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Tephra-stratigraphical Study of the 1988–1989 Eruptions of Tokachi-dake Volcano, Central Hokkaido.

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Twenty-three small-scale eruptions took place at Tokachi-dake from December 16, 1988 to March 5, 1989. The pyroclastic fall deposits, ballistic fragments, and pyroclastic surge and flow deposits were dispersed over the flank and leeward areas of the volcano. Because the pyroclasts of each eruption were well-preserved in snow during the winter, the stratigraphy and distribution of these deposits could be studied in detail. The volume of the pyroclastic fall deposits are nearly equal to those of the pyroclastic surge and flow deposits. The total volume of these pyroclasts is estimated to be $7.4 \times 10^5 m^3$.

Judging from the sequential changes of the volume and composition of the pyroclasts, the characteristic features of the eruption can be summarized as follows: At first, a vent was opened by ejection of altered rock fragments in December,1988. Then, essential fragments were ejected in January, 1989. Finally the activity level of magma declined and the altered rock fragments content increased again in February to March, 1989.

1. Introduction

Twenty-three eruptions from the 62-II crater of Tokachi-dake Volcano were recorded from December 16, 1988 to March 5, 1989. In spite of small-scale eruptions, pyroclastic flows and surges occurred frequently. While the 1926–1928 and 1962 activities were phreato-magmatic to magmatic (ISHIKAWA *et al.*, 1971; Katsui *et al.*, 1963), the 1988–1989 eruptions were of phreato-magmatic nature (KATSUI *et al.*, 1990; IKEDA *et al.*, 1990).

Generation of mudflows accompanied with eruptions was feared, because a mudflow originated from snow-melting by the heat of the eruptive products, killed 144 people in the 1926 eruption (Relief Society of the Tokachi-dake eruption, 1929). Fortunately, however, no large-scale mudflows occurred during and after the 1988–1989 eruptions.

Because the 1988–1989 eruption took place during the snowy season, deposits of each eruption were packed by contemporaneous snow falls. Generally, it is difficult to study sequences of pyroclastic fall deposits of small-scale eruptions. Therefore, the snow was useful for the study of small-scale eruptions that lasted very short time.

The materials of the pyroclastic surges and flows generated by these eruptions were also transported on snow field. Pyroclastic surge and flow deposits settled on snow have been studied

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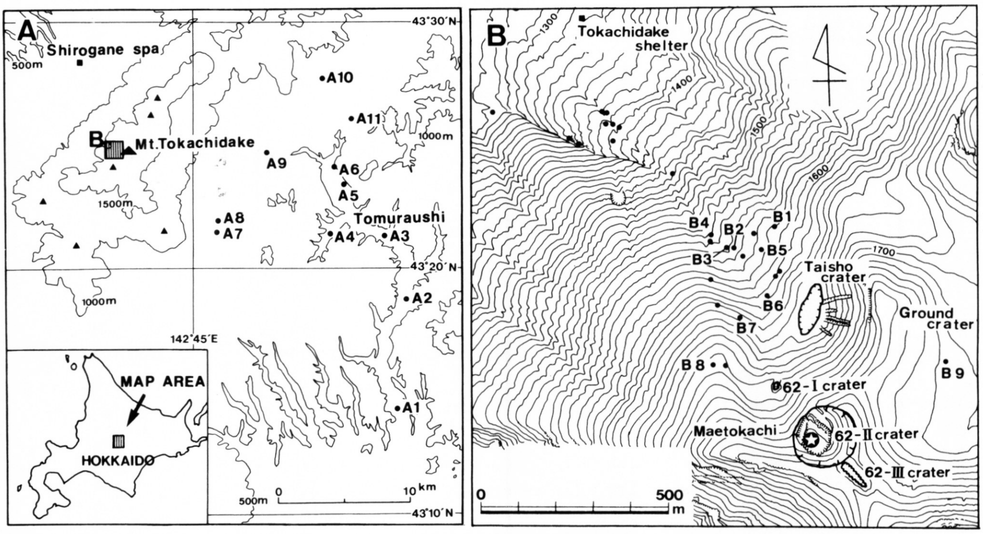

Fig. 1. Map showing the localities of test pits to observe the pyroclastic deposits in the distal (A) and proximal area (B) of Tokachi-dake.

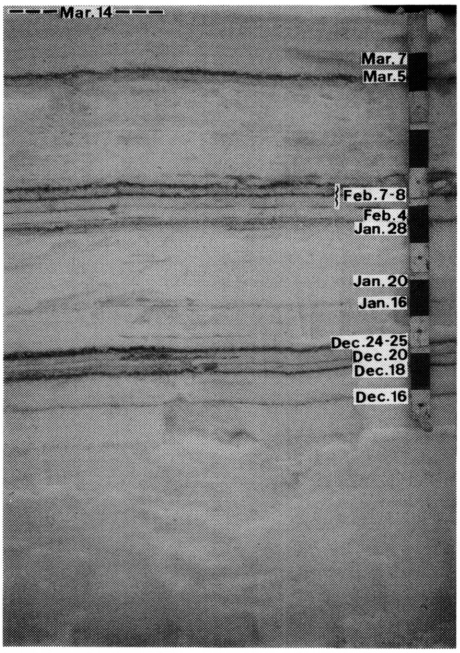

Fig. 2. Stratigraphy of the pyroclastic fall deposits and snows at site A7, 9 km south-east of Tokachi-dake, March 14, 1989. Scale in 1 m. (Photograph taken by N. Miyaji.)

(ARAMAKI, 1973; WAITT *et al.*, 1983; KATSUI *et al.*, 1986; MELLORS *et al.*, 1988). The description of the pyroclastic surge and flow deposits of the 1988–1989 eruption of Tokachi-dake Volcano will be useful for study on transportation and settling of eruptive products, and the mode of eruption in a snowy season.

We observed the pyroclastic deposits during and after the eruption in both the proximal and distal areas of Tokachi-dake Volcano. The proximal study area was close to the 62-II crater and the distal area was the northern part of Tokachi Plain. Some test pits were dug to observe every layer of pyroclastic deposits in the snow (Fig. 1).

In this paper, we will show the distribution, stratigraphy and lithological facies of the pyroclastic deposits and discuss the sequential change and characteristics of the eruption based on the tephra-stratigraphy.

2. Pyroclastic fall deposit

2–1 Distribution and stratigraphy

In the 1988–1989 eruption, most pyrocla-

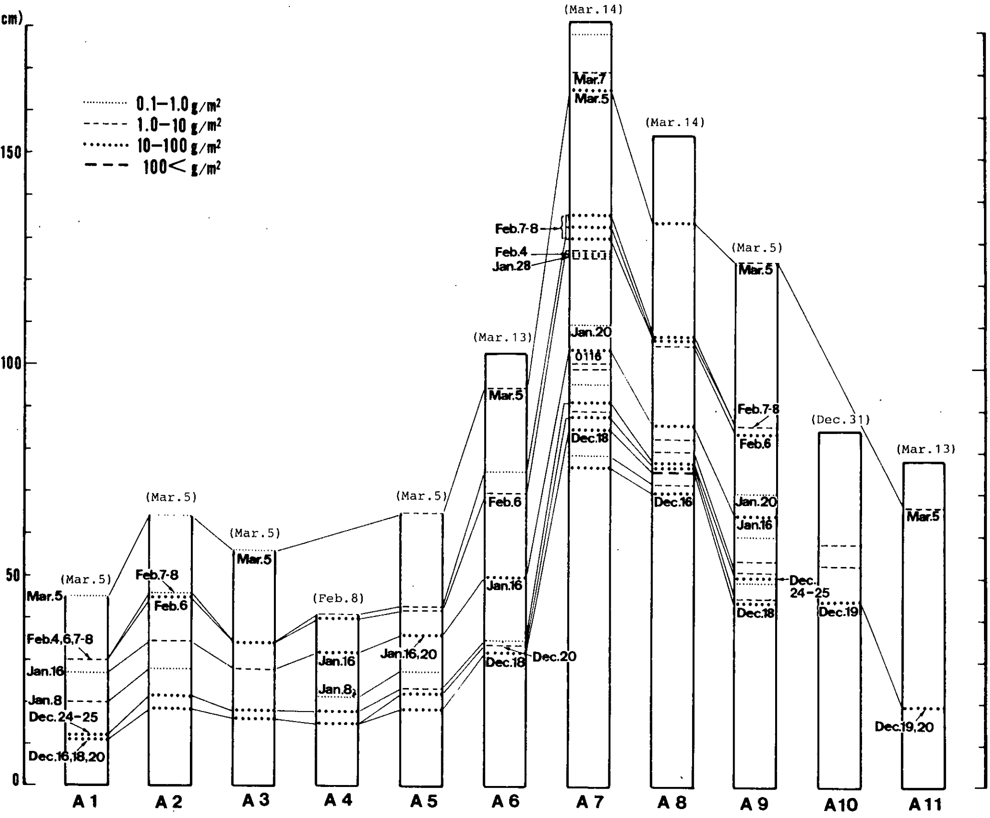

Fig. 3. Columnar sections showing the pyroclastic fall deposits in snow, the eastern area of Tokachi-dake. Dashed and dotted lines mean the weight per unit area of each layer. Base of each columnar section indicates the ground surface. Date above each columnar section means surveyed date. Locality of each columnar section is shown in Fig. 1(A).

stic falls dispersed to the leeward districts of Tokachi-dake Volcano, mainly to the northern part of Tokachi Plain. Japan Meteorological Agency (JMA) observed the pyroclastic falls fourteen times: December 16, 18, 19, 24 to 25, 30, 1988, January 8, 16, 20, 28, February 1, 4, 6, 7 to 8 and March 5, 1989.

The distributions of these deposits were made clear by the questionnaire investigation, the JMA research, and our field observation mainly at around the Tomuraushi district from late December, 1988 to late April, 1989. The questionnaire investigations were carried out by Professor Katsui, Hokkaido Univ. and one of our authors. JMA compiled distribution maps of these pyroclastic fall deposits based on the observations of Kushiro Local Meteorological Observatory and Obihiro Weather Station (JMA, unpublished).

Pyroclastic fall deposits were generally well-preserved in snow layers. Consequently it was possible to observe the detailed chronological sequence. The eruption dates of some pyroclastic beds could be confirmed by the field observation just after the eruptions. In order to establish

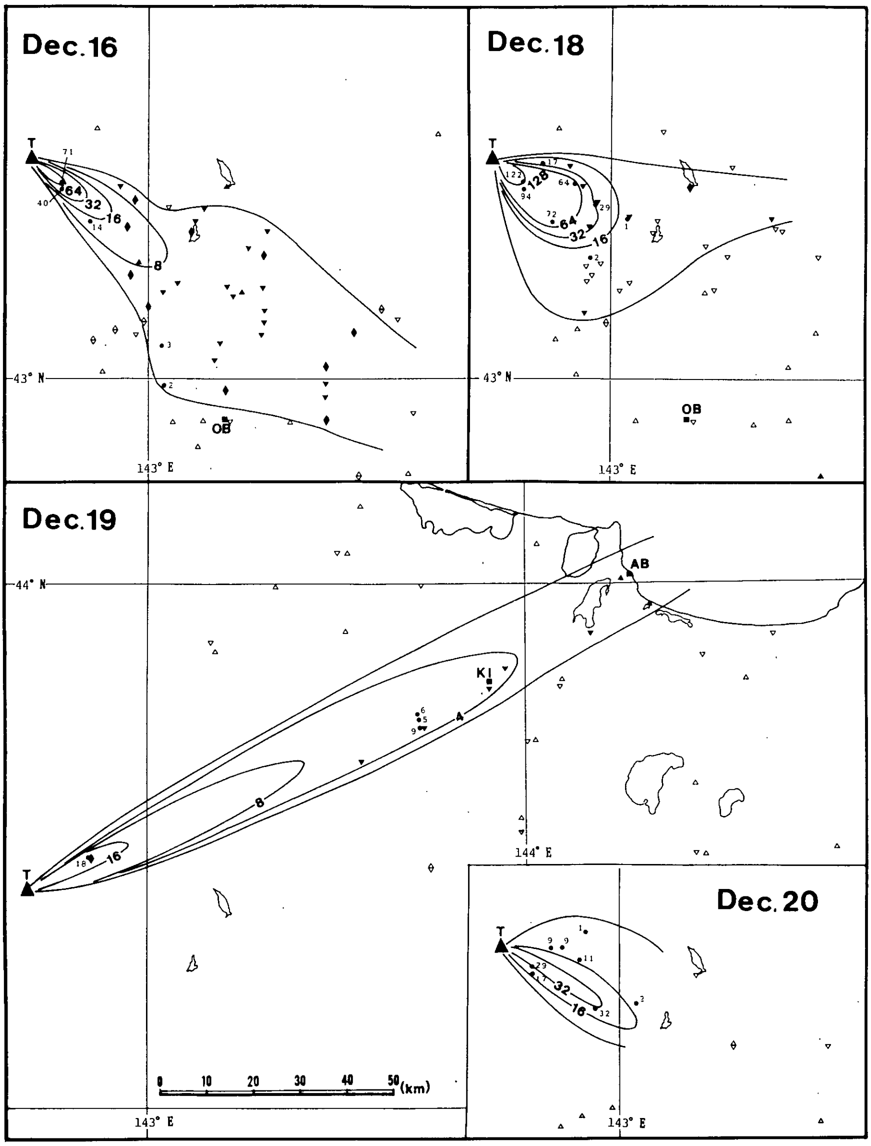

Fig. 4a. Isopleth maps of the pyroclastic fall deposits of the December 16 to 20 eruptions. Unit in g/m^2. Outermost lobe shows the discernible limit of each pyroclastic fall deposits. Solid triangle shows presence of the pyroclastic fall deposit and open triangle shows absence, which was confirmed by questionnaire, and solid reverse triangle shows the presence of the pyroclastic fall deposit and open reverse triangle shows the absence, which was observed by JMA. At the site of solid circle, the weight per unit area of pyroclastic fall deposits was measured (g/m^2). Some of the samples obtained from fixed area were provided by Professor Katsui, Hokkaido University, Laboratory Upland Soils of Hokkaido National Agricultural Experiment Station, and Laboratory Soil and Fertilizer of Hokkaido Prefectural Kitami Experimental Station. OB: Obihiro, KI: Kitami, KU: Kushiro, AB: Abashiri.

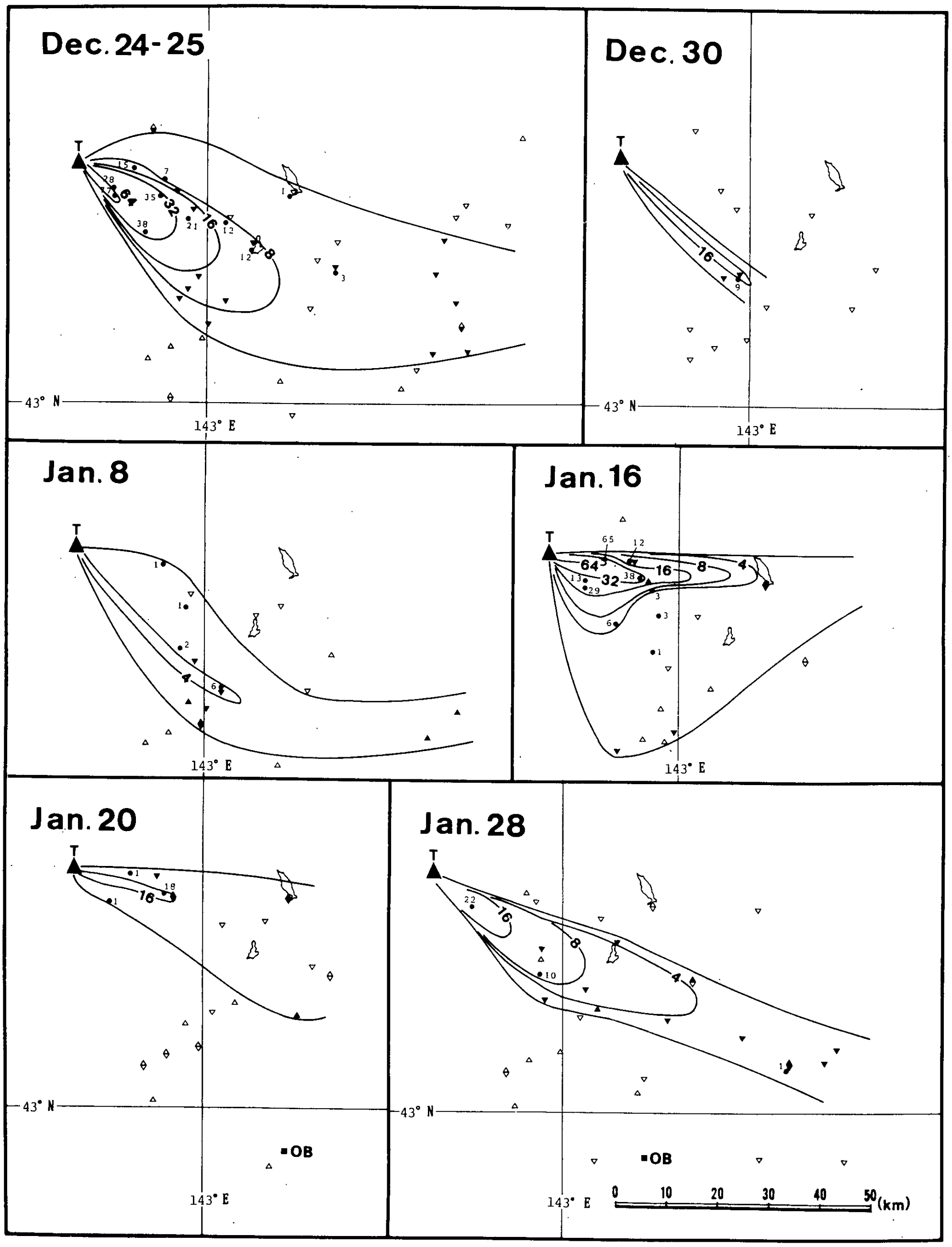

Fig. 4b. Isopleth maps of the pyroclastic fall deposits of the December 24, 1988 to January 28, 1989, eruptions. Symbols are shown in Fig. 4a. Unit in g/m^2.

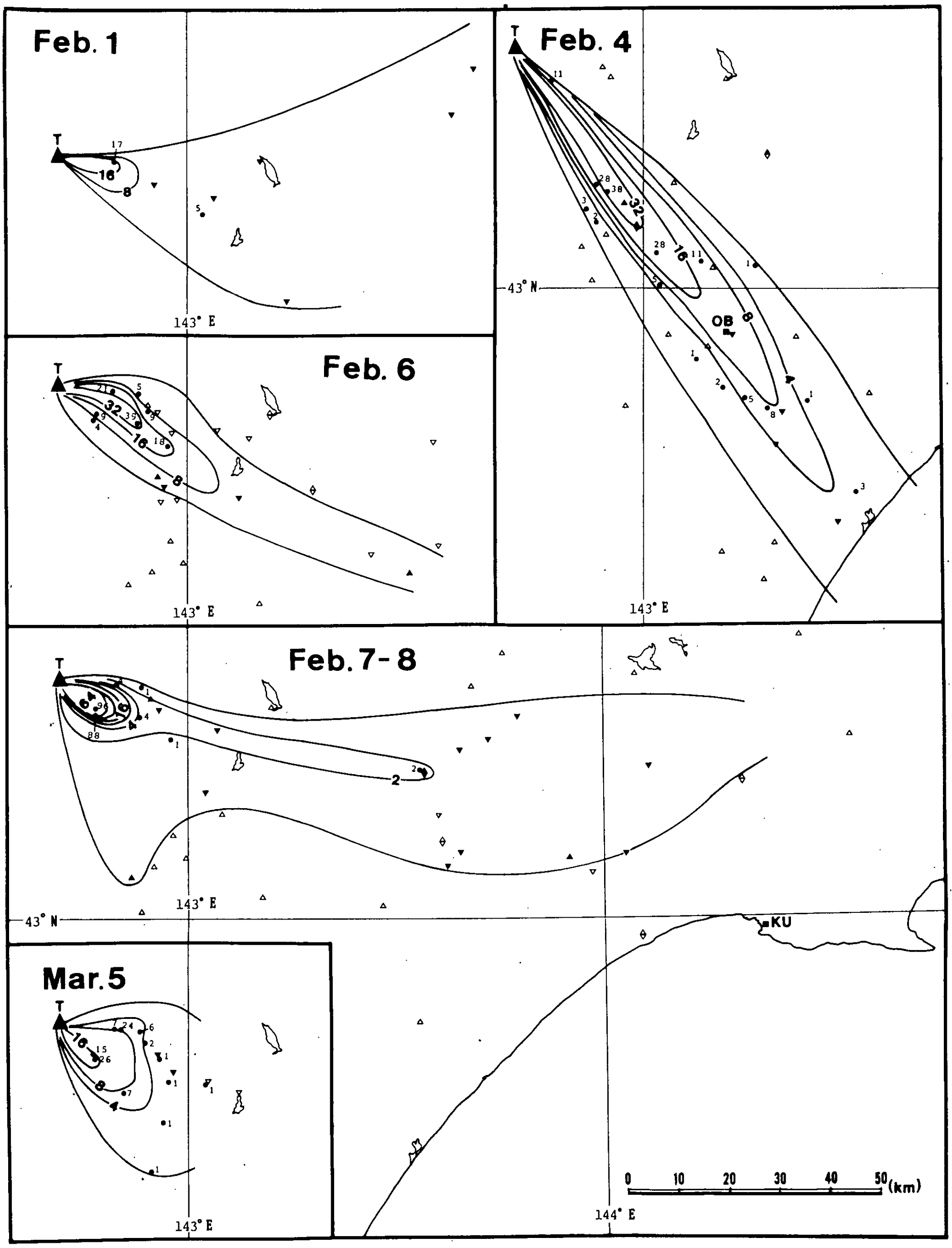

Fig. 4c. Isopleth maps of the pyroclastic fall deposits of the February 1 to March 5, 1989, eruptions. Symbols are shown in Fig. 4a. Unit in g/m^2.

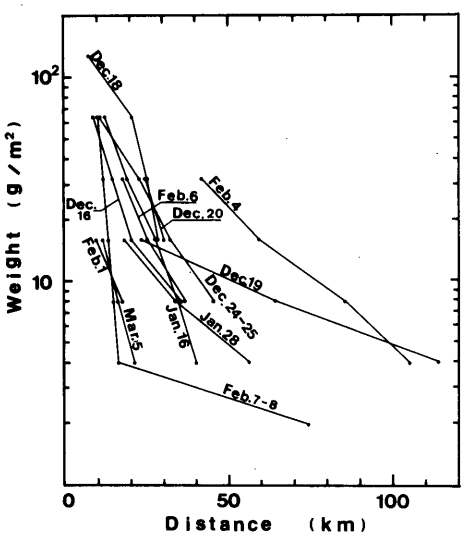

Fig. 5 Relationship between the weight per unit area of pyroclastic fall deposits and distance from the 62-II crater.

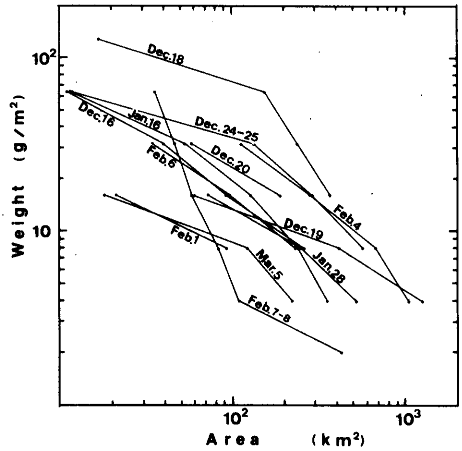

Fig. 6. Relationship between the weight per unit area of pyroclastic fall deposit and the area enclosed by each contour.

chronological framework, we correlated many pyroclastic beds with these known pyroclastic beds, based on the lithological facies, the thickness and combination of the pyroclastic beds and the thickness of the snow layers between the pyroclastic fall layers (Fig. 2).

Many pyroclastic layers in snow were too thin to be measured precisely. Each pyroclastic fall sample was collected in the field, and weighed in the laboratory after being dried out. The weight of the pyroclastic fall samples obtained from a fixed area is convertible to the thickness of the pyroclastic fall layer.

Some of the samples obtained from fixed area were provided by Professor Katsui, Hokkaido Univ., and the staff of Laboratory Upland Soils of Hokkaido National Agricultural Experiment Station, and Laboratory Soil and Fertilizer of Hokkaido Prefectural Kitami Experimental Station who helped to make the isopleth map of pyroclastic fall deposits.

Columnar sections of the snow containing pyroclastic fall layers are shown in Fig. 3. The weight of the pyroclastic fall samples are roughly illustrated in four classes between 0.1 and 150 g/m^2.

At times, it was possible to recognize surface layers of pyroclastic fall with similar curd texture to that of the ash erupted from Mt. St. Helens, March 29, 1980 (SARNA-WOJCICKI *et al.*, 1980).

Based on the data mentioned above, the distribution and isopleth maps of the pyroclastic fall deposits are drawn (Fig. 4a–c). The outer lines of the distribution represent the limit of occurrence of the pyroclastic fall deposit according to the questionnaire investigations.

From these isopleth maps, the characteristics of the distribution for the small-scale pyroclastic fall deposits are revealed. In general, the weight per unit area of each pyroclastic fall deposit decreases exponentially with increasing distance from the crater (Fig. 5). The areas enclosed by each contour are rather small (Fig. 6), and the low eruption column might be responsible for these distributions of the deposits.

Most of the pyroclastic fall deposits were distributed eastward or southeastward from crater to the northern part of Tokachi Plain. However, in the eruption on December 19, 1988, the eruption

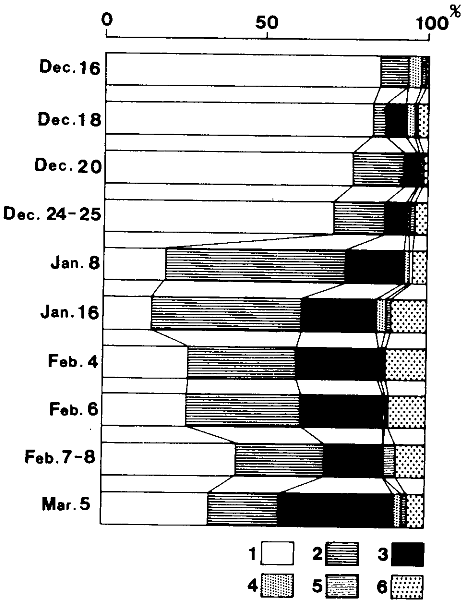

Fig. 7. Fragment composition of main pyroclastic fall deposits for 0.25–0.5 mm particles. 1: whitish altered rock, 2: grayish rock, 3: black glassy rock, 4: black scoria, 5: red scoria and red rock, 6: mineral.

cloud trailed toward the northeast and the pyroclastic fall was observed in the Abashiri district (Fig. 4a).

The pyroclastic falls on February 7 to 8, 1989 formed at least three units at the proximal sites of Tokachi-dake Volcano (*e.g.* A7 in Figs. 2 and 3). However, at the distal sites, it was difficult to distinguish them separately. Hence, the total weight of pyroclastic fall on February 7 to 8 at each site was used to compile the isopleth map (Fig. 4c).

An interesting fact was found during our field investigations. On March 7, 1989, we climbed Tokachi-dake Volcano and excavated a test pit in snow at site B4 (Fig. 1), finishing the work at one o'clock in the afternoon. In the next morning at ten o'clock, we went to the same point for further study. We found a new ash fall layer among the fresh snow. Although the eruption on March 7 to 8, 1989 was not reported, this pyroclastic fall layer suggests that the eruption occurred between 1 p.m. on March 7 and 10 a.m. on March 8.

Similar observation was also made on December 20, 1988. An ash fall and the deposit were observed at Tomuraushi district in the morning of December 20 in 1988 (Fig. 4a), although no eruption was reported.

Thus, the pyroclastic fall was observed sometimes, even no eruption was reported formally. As strong volcanic tremors were continuously or intermittently registered by seismometers during these eruptions, the strong tremors might be related to the generation of pyroclastic products.

2–2 Fragment composition

Samples of ten eruptions collected at the point of 10 to 20 km distant from the crater were used for the fragment composition study. The eruption dates of these fall deposits were December 16, 18, 20, 25, January 8, 16, February 4, 6, 7 to 8 and March 5, respectively. The 0.25 to 0.50 mm size grains were used for microscopic investigation.

The fragments are as follows: whitish altered rock, grayish rock, black glassy rock, black scoria, red scoria and red rock, mineral. Among them, whitish altered rock, grayish rock, and red scoria and red rock were supposed to be derived from the vent wall of the 62-II crater. The black glassy rock was considered to have originated from the mixing of altered rock fragments and essential magma (KATSUI *et al.*, 1990). Judging from the degree of weathering, most of the black scoria were derived from the 1962 eruptive products, although some of them might be of essential magma origin of the 1988–1989 eruption.

The composition of such fragments changed with the sequence of eruption (Fig. 7). The eruptions in December, 1988 were characterized by ejections of the abundant whitish altered rock fragments. In contrast the eruptions in January, 1990 were characterized by a decrease in whitish

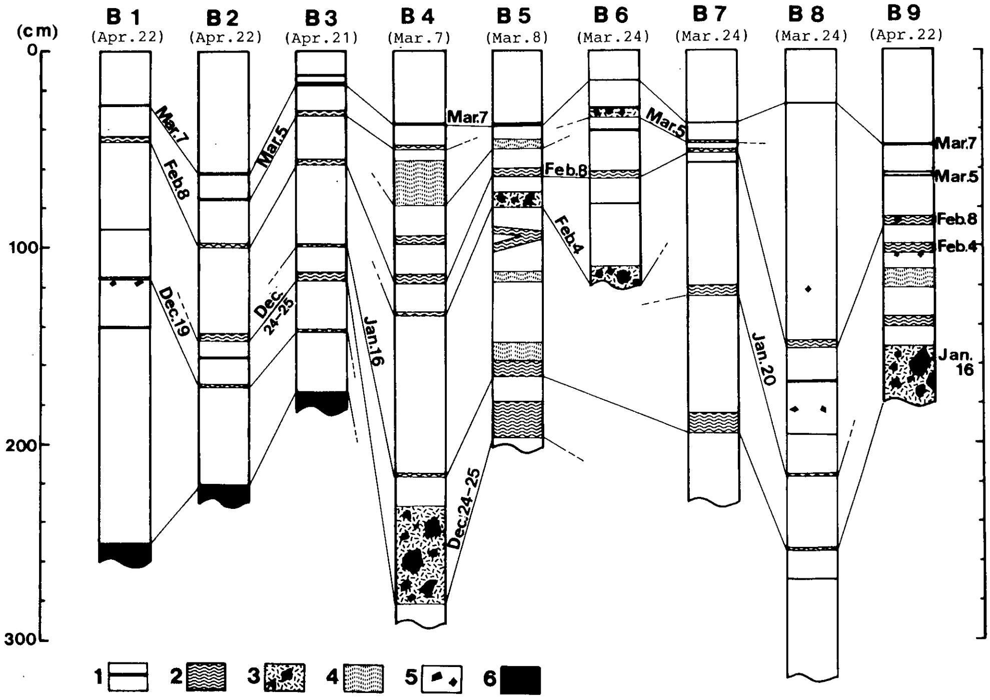

Fig. 8. Columnar sections showing the pyroclastic deposits in snow, around the 62-II crater. Date above each columnar section means surveyed date. Locality of each columnar section is shown in Fig. 1 (B). 1: pyroclastic fall deposit, 2: pyroclastic surge deposit, 3: pyroclastic flow deposit, 4: aeolian deposit, 5: lithic fragment, 6: ground surface material before the 1988–1989 eruption.

altered rock fragments and an increase in grayish and black glassy rock fragments. The eruptions in February to March were similar to those in January except that whitish altered rock fragments slightly increased in amount.

3. Ballistic fragments

Ballistic fragments were ejected during the most of the eruptions and distributed around the 62-II crater. In general, weakly or heavily altered accessory fragments or black glassy fragments sometimes including obsidian, were ejected. Those fragments were 0.1 to 10 m in diameter.

It was difficult to assign the eruption date for each fragment, because in every eruption similar types of rock fragments were ejected and they stuck into snow so deeply.

However, we could identify many of the fragments of the January 20 eruption. Because the mode of this eruption was recorded by video images, we could confirm the distribution of them. Furthermore, these giant fragments consisted mainly of fresh basaltic andesite which vesiculated on the surface, in a bread-crust and rice cake shape. No other eruption produced this kind of fragments. These fragments are considered to have originated from the essential magma (KATSUI *et al.*, 1990; IKEDA *et al.*, 1990).

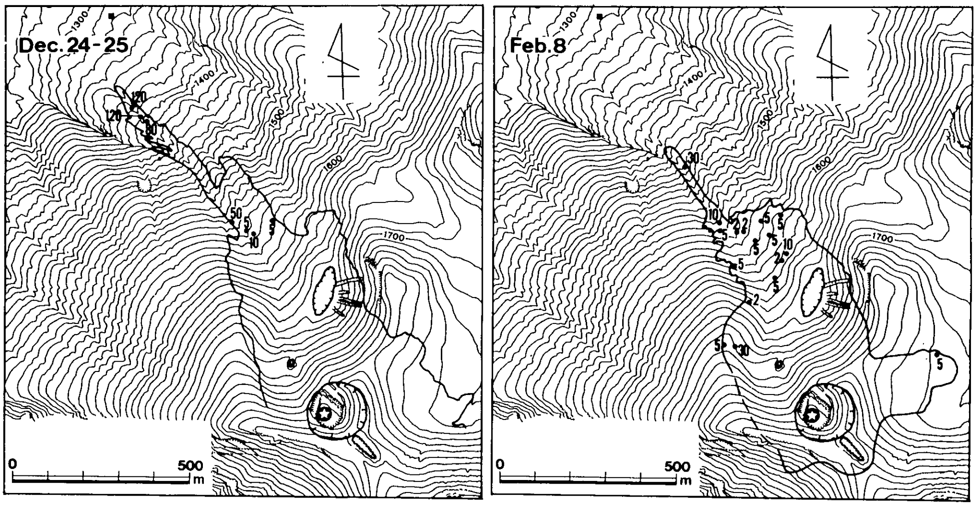

Fig. 9. Distributions and thicknesses of the pyroclastic flow and surge deposits of the eruptions of December 25, 1988 and February 8, 1989, eruptions. The outlines of pyroclastic surge and flow deposits are after KATSUI *et al.* (1990). Thickness in centimeter.

4. Pyroclastic surge and flow deposits

4-1 Distribution and chronology

Eruptions of pyroclastic surge were observed eight times, December 19, 25, January 8, 16, 20, February 4, 8, and March 5, and pyroclastic flows were six times, December 25, January 8, 16, February 4, 8, and March 5, respectively. The distribution of them are reported by KATSUI *et al.* (1990).

Around the 62-II crater, we excavated about thirty pits in snow and observed the deposits. To decide the eruption dates of these deposits, we referred the distribution map published by KATSUI *et al.* (1990) and the thickness of the snow between the pyroclastic beds. As a result, most of the deposits observed in the snow were dated (Fig. 8). The thickness of the pyroclastic surge and flow deposits are shown in Fig. 9.

4-2 Lithology

The pyroclastic surges and flows were hot enough to melt snow, and the layers of ice were found below the deposits, even though the thickness of the deposits were only few centimeters. On the contrary, the snow beneath the pyroclastic fall deposits did not turn to ice.

The pyroclastic flow deposits are poorly sorted and thicker than the pyroclastic surge deposits. They consist of angular to subangular boulders to silt size particles. Thickness of pyroclastic flow deposits is controlled by initial topography. The thicknesses of each flow deposit are 10–30 cm, and the maximum thickness is about 2 m. Flow levees could be seen in the down stream.

According to the observation immediately after the March 5 eruption, pyroclastic flow deposits had two different facies: one was dry and another was frozen. The dry facies, which was massive and consisted of unsorted blocks and ash, was observed at the proximal area around 1650 m in altitude. The frozen facies was observed at the distal area below 1550 m in altitude, which was

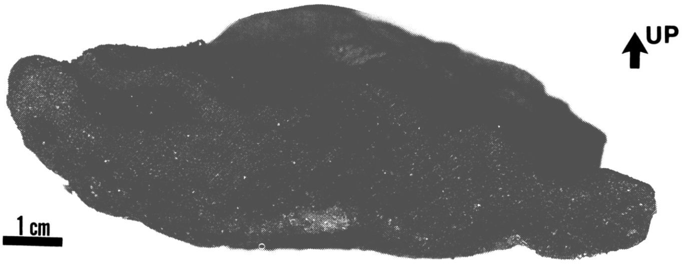

Fig. 10. Cross-section of frozen pyroclastic surge deposits of February 8, 1989 eruption, collected at site B5. This is one of the facies of pyroclastic surge deposits characterized by mud drops. Note the rough surface of this deposit. Scale in centimeter. (Photograph taken by T. Sone.)

similar to the dry facies, but was thinner than that, and had abundant ash particles completely frozen. This fact indicate that the frozen facies was formed from the water-saturated flow. Hence, the pyroclastic flow deposits were dry at the proximal area but were transformed to water-saturated debris flow at the distal area by the water supply from the melting snow.

Sometimes meltholes were found on the snow surface, especially on the surface of the pyroclastic flow deposits similar to that of the Mt. St. Helens 1986 event (MELLORS *et al.*, 1988). The meltholes are 0.5–1 m across and 0.1–2 m deep. In many cases, blocks were found at the bottom of the hole. On the snow surface around these holes, no deposits thrown out from the holes were found. Therefore, the meltholes must have been formed by the heat of hot blocks contained in the pyroclastic flow deposits, but some of them may have formed by the heat of ballistic blocks.

The pyroclastic surge deposits were better sorted and had smaller thickness than the pyroclastic flow deposits. They consist mainly of sand to silt size particles, and are few centimeters in thickness.

The lithological features of pyroclastic surges and flows differ with each eruption. The surge deposit of February 8, 1989, contained aggregations of homogeneous mud drops 1–3 cm in diameter. A section of the aggregation is shown in Fig. 10. This sample was taken at site B5 (Fig. 1) and was cut to observe in frozen state. The layer of aggregation has a rough upper surface and smooth bottom surface, and the drops in the lower part of aggregation are heavily deformed. These facts indicate the drops have fallen in the nearly water-saturated state.

The surge deposit of December 25, 1988 consisted of an alternation of ice and pyroclastic laminae. The existence of ice shows the laminae were hot enough to melt snow. Hence, this surge deposit might have been formed by the continuous hot pyroclastic-blasts.

The surge deposits of January 16 and March 5, 1989, were massive. In some parts, they include lithic fragments 2–3 cm across.

In addition to these deposits, "dune structure deposits" were observed at some horizons. These deposits were characterized by the cross-bedded structures consisted of snow and pyroclasts. Therefore, it is possible that these deposits were aeolian secondary deposits derived from the pyroclastic surge or flow deposits.

Tablel. Estimated volume of the pyroclastic fall, flow and surge deposits of the 1988–1989 eruptions.

Eruption time		Volume ($\times 10^4 m^3$)		
		fall	flow·surge	Total
05:24	Dec. 16/1988	1.4		1.4
08:38	Dec. 18	6.1		6.1
21:47	Dec. 19	6.4	2.0	8.4
morning	Dec. 20	1.0		1.0
22:12	Dec. 24	4.7	13.9	18.6
00:49	Dec. 25			
05:27	Dec. 30	0.1		0.1
19:38	Jan. 8/1989	0.5	3.8	4.3
18:55	Jan. 16	2.1	8.0	10.1
03:21	Jan. 20	*1.0	1.0	2.0
05:18	Jan. 28	2.1		2.1
06:11	Jan. 28			
07:00	Jan. 28			
18:18	Feb. 1	0.5		0.5
00:38	Feb. 4	4.5	1.0	5.5
09:37	Feb. 6	1.6		1.6
23:54	Feb. 7	4.1	3.6	7.7
04:02	Feb. 8			
05:22	Mar. 5	1.0	3.9	4.9
Total		37.1	37.2	74.3

* include the volume of the ballistic fragments.

5. Volume

The volume of pyroclastic fall deposits is estimated using the "Thickness-Isopach Area Curve" method (SUZUKI, 1981). The weight per square meter is converted to the thickness assuming the bulk density of the pyroclastic fall deposit as 1 g/cm^3. As a result, the volume is estimated to be 0.1–6.4 $\times 10^4$ m^3 (Table 1), the pyroclastic fall deposit of December 19, 1988, having the largest volume. For volume estimation of ballistic fragments, it is difficult to distinguish the distributions and numbers of ballistic fragments in each eruption.

However, only the fragments of the January 20 eruption may be distinguished by their different lithological and distribution characteristics. Based on the distribution inferred by the video images and field observations, the volume of the ballistic fragments is estimated to be 0.6×10^4 m^3. This is larger than the volume of pyroclastic fall deposits for this eruption, *i.e.* 0.4×10^4m^3. The volume of the pyroclastic fall deposits of the January 20 eruption, shown in Table 1, includes the volume of the ballistic fragments.

The volume of the pyroclastic surge and flow deposits are estimated based on the data of the distribution and average thickness for each deposit. As a result, the volume of the pyroclastic surge and flow deposits for each eruption is estimated to be 1.0–13.9$\times 10^4$m^3 (Table 1). The pyroclastic surge and flow deposit of December 25, 1988, has the largest volume.

The total volume of the pyroclastic fall deposits is estimated to be 37.1×10^4m^3, and the volume of the pyroclastic surge and flow deposits is 37.2×10^4m^3. The grand total volume of the pyroclasts is 74.3×10^4 m^3.

6. Characteristics of the eruptions

In the 1988–1989 eruption of Tokachi-dake Volcano, the composition of the fragments and the volume of the products obviously changed from the beginning to the end of the eruption. The whitish altered rock fragments must have been originated by heavy alteration of volcanic rocks in and around the vent. Hence, the variation of the whitish altered rock contents probably reflect the vent opening or burying and the magma rising at the time of eruptions.

The sequential change of the whitish altered rock contents with time in the pyroclastic fall deposits is shown in Fig. 11. The whitish altered rock contents of the January 16 to February 8 eruptions were estimated on the assumption that the January 20 eruption was the most magmatic.

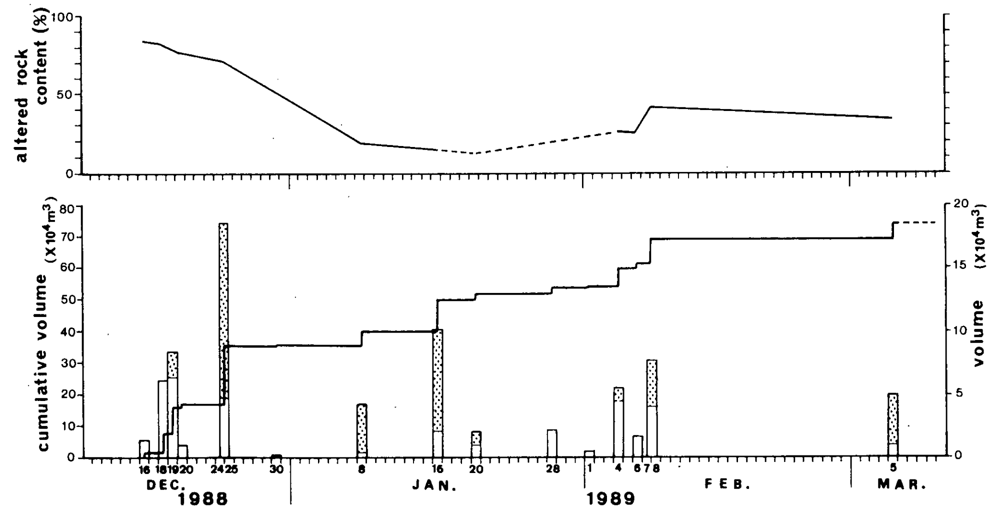

Fig. 11. The sequential change of estimated volume and altered rock content in the 1988–1989 eruptions. Each volume is represented by the bar chart. Open bar shows the volume of pyroclastic fall deposit and dotted bar shows the volume of pyroclastic surge and flow deposit. Note the difference of altered rock content in December, January and February to March. Detail of the fragment composition is shown in Fig. 7.

The black glassy rock fragments firstly occurred from the December 18 eruption. These fragments are considered to have originated from the melting and mixing of altered rocks and essential magma (KATSUI *et al.*, 1990). It is difficult to decide when the eruptions have changed completely from phreatic to phreato-magmatic, but at least the December 16 eruption was phreatic because no glassy rock fragments were ejected in the eruption.

Judging from the composition of the fragments and the volume of the pyroclasts, the 1988–1989 eruptions can be divided into three periods; December, January and February to March.

The eruptions in December were characterized by the abrupt decrease of whitish altered rock fragments and the increase of black glassy rock fragments. These facts suggest that the vent opened during the December 25 eruption, and that the magma had risen up through the conduit in this period.

The eruptions in January were characterized by fewer whitish altered rock fragments and ejection of essential ballistic fragments. These facts suggest that the magma reached near the crater in this period. Judging from the volume data, the conduit for the magma to rise upward must have been completed in the January 16 eruption.

The eruptions in February and March were characterized by the gradual increase of whitish altered rock fragments. This suggests that the magma drained back and the vent was buried by the altered rocks, only sometimes to be opened again by further small eruptions. The activity of the magma must have declined in the February and March eruptions.

7. Summary of results

1. The stratigraphy and distribution of the pyroclasts of the 1988–1989 Tokachi-dake erup-

tions are described in detail.

2. The volume of the pyroclastic fall deposits is nearly equal to the total volume of the pyroclastic surge and flow deposits. The total volume of these pyroclasts is estimated to be $7.4 \times 10^5 m^3$.

3. During the 1988–1989 eruptions, the vent had opened in December, 1988, and the essential magma rose close to the crater in January, 1989, then the magma drained back and the volcanic activity declined in February to March, 1989.

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1988〜1989年十勝岳噴火の火山灰層位学的研究

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十勝岳は1988年12月から1989年3月にかけて23回に及ぶ小噴火を繰り返し，山腹および風下の山麓部に度々，降下火砕物，放出岩塊，火砕流・火砕サージ堆積物をもたらした．今回の一連の噴火は積雪期に発生したため，火砕物の大部分は雪中に良好な状態で保存された．そこでこれらの火砕物の層序及び分布を明らかにした．このような火山灰層位学的研究に基づくと，降下火砕物の噴出量と火砕流・火砕サージ堆積物の噴出量はほぼ等しく，火砕物の総噴出量は$7.4 \times 10^5 m^3$と見積られる．

火砕物の構成物および噴出物量の経時変化から判断すると，今回の噴火ではまず，12月に多量の変質岩片を噴出することにより火道が形成された．1月にはこの火道を通じてマグマに由来する岩石を噴出したが，2月〜3月になるとマグマの活動レベルは低下し，再び変質岩片の量が増加した．