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FORMATION AND MAGMATIC EVOLUTION OF MASHU VOLCANO, EAST HOKKAIDO, JAPAN

by

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(with 11 Figures and 3 Tables)

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Abstract

Mashu volcano, located on the eastern wall of the Kutcharo caldera, east Hokkaido, is composed of lavas and pyroclastic deposits belonging to the successive stages of stratovolcano (ca.17-12$\times 10^3$ y. ago), caldera (11-7$\times 10^3$ y. ago), and central cone (4-1$\times 10^3$ y. ago). Chronological variation in composition of the Mashu volcanic products is represented in Fig. 10. Throughout the history, a general trend from mafic to felsic composition, together with the change of rock series from tholeiite to calc-alkali series through a transitional one, is traced. These products, however, have persistent chemical characters, i.e. poorness in K and Ba, Hf, Pb, Th, U, etc., chondrite-normalized REE patterns similar to those of the ocean ridge tholeiites, and low $^{87}Sr/^{86}Sr$ ratios. The order of eruption and the persistent chemical features of the products suggest that continuous fractional crystallization of a low-alkali (low-K) tholeiitic magma has been taken place under the volcano. A compositional variation in reverse order, from felsic to mafic, is also noticed within a short period of activity. This can be interpreted in terms of a zoned magma chamber.

Introduction

Mashu volcano which erupted on the eastern wall of the Kutcharo caldera, east Hokkaido, is famous for its beautiful caldera containing a clear lake (Fig. 1). Around the Mashu caldera, a number of pyroclastic deposits belonging to the successive stages of stratovolcano, caldera and central cone are widely developed, forming a vast volcanic ash field which represents one of the most remarkable areas for tephrochronology in Japan (Fig. 2). Since 1940, tephrochronological studies on these pyroclastic deposits have been carried out by pedologists for the purpose of agricultural development (Yamada, 1958; Seo et al, 1963). Then, the study of geology and petrography of Mashu vocano was

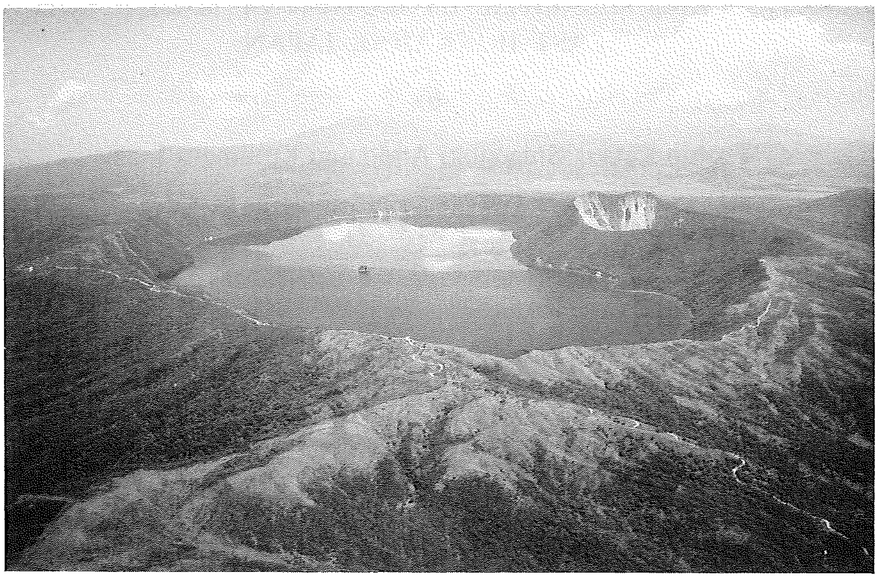


Fig. 1 The Mashu caldera, east Hokkaido, viewed from southwest. Two post-caldera volcanoes are seen; the Kamuishu lava dome at the center, and the Kamuinupuri cone with a large crater on the right.

undertaken (Katsui, 1955, 1962, 1963; Konoya et al, 1962).

The whole history of formation of the Mashu volcano may be obtained through the geologic survey on the caldera wall, where a thick pile of the somma lavas is well exposed, and the tephrochronological study of the successive pyroclastic deposits around the volcano. The volcanic products of Mashu are composed of basalt, mafic and felsic andesite, and dacite of the low alkali tholeiite series and its derivatives, which are characteristic of the volcanic rocks in island arcs. A trend of differentiation of the low alkali tholeiite magma may be traced from the somma lavas to the central cone products.

In his previous papers the senior author (Katsui, 1955 and 1963) reported a preliminary study of the geology and tephrochrology of the volcano, with special reference to the caldera-forming eruption. This paper concerns the compositional variation in products and the magmatic evolution throughout the history of Mashu volcano on the basis of recently obtained radiocarbon age data and chemistry of the volcanic products.

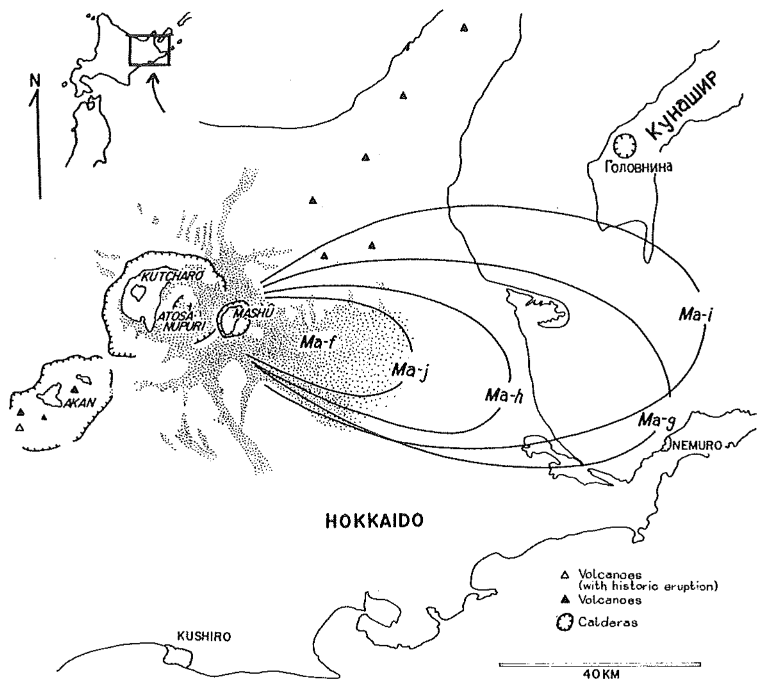
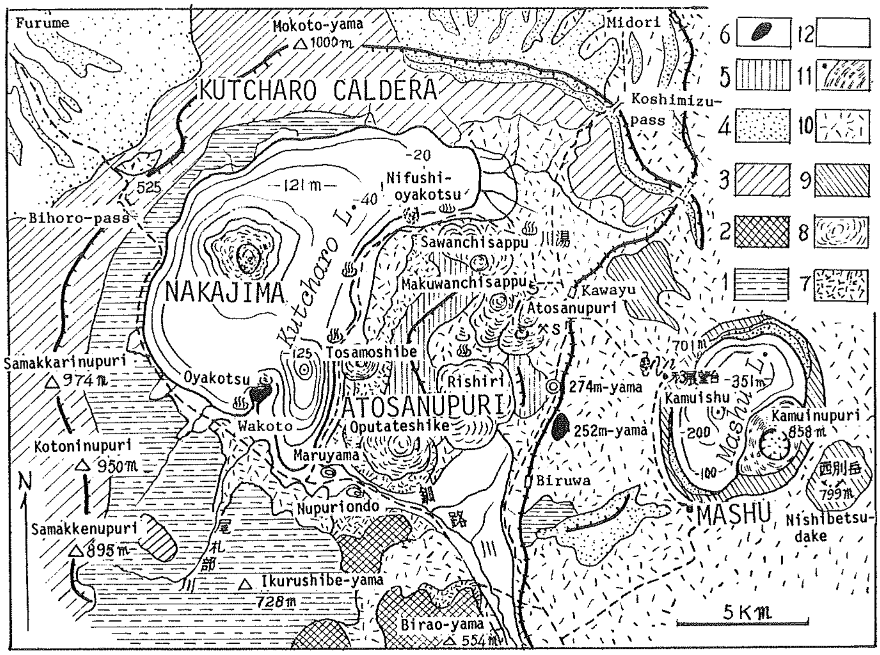


Fig. 2 The Quaternary volcanoes in east Hokkaido and the pyroclastic deposits around the Mashu caldera. Ash- and pumice-fall deposits (Ma-j – Ma-g) are indicated by 10cm contour lines, and pyroclastic flow deposit (Ma-f) is shown by dotted area (after Katsui, 1963). A full account of the distribution of pyroclastic deposits in this area is given by the Committee on Nomenclature of the Pyroclastic Deposits in Hokkaido (1974).

Geologic Setting

Mashu volcano is located on the eastern wall of the Kutcharo caldera (Fig. 3.). The volcano group of Kutcharo occupies the southwestern part of the Shiretoko-Akan volcanic chain which represents an échelon of the inner arc of the Kurile islands.

The Kutcharo caldera, which measures 26 x 20km across and contains the Kutcharo lake, is one of the largest calderas of the Krakatau type in the world. The ancestral cones of Kutcharo were built chiefly of lavas and fragments of basalt and andesite before the formation of the caldera. Then, repeated eruptions of pyroclastic flows and falls of dacite took place. This violent



1 Neogene volcanic & sedimentary rocks
2 Sattomonai volcanic rocks (Neogene ?)
3 Kutcharo somma lava
4 Kutcharo pyroclastic flow deposits
5 Atosanupuri somma lava
6 Oyakotsu & 252m-yama dome lavas
7 Atosanupuri pyroclastic deposits
8 Nakajima & Atosanupuri dome lavas
9 Mashū somma lava
10 Mashū pyroclastic deposits
11 Kamuishu & Kamuinupuri lavas
12 Terrace deposits & alluvium

Fig. 3 Geologic sketch map of the Kutcharo caldera area (after Katsui, 1962).

activity resulted in the formation of the caldera. The final event of these catastrophic eruptions occurred 29,400± 1,800 (GaK-867) or $32{,}200^{+3{,}000}_{-2{,}000}$ (GaK-866) y.B.P. (Katsui, 1962; Satoh, 1969) A gravity low, reaching −46 milligals, is found, with isoanomaly contour lines conforming to the caldera shape (Yokoyama, 1958). The existence of a layer of coarse pumice and/or some low density materials thickenning toward the center is required for such anomalies.

After the depression of the Kutcharo caldera, three volcanoes were formed along a line trending WNW to ESE across the caldera, i.e. Nakajima, Atosanupuri, and Mashu (Fig. 3). Atosanupuri volcano erupted at the center of the caldera; it is composed of the successive products of somma lavas of andesite, dacite pumice deposits, and many dacite lava domes. Nakajima volcano consists of double lava domes of dacite and is considered to have erupted during the activity of the older lava domes of Atosanupuri. The

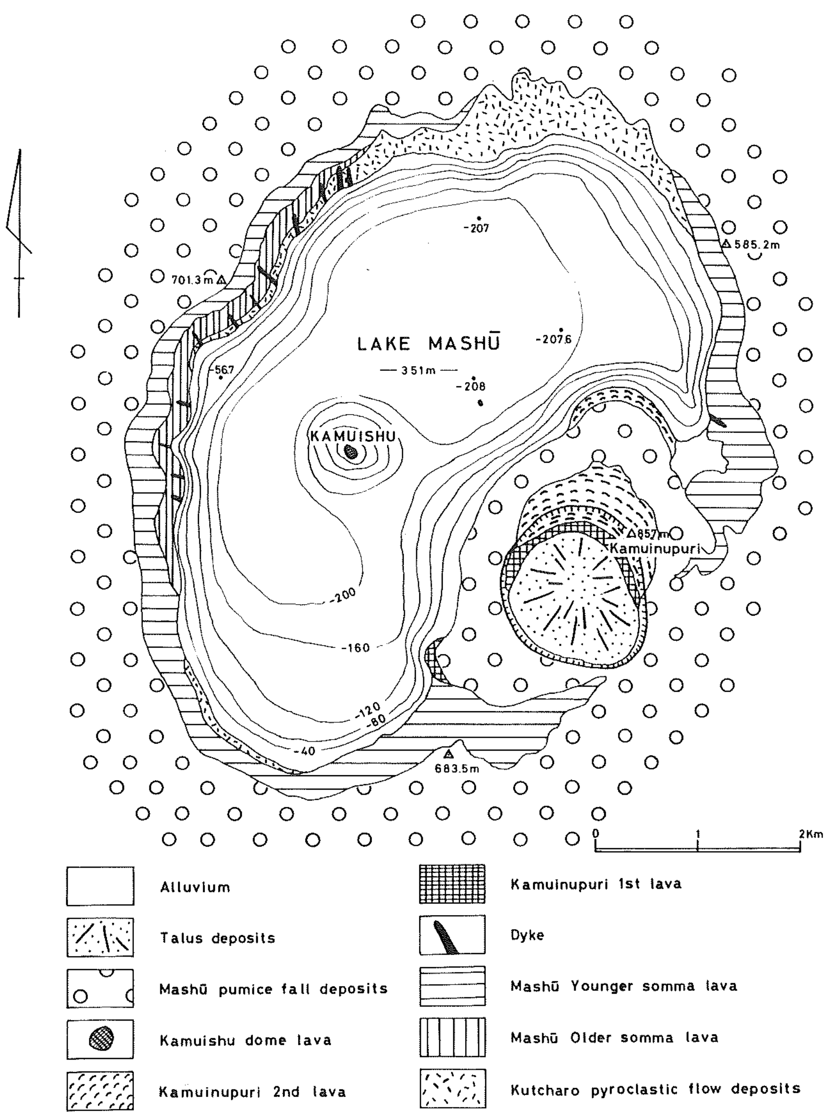


Fig. 4 Geologic map of Mashu volcano, east Hokkaido.

youngest lava dome of Atosanupuri which extruded about one thousand years ago, still retains solfataric activity.

The Mashu caldera exhibits a deep and oval-shaped depression, 7.5 x 5.5km in diameter, 33km^2 in area and 9km^3 in volume, and contains the Mashu lake which has a flat floor with a maximum depth of 208m (Fig. 4). The lake's water, as clear as crystal, has a record of the maximum transparency of 41.6m in 1931, although it measures about 29m at present. The caldera wall, 500 – 700m above sea level and 150 – 350m high from the lake, is made up of a thick pile of the somma lavas of basalt and mafic to intermediate andesite which erupted in the stratovolcano building stage. The pyroclastic flow deposits from the Kutcharo caldera crop out beneath the Mashu lava (Fig. 5). More than ten dykes which intruded in the somma lavas are found at the caldera wall, showing a radial strike from the center of the caldera. It is noted that they are mainly concentrated in the WNW and ESE sectors of the caldera wall, the trend of which is conformable to the alignment of the post-caldera volcanoes of Kutcharo and Mashu.

Southeast of the Mashu caldera, there is a ruined volcano of andesite, the Nishibetsu-dake, which is probably a satellitic volcano formed during the stratovolcano building stage of Mashu.

Inside of the Mashu caldera, two post-caldera volcanoes erupted, i.e. Kamuishu, a small dacite lava dome, at the center of the lake, and Kamuinupuri, a steep-sided stratovolcano of felsic andesite with a large crater, 1.2 x 1.5km in diameter and 270 – 470m in depth, at the southeastern of part of the caldera. The final activity of Kamuinupuri dates back to one thousand years ago, however, no indication of volcanic activity, such as fumaroles and hotsprings, can be observed at present.

History of Mashu Volcano

The detailed history of the development of Mashu volcano can be compiled from the sequence of the somma lavas exposed at the caldera wall (Fig. 5) and the stratigraphy of the pyroclastic deposits around the volcano (Fig. 6). Radiocarbon dates recently obtained by Katsui (1963), Satoh (1969), Sakai et al. (1972) and Shoji and Masui (1974) enable us to know the age of the main events. On the basis of the above mentioned data, the history of Mashu volcano can be divided into the following three stages:

1) Stratovolcano building stage: ca.17 – 12 x 10^3 y. age
2) Caldera building stage: 11 – 7 x 10^3 y. age
3) Central cone building stage: ca.4 – 1 x 10^3 y. age

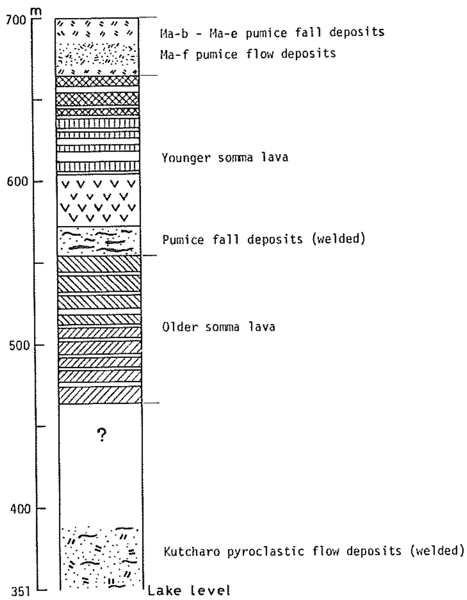


Fig. 5 A columnar section at the northwestern part of the Mashu caldera.

1) Stratovolcano building stage

About 17,000 years ago, mafic and intermediate andesite lavas began to erupt with ejection of scoria and lapilli, constructing a stratovolcano on the eastern wall of the Kutcharo caldera. The volcanic ash layers, Ma-α – Ma-ζ as shown in the columnar section (Fig. 6), were deposited during this stage. All of the somma lavas are considered to have been discharged by intermittent eruptions without any interruption of activity for a long time, except for a quiescent epoch which subdivides the somma lava stage into the older and the younger substages (Fig. 5).

In the substage of the older somma lava, recurrent eruptions of nearly aphyric andesite took place at the beginning (Older somma lava 1). They were followed by eruptions of prophyritic andesite of a more mafic composition (Older somma lava 2). Several dykes of the same composition intruded in the lava flows at the northwestern part of the caldera wall. A lava flow poured out directly from a dyke feeder is observed on the caldera wall.

The older somma lavas are composed of pyroxene andesite and basalt (types Ic and Vc*). The earlier lavas (Older somma lava 1) are hypersthene andesite of nearly aphyric variety (type Ic). Then, the lavas became porphyritic and more mafic in composition (Older somma lava 2). Thus, hypersthene andesite (type Ic), augite hypersthene andesite (type Vc) and hypersthene basalt (type Ic) followed in this order. Their groundmass, however, is persistently the same and consists of plagioclase, clinopyroxene, iron ore and cristobalite, commonly showing an intersertal texture. Calcic plagioclase

* Symbols of Kuno's classification based on the ferromagnesian silicate mineral assemblage (Kuno, 1950).

megacrysts (calcic bytownite) are present in the later porphyritic lavas.

After a quiescence, the activity of the younger somma lava began with eruption of felsic andesite pumice. This pumice fall was mainly accumulated in the northwestern direction, attaining about 20m in thickness at the northwest part of the caldera wall where it is strongly welded. Intrusion of several dykes of felsic andesite was taking place, probably related to the eruption of pumice. This intrusion was succeeded by the eruption of a large amount of porphyritic andesite lava. Then, lavas of slightly porphyritic type, 2 – 10m in thickness, intermittently erupted.

The younger somma lavas are mostly composed of hypersthene andesite (type Id→c) and augite hypersthene andesite (type Vd→c), all of which are intermediate in composition except the felsic andesitic pumice and dykes. Their groundmass is made up of plagioclase, clinopyroxene, orthopyroxene rimmed with clinopyroxene, iron ore and cristobalite, and shows an intersertal texture. Some of the uppermost, younger somma lavas, are augite hypersthene andesite (type Vd) whose groundmass is characterized by the presence of both ortho- and clino-pyroxenes without reaction relation. Phenocrysts of olivine, which are almost entirely absent in the Mashu volcanic products, are exceptionally found as a minor constituent in the uppermost lavas.

2) Caldera building stage

Subsequent to the effusion of the somma lavas, after a long period of quiescence, the type of activity changed to highly explosive eruptions. Thus, felsic andesite pumice (Ma-l) and ash (Ma-k) were ejected. After a long quiescence, about seven thousand years ago, the culminating activity that led to the formation of the caldera began with the blowing away of pulverulent solidified lavas as an ash-fall (Ma-j). This was followed by successive pumice-fall eruptions of highly vesicular white pumice (Ma-i) and light gray pumice with lithic fragments (Ma-h and Ma-g). Subsequently, the type of activity was converted into a pyroclastic flow of a great volume of gray pumice and ash with lithic fragments (Ma-f). The pumice of Ma-f is dark, little vesiculated, and characteristically rounded due to abrasion. All of the pumice discharged during the culminating eruption are augite hypersthene felsic andesite (type V), except that of Ma-f which is more mafic in composition.

This violent activity from Ma-j to Ma-f took place within a short time, and caused the depression of the Mashu caldera, as discussed by Katsui (1963). The air fall pumices and ash were transported by the westerlies and accumulated to the east of the caldera, while the pyroclastic flow deposits were distributed in all directions (Fig. 2). At the eastern part of the caldera wall, the Ma-i pumice fall deposit is fairly welded. Due to the catastrophic event the vegetation was

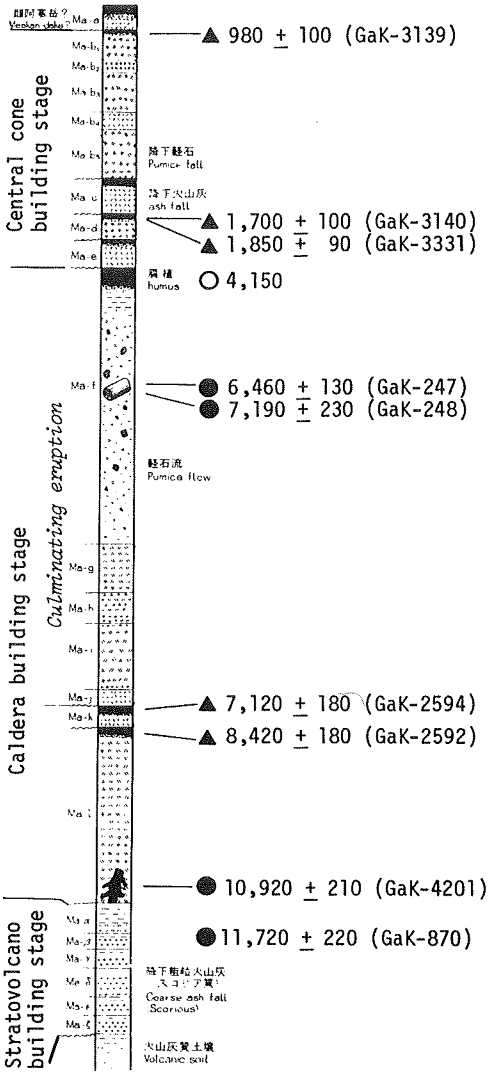


Fig. 6 Standard columnar section and radiocarbon dates of the Mashu pyroclastic deposits. Materials for radiocarbon age determination: solid cricles – charcoal, and solid triangles – humic acid. An obsidian hydration date of stone implements is shown by open circle. Source of data: Katsui, 1963: Katsui and Kondo, 1965: Satoh, 1969; Sasaki et al, 1971; Shoji and Masui, 1974.

widely devastated. A number of ancient sand dunes found on the east side of the caldera, were formed just after this event (Tomioka et al, 1974).

3) Central cone building stage

After a long quiescence of 2,500 or 3,000 years, about 4,000 years ago, Kamuinupuri volcano began to erupt in the southeast side of the caldera. This activity started with ejection of felsic pumice and was followed by the eruption of the first lava of andesite. Then, the second lava of felsic andesite poor in phenocrysts erupted, forming a steep-sided cone.

About one thousand years ago, an explosive activity occurred, ejecting successive pumices of felsic andesite (Ma-b_5 to Ma-b_1). This pumice eruption caused the formation of a large crater or small caldera, 1.2 x 1.5km across, on the top of the Kamuinupuri (Ishikawa et al, 1969). The pumice fall deposits of Ma-b_5 and Ma-b_3 are thickly accumulated near the crater, being partly welded.

During the activity of the Kamuinupuri, a dacite lava dome, the Kamuishu, erupted at the center of the caldera floor, although its definite age is uncertain.

The first lava of the Kamuinupuri is augite hypersthene andesite (type Vd), and the second lava is augite hypersthene felsic andesite (type Vd). The lava dome of the Kamuishu is augite hypersthene dacite (type Vd). Both the second lava of the Kamuinupuri and the lava dome of the Kamuishu are poor in phenocrysts and quite similar in petrography. Their groundmass is composed of plagioclase, cristobalite, and a small amount of alkali-feldspar, iron ore, orthopyroxene, clinopyroxene and apatite, and shows a felsitic texture.

Table 1 Chemical compositions of the older somma lavas.

	Samples collected at the NW wall of the caldera in order of eruption										Samples collected at other localities				
No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
	M-38	M-39	M-40	M-41	M-42	M-43	Dyke	M-44	M-45	M-46	KI-9	YK-II	M-4	M-5	YK-I
SiO_2	56.24	57.43	54.79	58.16	56.08	54.56	52.51	52.80	53.53	52.39	52.38	52.78	54.05	54.76	55.08
TiO_2	.60	.57	.65	.57	.60	.68	.72	.72	.68	.75	.49	.71	.68	.67	1.19
Al_2O_3	14.96	15.30	15.90	14.62	16.91	17.39	19.04	17.72	16.06	16.86	17.36	19.01	17.03	16.89	15.92
Fe_2O_3	4.41	3.08	5.34	3.70	5.12	3.11	1.26	3.45	3.80	4.41	4.17	2.48	3.40	3.36	3.83
FeO	8.43	8.56	7.83	7.87	5.88	7.11	8.48	7.43	8.09	7.47	7.92	7.15	7.81	7.93	8.16
MnO	.26	.25	.28	.20	.23	.21	.18	.23	.20	.20	.20	.18	.22	.21	.22
MgO	3.41	2.86	3.52	3.48	2.70	4.00	4.23	4.43	4.75	4.81	5.28	3.78	4.09	3.58	3.19
CaO	8.73	8.08	8.61	7.34	9.34	9.75	10.26	10.06	9.44	9.90	9.59	11.08	9.25	9.34	9.02
Na_2O	2.50	2.73	2.46	2.86	2.53	2.19	2.25	2.07	2.25	2.04	2.29	2.21	2.30	2.31	2.48
K_2O	.28	.32	.23	.32	.22	.19	.22	.19	.20	.16	.25	.30	.20	.19	.44
P_2O_5	.23	.20	.19	.22	.21	.17	.25	.19	.20	.24	.11	.25	.21	.24	.21
H_2O (+)	.11	.10	.08	.03	.08	.05	.11	.15	.13	.15	.27	.19	.20	.10	.25
H_2O (-)	.06	.04	.02	.00	.12	.02	.18	.10	.08	.04	.00	.18	.12	.04	.14
Total	100.22	99.52	99.90	99.37	100.02	99.43	99.69	99.54	99.41	99.42	100.31	100.30	99.76	99.52	100.13
MgO	17.9	16.3	18.1	19.1	16.4	23.3	25.7	25.2	24.9	25.5	26.5	23.7	23.0	20.6	17.7
FeO	67.5	66.3	68.0	63.5	66.9	62.9	59.3	61.9	62.3	62.8	60.7	60.5	63.0	65.0	66.2
Na_2O+K_2O	14.6	17.4	13.9	17.4	16.7	13.8	15.0	12.9	12.8	11.7	12.8	15.8	14.0	14.4	16.1
D.I.	37.95	40.73	36.45	43.08	39.39	31.63	26.85	28.67	30.84	28.63	28.26	28.56	32.23	33.49	37.06
C.I.	33.32	30.11	31.69	30.15	26.31	31.26	31.36	32.13	35.23	34.21	35.43	30.31	31.46	30.73	31.67

1-4 Hypersthene andesite (nearly aphyric), lava, foot of the northwestern part of the caldera.

5-6 Hypersthene andesite (porphyritic), lava, loc. ditto.

7 Hypersthene andesite (porphyritic), dyke, loc. ditto.

8 Hypersthene andesite (porphyritic), lava, loc. ditto.

9 Augite-bearing hypersthene basalt, lava, loc. ditto.

10 Augite hypersthene mafic andesite (porphyritic), lava, foot of the northwestern part of the caldera.

11 Hypersthene basalt (porphyritic), lava, foot of the western part of the caldera.

12-14 Hypersthene andesite (porphyritic), lava, loc. ditto.

Correlation in order of eruption: Nos.1-4 - No.15, Nos.5-6 - Nos.13-14, and Nos.8-10 - Nos.11-12.

Anasyses: Nos.1-10, 13 & 14 by S.Ando (new data), Nos.12 & 15 by Y.Katsui (1955), and No.11 by K.Inaba.

Chemistry of the Volcanic Products

Thirty eight major element chemical analyses are now available for the lavas and pyroclastics of Mashu volcano as shown in Tables 1 – 3, of which 30 are new analyses and the rest were published by Katsui (1955, 1963). All of them were obtained by means of the conventional wet method.

The rocks of Mashu volcano range from 52.38% to 72.96% in silica content. As shown in Figs.7 and 8, the variation diagrams for the Mashu rocks exhibit a nearly smooth curve for each oxide against SiO_2. The most characteristic feature of the Mashu rocks is their scarcity in alkalies, especially in K_2O, and their high content of CaO. Peacock's alkali-lime index for the Mashu rocks is 65.5, the highest value known for a calcic rocks series in the world. In consistence with the low K content, trace elements such as Ba, Hf, Pb, Th and U are depleted in the Mashu rocks, as indicated by the data given by Ando, Nishimura and Masuda on several selected rocks (Ando, 1972; Katsui et al, in press). This might be expected from their similarity in ionic radii as compared

Table 2 Chemical compositions of the younger somma lavas.

	Samples collected at the NW wall of the caldera in order of eruption										Samples from other locs.			
No.	16	17	18	19	20	21	22	23	24	25	26	27	28	29
	pumice	dyke	M-48	M-49	M-50	M-51	M-52	M-53	M-54	M-55	KI-013	KI-7	KI-5	YK-V
SiO_2	66.64	65.82	55.89	60.81	59.73	60.18	59.89	59.43	61.20	59.41	55.32	56.01	59.70	60.05
TiO_2	.78	.88	.67	.55	.58	.57	.56	.63	.54	.66	.45	1.00	.49	.51
Al_2O_3	15.59	14.72	18.10	14.70	18.03	17.18	17.69	17.52	17.80	16.88	18.18	18.57	17.21	17.07
Fe_2O_3	1.59	1.88	3.91	2.81	2.13	2.17	1.64	3.44	2.34	3.14	3.53	2.86	3.14	2.25
FeO	3.69	4.66	5.66	7.48	6.02	5.30	5.81	4.60	5.01	6.04	7.40	6.14	5.72	6.18
MnO	.22	.22	.18	.16	.14	.13	.16	.15	.19	.11	.22	.24	.25	.14
MgO	1.38	1.75	3.02	2.69	2.47	2.49	2.16	2.25	2.14	1.92	3.52	2.70	2.26	2.33
CaO	5.40	5.52	8.97	6.35	7.24	7.37	7.42	7.55	7.56	7.59	9.01	9.34	7.64	7.90
Na_2O	3.64	3.91	2.57	3.41	3.23	3.30	3.47	3.29	3.28	3.38	2.81	2.56	3.00	2.66
K_2O	.45	.46	.20	.36	.26	.27	.25	.26	.24	.23	.30	.23	.28	.50
P_2O_5	.17	.18	.13	.24	.19	.23	.25	.22	.25	.27	.11	.13	.16	.25
H_2O (+)	.63	.08	.13	.40	.03	.25	.15	.20	.18	.10	.23	.48	.00	.28
H_2O (-)	.06	.22	.08	.14	.02	.06	.10	.26	.12	.14	.06	.05	.08	.10
Total	100.24	100.30	99.51	100.10	100.07	99.50	99.55	99.80	100.85	99.87	100.16	100.31	99.93	100.22
MgO	12.8	13.8	19.7	16.1	17.5	18.4	16.2	16.3	16.5	13.1	20.0	18.6	15.7	16.7
FeO	49.1	51.7	62.3	61.4	57.8	55.2	55.9	58.0	56.5	62.4	62.3	62.1	61.5	60.6
Na_2O+K_2O	38.1	34.5	18.0	22.5	24.7	26.4	27.9	25.7	27.0	24.5	17.7	19.3	22.8	22.7
D.I.	62.14	61.55	38.36	50.06	46.40	48.14	47.91	48.37	49.22	48.23	36.13	37.59	46.39	45.32
C.I.	12.54	17.17	23.79	25.77	19.68	19.78	19.43	18.73	18.20	21.21	28.63	23.70	20.79	21.36

16 Hypersthene andesite (nearly aphyric), welded pumice fall deposit, northwestern part of the caldera.

17 Aphyric andesite, dyke, loc. ditto.

18 Hypersthene andesite (porphyritic), lava, loc. ditto.

19 Aphyric andesite, lava, loc. ditto.

20-25 Augite-bearing hypersthene andesite (porphyritic), lava, loc. ditto.

26 Hypersthene andesite (porphyritic), lava, western part of the caldera.

27-28 Augite-bearing hypersthene andesite (porphyritic), lava, loc. ditto.

29 Augite hypersthene andesite (porphyritic), lava, loc. ditto.

Correlation in order of eruption: No. 18 - No. 26, and Nos. 20-25 - Nos. 27-29.

Analyses: Nos. 16, 17, & 26-28 by K.Inaba, Nos. 18-25 by S.Ando, and No. 29 by Y.Katsui (1955).

with potassium. The pattern of chondrite-normalized REE (La, Ce, Sm, Eu, Tb, Yb and Lu) prepared by Nishimura and Masuda, for the four representative rocks with a silica content ranging from 52.78% to 72.96% shows a tendency toward depletion or equality of the light REE over the heavy REE, being similar to that of the ocean ridge tholeiites (Katsui, et al, in press).

Another feature of the Mashu rocks is richness in $FeO+Fe_2O_3$ and poorness in MgO. As shown in Fig. 9, the Mashu rocks exhibit a strong iron enrichment trend.

The chemical character of the Mashu rocks, as described above, is quite similar to that of the low alkali (low-K) tholeiites or to the island arc tholeiitic series as exemplified by the volcanic rocks of the active island arcs of

Table 3 Chemical compositions of the volcanic products of the caldera and central cone stages.

	Caldera building stage					Central cone stage					
No.	30		31	32	33	34		35	36	37	38
	Ma-1 pumice	H_2O free	Ma-i pumice	Ma-h pumice	Ma-f pumice	Ma-d pumice	H_2O free	Kamui-nupuri	Kamui-shu	Ma-b5 pumice	Ma-b3 pumice
SiO_2	61.16	65.79	67.57	66.65	65.73	60.24	63.55	69.73	72.96	65.53	66.37
TiO_2	.34	.37	.55	.69	.62	.34	.36	.69	.33	.36	.26
Al_2O_3	16.48	17.77	14.75	15.27	15.29	16.31	17.21	13.64	12.54	14.72	15.27
Fe_2O_3	2.63	2.83	2.16	2.40	2.15	2.88	3.04	4.63	2.01	2.48	2.08
FeO	2.60	2.80	2.25	2.73	3.25	3.69	3.89	.58	2.09	3.21	3.48
MnO	.21	.23	.10	.14	.13	.19	.20	.15	.08	.10	.19
MgO	1.36	1.46	1.52	1.70	1.99	1.72	1.81	1.24	.99	1.49	1.62
CaO	4.03	4.34	4.18	4.53	4.74	5.16	5.44	4.33	3.29	4.42	4.88
Na_2O	3.54	3.81	4.21	4.15	4.10	3.62	3.82	4.21	3.66	3.54	4.03
K_2O	.43	.46	.91	.78	.75	.48	.51	.60	1.07	.85	.67
P_2O_5	.18	.19	.23	.29	.25	.16	.17	.17	.29	.20	.16
H_2O (+)	4.55	-	1.04	.44	.40	2.43	-	.05	.41	2.71	.76
H_2O (-)	2.76	-	.43	.32	.33	1.88	-	.09	.30	.20	.16
Total	100.27	100.01	99.90	99.89	99.73	99.10	100.00	100.11	100.02	99.81	99.67
MgO		12.9	13.8	14.5	16.3		13.9	11.0	10.0	12.9	13.6
FeO		49.5	39.9	43.6	44.1		53.0	46.3	41.8	49.2	46.8
Na_2O+K_2O		37.6	46.3	41.9	39.6		33.1	42.7	48.2	37.9	39.6
D.I.		64.69	69.41	66.85	64.33		58.83	72.29	76.35	63.97	64.25
C.I.		11.50	10.35	11.85	13.57		14.40	11.13	8.46	11.89	13.16

30 Augite hypersthene felsic andesite, pumice from the Ma-1 pumice fall deposit, Kenebetsu, east of the Mashū caldera.

31 Augite hypersthene felsic andesite, pumice from the Ma-i pumice fall deposit, Nijibetsu, east of the Mashū caldera.

32 Augite hypersthene felsic andesite, pumice from the Ma-h pumice fall deposit, loc. ditto.

33 Augite hypersthene andesite, pumice from the Ma-f pumice fall deposit, loc. ditto.

34 Augite hypersthene andesite, pumice from the Ma-d pumice fall deposit, top of the northwestern part of the Mashū caldera.

35 Augite hypersthene felsic andesite (nearly aphyric), the 2nd lava, summit of Kamuinupuri.

36 Augite hypersthene dacite (nearly aphyric), dome lava, Kamuishu island.

37 Augite hypersthene felsic andesite, pumice from the Ma-b5 pumice fall deposit, top of the Mashū caldera.

38 Augite hypersthene andesite, pumice from the Ma-b3 pumice fall deposit, top of the Mashū caldera.

Analyses: Nos.30, 34, 35 & 38 by K.Inaba and Nos.31-33 & 36-37 by Y.Katsui (1955, 1963).

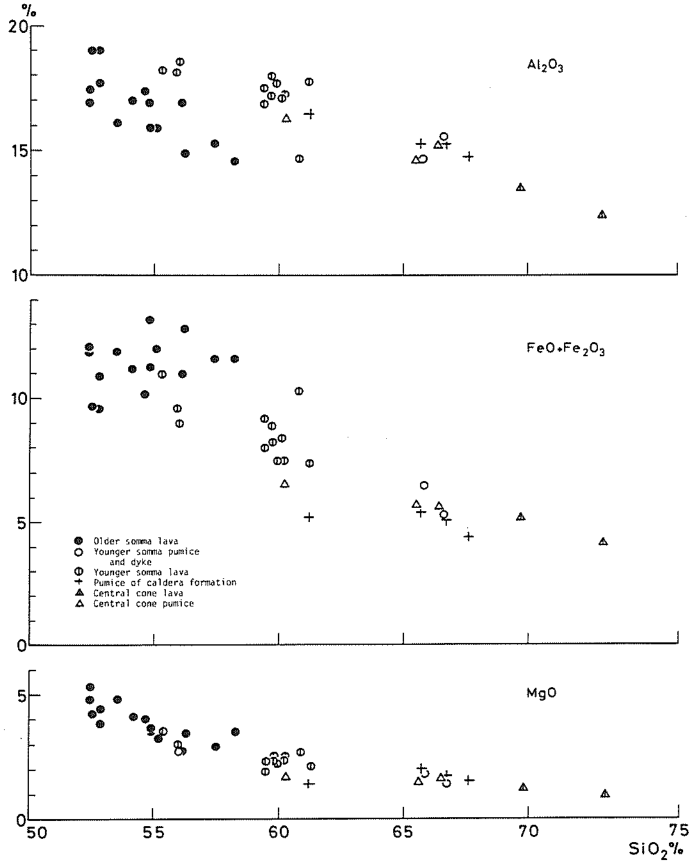


Fig. 7 Al_2O_3, $FeO+Fe_2O_3$, and MgO versus SiO_2 for the Mashu rocks.

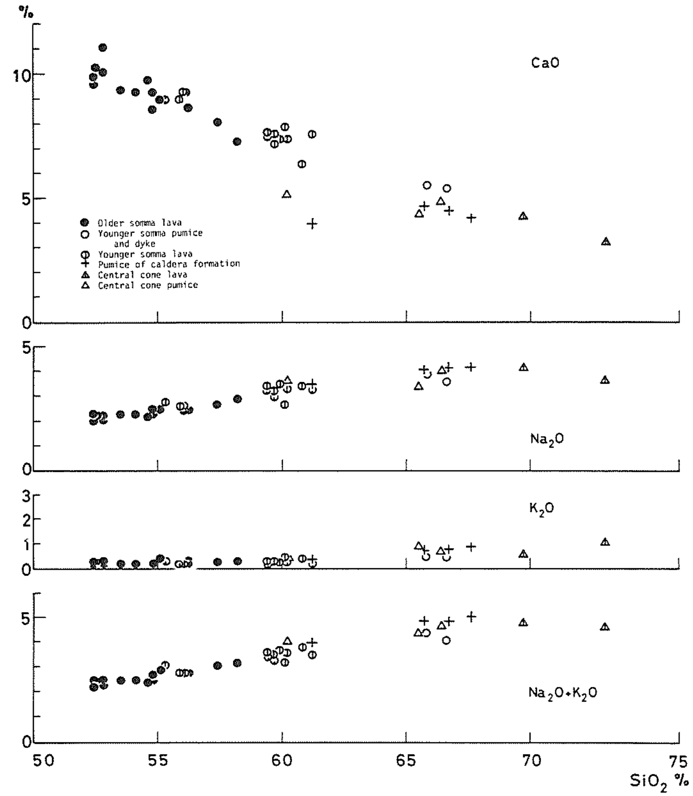


Fig. 8 CaO, Na_2O, K_2O and Na_2O+K_2O versus SiO_2 for the Mashu rocks.

Izu-Mariana, Tonga, and South Sandwich (Jakeš and Gill, 1970; Katsui, 1972). The older somma lavas of Mashu represent a typical rock suite of the low alkali (low-K) tholeiite series in both chemistry and mineralogy. However, the central cone lavas of Mashu would be classified into the calc-alkali series, if this last term is used for the hypersthenic rock series which is characterized by the occurrence of groundmass orthopyroxene as proposed by Kuno (1968). The younger somma lavas, in turn, may be regarded as a transitional type between the above two series, while some of the uppermost ones are comprised in the calc-alkali series.

Thus, the Mashu rocks vary from the tholeiite to the calc-alkali series through a transitional one, however, it is evident that their chemical features are persistent throughout the whole history of the volcanic complex as stated above. This chemical similarity and the order of eruption suggest that the Mashu rocks have been derived from a low alkali (low-K) tholeiitic magma as discussed in later.

Chronological Variation in Composition of the Volcanic Products

Chronological variation in composition of the Mashu volcanic products is

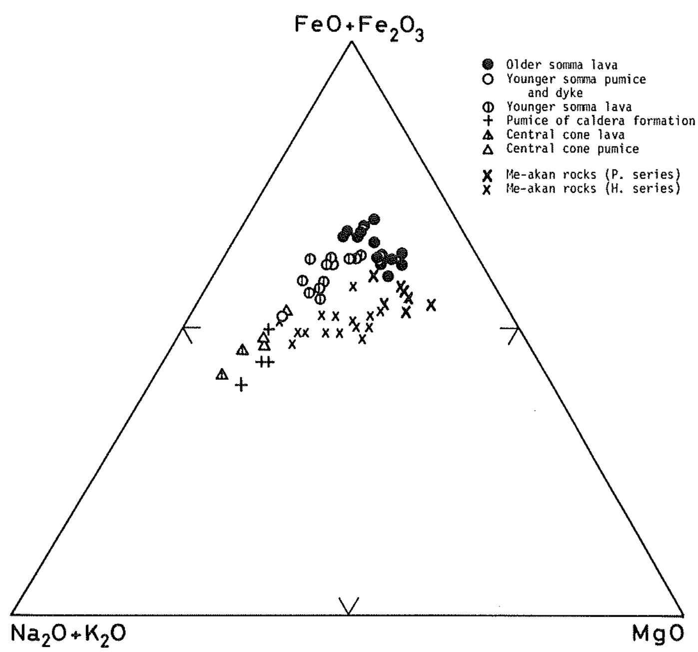


Fig. 9 Triangular variation diagram for MgO – $FeO+Fe_2O_3$ – Na_2O+K_2O. The data of the Me-akan rocks are mainly given by S. Ando (unpublished).

presented in Fig. 10. As shown in this figure, this variation can be divided into two trends, i.e. variations of long term and short term.

A general trend from mafic to felsic composition can be traced throughout the products of the whole volcanic history. In the earlier stage of the Mashu volcano activity, recurrent eruptions of mafic lavas were taking place, while toward the later stage, eruptions were interrupted by long periods of quiescence and became explosive and more felsic materials were produced. This implies that a persistent differentiation of basaltic magma has taken place without any supply of new magma. A compositional variation in the reverse order, from felsic to mafic, is also noticed within a short period of activity. This may be interpreted in terms of a zoned magma chamber, as will be mentioned below.

As shown in Fig. 11, the older somma lavas display the tholeiitic trend characterized by increasing iron like in the rocks of Thingmuli (Carmichael, 1964) and Usu (Oba, 1966), although the degree of iron concentration is slightly different from each other. The older somma lavas can be interpreted as being derived from the tholeiitic magma through fractional crystallization under the condition of lower oxygen partial pressure as discussed by Osborn (1959). A sequence of eruption from nearly aphyric to porphyritic lavas is recognized in the older somma lava (Fig. 10). This suggests that crystal fractionation took place in the magma chamber prior to the eruption. The earlier lavas must have been derived from the upper part of the magma chamber where crystals were depleted.

The younger somma lavas, in turn, are converted into the calc-alkali trend which is represented by increasing SiO_2 and a constancy of iron content (Fig. 11). The products of the caldera and the central cone stages, similarly follow the calc-alkali trend. This trend might be interpreted by a process involving contamination of magma by older crustal materials. The strontium isotopic ratios, $^{87}Sr/^{86}Sr$, determined by Kurasawa and Fujimaki (Katsui et al, in press) for the four selected rocks of Mashu, however, do not support such an interpretation because the values obtained are quite low and fall within a very limited range from 0.7031_8 to 0.7039_4. No systematic change with respect to their silica content or chronological order of eruption, can be found. Based on the order of eruption and the chemical similarities, it is here suggested that the rocks of the calc-alkali trend have been derived from the same tholeiitic magma through fractional crystallization involving separation of magnetite under higher Po_2 towards the later stage, as interpreted for the felsic rocks of Iceland (Carmichael, 1964) and Usu (Oba, 1966).

Oxygen fugacity may be intimately related to water content in magma. As it has been pointed out by Kennedy (1955), water would diffuse and distribute

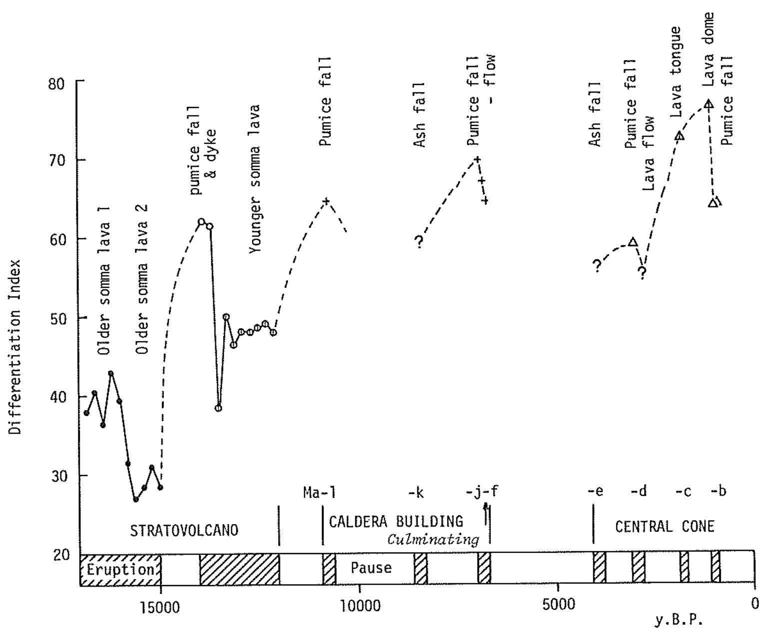


Fig. 10 Chronological arrangement of the Mashu volcanic products plotted against their differentiation index (D.I.). Data for the stratovolcano building stage are based on the samples which were systematically collected from the northwestern part of the Mashu caldera wall.

itself in a magma chamber so that the chemical potential of water becomes almost the same throughout the chamber. Accordingly, water tends to be concentrated in that part of the chamber having the lowest pressure and temperature. Thus, as the fractional crystallization proceeds, the water in the magma would be concentrated at the top of the chamber. Under such circumstances, the conversion of the tholeiitic to the calc-alkali trend probably took place during a long period of quiescence preceding the eruption of the younger somma lava. For a similar chemical trend of conversion of the products of Newberry volcano, Higgins (1973) considered the rôle of the water of the caldera lake which must have had a profound effect on the differentiating magma. However, such interpretation does not apply to the Mashu volcano, because the conversion of the trend occurred before the caldera depression.

At the opening of the younger somma stage, a compositionally zoned magma chamber is considered to have formed, i.e. a felsic magma enriched in water but depleted in crystals was produced at the uppermost level of the magma chamber. For this reason, the first activity was characterized by the eruption of the felsic pumice and the intrusion of the radial dykes which originated from the top of the magma column. Then, due to the decrease of vapour pressure in the magma, the type of activity was changed into recurrent eruptions of lava flows of intermediate composition. Such sequence of eruption is also reported for the Plinian eruption (AD 79) of Vesuvius (Rittmann, 1962a; Lirer et al, 1973), the 1947–1948 activity of Mt. Hekla (Thorarinsson, 1967), and the 1707 eruption of Mt. Fuji (Tsuya, 1955). All of them similarly occurred subsequent to a period of long quiescence.

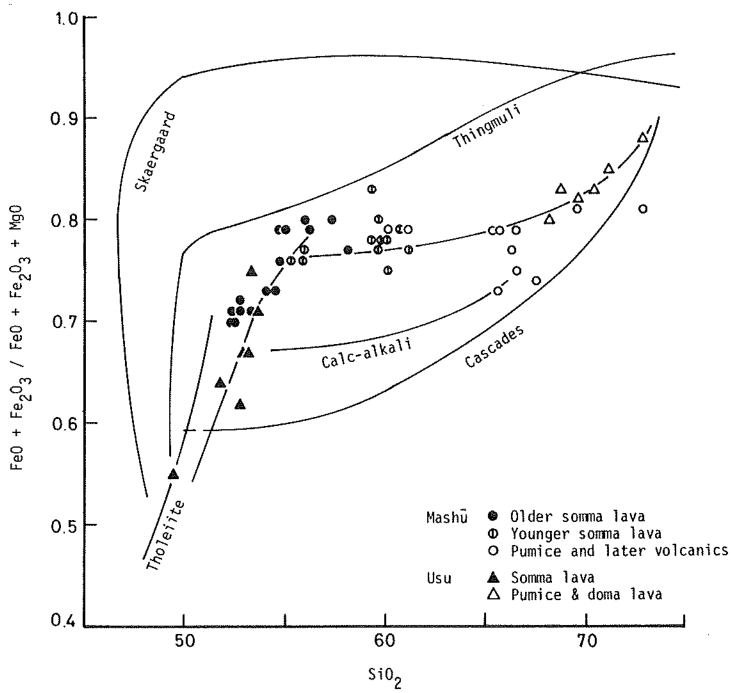


Fig. 11 $FeO+Fe_2O_3$ / $FeO+Fe_2O_3+MgO$ – silica diagram for the rocks of Mashu and Usu. Data of Usu given by Oba (1966) and the trends of other rock suites by Carmichael (1964).

After the effusion of the somma lavas, the periods of activity were interrupted by longer quiescence, during which a larger amount of felsic magma was yielded. Thus the purely explosive eruptions of the caldera building stage occurred. At the culminating eruption, the first magmatic explosion began to throw vertically the highly vesicular felsic pumice (Ma-i) which originated from the top of the magma column where water together with alkalies and silica was concentrated. Then, after ejection of the Ma-h and Ma-g pumices with lithic fragments, the type of activity changed into the out-flow of a great volume of more mafic pumice and ash with lithic fragments (Ma-f) which was derived from a deeper level of the magma column. The change of eruptive type was probably caused by the decrease of vapor pressure in the magma and the enlargement of the crater as discussed by Katsui (1963).

In the famous activity of Krakatau in 1883 and in almost all explosive eruptions that lead to the formation of calderas of the Krakatau type, the initial pumice falls are followed by less violent but more voluminous discharge of foaming lava (Williams, 1941; Williams and McBirney, 1968). Compositional variations such as those observed in the products of the culminating eruption of Mashu have been reported from Shikotsu (Katsui, 1963), Southern Nevada (Lipman et al, 1966), Crater Lake (McBirney, 1968) and others. In each case, a variation upward to more mafic products richer in phenocrysts, is shown. Such change in composition as well as in eruptive type within the culminating activity can be interpreted in terms of zoned magma chamber and enlargement of vent and crater as mentioned above. Ascending of the explosion level may also result in the change of eruptive type into ash flow, as discussed by Rittmann (1962b).

Finally, after the depression of the caldera, the magma became more viscous probably due to releasing of water and decreasing of activity. Thus, a small lava dome and a steep-sided cone were produced accompanied by pumice eruptions.

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