THE RECENT MAJOR ERUPTION OF CHANGBAI VOLCANO AND ITS ENVIRONMENTAL EFFECTS

Hiroshi MACHIDA, Hiroshi MORIWAKI* and Da-Chang ZHAO**

Abstract This paper deals with nature, age and disaster of the recent explosive activity of Changbai volcano in terms of tephrostratigraphic studies. The *c*. 1,000 yr.BP. eruption of Changbai should have been one of the greatest volcanisms in the world, because bulk volume of tephra erupted was over 50 km^3. The eruption reveals two distinct orderly progressions of activity, *i.e.*, an initial silicic tephra falls followed by formation of large pyroclastic flow and the later, rather less silicic falls and flows, associated with debris avalanches and pyroclastic surge. The widespread ash fall deposit, B-Tm, is considered to be a combined product at the middle to late eruptive phases, forming a major component of all members. The magnitude of volcanic impact on human environments is exemplified by the extensive burial of forest under the pyroclastic flow, debris flow and Plinian fall deposits.

Key words: tephra, distal ash, pyroclastic flow, volcanic impact, buried forest

1. Introduction

Changbai (Baegdu) volcano is the large composite volcano with a prominent caldera situated on the Chinese-North Korean border[1]. This paper presents case studies on the large-scale explosive volcanism of Changbai volcano possibly in the 10th century and assesses the ecological significance of such events for the surrounding area. Our studies started with discoveries of extensive ash layer, Baegdusan-Tomakomai ash (B-Tm), derived from this volcano in northern Japan and the Sea of Japan (Fig. 1; Machida, *et al.*, 1981; Machida & Arai, 1983). In this paper we report the results of a field study of the 1,000 yr.BP (1 ka) deposits on the north and east flanks of this volcano in Chinese territory with an emphasis on the stratigraphy and petrography of the various tephra deposits and forest devastation associated with this volcanic activity.

* Faculty of Law & Letters, Kagoshima University
**Institute of Applied Ecology, Academia Sinica, Shenyang, China

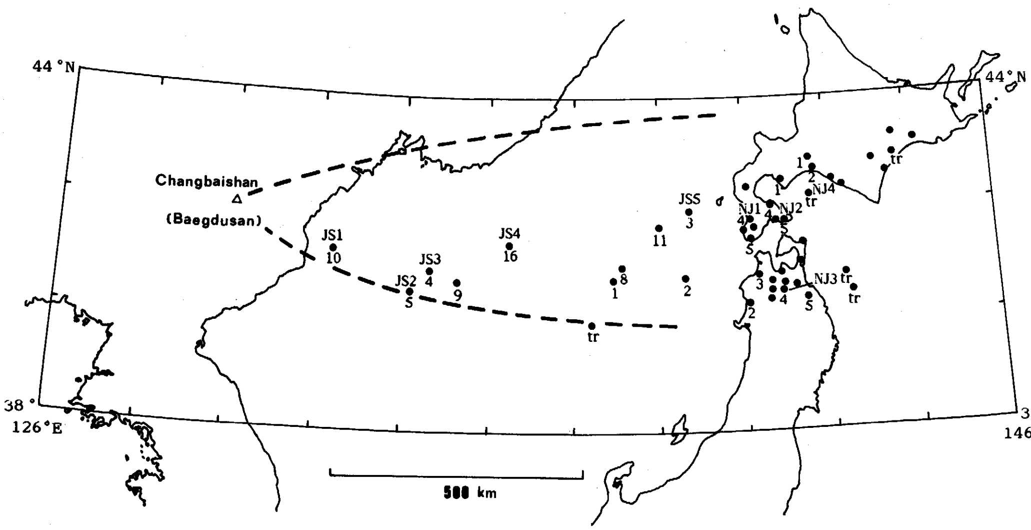

Fig. 1 Map showing localities where the Baegdu-Tomakomai ash (B-Tm) from Changbai volcano has been identified
Thicknesses of B-Tm are shown in cm by numerals. JS1=St.6913, JS2=St. 6920, JS3=KH69-2-25, JS4=KH69-2-23, JS5=KH79-3-C2, NJ1=Otobe, NJ2=Menagawa, NJ3=Tashirotai, NJ4=P81, off Tomakomai

2. Regional Setting

Changbai volcano is located on an extensive lava plateau, Gaima plateau, on the Chinese-Korean border (Figs. 2 & 3). The Gaima plateau is a cluster of shield volcanoes, approximately 600 m to 1,000 m in elevation. This shield has numbers of scoria cones, some of which have elevations of 1,300 m and youthful, undissected morphology. Most of these vents have produced basaltic lava flows. On this plateau two prominent stratovolcanoes arise, *i.e.*, Wangtian-e and Changbai volcanoes. The former is situated south-southeast of the latter and is highly dissected.

Changbai volcano has a diameter of *c.* 60 km on the plateau and rises to an elevation of 2,749 m. Its summit is occupied by a caldera a part of which was formed during the last major eruption as will be reported in this paper. The caldera is about 4.5 km in diameter, 850 m deep and has a prominent lake called Tianchi (Sky lake, Photo 1).

Exposures in the caldera and valley walls indicate that the volcano is built up primarily of lava flows followed by several welded tuff sheets associated with tephra falls. A large-volume pyroclastic flow deposit of silicic composition centered on the summit caldera. These products consist of a wide range of magmatic compositions from alkaline basalt to alkaline rhyolite (mostly trachyte and pantellerite).

There is little information about the eruptive history of the volcano prior to the last catastrophic volcanism. Our observations indicate that major Plinian and ignimbrite

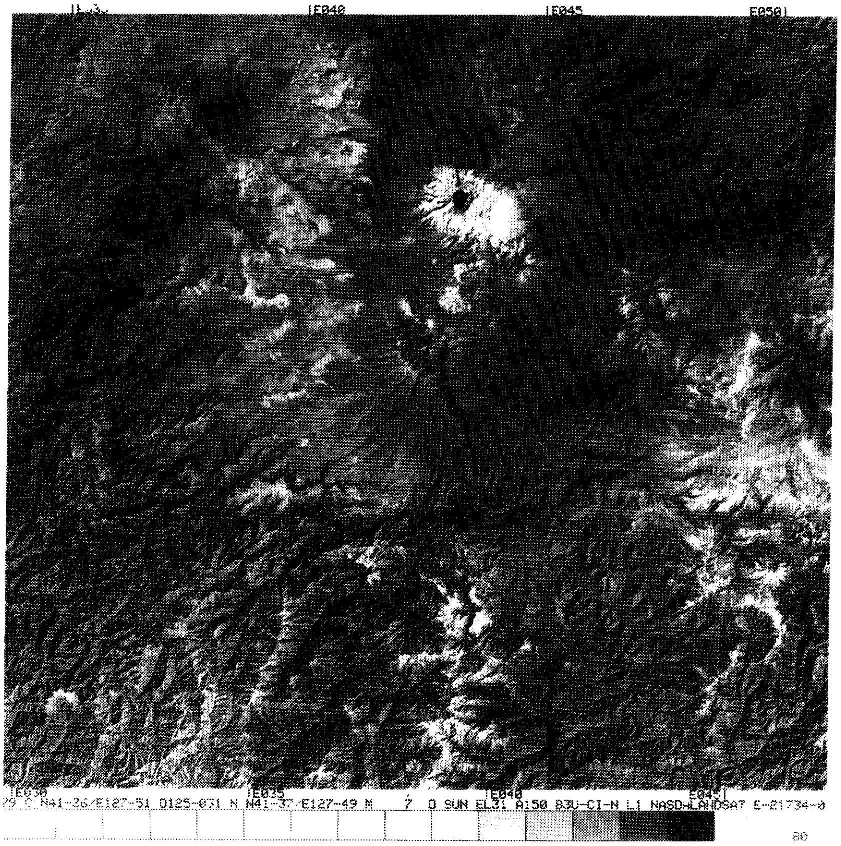

Fig. 2 Landsat satellite image of Changbai volcano (snow-covered mountain) and surrounding lava plateau

forming eruptions occurred more than four times preceding the last one. One of them should assign to the pumice fall deposit comprising the summit of Tianwenfeng peak on the present caldera rim. In addition, an alkaline ash layer found in the two piston cores in the northwest part of the Sea of Japan (JS1 & JS2 in Fig. 1) should be of Changbai origin from petrographic character and distribution. It occurs below the B-Tm ash and above the 22 ka AT ash in these cores, suggesting its eruption age around 12-13 ka. The other older ash has recently been found in the middle Pleistocene marine sequence of Oga peninsula, northeast Honshu (Arai *et al.*, unpublished). Petrographic characters of the ash are very similar to those of Changbai volcanic products. Consequently, the present caldera was formed as a result of multicyclic explosive activities through middle to late Quaternary.

Historical documents indicate that Changbai volcano has erupted four times since the 15th century, in 1413, 1597, 1668, 1702 AD. However, these activities do not correspond with the major eruptions generating voluminous tephra reported in this paper, but could have been minor ones.

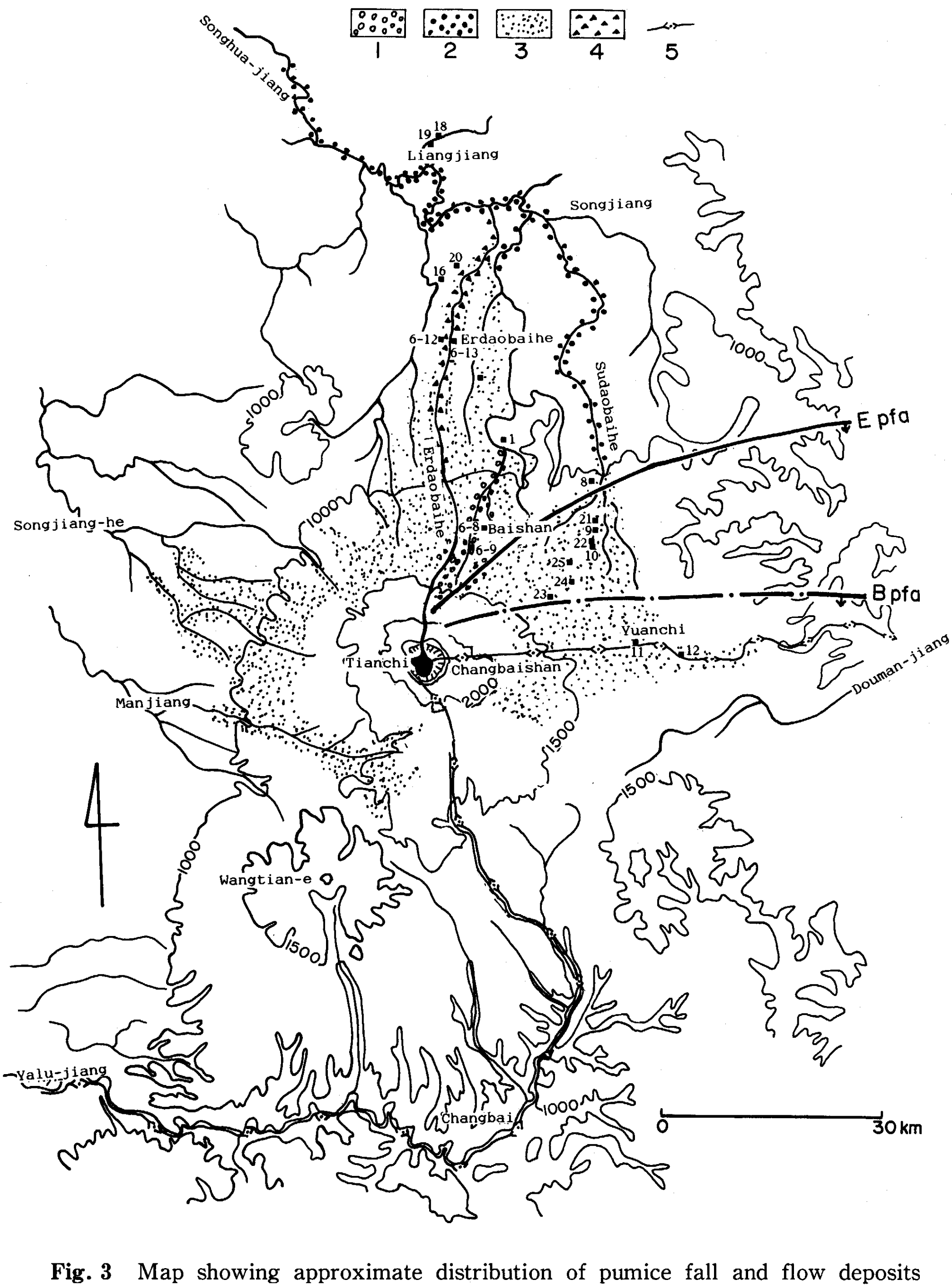

Fig. 3 Map showing approximate distribution of pumice fall and flow deposits around Changbai volcano
1 = F pfl, 2 = D mfl, 3 = C pfl, 4 = A dfl, 5 = borderline between China and Korea. Approximate northern limits of fall-out area of E pfa and B pfa are shown. Solid boxes with numerals are reference sections.

3. Sequence of Tephra Formation from the Last Major Eruption

Previous authors reported that Changbai volcano is extensively covered by pumice deposits (*e.g.*, Kano, 1937; Asano, 1948). We discriminated the products of the last major eruptions from numbers of eruptive materials and established the eruptive sequence (Fig. 4). A well development of mature soil and loess-like deposit below the top tephra formation suggests a long quiescent period preceding the last major eruption. It was a complex series of events which include a number of pyroclastic flows and falls without any significant hiatus. A standard stratigraphic section of the tephra layers can be established at the two sites near Yuanchi, 30-38 km east of the summit caldera (Locs. 11 & 12, Fig. 3). Columnar sections of tephra and associated deposits are shown in Figs. 5 and 6.

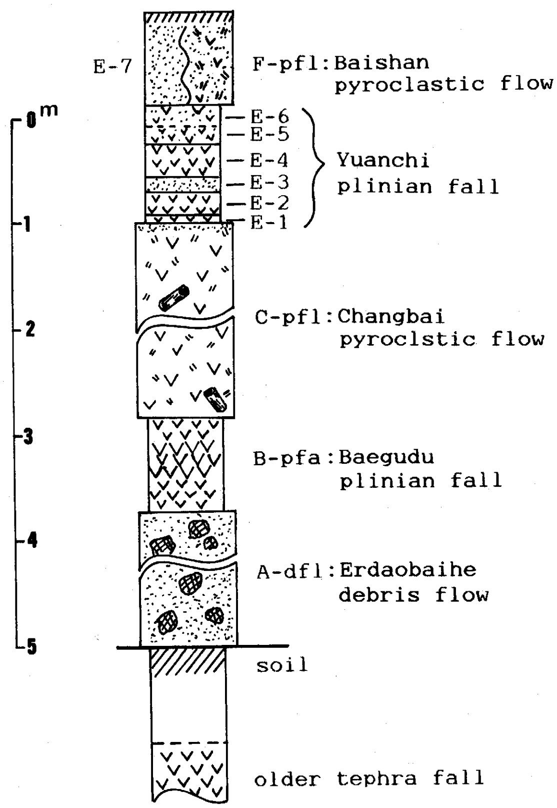

Fig. 4 Stratigraphy of the 1 ka Changbai tephras on the eastern slopes of the volcano near Yuanchi (modified from sites of Locs. 11 and 12)
pfa = Plinian fall deposit, pfl = pyroclastic flow deposit, dfl = debris flow deposit

Pyroclastic deposits from the recent activity of Changbai volcano show that there were six phases, A to F (Fig. 4). The first activity produced debris flows (A) probably preceding the Plinian phase B. On most parts of the volcano the initial sequence of the B pumice fall layer is overlain by a thick section of the C pyroclastic flow. The C pyroclastic flow deposit is voluminous and occurs as mudflow deposits along the lower reaches of major rivers (phase D). After a short hiatus, explosive activity produced members of tephra falls (phase E, E-1 to E-6), followed by relatively small scale pyroclastic flows (phase F). A distal ash fall layer named B-Tm (Machida *et al.*, 1981) is considered to be a combined product at the eruptive phases of C, E and F, forming the most voluminous component of all members. Stratigraphic nomenclature of these members follows Fig. 4.

Phase A: Erdaobaihe debris flow deposits (A dfl)

This occurs near the town of Erdaobaihe on the northern flank along the Erdaobai River c.50 km distant from the summit (Fig. 3), and is characterized by abundant huge lava boulders bearing few pumice lumps. Lithology and distribution of this deposits suggests that large-scale rockslide avalanche occurred on the source slopes of the Erdaobai River where magnificient landslide morphology develops around the Changbai hot spring (Photo 2). It is possible to estimate that pre-eruption earthquakes or shocks associated with the first plinian activity (Phase B) caused large-scale rockslide avalanche resulting in this debris flow deposit.

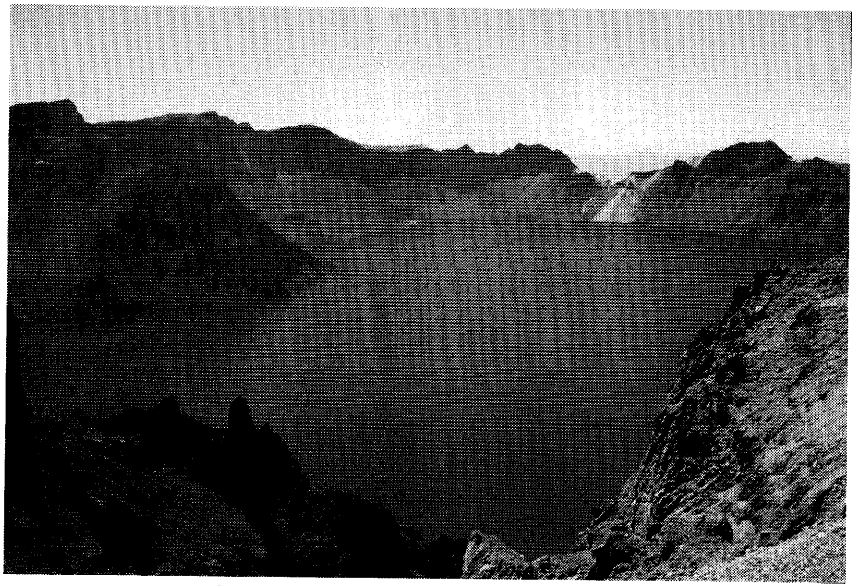

Photo 1 Summit caldera, Tianchi (Sky lake)

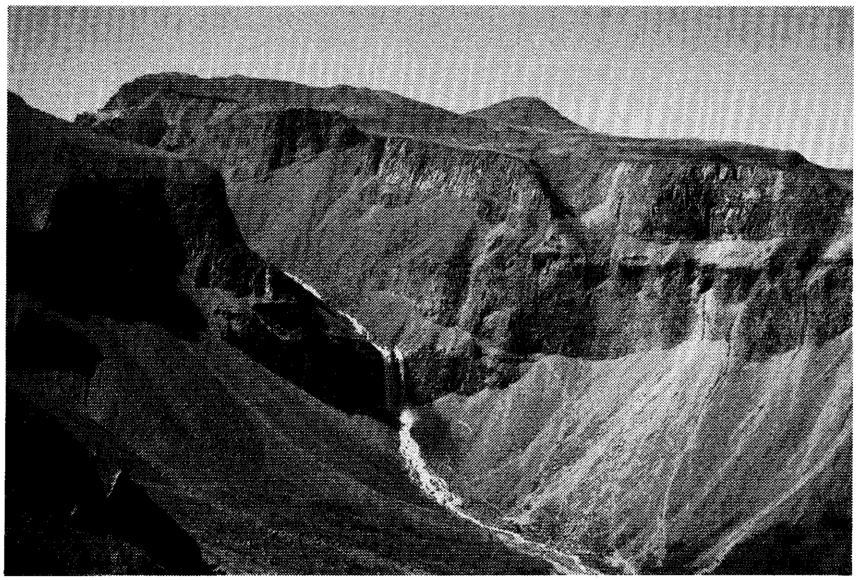

Photo 2 Landslide landscape around the Changbai hot springs

Phase B: Baegdu Plinian pumice fall deposits (B pfa)

The first magmatic product of the eruptive sequence is a light colored, silicic pumice fall layer. It is 90 cm thick at the reference section near Yuanchi, Loc. 12, but thins rapidly towards north. Although we could not carry out field studies on the southeastern flank of Changbai volcano, an approximate northern margin of this fall-out area as shown in Fig. 3 implies that this member occurs thicker on the southeastern flank. This member is named after the Korean name of this volcano.

The B pfa layer comprises highly vesicular light colored pumice and is well sorted. The lower half is reversely graded, and the upper half is normally graded. The average maximum grain-size is 2.5 cm at the type section. Silicic pumice of narrow ranged composition with small amount of basaltic fragment is the most abundant component, indicating the homogeneous magma discharge during the first stage.

Phase C: Changbai pyroclastic flow (C pfl)

Immediately after deposition of B-pfa a major change occurred in the style of eruption, *i.e.*, from Plinian eruption to the generation of major pyroclastic flows. Some localities c. 26 km northeast of summit give us an information that a pyroclastic surge occurred immediately before the generation of pyroclastic flow on the northeastern slope. This deposit is a crudely stratified, gray sandy ash surge layer with thickness of less than 2 m (Loc. 25, Fig. 5). Areal distribution and significance of this deposit are open to future works.

This surge is covered by a white to gray, thick pyroclastic flow deposit, named Changbai pyroclastic flow (C pfl) in this paper. This is the earliest and largest flow generated during the 1 ka Changbai eruption. Asano (1948) described 'mud-lava' occur-

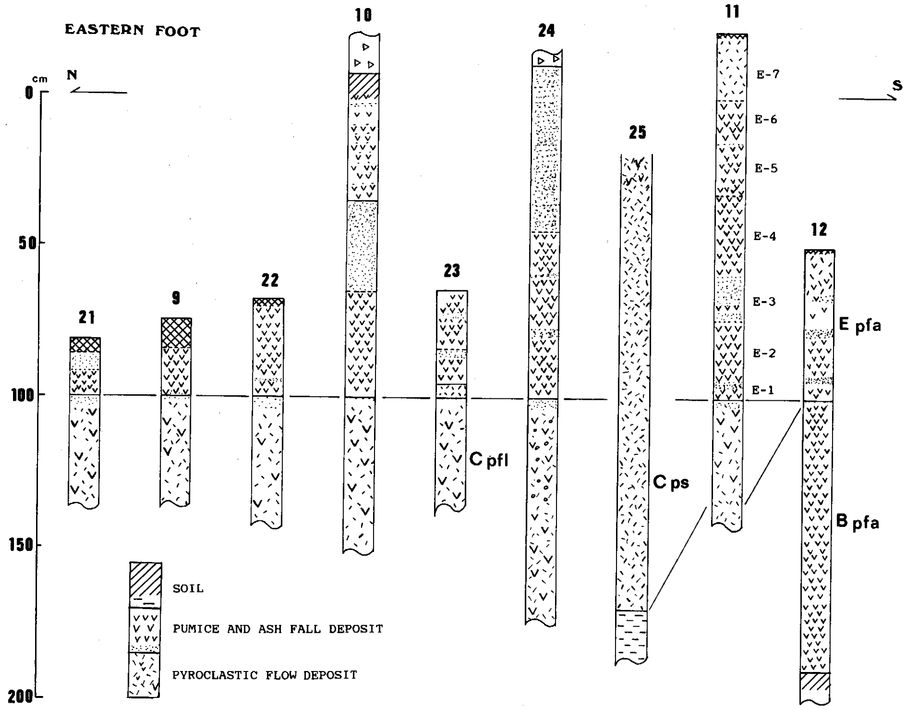

Fig. 5 Representative columnar sections on the eastern slope of Changbai volcano Localities are shown in Fig. 2.

Photo 3 Carbonized tree trunks buried in the C pfl deposit

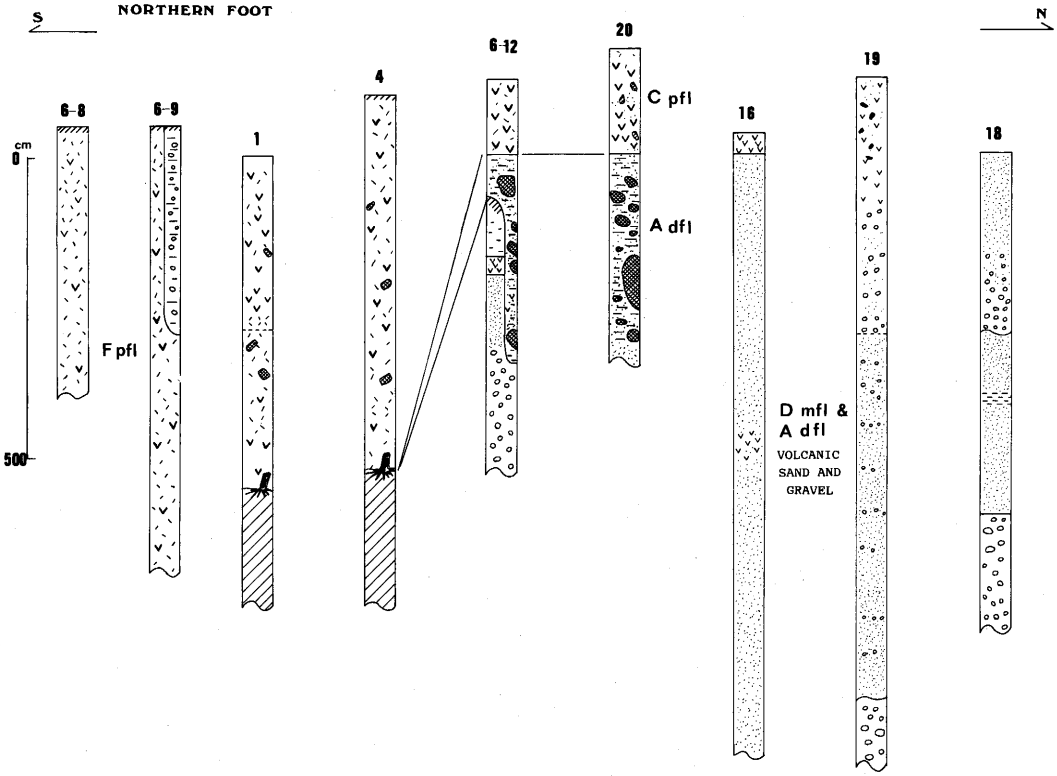

Fig. 6 Representative columnar sections on the northern slope of Changbai volcano Localities are shown in Fig. 2.

ring on the north to west slope of the volcano. This product should be identical to the C pfl or F pfl deposit. Our observation indicates that this deposit covers almost all gentle slopes of the volcano, possibly including the North Korean sector. Areal distribution of the C pfl deposits in Chinese territory is shown in Fig. 3, based on a combination of field observation and a morphological analysis of the slope where pyroclastic flow deposition was likely to occur. At the locality *c.* 90 km southeast of Changbai volcano in the Korean sector, buried carbonized woods had been found within 'volcanic sand layer' with thickness of 30 cm by Kohyama (1943). His description implicates that this volcanic sand layer should be of pyroclastic flow origin. Hence, the flow must have reached to the lower flood plains in most directions from Changbai volcano.

The C pfl deposit is composed of light- and dark-colored pumices and glass shards and lithic fragments, bearing abundant carbonized tree trunks (Photo 3). Refractive index determination and microprobe analysis of these glasses show that the color distinction is reflected in the chemical composition of them. Dark-colored pumices and glass shards are less silicic than light-colored ones which are similar to those of B pfa (Fig. 7). Banded pumice lumps are common in the C pfl deposit.

As the flow deposit occurs on gentler slopes of the mountain lower than *c.* 1,500 m in elevation, a total deposition area of *c.* 2,000 km^2 is roughly estimated. Apparent bulk volume of this deposit can be estimated *c.* 10 km^3 based on an assumption of the average thickness of *c.* 5m.

Phase D: Liangjiang mudflow deposit (D mfl)

Around Liangjiang along the Erdao River, c. 70 km north of summit, there develops a flight of terrace composed of volcanic materials with maximum thickness of 10 m (Photo 4), *i.e.*, rounded pumice and scoria, volcanic sand, vitric ash and rounded non-volcanic gravels bearing numbers of small flakes of carbonized wood. This deposit can be traced from Erdobaihe township to Liangjiang for 25 km and should extend downstream to an unknown extent. This deposit clearly implicates that an unusual mudflow happened along the river immediately after the eruptive phase(s) of C and possibly E and F. Some photographs showing a flight of river terraces taken near Changbai township along the Yalu River, 60 km south of Changbai volcano, indicates that another mudflow occurred to the south resulting in a valley fill. Hence it is possible to discuss that such volcanic mudflow occurred in almost all large rivers associated with the major eruption.

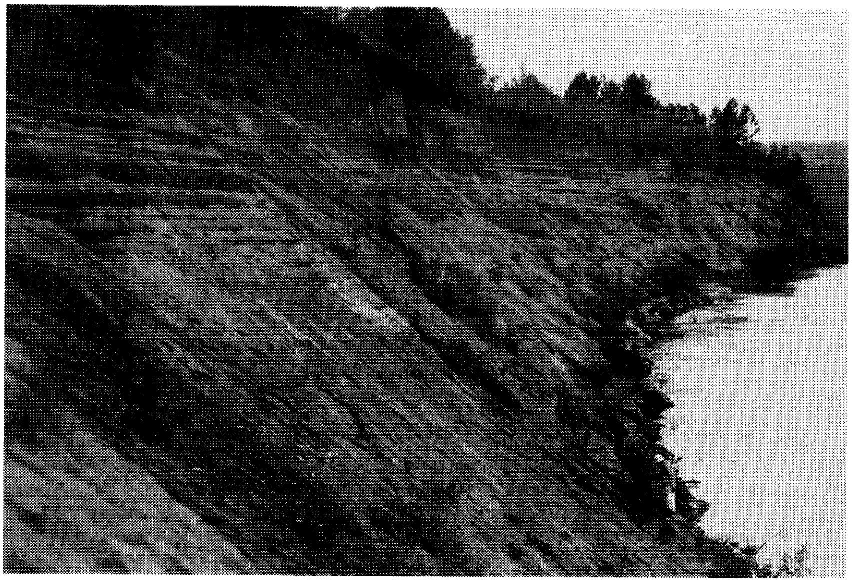

Photo 4 Fill-top terrace composed of volcanic sands and gravels at Liangjiang

Phase E: Yuanchi tephra falls (E pfa)

The C pfl deposit is not the post-plinian pyroclastic flow but the intra-plinian deposit, because an overlying, extensive tephra fall layer occurs to the east of Changbai volcano. When we drive from north to south on the northeastern flank along the Sudao River, we cross a marked transitional zone of forest assemblage, *i.e.*, from the thickly vegetated, mature conifer forest on the north side to the poorly grown, immature *Larix* and *Betula* forest on the south. It is interesting that this transitional zone is very close to the northern limit of the E tephra fall-out area (Fig. 3). To the north of this boundary C pfl is a surface forming material, whereas the overlying dark-colored pumice and ash fall layers increase their thickness to the south, forming sand dunes. Total thickness of these deposits attains 130 cm at the reference section near Yuanchi (Loc. 11). An unusually extensive *Larix* forest characterizes the vegetation to the east of Changbai volcano. It seems possible that such vegetation has been highly controlled by the tephra mantle of B pfa and E pfa. Relationships between vegetation and tephra will be discussed later.

After the deposition of C pfl a short period of quiescence of eruption might have happened, as a very thin and immature soil-like bed is observed at the top of C pfl and is covered by the E tephra fall deposit. This tephra fall member is an alternation of gray pumice and ash layers, named Yuanchi tephra fall after the place name of reference section and is abbreviated as E pfa. It can be subdivided into four plinian pumice fall units (E-1, 2, 5 & 6) and three phreato-magmatic ash fall units (E-3, 4 & 7) at the reference section (Fig. 4).

The lower two Plinian pumice layers (E-1 & 2) comprise well-sorted, dark-colored vesicular pumice fragments with maximum grain-size of 3 cm. The E-5 Plinian deposit overlying the phreatomagmatic, dark-gray sandy ash (E-3, 4) is composed of well-sorted, silicic pumice with thickness of 27 cm and maximum grain-size of 7 cm. The E-6 unit is poorly sorted and consists primarily of blocky to vesicular, gray pumice and glass shards. A presence of very large blocks of pumice with maximum grain-size of 12 cm characterizes the top of this unit, which is covered by a marked fine-grained vitric ash deposit (E-7) with thickness of *c.* 30 cm.

Although the E-6 and E-7 units occur as airfall deposits at the reference section on the eastern flank, they suggest some generation of pyroclastic flow at this eruptive phase because of their poorly sorted characters. It may be significant that E-7 is very similar to the distal B-Tm ash in lithology and composition, which will be described later.

Phase F: Baishan pyroclastic flow (F-pfl)

At Baishan station (Loc. 6-8), 21 km north-northeast of the caldera, a dark-colored pyroclastic flow deposit is exposed in the valley wall with thickness of more than 8 m. This is a surface forming deposit there except for the overlying, local fluvial sediments. This member, named Baishan pyroclastic flow or F pfl, is apparently different from C pfl not only in lithology but also in composition. This is composed of fine-grained, dark-colored pumices and glass shards with lithic fragments. No carbonized woods are found in this deposit. The distribution of this member is not shown in Fig. 3 except for limited area near the type section because of insufficiency of field work, but it may occur on gentle surface between 1,800 m and 1,100 m on the northern flank of the volcano, possibly extensive in all directions. Volume of this deposit, however, may be smaller than that of C pfl. Petrographic similarity of constituent material between F pfl and E-7 afa indicates that both units would be simultaneous, final products of the 1 ka major eruption of Changbai volcano.

The distal B-Tm ash

As shown in Fig. 1, the distal vitric ash, B-Tm, occurs in the deep sea sediments of the northern part of the Sea of Japan and in northern Japan. This ash is considered to be a product of the 1 ka large eruption of Changbai volcano based on several evidences; similarity of composition and stratigraphic position or age between this ash and the proximal tephra and a fall-out area to the east of Changbai volcano (Machida *et al.*, 1980; Machida *et al.*, 1987). A degree of systematic thinning and decrease in grain-size with increasing distance from source is very small as compared with usual plinian falls (Machida *et al.*, 1980). The deposit is rather massive with no systematic grading and compositional zonation from the base to the top at the JS4 site (KH69-2-23) where the ash layer is the thickest in the abyssal cores.

A problem to be solved still remains ; mechanisms of its generation. One of the keys to this problem may be a field work on strict stratigraphic relations between the distal ash and the Changbai tephra members to the east of Changbai volcano, especially in North Korean sector. Another key will be given by petrographic analysis, because the 1 ka Changbai tephra formation is characterized by large compositional variations from layer to layer.

Extensive occurrence of B-Tm ash indicates that it represents the largest part of the total 1 ka fall deposit. Machida *et al.* (1987) estimated that the total bulk volume attains more than 50 km^3. Proximal Plinian fall and pyroclastic flow deposits may roughly be estimated less than 20 km^3 in total bulk volume. Hence, the 1 ka Changbai eruption should have been one of the largest eruptions in the historic age of the world.

4. Petrographic Characters of Changbai Tephra

On the basis of whole rock composition, the 1 ka Changbai tephra is an alkaline rhyolite with small amount of alkaline feldspar and aegirine augite. Results of determination of refractive index and EDS analysis of major element concentrations of glass seperates[2)] are shown in Figs. 7 and 9 (A & B) and Table 1 (A). The analysed samples were taken from all the fall and flow units at several reference sections. The refractive indices and major element concentrations of the B pfa glass fall within a narrow range, whereas those of other members and units have a wide range with bimodality in some cases. As described earlier, the 1 ka Changbai tephra layers are composed of light- and dark-colored pumice and glass shards except for B-pfa. Light-colored one is characterized by lower index of refraction and higher concentration of SiO_2 than dark-colored. A field observation indicates that abundance of dark-colored pumice or scoria increases with stratigraphic level. This is consistent with the systematic variations of refractive index of glass shards. Variations in major element concentrations show the same tendency as in refractive indices with stratigraphic level so far as the analytical data of matrix glass are concerned. These should indicate some compositional stratification of the magmatic reservoir.

Analytical data of the distal ash fall, B-Tm, are shown in Figs. 8 and 9(C) and Table 1 (B)[3)]. The samples are taken from five abyssal sediment cores and terrestrial deposits. Refractive indices and major element compositions of glass shards range as wide as those of matrix glass shards from the C, E and F members. No systematic variations can be seen with stratigraphic level in the JS4 core. Furuta *et al.* (1986) discussed that glass

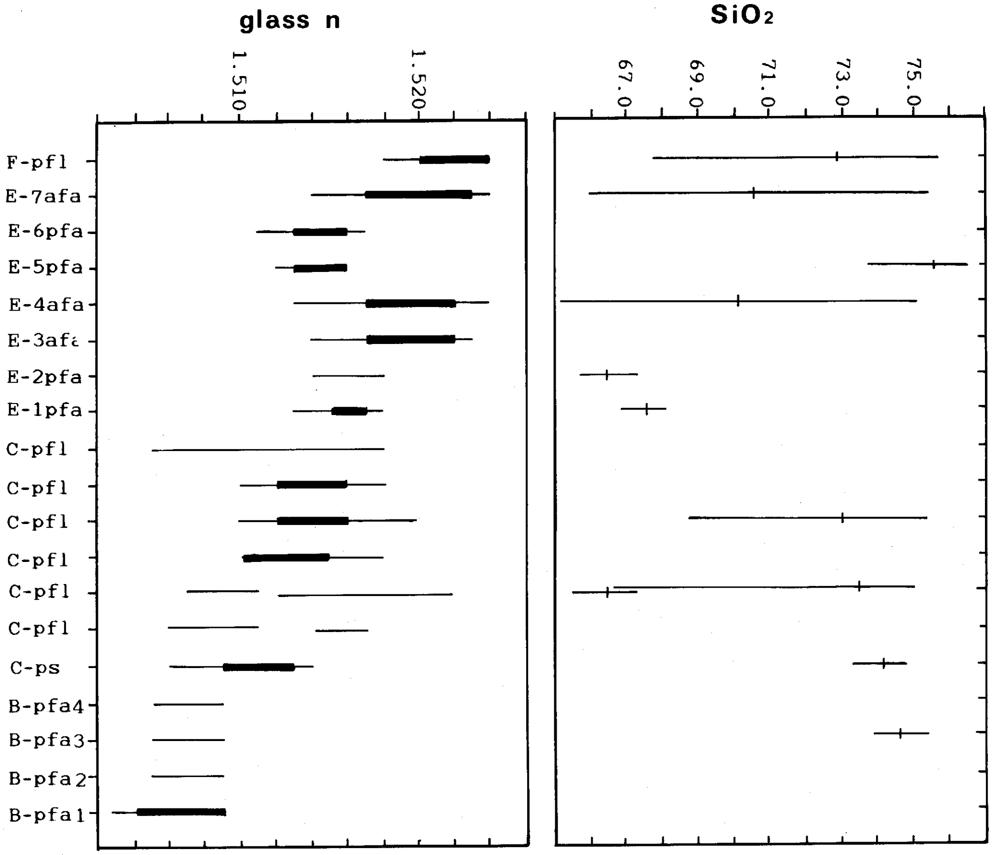

Fig. 7 Variations in refractive index and SiO_2 content of glass shards from the 1 ka Changbai tephra formation
Sample locality: F-pfl, loc. 6-8; E-tephras, loc. 11; C-pfl, locs. 11, 4 (3 samples), 1, 6-12 from top to bottom; C-ps, loc. 25; B-pfa, loc. 12.

shards from the B-Tm layer can be classified into two groups, *i.e.*, silicic and less silicic, suggesting two different fractionation stages of a magma. The present data show no clear bimodality but some wide and continuous variations of glass shard composition, indicating some stratification of magma as stated above.

It may be possible to discuss that B-Tm ash was not produced by the Plinian B-phase eruptions but asociated with the E-phase Plinian eruptions, the C and F ignimbrite eruptions, or with both. However, we will not be able to conclude regarding the emplacement mechanism of the distal B-Tm ash until much data are available from the North Korean district.

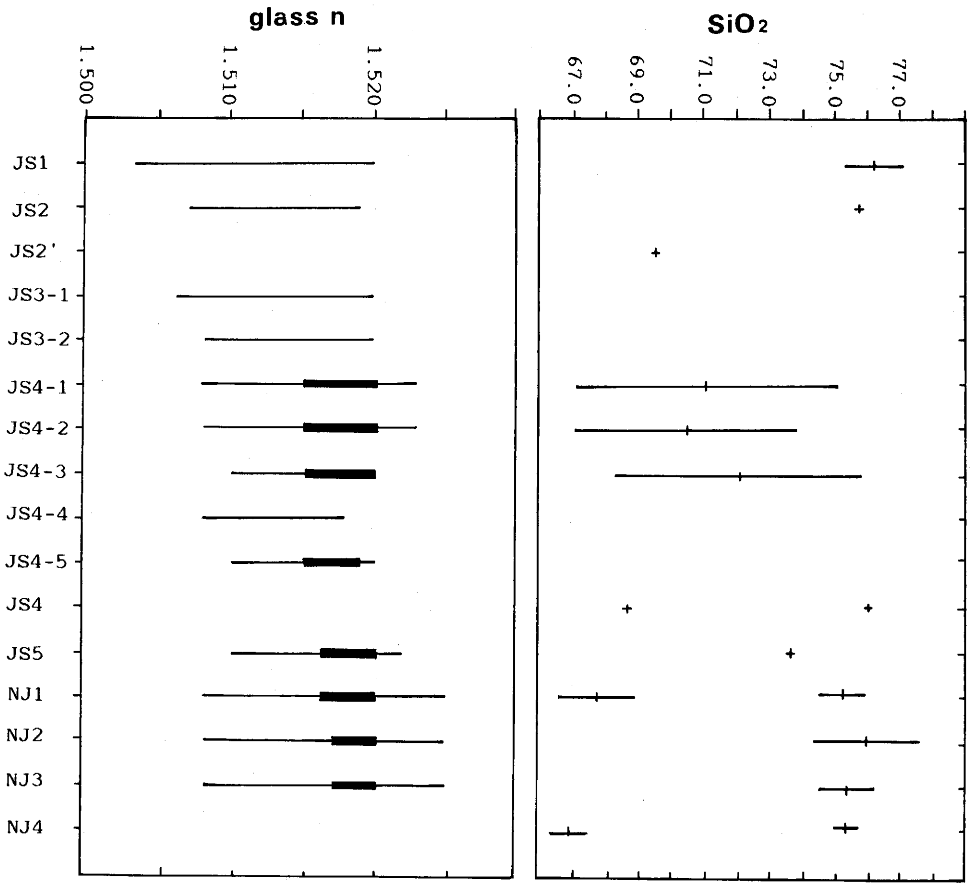

Fig. 8 Refractive index and SiO_2 content of glass shards from the distal B-Tm ashes Sample locality: see in Fig. 1. Hyphened numerals indicate stratigraphic level from the top.

5. Age of Eruption

Earlier opinions vary on the age of the recent eruption of Changbai volcano: Most geologists believed that the eruptions preceded the last glaciation of Changbaishan based on the observation on relationship between tephra and glacial morphology (*e.g.* Asano, 1948). In contrast, forest ecologists were of the opinion that the eruption occurred more recently, probably with recorded history (Kohyama, 1943). Stratigraphic observations and some radiocarbon age determinations on woods clearly support the latter.

Zhao (1981, 1987) reported the three radiocarbon ages of the carbonized woods included in the C pfl deposit: 1,050±70 and 1,120±70 yr.BP. from the northern slope and 1410± 80yr. BP. from the western slope. Other chronological and archaeological data are available from north Japan, indicating that B-Tm ash occurred between 915 AD and 1334

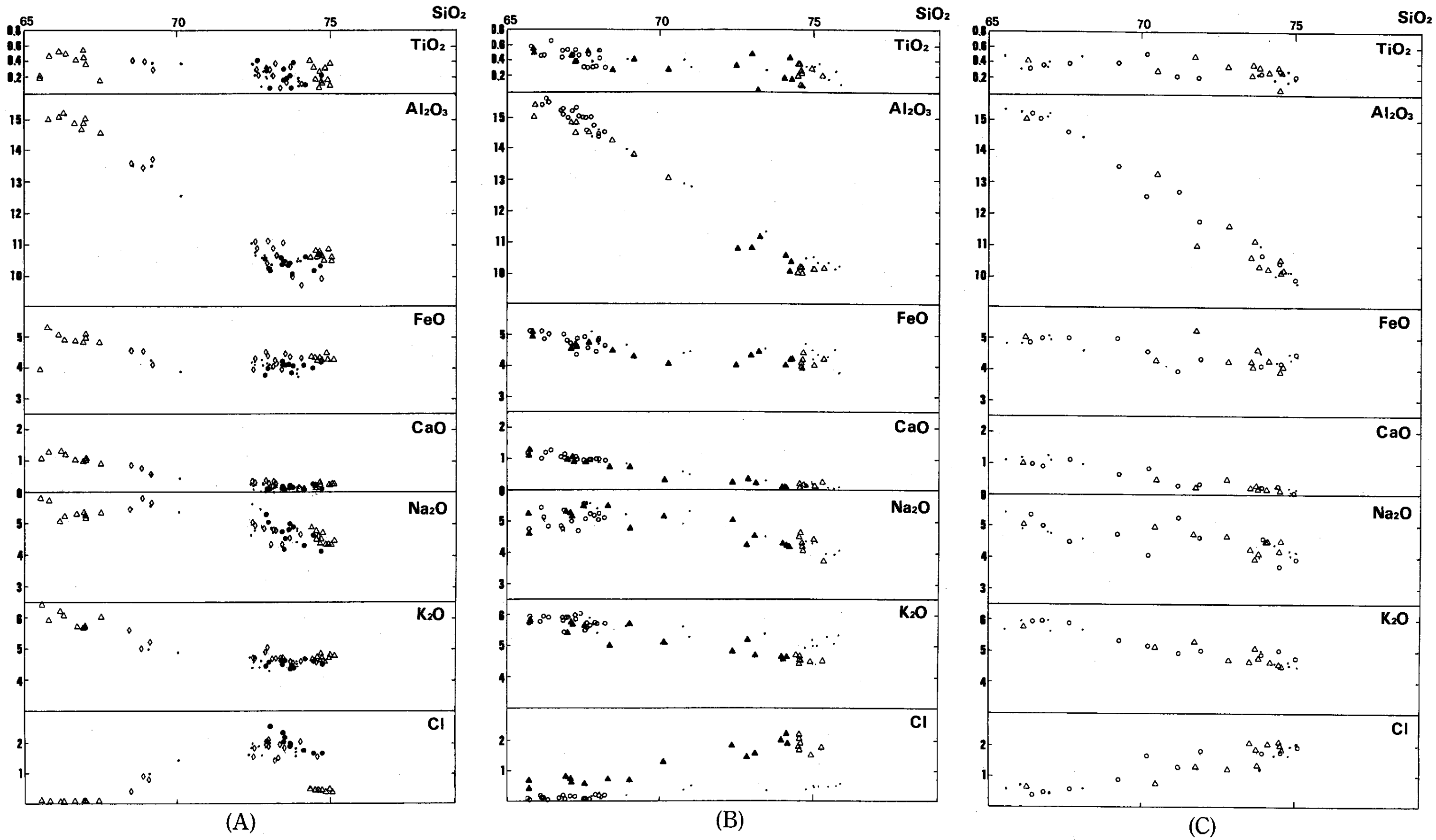

Fig. 9 (A) Silica diagram for the Changbai tephra formation (B pfa-C pfl)
solid circle = B pfa, dot = C ps, open triangle = C pfl(Loc. 11), open diamond = C pfl(Loc. 4)
(B) Silica diagram for the Changbai tephra formation (E pfa & F pfl)
open circle = E-1 pfa, open triangle = E-6 pfa, solid triangle = E-7 afa, dot = F pfl
(C) Silica diagram for the B-Tm ash from JS4 (KH69-2-23)
open triangle = lower unit, open circle = middle unit, dot = upper unit

Table 1 Major element concentrations of Changbai teplna (A) and B-Tm ash (B)
Standard deviation is shown in a parenthesis.

(A)	SiO_2	TiO_2	Al_2O_3	FeO*	MgO	MnO	CaO	Na_2O	K_2O	total	N	Analyst
F-pfl	72.86 (2.99)	0.29 (0.11)	11.65 (1.70)	4.43 (0.29)	0.11 (0.09)	0.07 (0.07)	0.35 (0.31)	4.61 (0.57)	5.28 (0.28)	99.65	13	TOKUI
E-7afa	70.56 (3.43)	0.37 (0.16)	13.14 (1.99)	4.53 (0.33)	0.13 (0.07)	0.06 (0.10)	0.66 (0.43)	4.94 (0.44)	5.24 (0.49)	99.63	15	TOKUI
E-5pfa	75.62 (0.54)	0.23 (0.10)	10.12 (0.36)	4.10 (0.18)	0.12 (0.09)	0.03 (0.06)	0.11 (0.06)	4.34 (0.26)	4.55 (0.12)	99.22	22	TOKUI
E-4afa	70.14 (3.26)	0.34 (0.13)	13.27 (1.94)	4.57 (0.36)	0.11 (0.09)	0.05 (0.07)	0.67 (0.37)	5.26 (0.50)	5.28 (0.48)	99.69	21	TOKUI
E-2pfa	66.53 (0.53)	0.53 (0.07)	15.42 (0.29)	4.98 (0.14)	0.14 (0.08)	0.15 (0.15)	1.17 (0.10)	5.04 (0.23)	5.92 (0.10)	99.88	10	TOKUI
E-1pfa	67.66 (0.38)	0.41 (0.09)	14.87 (0.29)	4.74 (0.19)	0.17 (0.11)	0.04 (0.06)	1.01 (0.05)	5.26 (0.17)	5.68 (0.12)	99.84	10	TOKUI
C-pfl	73.14 (2.04)	0.27 (0.10)	11.33 (1.33)	4.39 (0.19)	0.07 (0.08)	0.03 (0.09)	0.32 (0.23)	4.99 (0.50)	4.86 (0.27)	99.40	15	TOKUI
C-pfl	73.55 (2.77)	0.23 (0.12)	11.27 (1.49)	4.41 (0.22)	0.13 (0.11)	0.05 (0.12)	0.33 (0.29)	4.67 (0.35)	4.93 (0.45)	99.57	13	TOKUI
C-pfl	66.55 (0.56)	0.44 (0.10)	15.13 (0.44)	4.93 (0.36)	0.09 (0.08)	0.12 (0.10)	1.14 (0.13)	5.50 (0.24)	5.98 (0.23)	99.88	10	TOKUI
C-ps	74.24 (0.58)	0.25 (0.07)	10.58 (0.28)	4.13 (0.19)	0.09 (0.06)	0.12 (0.12)	0.14 (0.09)	4.99 (0.35)	4.56 (0.14)	99.10	13	TOKUI
B-pfa	74.74 (0.41)	0.23 (0.10)	10.51 (0.16)	4.09 (0.14)	0.05 (0.06)	0.1 (0.11)	0.09 (0.07)	4.7 (0.37)	4.53 (0.09)	99.04	11	TOKUI
(B)												
JS1	76.20 (0.89)	0.22 (0.01)	10.49 (0.19)	4.08 (0.08)	0.01 (0.01)	0.06 (0.03)	0.21 (0.02)	4.49 (0.19)	4.23 (0.05)	99.99	7	FURUTA
JS2 Gl-1	75.01 (0.63)	0.23 (0.03)	10.47 (0.30)	4.06 (0.10)	0.02 (0.02)	0.09 (0.04)	0.25 (0.04)	5.41 (0.44)	4.45 (0.11)	101.60	24	FURUTA
JS2 Gl-2	68.20 (1.21)	0.37 (0.03)	14.56 (0.42)	4.48 (0.20)	0.08 (0.02)	0.12 (0.04)	0.98 (0.09)	5.92 (0.67)	5.29 (0.12)	102.69	11	FURUTA
JS4-1	71.09 (4.00)	0.32 (0.13)	12.87 (2.36)	4.56 (0.36)	0.10 (0.09)	0.07 (0.08)	0.67 (0.48)	4.88 (0.53)	5.13 (0.56)	98.99	20	TOKUI
JS4-2	70.53 (3.42)	0.33 (0.11)	13.24 (1.97)	4.60 (0.39)	0.10 (0.07)	0.07 (0.10)	0.68 (0.41)	4.92 (0.54)	5.23 (0.47)	99.70	20	TOKUI
JS4-3	72.16 (3.82)	0.32 (0.14)	12.19 (2.17)	4.52 (0.43)	0.14 (0.13)	0.11 (0.14)	0.45 (0.43)	4.69 (0.44)	5.05 (0.52)	99.63	17	TOKUI
JS4 Gl-1	75.41 (0.91)	0.24 (0.03)	10.48 (0.28)	4.04 (0.09)	0.03 (0.01)	0.09 (0.03)	0.24 (0.04)	5.00 (0.86)	4.46 (0.10)	102.25	23	FURUTA
JS4 Gl-2	67.09 (0.63)	0.43 (0.04)	15.16 (0.27)	4.74 (0.15)	0.14 (0.04)	0.13 (0.02)	1.19 (0.09)	5.62 (0.86)	5.47 (0.15)	102.08	23	FURUTA
JS5 Gl-1	75.36 (0.70)	0.24 (0.03)	10.57 (0.66)	4.38 (0.64)	0.19 (0.01)	0.07 (0.03)	0.26 (0.08)	4.72 (0.40)	4.21 (0.16)	100.00	12	FURUTA
JS5 Gl-2	67.86 (1.16)	0.36 (0.05)	15.21 (0.57)	4.71 (0.13)	0.10 (0.03)	0.10 (0.03)	1.06 (0.09)	5.46 (0.16)	5.13 (0.28)	99.99	3	FURUTA
NJ2	76.09 (1.66)	0.21 (0.02)	10.80 (0.36)	4.01 (0.14)	0.02 (0.00)	0.07 (0.02)	0.21 (0.03)	4.80 (0.18)	3.78 (0.11)	99.99	4	FURUTA
NJ3	75.50 (0.84)	0.23 (0.03)	10.81 (0.47)	4.34 (0.71)	0.02 (0.01)	0.07 (0.05)	0.25 (0.06)	4.98 (0.57)	3.81 (0.10)	100.01	5	FURUTA
NJ4 Gl-1	75.50 (0.32)	0.21 (0.07)	10.43 (0.22)	3.98 (0.16)	0.12 (0.05)	0.03 (0.03)	0.20 (0.09)	4.48 (0.18)	4.53 (0.20)	99.48	8	TOKUI
NJ4 Gl-2	66.99 (0.59)	0.51 (0.08)	14.99 (0.21)	4.92 (0.22)	0.12 (0.05)	0.12 (0.12)	1.21 (0.15)	5.28 (0.22)	5.72 (0.21)	99.86	4	TOKUI

AD (Machida *et al.*, 1981). Recent archaeological data and stratigraphic relations with the overlying 915 AD Towada ash from north Honshu suggest that it occurred some time in the 10th century. We want to know the strict age of eruption, because there rises a problem whether the 926 AD decline of the ancient nation, "Bohai", was triggered by the great eruption or not. The Gaima lava plateau and adjacent areas had been governed by this country as one of the centers from 698 to 926 AD. This problem also arises from the fact that the Changbai eruption gave a heavy impact on human environments in this area.

6. Volcanic Impact on Vegetation

It seems likely that pyroclastic flows and associated mud-flows should have caused the greatest destruction to the extensive area covered. The ash falls generated as co-ignimbrite or phreatoplinian type might also have given a heavy impact over a great area to the east of volcano.

Earlier botanists found buried forests consisting of *Pinus* spp. (pine), *Picea* spp. (spruce) and broadleaved trees in the pumiceous deposits at several localities high above the present timber-line (*eg.* Asano, 1948; Takahashi, 1963). Zhao (1981) also reported buried forests in the present, densely forested flanks to the north and west of volcano. Kohyama (1943) reported a result of spieces analysis of three carbonized woods buried in volcanic sand deposit from the section c.90 km southeast of the volcano.

As the C pfl deposit bears abundant carbonized and non-carbonized wood trunks, we conducted a spieces analysis of buried woods to reconstruct the pre-eruption forest on the northern and eastern flanks of Changbai volcano. The analysed samples were taken from woods keeping original growth position in pyroclastic flow deposit as a rule. The analysis was carried out by precise microscopic observation on fiber of trunks by Guo Derong. Sampling localities are shown in Fig. 10. Results of analyses are shown in Table 2.

Table 2 Frequency of a genus analysed from woods occurring in the C pfl deposits on the flanks of Changbai volcano

Locality	Elevation	*Picea*	*Pinus*	*Larix*	*Tilia*	*Populus*	*Betula*	*Fraxinus*	total
Northern area									
	(m)								
Loc. 8	1030	11							11
1	950	9	2		1	2			14
16	660	2	3	1	2				8
20	640	1	3		1		1		6
19	470	1			2	1	1	1	6
Eastern & Northeastern area									
23	1345	11							11
24	1280	9		3					12
11	1280	7	2	4	1				14
9	1090	1	1	4	2		1	1	10
21	1070	25	7		2				34

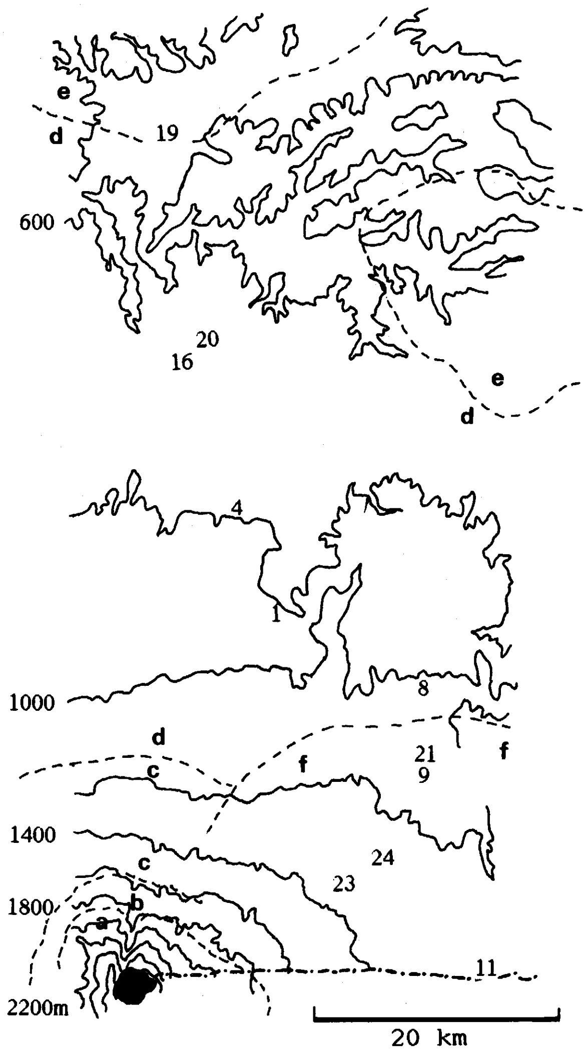

Fig. 10 Map showing sample localities of buried woods and present forest zones on the north and east flanks of Changbai volcano
a = alpine tundra, b = *Betula ermanii* forest, c = *Abies* and *Picea* forest, d = mixed forest (*Pinus koraiensis* and deciduous broad-leaved tree) with man-induced forest, e = *Quercus mongolica* forest and man-induced forest, f = *Larix* forest

Present vegetation on the northern flank of Changbai volcano shows a distinct, zonal arrangement due to elevation (Fig. 10); *i.e.*, a) Alpine tundra higher than *c.* 2,000 m above sea level (asl.); b) *Betula ermanii* forest between 2,000 m and 1,700 m asl.; c) *Picea jezoensis* and *Abies holophylla* forest between 1,700 m and 1,150 m asl.; d) Mixed forest of *Pinus koraiensis* and deciduous broad-leaved trees between 1,150 m and 550 m asl.; e) Man-induced forest mainly composed of *Quercus mongolica*, below 550 m asl.

The analysis indicates that the transitional zone between c) and d) was slightly higher than it is today and that there was a mixed forest of *Picea jezoensis, Pinus koraiensis* and deciduous broad-leaved trees below 950 m asl. immediately before the eruption.

In contrast, *Larix olgensis* or *Larix koraiensis* dominates the present vegetation on the eastern flank of Changbai volcano below 2,000 m asl. as stated earlier. An analysis of buried woods, however, clearly shows that the pre-eruption vegetation was characterized by a vertical zonation; *i.e.*, Conifer forest of *Picea jezoensis* and *Abies holophylla* above *c.* 1,300 m asl. and mixed forest of *Pinus koraiensis* and deciduous broad-leaved trees below.

Consequently we can discuss the following points. 1) The pre-eruption vegetation was more stable than it is today on northern as well as eastern flanks. 2) This mature forest was totally destroyed by the great eruption especially by the C pfl and Plinian or co-ignimbrite ash fall events. The forest devastation should have happened over a greater area, presumably more than 4,000 km^2 in area. 3) Recovery of vegetation is more or less complete on the surface composed of pyroclastic flows because of their stability, but is still far from maturity on the eastern flank covered by unstable tephra falls. Also, it is clear that timber line of Changbai volcano is slowly moving upwards today.

6. Conclusive Remarks

The 1 ka Changbai volcanism was a complex series of events, which comprise two rather orderly progressions of eruptive styles from Plinian to pyroclastic flow activity and two debris flows associated with these magmatic activities. Fine-grained vitric ashes were produced by the middle to late eruptions, travelled to the east more than 1,000 km far from source. This ash is a major component from this explosive event. A large volume of tephra suggests that the 1 ka Changbai eruption should be one of the greatest explosive volcanisms during the past 2,000 years in the world.

The volcanic impact on vegetation was very great in extent as well as in degree. Recovery of vegetation has not yet been complete on the eastern flank covered by tephra falls and in alpine region.

Our study is still incomplete, because we have a lot of field works to do in the North Korean territory where important information will be given on the Changbai explosive volcanism.

Acknowledgements

This research was carried out in collaboration with the Institute of Forestry and Soil Science, Academia Sinica, China. We greatly acknowledge funding for field work from the Fukutake Science and Culture Foundation and Tokyo Geographical Society. We thank Professor Fusao Arai for determination of refractive index and Miss Yumi Tokui and Mr Toshio Furuta for their valuable assistance with microprobe analysis and Mrs Guo Derong for spieces analysis of buried wood .

We would like to dedicate this paper to Professor Sohei Kaizuka in commemoration of his retirement from Tokyo Metropolitan University.

Notes

1) This volcano has numbers of local names: Changbaishan and Paitoushan (China), Baegdu-san and P'aektu-san (Korea), and Hakuto-san (Japan).
2) The constituent glasses were analyzed by using energy dispersive spectrometer (EDS) in National Science Museum by Y. Tokui.
3) T. Furuta's analytical procedures for chemical compositions were described in Furuta *et al.* (1986).

References Cited

Asano, G. (1948): Several discoveries obtained from the Hakutousan (Baegdusan) Expedition in 1942-1943. *Mineral. Geol.*, **1**, 27-31, 71-75, 128-130, 181-184, 228-231, 267-270.

Furuta, T., Fujioka, K. and Arai, F. (1986): Widespread submarine tephras around Japan-Petrographic and chemical properties. *Marine Geol.*, **72**, 125-142.

Kano, T. (1937): Glacial topography of the mountains of northeastern Korea. *Geogr. Rev. Japan*, **13**, 1126-1145.

Kohyama, N. (1943): The species of forest immediately before the eruption in the area around Hakutou volcano. *Botanical Mag.*, **57**, 258-273.

Machida, H., Arai, F. and Moriwaki, H. (1981): Two Korean tephras, Holocene markers in the Sea of Japan and the Japan islands. *Kagaku*, **51**, 562-569.

——— and Arai, F. (1983): Extensive ash falls in and around the Sea of Japan from large late Quaternary eruptions. *Jour. Volcanol. Geotherm. Res.*, **18**, 151-164.

——— Moriwaki, H., Lee, B.S. and Arai, F. (1987): Historical eruptions of Changbai volcano resulting in large-scale forest devastation-deduced from widespread tephra -. In Hanxi, Y., Zhan, W., Jeffers, J.N.R. & Ward, P.A.(eds.) "*The Temperate Forest Ecosystem*", ITE symposium No. 20, Institute of terrestrial ecology, The Lavenham Press, UK., 23-26.

Takahashi, M.(1963): Vegetation in alpine and subalpine zone and experimental ecology. *Iden*, **17**, 10-15.

Zhao, D.(1981): Preliminary investigation on relation between volcanic eruption of Changbai mountain and the succession of its vegetation. *Res. Forest Ecosystem*, **2**, 81-87.

——— (1987): Preliminary studies on volcanic eruptions and historical vegetation succession in the eastern mountain area of north-east China. In Hanxi, Y., Zhan, W., Jeffers, J.N.R. & Ward, P.A.(eds.) "*The Temperate Forest Ecosystem*", ITE symposium No. 20, Institute of terrestrial ecology, The Lavenham Press, UK., 27-28.