Fig. 4. Modal compositions of heavy minerals contained in pumice crusts

III. Chronology of tephra and tephric loess

Figure. 6 exhibits the accumulation rate of tephric loess around Bandai volcano. For age control, the age of the cold climate horizons was determined by applying the curve of climatic changes of Imbrie *et al.* (1984) to the cold climate horizons (Suzuki, K. *et al.*, 1977 ; Sohma, 1984 ; Chuman and Yoshida, 1984) found in sub-aqueous deposits around Bandai volcano. Cold climate horizons have been referenced and compared with the ages of widespread tephras (Chiba *et al.*, 1994 ; Kimura, 1996). Chiba *et al.* (1994) pointed out that the accumulation rate of the tephric loess is extremely constant. However, they noted the rate was somewhat slower in the older MLF. The age of widespread tephra of the Apm tephra proup (A1pm-A4pm correlated to MC4-MC1) has been reported to be 200-600 ka (e.g., Suzuki, M., 1988 ; Suzuki, T. and Hayakawa, 1990). The less reliable radiometric dating of younger ages has given an even greater deviation. Most researchers believe the age of the Apm tephras to be around 350 ka. Recently, Hayatsu et al. (1994) have reported highly precise K-Ar ages from the lavas of the Myoko Volcano Group. The result involved K-Ar ages of lavas that are underlain and overlain by Apm tephras. The former lava gave the age of 0.25±0.03 Ma, and the latter showed 0.26±0.02

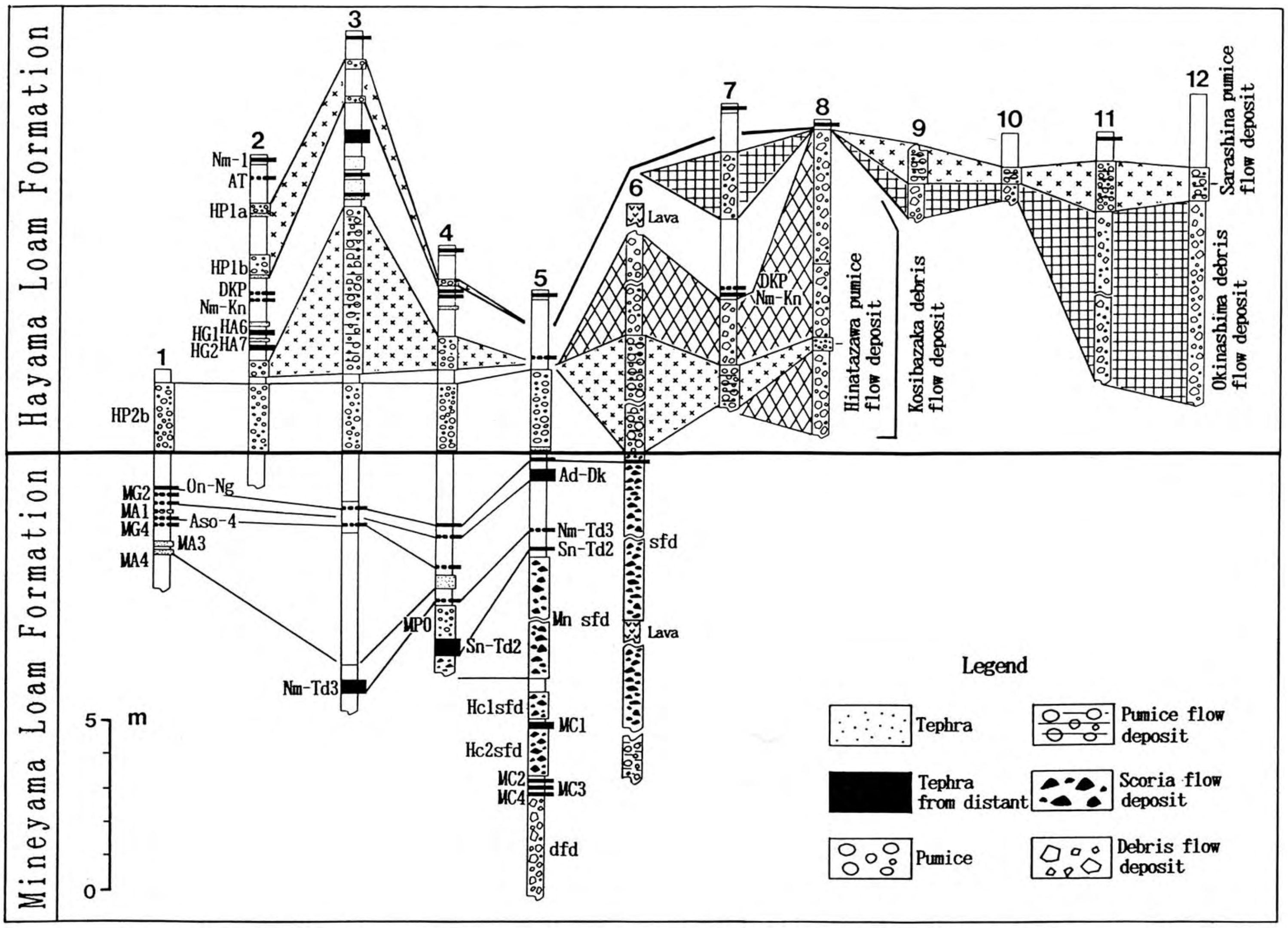

Fig. 5. Columnar sections showing debris flow deposits and related key tephra

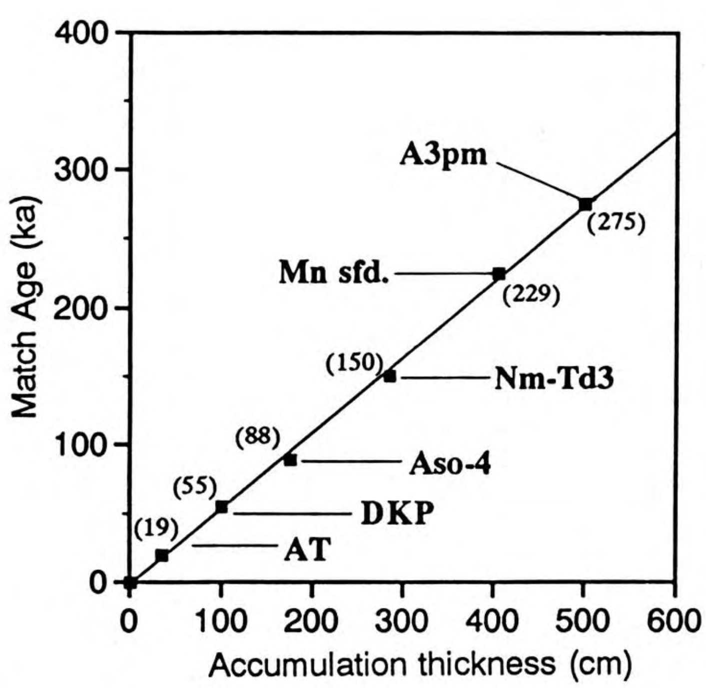

Fig. 6. Correlation between accumulation thickness of tephric loess and age. Ages are controlled by a correlation to oxygen isotope stratigraphy chronology data.

Ma and 0.30±0.03 Ma. The K-Ar ages of Apm tephras are then considered to be 0.25-0.30 Ma. These ages agree very well with the estimated ages from tephric loess depositional rate chronology by Kimura (1996), that is 275 ka for A3pm and 300 ka for A1pm. The tephric loess accumulation rate becomes similar both in HLF and MLF to be 18.1mm/ky if we assume the age of A3pm (MC2) as 275 ka. The calculated error of least square regression gives a very reliable value $r^2=0.99$, equivalent to 5ky age error calculated from thickness of the tephric loess.

The age of tephra layers originating from Bandai volcano were determined from interpolation of the age versus rate of accumulation curve (see Fig. 6). Thick scoria and pumice layers would represent larger eruption episodes of Bandai volcano, which include magmatic eruption. There were six large eruption phases starting about 265 ka, 210 ka, 165 ka, 80 ka, and 50 ka, and the most common phase intervals are about 50 ky. The period, in which the nonconformity was found within the tephric loess sequence, represents an exceptionally long dormant period (80 ky) of Bandai volcano and lasted about 80 ka.

IV. Volcanic activity of Bandai volcano deduced from tephro-stratigraphy

1) Eruption phases and their characteristics

We have deduced the magma eruption phases of Bandai volcano from the tephra-tephric loess sequence. There were six major eruption phases, during the Pleistocene age. We give a brief description of each of the eruption phases. A debris flow deposit is overlain by A1pm (MC4) along the southeast flank at Hanokisawa, which suggests the existence of a volcano prior to the deposition of A1pm (Phase 1 in Fig. 7). TcP1 is a pumice layer that is intercalated in lava flows. The stratigraphic relationship with other tephras is unknown, however, based on the lithofacies of the lava flows, it is considered to be the eruptive products of Phase 1. During the period of deposition of A1pm-A4pm (0.30-0.27 Ma), scoria flow deposits (Hc 1 and Hc 2 sfds.) were also erupted (Phase 2). Pumice fall (MP1) and a scoria flow deposit (Mn sfd.) erupted about 0.21 Ma (Phase 3). Immediately following a pumice fall eruption (MA 4), vulcanican andesite ash falls (MA 3-1) subsequently erupted about 0.16 Ma. This eruption phase was followed by a longer dormant period that lasted about 80 ka. Violent eruption activities reoccurred about 80 ka, following the pumice eruptions (HP2b and HP2a) associated with pumice flow (Hinatazawa pumice flow deposit), a

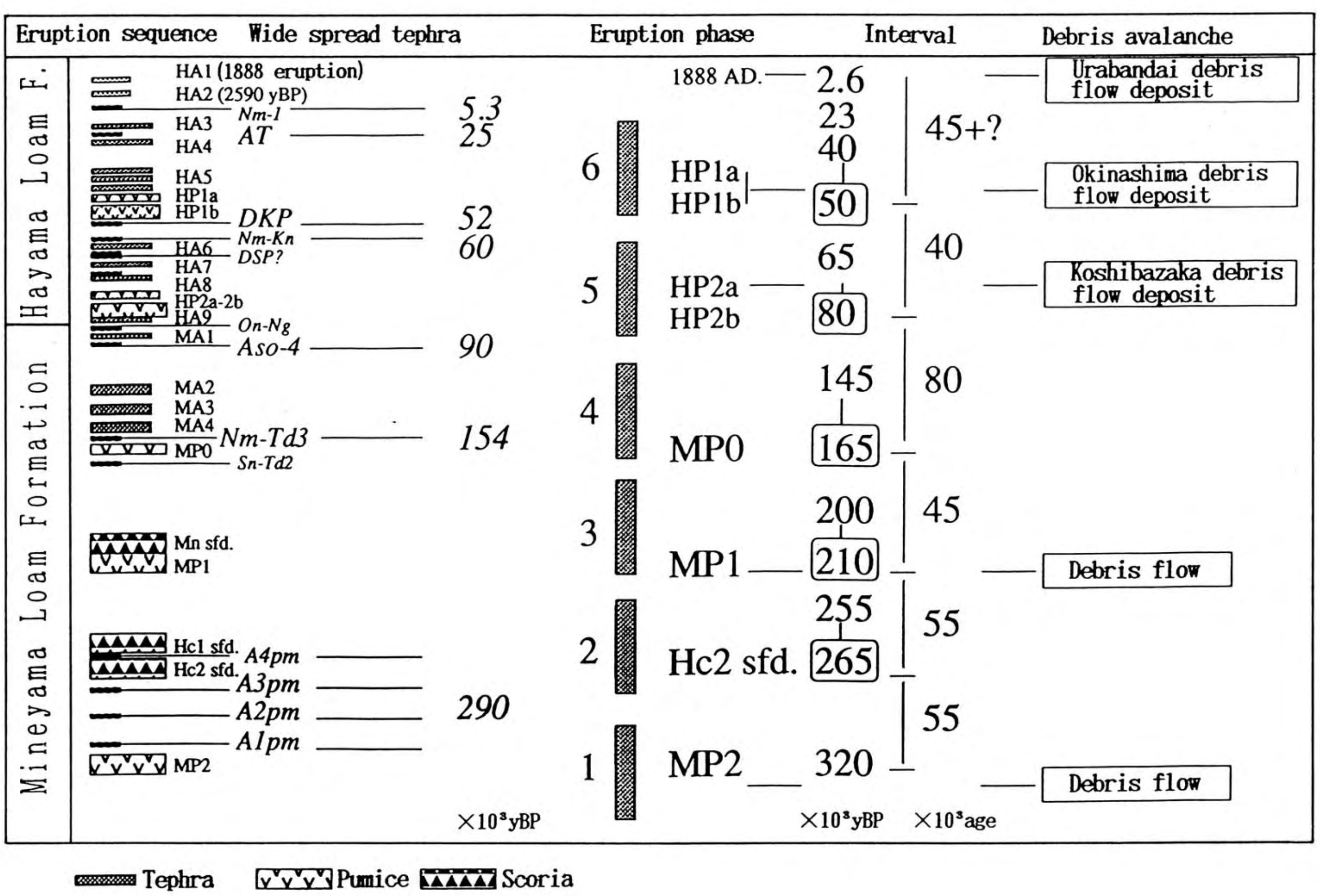

Fig. 7. Eruption phases and extinction intervals at Bandai volcano with horizons of debris flow deposits

series of vulcanian andesite ashes (HA8-6) was erupted (Phase 5). A similar eruption sequence was repeated in Phase 6, where pumice eruptions (HP1b and HP1a) were associated with a pumice flow (Sarashina pumice flow deposit), and subsequent vulcanian andesite ash falls (HA5-3). Later, the volcanic activity shifted to phreatic eruptions (HA2-1). The eruption of HA1 triggered a huge collapse of the volcanic body produced the 1888 debris flow deposit.

2) Stratigraphic horizon and origin of debris flow deposits along the southern flank of Bandai volcano

The debris flow deposits along the southern flank of Bandai volcano are subdivided into at least two distinctive deposits. These are the Koshibazaka debris flow deposit (new nomination), and the Okinashima debris flow deposit. It has been determined that the deposits were produced by a collapse of the volcanic body induced by the plinian pumice eruptions of HP2a and HP1b or HP1a, respectively. Following is the discussion of this reasoning.

Based on the modal composition of phenocrystic minerals, there is a possibility that the Sarashina pumice flow deposit (Koarai *et al.*, 1994), which overlies the debris flow deposits in the Okinashima hills and Numata region (see Fig. 1), can be correlated to the HP1b-HP1a pumice falls. In these regions, there are no remarkable key tephras other than AT covering above the Sarashina pumice flow deposit, and the covering tephric loess is thin. No tephra layers from Bandai volcano are attributed in this region, however, the relatively thick deposit of Nm-Kn should be present, if the Sarashina pumice flow deposit is older than the Nm-Nn (for the distribution of Nm-Kn see Suzuki, T. and Soda, 1994). Since these deposits cannot be found in the upper tephric loess beds, the Sarashina pumice flow deposit must overlie Nm-Kn tephra. As the Sarashina pumice flow deposit conformably overlie on Okinashima debris flow deposit, it has been speculated that the debris flow may have originated along with the plinian eruption of the HP1b or HP1a.

The Hinatazawa pumice flow deposits (new nomination) conformably underlain by On-Ng, and is considered to be correlative to the HP2b or HP2a pumice falls by its stratigraphic position and petrographic characteristics. Further, the HP2a at Mineyama (Fig. 5, loc. 3) shows the lithofacies of a pumice flow deposit. HP2a, there, has matrix-support texture and the pumice crusts show a coarsening-upward sedimentary structure, suggesting one of the typical pumice flow sedimentary structures (Cas and Wright, 1987). In particular, the much thicker portion of the iso-pach map of the HP2a forms a tongue-shaped distribution (Chiba *et al.*, 1994; Fig. 8). It supports the thought that some part of the distribution consists of pumice flow and part consists of air-fall pumice. All the observations above combine to support the assumption that the Hinatazawa pumice flow deposit was produced by HP2a plinian pumice eruption. Such the co-plinian pumice flow has been reported and is thought to be formed by gravitational collapse of a plinian eruption column (e.g., Cas and Wright, 1987). At Aza-Bandai-San (Fig. 5, Loc. 6), an outcrop exhibiting a HP2 horizon of pumice flow deposit immediately overlies a debris flow deposit. At another outcrop at Koshibazaka (Fig. 5, Loc8), a part of the pumice flow deposit is interbedded within the debris flow. The pumice from the outcrop also has a similar modal composition to HP2a. Therefore, the horizon of those debris flow deposits distributed in the regions, including Hinatazawa and Koshibazaka, are near comparable with the HP2a horizon. We have named the deposit the Koshibazaka debris flow deposit. This debris flow deposit contains several flow units (see Fig. 5).

The age of HP2a is about 80 ka and HP1b-HP1a are about 50-45 ka, based on tephric loess depositional rate chronology. The ages of the tephras are calculated by interpolation of the accumulation rate of

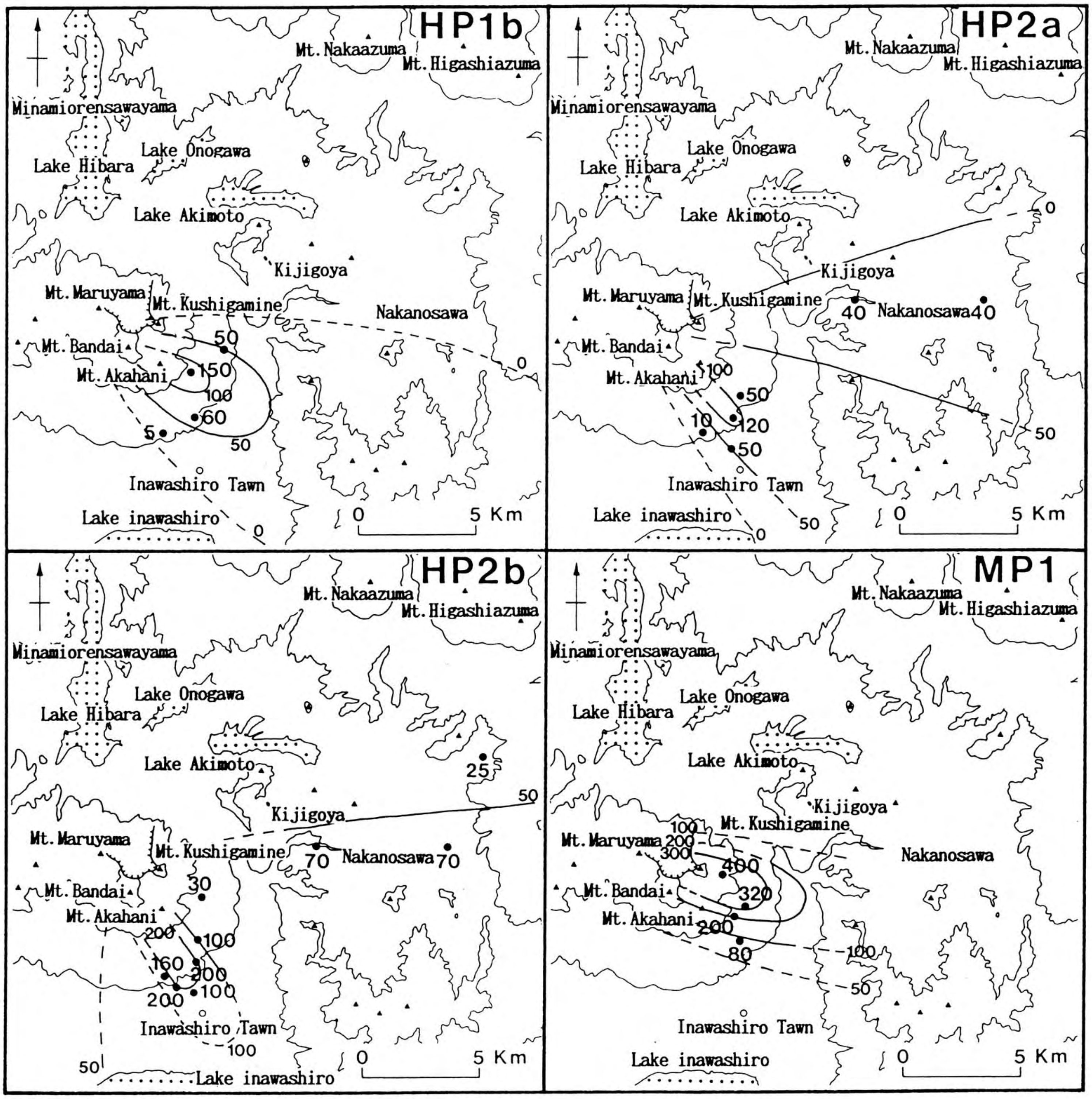

Fig. 8. Iso-pach maps of plinian pumice from Bandai volcano

tephric loess (see Fig. 6). We examine the consistency of the ages in this chapter comparing them with age data which has already been published. Suzuki, K. and Manabe (1981) examined a core sample of sediments from Lake Inawashiro which were deposited above the Okinashima debris flow deposit at Hoshojiri, and identified AT tephra at about one third of the depth of the core sample sequence. Based on pollen fossil analysis, Sohma (1984) identified the horizon of the last glacial maximum to be about 19 ka, and an interstadial period below the horizon to be 35-40 ka. He also demonstrated that the area experienced a cooler climate prior to the interstadial. A cold climate period below DKP, at about 55-60 ka, has been reported in many localities (Palynological Research Group for Nojiri-ko Excavation, 1991, and others).

The older cold climate horizon reported by Sohma (1984) can be assigned to the horizon. Suzuki, K. and Manabe (1981) have not identified the DKP layer in the core sample yet, therefore it is assumed that the lower portions of the core sample represent deposits which started sedimentation after 50 ka. This age would have been the transitional period from the cold climate of 55-60 ka to the interstadial. It is inferred that these sediments began deposition immediately after the deposition of the Okinashima debris flow deposit which formed about 50-45 ka. This estimate is supported by the dates obtained from the tephric loess chronology. Thus, this does not contradict the stratigraphic correlation and dating theory.

The estimated age of the Koshibazaka debris flow deposit is about 80 ka. This is based on the tephric loess depositional rate chronology, controlled by the ages of DKP and Aso-4 tephras. The ^{14}C dating of DKP has been reported to be 50 ka (Takemoto, 1993), and the age of Aso-4 has been dated by $\delta^{18}O$ stratigraphy as 88 ka (Oba, 1991). The stratigraphic position of HP2a lies at about one fifth measured from Aso-4 in the tephric loess sequence. The given age of 80 ka to HP2a would be reliable considering the discussion for HP1a and HP1b above.

Conclusively, the Koshibazaka and the Okinashima debris flow deposits originated from rock slide avalanches which were induced by the plinian pumice eruptions of HP2a (80 ka) and HP1a-HP1b (50- 40 ka), respectively. The outcrop, where the Hinatazawa pumice flow deposit is exposed, forms part of a large horseshoe-shaped caldera (Koarai *et al.*, 1994 ; also see Fig. 1). It is suspected that the caldera was formed by a volcanic body collapse which occurred at the formation period of the Okinashima debris flow deposit. The location of the collapse caldera for the Koshibazaka debris flow deposit is unknown.

V. Summary

The volcanic activities of Bandai volcano in the Quaternary age are divided into six phases according to the tephric loess chronology and eruption sequences deduced from tephra layers. In most of the cases, each eruption phase commenced with a plinian pumice eruption, and then shifted to vulcanian eruptions with accompanying lava flows. Debris flows occurred at each of the early phases triggered by plinian pumice eruptions. Huge debris flow deposits distributed along the southeastern flank are subdivided into at least two, the Koshibazaka and Okinashima debris flow deposits. These deposits are considered to have originated and been deposited by rock slide avalanches induced by the plinian pumice eruptions of HP2a and HP1b or HP1a, respectively. Tephric loess depositional rate chronology estimated the ages of each the eruption phases and the formation periods of the debris flows. The estimated ages of the Koshibazaka and Okinashima debris flow deposits are 80 ka and 50- 45 ka, respectively. The magma accumulation to Bandai volcano was predominant at about 50 ky each. The differentiation state of the erupted magma has been similar since 160 ka. Violent plinian pumice eruptions which occurred in the beginning of the phases would have destroyed the volcanic body that had been formed before. The following vulcanian eruptions with accompanying lava started to form a new volcanic body that was again destroyed by a new output of magma in the next eruption phase. These habitual cycles have been present since 160 ka at Bandai volcano.

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