EVOLUTION AND MAGMATIC HISTORY OF SOME KRAKATOAN CALDERAS IN HOKKAIDO, JAPAN

By

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Introduction

"A field of unusual interest awaits the Japanese volcanologists in Hokkaido"—Calderas and their origin, 1941, p. 284 H. WILLIAMS.

There are some ten calderas in Hokkaido, northernmost island of Japan (Fig. 1). Around these calderas, a number of felsic pyroclastic deposits of Pleistocene to Holocene, are widely developed, forming vast

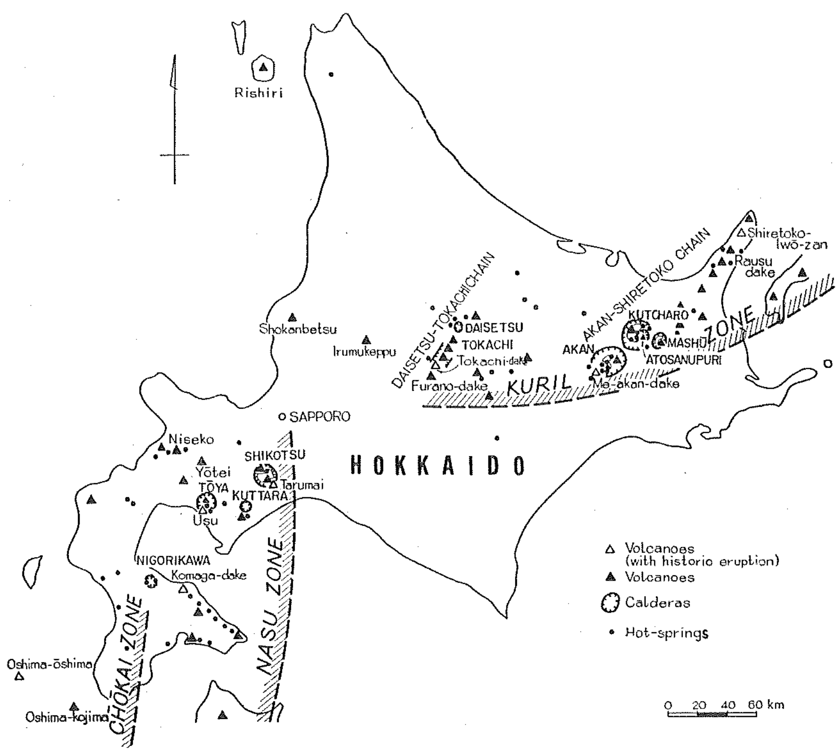

Fig. 1. Distribution of the Quaternary calderas in Hokkaido.

pyroclastic plateaux (ISHIKAWA and others, 1957). It is considered most likely that all of the calderas were collapsed as the result of rapid outflow of a great deal of felsic magma mainly in a form of pumice flow. Therefore, these calderas belong to "Krakatau type" as WILLIAMS (1941) defined.

Not a few geologists have made studies on these calderas and surrounding areas (TANAKADATE, 1930; SUZUKI and ISHIKAWA, 1933; DOI and OSANAI, 1956; MINATO, ISHII and KUMANO, 1955; and others). In order to study evolution of calderas of pre-historic time, it is very important to make a stratigraphical survey on the pyroclastic deposits around the calderas. Even the famous activity of Krakatau in 1883 did not reveal the real origin of caldera formation, until VERBEEK (1886) and STEHN (1929) carried on careful work on the deposits of well-bedded pumice and unbedded pumice. Fortunately, excellent pedologists have been carried on the tephro-chronology of the Holocene pyroclastic deposits in Hokkaido, for the purpose of agricultural development (YAMADA, 1958; and others). The writer's work has been started on the tephro-chronology of the pyroclastic deposits around the calderas. (KATSUI, 1955, 1958, 1959 & 1962; KATSUI and MURASE, 1960). In the present paper, the evolution and magmatic history of some calderas of Krakatau type, namely Shikotsu and Mashû, are considered.

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Brief history of the Shikotsu caldera

The Shikotsu caldera, embracing Lake Shikotsu, in southwestern Hokkaido, was formed ca. 20,000 years ago (Würm ice age) judging from C^{14} dating performed by Dr. Shima on some carbonized trunks of *Picea jezoensis* found buried in pumice deposits. From about 70 columnar

Table 1. Stratigraphical position of the Shikotsu pumice-fall and -flow deposits.

Age	Formation		Note
Holocene	Tarumai pumice-fall deposit	Ta	1739 A.D.*
		Tb	1667 A.D.*
		Tc	800–900 ys B.P.*
		Td	2000–5000 ys B.P.*
	Eniwa pumice-fall deposit	Ea, Eb	more than 5000 ys B.P.*
Upper Pleistocene (Würm)	Ashiribetsu sand & gravel bed and loam		Human remains of Shinyoshino**
	Shikotsu pumice-flow deposit	Spfl–1	Culminating eruption which led to formation of the Shikotsu caldera (ca. 20,000 ys B.P.***) Bibi fossil forest****
	〃	Spfl–2	
	Shikotsu pumice-fall deposit	Spfa–1	
	Shikotsu pumice-fall deposit	Spfa–2	
	〃	Spfa–3	
	〃	Spfa–4	
	〃	Spfa–5	
	Shikotsu scoria-fall deposit	Ssfa	Strato-cone building stage
	Lower terrace deposit		*Mammonteus primigenius primigenius* BLUMENBACH*****

* YAMADA (1958), ** SERIZAWA (1957), *** dating by Dr. SHIMA, **** KATSUI (1958), ***** MINATO (1955)

sections of the pyroclastic plateau and pumice-fall area, it is possible to trace the detailed evolution of this caldera (Table 1 and Fig. 2).

In early stage, the Shikotsu volcano was constructing a strato-cone by alternate eruptions of mafic andesite lavas and scoriae, but this cone later vanished due to caldera depression. Scoria-fall deposit (Ssfa) of this activity is distributed in the eastern area of the caldera. Then, prior to the culminating phase of the caldera building activity, pumice-falls occurred intermittently (Spfa-5, 4, 3, 2). During these preliminary eruptions, the nature of the magma varied from intermediate andesite to dacite composition.

After a long quiescence, the activity of the Shikotsu volcano was converted into the culminating phase of caldera building stage. MINATO and coworkers (1959) made an interesting study on the basis of the older topographies and reliefs buried under the Shikotsu pumice-flow deposit. The result showed that some type of upheaving and faulting might have happened near the center of eruption just before the climactic

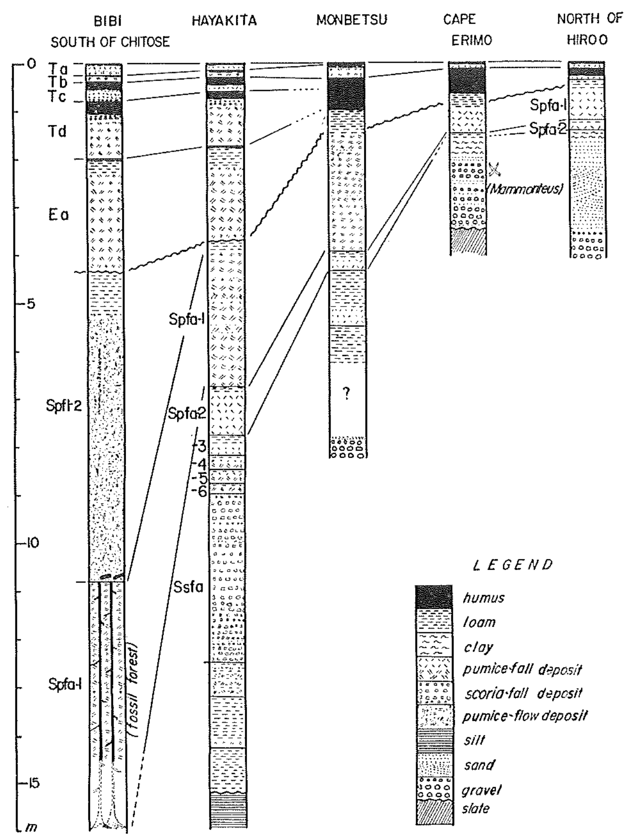


Fig. 2. Columnar sections of the pyroclastic deposits in the east of the Shikotsu caldera.

eruption. The first explosion of the culminating phase began to throw the highly vesicular rhyolite pumice high into the air (Spfa-1). This was followed by the out-flow of a great deal of dacite pumice-flow (Spfl-2) and a small amount of andesite pumice-flow (Spfl-1), successively. It can be said that all of the pumice-fall and -flows escaped within a short period, since there are no soil layers, no water-sorted lenses, nor any other evidence of quiet intervals among these deposits; though, as an exceptional case, wash-out lenses are found thinly between Spfl-1 and Spfl-2 along the Chitose river, east of the caldera. This violent activity caused a depression of the Shikotsu caldera, 13×15 km in diameter and 8×10^{10} m^3 in volume.

After the depression, three younger volcanoes, Fuppushi, Eniwa and Tarumai, composed of pyroxene andesite lava and fragments, were formed along the fissure which trends N30°W across the caldera. Among them, Tarumai has continued active during historic time.

The following estimations of the culminating phase of the caldera building activity are obtained from some field observations on the pumice deposits, viz., distribution of thickness and grain-size, specific gravity and porosity of pumice, and content of included lithic fragments, etc.:

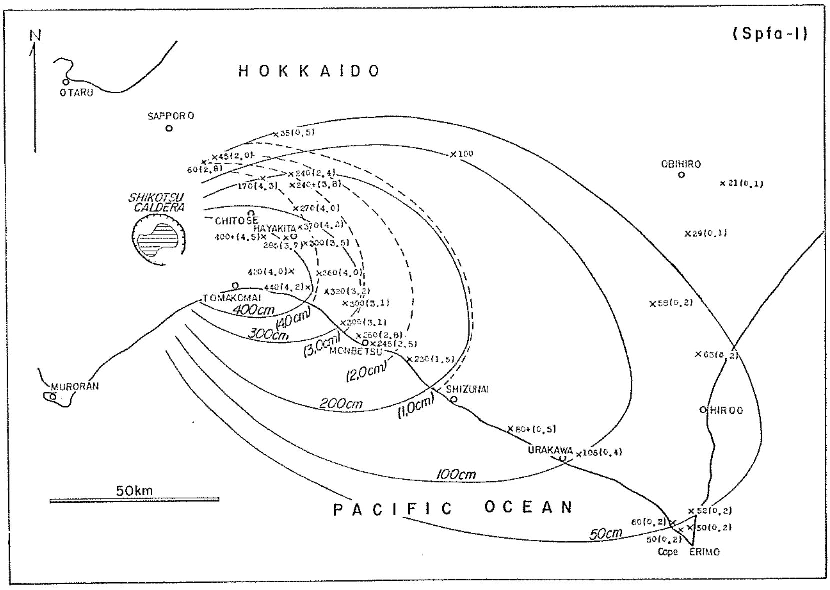
height of cloud (pumice-fall): ca. 45 km.
initial velocity (pumice-fall): ca. 450 m/sec.
pressure of explosion (pumice-fall): ca. 2.5 k bar.
mass of pumice-fall: 12.5×10^{9} tons (including 4% of lithic fragments).
total mass of pumice-flows: 130×10^{9} tons (including 13% of lithic fragments).
released kinetic energy: 1×10^{25} ergs.
released thermal energy: 1×10^{27} ergs.

(after KATSUI and MURASE, 1960)

The whole picture of this activity of Shikotsu much resembles the description of the famous eruption of Krakatau in 1883 (VERBEEK, 1886; STEHN, 1929), although it must have been rather larger in scale of activity than that of Krakatau.

The Shikotsu pumice-fall deposit (Spfa-1), composed of well sorted and highly vesicular pumice, is distributed in a fan-shaped area widening out southeastward from the caldera, decreasing in thickness as well as in grain size as the distance from the source increases; it is actually traceable for more than 200 km from the caldera, beyond the Hidaka mountain range (Fig. 3). This deposit is covered by stream terrace deposits at some places and cut by a neolithic beach line; it covers the *Mammonteus* bed at Cape Erimo, and embeds a fossil forest composed of a number of erect trunks of *Picea jezoensis* in the Sapporo-Tomakomai low-land.

The Shikotsu pumice-flow deposits (Spfl-2 & 1) are distributed around the caldera, forming a pyroclastic plateau which extends about 40 km from the source (Fig. 4). The deposits are characterized by absence of bedding, lack of sorting, abundance of glass shards and richness in foreign lithic fragments. Compared with the pumice-fall deposit, any consistent decreasing of grain size of pumice lumps can not be traced with increase of distance from the source. However, near the end of the pumice-flow, pumice lumps in the deposit become small and few (Fig. 5). In thickly piled area or near the center of the eruption, welding and rude prismatic joints are developed at the middle to lower part in a single



full line : thickness contour of the deposit.
broken line: contour of arerage of maximum grain size of pumice.
x : observed point showing thickness and grain size in cm.

Fig. 3. Distribution of the Shikotsu pumice-fall deposit (Spfa-1).

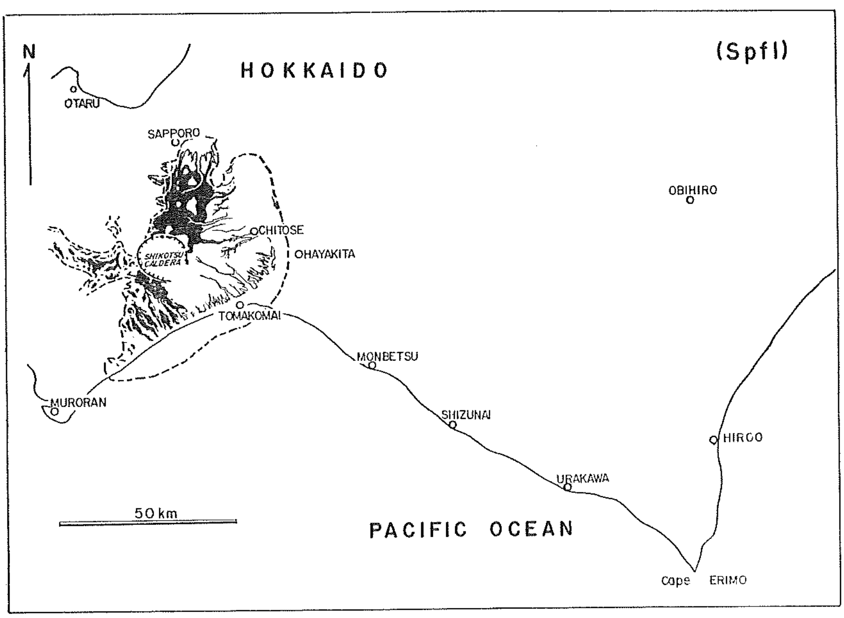
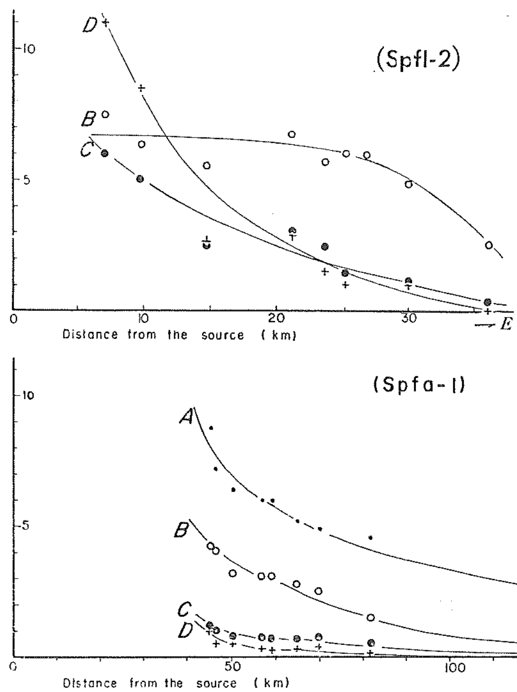


Fig. 4. Distribution of the Shikotsu pumice-flow deposit (Spfl-1 and 2). after DOI and OSANAI (1956)



A: thickness of deposit (m) (represented by observed thickness ×2).
B: average of maximum grain size of pumice (cm).
C: average of maximum grain size of lithic fragment (cm).
D: number of lithic fragment (>1 cm in diameter) per m^2. (represented by observed number $\times 10^{-2}$).

Fig. 5. Variation of grain size of the Shikotsu pumice-fall deposit (Spfa-1) and the Shikotsu pumice-flow deposit (Spfl-2).

deposit; at the same time numerous evidences of secondary fumarole are seen near the surface. From the natural remanent magnetism of the deposits, the temperature of the pumice-flows just after their emplacement is estimated as 570~600°C at the margin of welded parts of the deposits, about 26 km from the source, and 430~510°C at the terminal of the flow (SUZUKI, 1962). As the front part of such hot flow-mass is constantly fluidized by fresh supplies of air, high mobility of the pumice-flows would result, as MACTAGGAR (1960) suggested.

Brief history of the Mashû caldera

For the first time, tephro-chronological work on the Mashû pyroclastic deposit has been carried on by pedologists (YAMADA, 1958; and others). KATSUI (1955 and 1962) succeeded to this work and made geological and petrological studies.

The whole history of the activity of the Mashû caldera, eastern Hokkaido, quite resembles that of the Shikotsu caldera. In early Holocene, on the eastern wall of the Kutcharo caldera, Mashû volcano was being constructed by alternate eruptions of mafic andesite lavas and scoriae (Ma-$\zeta \sim \alpha$) (Fig. 6). Then, after the effusion of the somma lavas, the

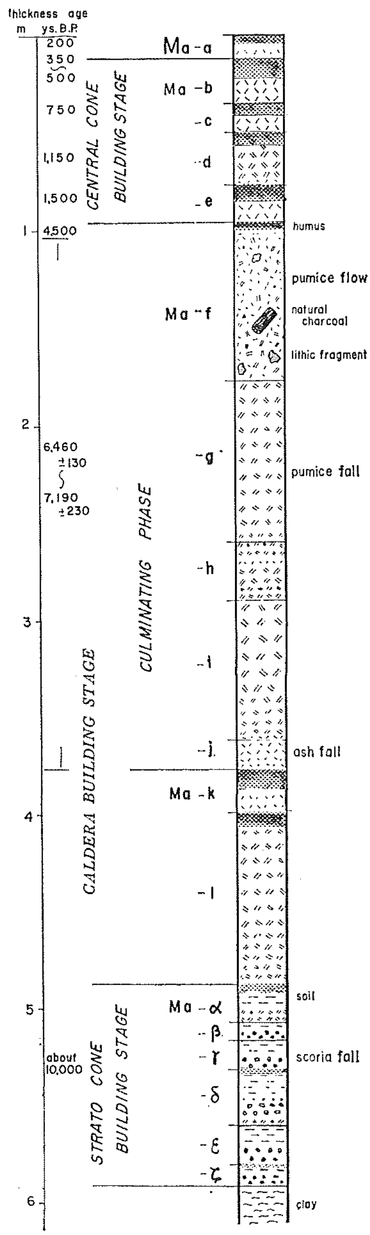


Fig. 6. Columnar section of the Mashû pyroclastic deposit at Kenebetsu, 35km east of the Mashû caldera.

activity was converted into explosive eruptions of intermediate andesite pumice and ash (Ma-l & k). After a long quiescence, about several thousand years ago*, the culminating activity of the Mashû volcano began with blowing away of pulverulent solid 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 (Ma-h & h). Then, the activity changed its form into an out-flow of a great deal of gray pumice (Ma-f). This continuous violent activity caused the formation of the

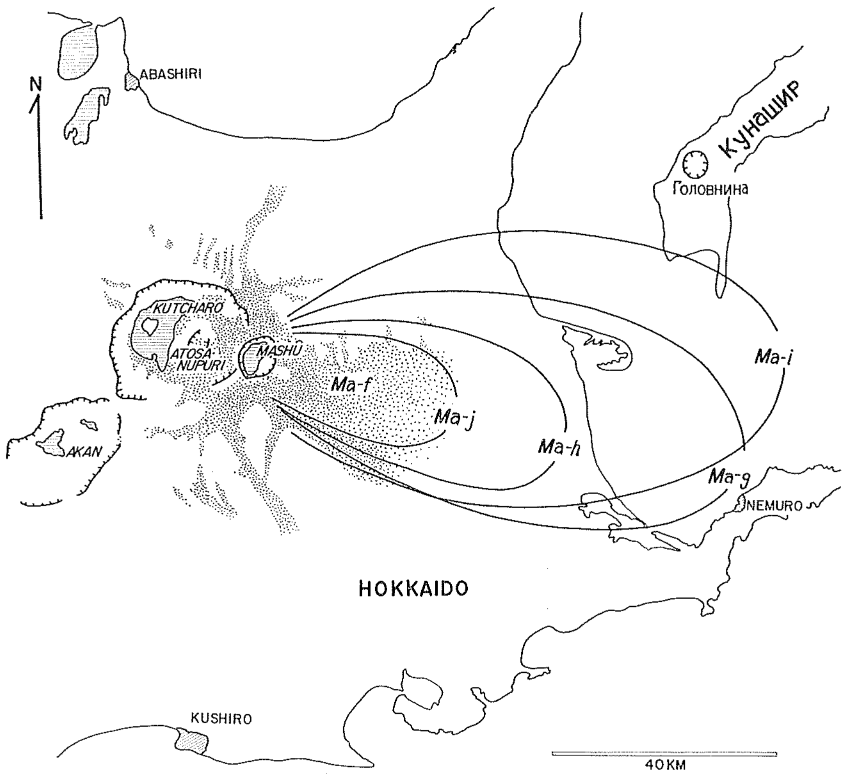


Fig. 7. Map showing the distribution of the Mashû pyroclastic deposits erupted during the culminating phase.
Ash-fall and pumice-fall deposits, Ma-j, i, h and g, are represented by 10cm thickness contour lines; and pumice-flow deposit, Ma-f, is shown by dotted area.

* Very recently, C^{14} dating on the carbonized woods included in the pumice-flow deposit (Ma-f) was made by Prof. Kigoshi of Gakushuin University. According to his personal communication, 6,460±130 ys. B.P. and 7,190±230 ys. B.P. were obtained.

Mashû caldera (7.5×5.5 km in diameter). After the formation of the caldera, a small felsic lava dome and a steep-sided cone erupted at the inside of the caldera. As shown in Fig. 7, the pumice-falls (Ma-i, h & g) of the culminating phase are widely distributed in the east of the caldera, while the pumice-flow (Ma-f) is all around the caldera. The nature of these deposits is very similar to those of the Shikotsu caldera, though no welded facies can be seen anywhere.

Mechanism of the caldera depression

It has been clarified that the calderas of Krakatau type were formed by a collapse following violent eruption of a tremendous amount of felsic magma, most of which was erupted in a form of pumice flow or ash flow (WILLIAMS, 1941).

The volume of the Shikotsu pumice-fall and -flow deposits was reliably computed on the basis of the isopach maps (KATSUI, 1959; MINATO et al., 1959) (Table 2). The calculated volume of the erupted material of the

Table 2. Volume of the Shikotsu pumice-fall and -flow deposits

	Volume	Mean of apparent density	Mass	Included lithic fragments		Juvenile material	
	km^3		×10^9 ton	Mass ×10^9 ton	Volume km^3	Mass ×10^9 ton	Volume as liquid magma km^3
Pumice-flows (Spfl-1+2)	100	1.3	130	17.0	8.8	113	52
Pumice-fall (Spfa-1)	25	0.5	12.5	0.5		12	

Comparison:
Volume of the vanished material
as a result of caldera depression ≒80 km^3
Volume of the erupted material
dry liquid magma+lithic fragment ≒61 km^3
wet liquid magma+lithic fragment ≒80 km^3
(contains ca. 5 wt% of water)

Shikotsu caldera is nearly comparable with that which vanished by the caldera depression. A slight deficiency of the erupted material is calculated, as in the case of other calderas of the world. The residual magma in equal volume to the deficiency might be drained in some form of deep seated intrusion as WILLIAMS (1941) and KUNO (1953) suggested. The actual magma, however, was not dry melt; it must have dissolved a fair amount of water, most of which was released at the eruption. If the magma contained ca. 5% of water at the start of the eruption, the volume of the ejected material was computed approximately to be the same as that of the subsidence, according to the experimental data of GORANSON (1938) (KATSUI & MURASE, 1960). Similar results were obtained in calculations of the cases of the younger caldera of Hakone (YAMASAKI, 1959) and the Mashû caldera. Accordingly, if such amount of water be considered, it is possible that these calderas were formed *only* as the result of a withdrawal of magmatic support owing to the rapid eruption of magma. So, it is inferred that the climatic activity that blew out a great deal of magma could continue as a compensation for subsidence of the volcanic body.

Sudden change in composition of pumice and eruptive type during a culminating phase of the caldera building activity

The next important problem is the sudden change in composition of the erupted material as well as the eruptive type within a culminating phase of the caldera building activity, as shown in the activities of Shikotsu and Mashû (Table 3 & 4). Similar sequence is also traceable in climactic eruption of Mt. Mazama which led to the formation of the Crater Lake caldera, Oregon (WILLIAMS, 1942). The succession of events is outlined as follows: as the eruption proceeded, the activity changed its form from pumice-fall to pumice-flow (and scoria-flow), and the ejected essential materials became denser in apparent S.G., darker in colour and richer in phenocrysts. The successive changes in chemical composition are shown in a reverse order to that of the normal differentiation of magma (Figs. 8, 9 and 10).

Most of the foreign lithic fragments included in the Shikotsu and Mashû pyroclastic deposits are derived from somma lavas and basement Tertiary rocks. Additionally, deep-seated granite, quartz-diorite and hornfels which are not exposed anywhere else in the vicinity, are found only in the pumice-flows. They are never included in the pumice-falls which preceded the pumice flows. This signifies that the explosion must have started from the top of the magma column, and descended towards the deeper level.

As has been pointed out by KENNEDY (1958), water would diffuse and distribute itself in a magma chamber so that the chemical potential of the water becomes almost the same throughout the magma chamber. So, water tends to be concentrated in the regions of lowest pressure

Table 3. Chemical compositions of scoria, pumice and welded tuff from the Shikotsu volcano.

No.	1	2	3	4	5	6
SiO_2	51.40	64.92	72.41	69.05	70.87	63.46
TiO_2	0.92	0.52	0.31	0.42	0.06	0.26
Al_2O_3	19.20	15.08	12.83	14.76	14.13	15.34
Fe_2O_3	3.96	1.81	1.36	1.87	1.52	4.90
FeO	5.82	2.24	1.20	1.27	1.70	2.96
MnO	0.27	0.07	0.05	0.09	0.19	0.02
MgO	3.84	0.81	0.45	0.68	0.98	1.90
CaO	9.94	3.98	2.04	3.19	2.81	5.20
Na_2O	2.67	3.40	3.35	3.91	3.22	2.50
K_2O	0.65	1.71	3.50	2.45	1.98	1.45
P_2O_5	0.20	0.10	0.13	0.11	1.21	0.15
H_2O (+)	0.83	4.20	2.64	2.57	2.53	2.12
H_2O (−)	0.27	0.94	0.19	0.28		
Total	99.97	99.78	100.46	100.65	100.20	100.26
Colour index	28.5	9.0	5.0	6.0	7.0	13.5

1. Olivine-augite-hypersthene andesite. Scoria from the Shikotsu scoria-fall deposit (Ssfa). Hayakita. (KATSUI, 1961)
2. Augite-hypersthene dacite. Pumice from the Shikotsu pumice-fall deposit (Spfa-2). Hayakita. (KATSUI, 1961)
3. Augite-hornblende-hypersthene rhyolite. Pumice from the Shikotsu pumice-fall deposit (Spfa-1). Bibi, south of Chitose city. (KATSUI, 1961)
4. Hornblende-augite-hypersthene dacite. Pumice from the Shikotsu pumice-flow deposit (Spfl-2). Shimamatsu, north of Chitose city. (KATSUI, 1961)
5. Hornblende-augite-hypersthene dacite welded tuff. Average of 5 analyses of welded part of the Shikotsu pumice-flow deposit (mostly Spfl-2). (SATO and KAGAWA, 1956)
6. Augite-hypersthene felsic andesite welded tuff. Welded part of the Shikotsu pumice-flow deposit (Spfl-1). Betsubetsu-gawa, west of the Shikotsu caldera. (SATO and KAGAWA, 1956)

and temperature in the magma reservoir. Alkalies and silica will co-ordinate with the water; and they are apt to be concentrated in the apices of the magma column. Such distribution of water in magma would be attained during a long quiescence preceding the culminating activity. Simultaneously, crystal settling would take place in the reservoir.

For this reason, the first explosion of the culminating phase, began to throw high into the air the highly vesicular felsic pumice which originated from the apex of the magma column. Then, due to the decrease of vapour pressure in magma and enlargement of crater, this form of activity was converted into the out-flow of a great deal more fafic pumice,

Table 4. Chemical compositions of lava and pumice of the Mashu volcano.

No.	1	2	3	4	5	6
SiO_2	55.08	52.78	60.05	67.57	66.65	65.73
TiO_2	1.19	.77	.51	.55	.69	.62
Al_2O_3	15.92	19.01	17.07	14.75	15.27	15.29
Fe_2O_3	3.83	2.48	2.25	2.16	2.40	2.15
FeO	8.16	7.15	6.18	2.25	2.73	3.25
MnO	.22	.18	.14	.10	.14	.13
MgO	3.19	3.78	2.33	1.52	1.70	1.99
CaO	9.02	11.08	7.90	4.18	4.53	4.74
Na_2O	2.48	2.21	2.66	4.21	4.15	4.10
K_2O	.44	.30	.50	.91	.78	.75
P_2O_5	.21	.25	.25	.23	.29	.25
H_2O (+)	.25	.19	.28	1.04	.44	.40
H_2O (−)	.14	.18	.10	.43	.32	.33
Total	100.13	100.36	100.22	99.90	99.89	99.73
Colour index	32.0	30.5	21.5	10.5	12.0	13.5

1. Augite-bearing hypersthene-andesite, a somma lava corresponding to the Ma-ζ scoria-fall deposit. Western part of the Mashû caldera. (KATSUI, 1955)
2. Hypersthene-andesite, a somma lava corresponding to the Ma-ε scoria-fall deposit. Loc. ditto. (KATSUI, 1955)
3. Augite-hypersthene-andesite, a somma lava corresponding to Ma-β scoria-fall deposit. Loc. ditto. (KATSUI, 1955)
4. Augite-hypersthene- felsic andesite, pumice from the Ma-i pumice-fall deposit. Nijibetsu, east of the Mashû caldera. (analyst Y. KATSUI)
5. Augite-hypersthene-andesite, pumice from the Ma-h pumice-fall deposit. Loc. ditto. (analyst Y. KATSUI)
6. Augite-hypersthene-andesite, pumice from the Ma-f pumice-flow deposit. Loc. ditto. (analyst Y. KATSUI)

derived from the deeper level.

Similarly sudden changes within a single cycle of eruption are found not only in caldera building activities, but also in other eruptions, namely those of the Plinian type. The favourable conditions which led to such differentiation of magma, are considered to be a) long quiescence preceded eruption, b) high water content in magma, and c) low viscosity of magma.

On the contrary, when such conditions were insufficient, an activity may continue changing its eruptive form; however, composition of the erupted material would not show successive variation, as manifested in 1783 activity of Mt. Asama, central Japan. Mt. Asama has almost 12

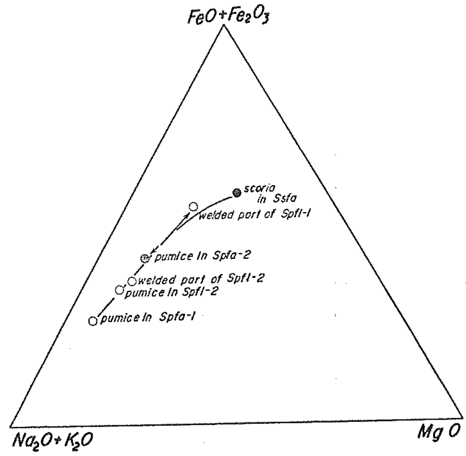


Fig. 8. Variation in composition of the ejecta from the Shikotsu volcano.

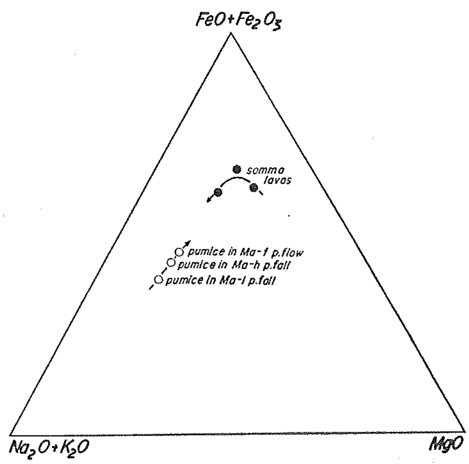


Fig. 9. Variation in composition of the somma lavas and pumice of the culminating eruption of the Mashû volcano.

records of activity in the 18th century. The 1783 activity started from pumice fall followed by nuée ardent, and ceased in an out-flow of block lava. However, no distinct difference of composition can be seen among these products (Fig. 11). Magmas which generate nuée ardent in strict sense seem to be more viscous than those which erupt pumice flow (ARAMAKI, 1956~1957).

Even mafic magmas, under favourable conditions, may become highly

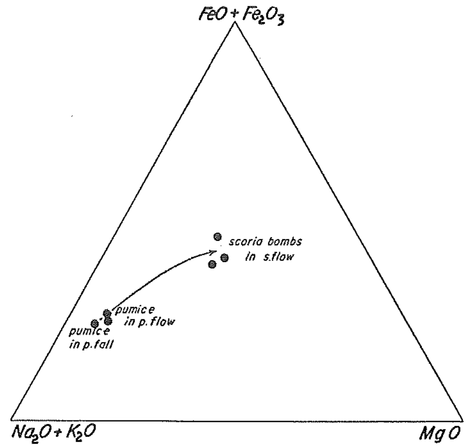


Fig. 10. Change in composition of the successive ejecta in the culminating eruptions of Mt. Mazama. (after WILLIAMS, 1942)

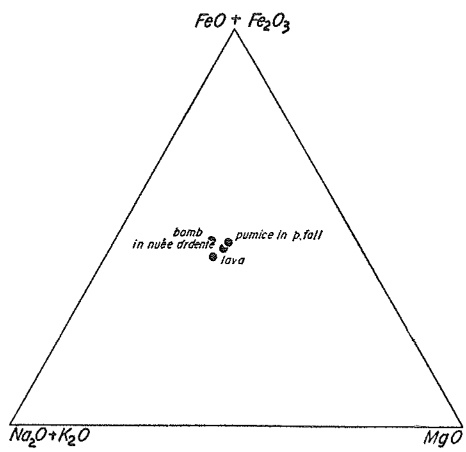


Fig. 11. Chemical composition of the materials of 1783 activity of Mt. (after ARAMAKI, 1957)

explosive, as manifested in the Plinian eruption (AD 79) of Vesuvius (RITTMANN, 1960), 1947~1948 activity of Mt. Hekla (THORARINSSON, 1950), and 1707 activity of Mt. Fuji (TSUYA, 1955).

According to THORARINSSON, 1947~1948 activity of Mt. Hekla was characterized by pumice eruption of Plinian type in initial phase, which was followed by lava pouring of "Vesuvian" or "Laki" type. The volcanic products converted from soda-rhyolite to pigeonite-andesite (Fig. 12).

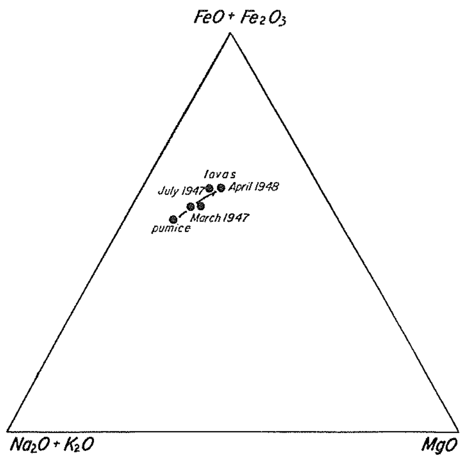


Fig. 12. Change in composition of 1947–1948 products of Mt. Hekla. (after THORARINSSON, 1950)

Such sequence in the change of composition within a continuous eruption can be traced throughout the post glacial volcanic activities of Mt. Hekla. Silica content of the initial product of an eruption increases with the length of the preceding interval of quiescence.

The eruption of Mt. Fuji in 1707 was studied by TSUYA (1955). According to him, after the quiescence prolonged for 1.5 century, the famous 1707 eruption of Mt. Fuji began with ejection of juvenile felsic pumice and obsidian for the first several hours. Subsequent to this, lapilli and bombs of basalt were expelled during two weeks. The felsic material

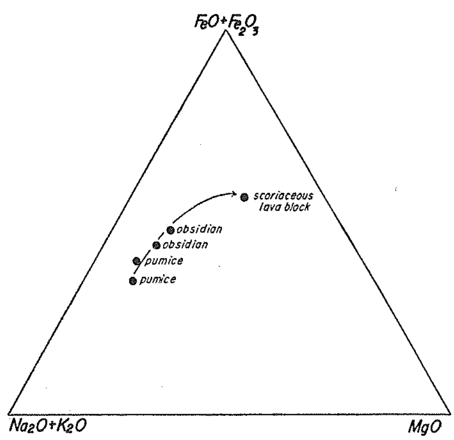


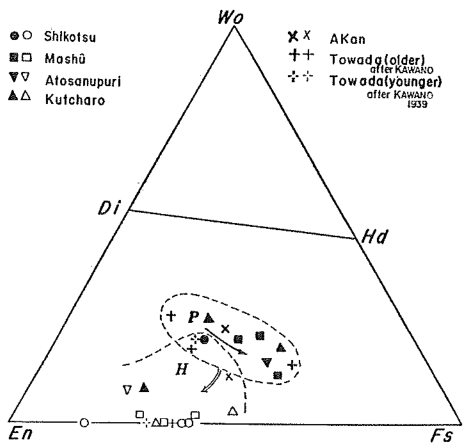
Fig. 13. Variation in composition of 1707 ejecta of Mt. Fuji. (after TSUYA, 1955)

is interpreted as having been derived through a process of crystallization-differentiation from the basaltic magma underlying the volcano (Fig. 13).

It is needless to say that differentiation of mafic magmas in the gravitational field does not necessarily retention of high water content as much as that in felsic magma. In this connection, VLODAVETZ (1959) gave an interesting example of 1937~1939 activity of the Kliuchevsky volcano, Kamchatka. This eruption took place from the summit crater at first, and proceeded to the lateral craters. As the eruption continued, the lavas became more mafic, that suggests the normal differentiation of basalt magma had taken place in the reservoir.

Origin of a great quantity of the felsic magma erupted during the caldera-building activity

There is, as yet, no satisfactory explanation for this problem. It is quite difficult to consider that great amounts of felsic magma are derived from basaltic magma through simple fractional cystalliaztion. As to this problem, three ideas may be considered that the felsic magmas are derived (1) from basaltic magma through contamination by wall rock, (2) from remelting of crust, or (3) from upper mantle as a primary magma. A tremendous amount of felsic magma exceeding a thousand km³ or more in volume may be originated in the latter two ways, because



P area: pigeonitic rock series *H* area: hypersthenic rock series

Fig. 14. Norm pyrxene composition of the volcanic products in strato-cone building stage (solid or thick marks) and caldera building stage (open or thin marks) of some Krakatoan calderas in north Japan.

the magmas are usually rhyolitic in composition and have not always intimate relation to basaltic magmas in their eruption.

However, felsic magmas less than several hundred km^3 in volume erupted usually after the effusion of somma lavas of basalt and andesite; their composition ranges from rhyolite, dacite to andesite, as shown in the following examples. Possibly, such felsic magmas were derived from basaltic magma in some way.

In Figure 14, compositions of the pumice and pumice-flow deposits of caldera building activity on representative ten volcanoes of north Japan are shown in comparison with those of the lavas and scoriae of their strato-cone building stage. All of them belong to the same petrographic province which is considered to be tholeiite magma in origin (KATSUI, 1961).

Concerning normative pyroxene, most of the somma lavas and scoriae are plotted in a high Wo and Fs area. Such chemical characteristics as well as their mineralogy suggest that they were originated through simple fractional crystallization of the tholeiite magma; that is the pigeonitic rock series of KUNO (1950), (KATSUI, 1961). On the contrary, all of the pumice and pumice-flow deposits are plotted in a Wo- and Fs-low area. Decreasing of Fs value must have resulted from oxidation of ferrous to ferric iron due to increasing of vapour pressure (KENNEDY, 1958; OSBORN, 1959) which would be ascribed to sialic contamination

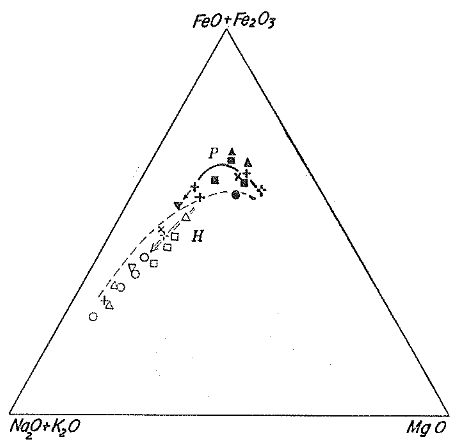


Fig. 15. MgO-FeO+Fe_2O_3-Na_2O+K_2O diagram for the volcanic products in strato-cone building stage (solid or thick marks) and caldera building stage (open or thin marks) of some Krakatoan calderas in north Japan. (Symbols same as Fig. 14)

as well as fractional crystallization of the magma. Decreasing of Wo value, nearly to zero, seems to be attributable also to sialic contamination (READ, 1923; KATSUI, 1961). Similar process is also shown in the $MgO-FeO+Fe_2O_3-Na_2+K_2O$ diagram (Fig. 15). The trend of evolution is usually from the composition of the parent series toward an increase in alkalies, never toward iron enrichment. A great deal of contaminated felsic magma must have been originated during a long period of quiescence which preceded the culminating phase.

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