



Title	Petrology of Historic Rhyolite and Dacite from Utsu Volcano (North Japan)
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Citation	北海道大学理学部紀要 2014 275 290
Issue Date	1983 11
Doc URL	http://hdl.handle.net/2115/36722
Type	bulletin (article)
File Information	2014p275-290.pdf



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PETROLOGY OF HISTORIC RHYOLITE AND DACITE FROM USU VOLCANO, NORTH JAPAN

by

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(with 5 text-figures and 5 tables)

Abstract

After several thousand years of dormancy, Usu Volcano renewed its activity in 1663, and seven eruptions occurred up to the present. The essential products are typical of low-K rhyolite and dacite, and varied with time from rhyolite to dacite, decreasing in silica and increasing in Al_2O_3 , CaO, MgO, and $FeO + Fe_2O_3$ contents, with a slight variation in trace-element abundances, but their Sr isotope ratios remains almost constant (0.70396 — 0.70399). In consistent with the variation in chemistry of the rocks, most of the plagioclase phenocrysts become more calcic and orthopyroxene more magnesian. The sequence of historic eruptions and the variation in composition of the products can be interpreted in terms of a compositionally zoned magma chamber which has formed before the first historic eruption. The presence of disequibrated phenocrysts in the historic felsic rocks, i.e. calcic plagioclase, magnesian orthopyroxene, clinopyroxene, and pargasitic hornblende, indicates a complex magma process. The process of incorporation of these crystals into the felsic magma and the formation of the zoned magma chamber are discussed.

Introduction

Mt. Usu, an active volcano, is situated on the southern rim of the Toya caldera in southwest Hokkaido, and seven eruptions have been recorded at this volcano since 1663. The volcanic edifice of Usu consists of a somma volcano, three lava domes and seven cryptodomes (Katsui et al., 1981; Soya et al., 1981).

The main body was formed by repeated eruptions of lava flows and scoriae of basalt and mafic andesite in the early Holocene age (Ōba, 1966). After the completion of a stratovolcano, about 7 or 8 thousand years ago, its summit was broken by a phreatic explosion accompanying a large debris avalanche, which resulted in the formation of a somma, 1.8 km in diameter and about 500 m in elevation. Thereafter the volcano had been in a dormant state for several thousand years. During this long period of quiescence, a felsic magma is considered to have been produced.

In 1663 Usu Volcano resumed its activity with a Plinian eruption which ejected rhyolite pumice amounting to as much as 6.5×10^8 tons (Ōba and Kondo, 1964; Ōba, 1966). This activity was followed by phreatic explosions accompanying base surges. Since then, six explosive eruptions have been recorded in 1769, 1822, 1853, 1910, 1943-1945, and 1977-1978, being sometimes accompanied by pyroclastic flows and volcanic mudflows. Occurrence of conspicuous crustal movements with earthquake

Contribution from the Department of Geology and Mineralogy, Faculty of Science, Hokkaido University, No. 1817.

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swarms and formation of lava domes or cryptodomes are the characteristic feature of the historic activities, which may be interpreted as due to the high viscosity of magma (Minakami et al., 1951; Yokoyama et al., 1973; Katsui et al., 1978b; Niida et al., 1980; Yokoyama et al., 1981). The sequence of the historic eruptions and their products is summarized in Table 1.

Table 1 Historic tephtras and domes of Usu Volcano

Year (AD)	Tephtra	Volcanic edifice newly formed
1663	Us-b pumice-fall (1 — 7) Us-b ₁ ~b ₆ ash fall & base surge	Ko-Usu lava dome (8)
1769	Us-Va pumice & ash-fall (9 & 10) Meiwa nuée ardente	⋮ ?
1822	Us-IVa pumice & ash-fall (11 & 12) Bunsei nuée ardente	Ogari-yama cryptodome (13 & 14)
1853	Us-IIa pumice & ash-fall (15) Kaei (Tateiwa) nuée ardente	O-Usu lava dome (16)
1910	Us-IIa ash-fall (phreatic) Volcanic mudflow	Meiji-Shinzan cryptodome
1943 -45	Us-Ia ash fall (phreatic)	Showa-Shinzan lava dome (17)
1977 -78	Us-1977 pumice & ash-fall (18 — 28) Us-1978 ash & pumice-fall (29 — 33)	Usu-Shinzan cryptodome (34)

Sequence of the tephtras based on Katsui et al. (1981). Figures in parentheses are the analysis numbers of Table 4.

The rocks of Usu Volcano occur bimodally, i.e. the somma lavas and scoriae are basalt and mafic andesite ($\text{SiO}_2 = 49.36 - 54.33\%$) of the low-K tholeiitic rock series (Ōba, 1966), whereas the historic dome lavas and essential tephtras are dacite and rhyolite ($\text{SiO}_2 = 67.70 - 73.29\%$) of the calc-alkaline (or hypersthenic) rock series of Kuno (1968). Intermediate rocks are lacking in this volcano.

Several chemical analyses of the rhyolite and dacite from Usu have been reported before the 1977-1978 eruption (Minakami et al., 1951; Ōba, 1966), and now about fifty major element analyses are available together with trace element and Sr isotope data for selected rocks. It is noticed that the composition of the historic products varies with time from rhyolite to dacite (Ōba et al., 1979). This evidence may be interpreted in terms of a compositionally zoned magma chamber (Katsui et al., 1978b; Ōba and Katsui, 1983). Recently, on the basis of mineralogy Okumura et al. (1980, 1981) showed that the zoned magma chamber was formed by mixing of andesitic magma into rhyolitic magma prior to the beginning of historic eruptions. This paper presents the results of detailed studies on mineralogy and chemistry of the historic rhyolite and dacite, with a discussion on the complex magma process.

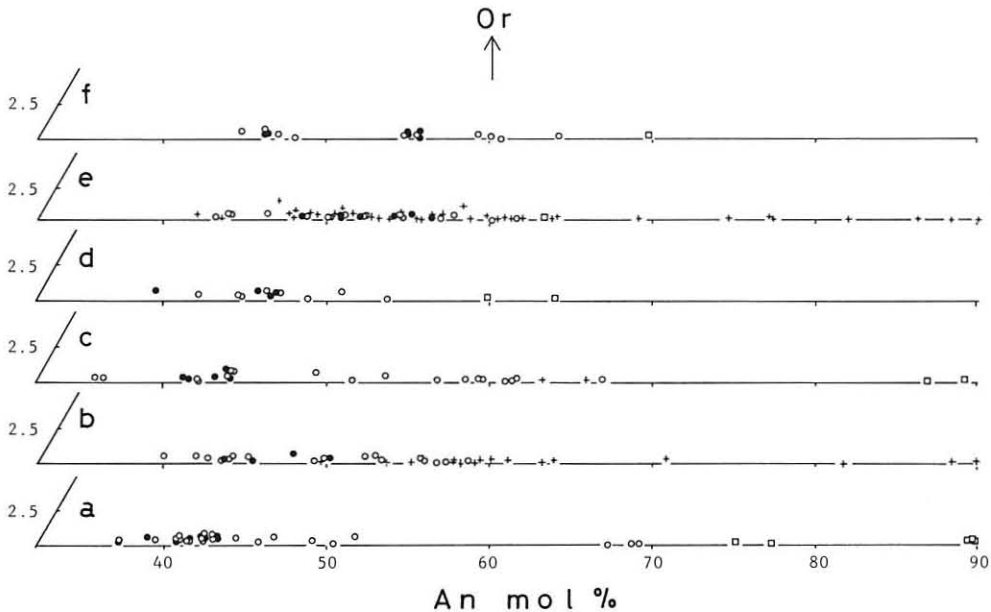
Petrography

The historic pumice and dome lavas are slightly porphyritic, but the total phenocrysts are less than 14% in volume. Plagioclase is most abundant, and orthopyroxene and titanomagnetite are subordinate. In places resorbed green amphibole and subhedral clinopyroxene phenocrysts are included in the earlier historic products, e.g. Us-b (1663) pumice, Us-Va (1769) and Us-IVa (1822) essential fragments, and rarely in pumice of Bunsei (1822) nuée ardente. In addition to both minerals, a few corroded quartz phenocrysts are found in Ko-Usu dome lava (1663 or 1769). These phenocrysts, however, are scarcely recognized in the products of recent years.

The groundmass of the pumice consists largely of silicic glass, but that of the dome lavas and essential blocks is more or less crystalline and composed of plagioclase, anorthoclase, cristobalite, orthopyroxene, and Fe-Ti oxide, with or without quartz, apatite, and glass.

Plagioclase, pyroxene and amphibole phenocrysts from the representative rocks were analyzed by EDX (Hitachi X-560S; Fujimaki and Aoki, 1980). The results are shown in Text-fig. 1 (plagioclase), Text-fig. 2 (orthopyroxene), and Table 2 (amphibole).

Plagioclase phenocrysts in the historic rhyolite and dacite usually show a complex



Text-fig. 1 Composition of plagioclase phenocrysts in the rhyolite and dacite from Usu Volcano (Ōba and Katsui, 1983, with additional data)

a: Us-b pumice, b: Ko-Usu dome lava, c: Us-Va essential fragment, d: Us-IVa pumice, e: Showa-shinzan dome lava, and f: Us-1977-II pumice.

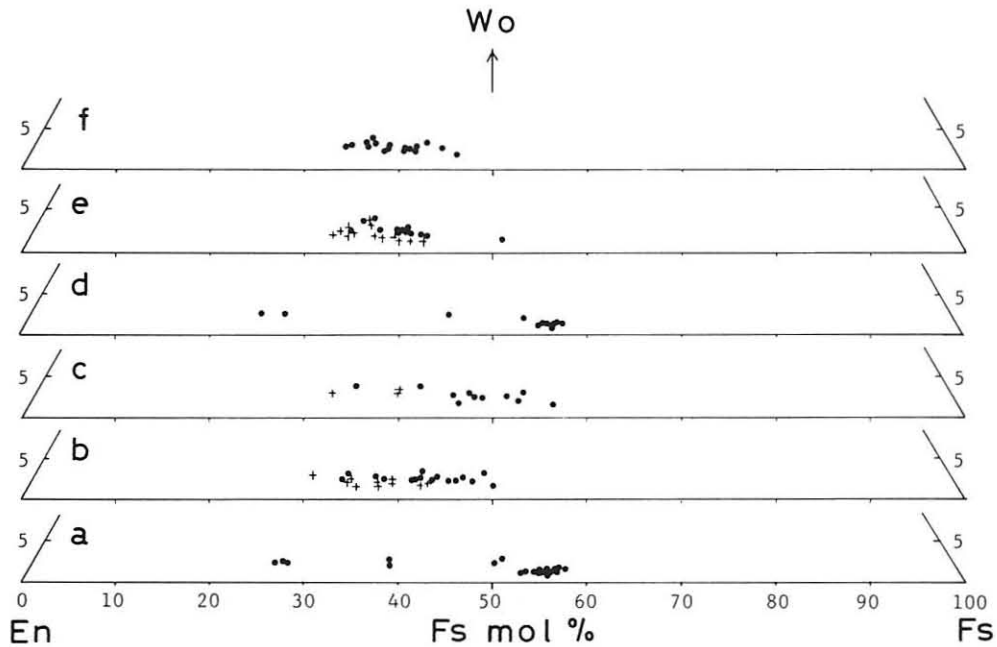
open circles: phenocrysts, solid circles: rims of phenocryst, open squares: calcic cores with dusty inclusion, and crosses: specimens in crystal clots.

zoning and have a wide range of composition (Text-fig. 1). Calcic plagioclase is included as a core in some phenocrysts as noticed by Ōba (1966), Katsui et al. (1978b) and Okumura et al. (1979, 1980). It is worthy to note that during historic time the An content of plagioclase increases with time especially at phenocryst rims as reported by Okumura et al. (1980, 1981), which is consistent with the increase in CaO content of the rocks as described later.

Orthopyroxene phenocrysts have also a wide range of composition from bronzite to ferrohypersthene (Text-fig. 2). During historic times their Fs content appears to decrease, and the range of compositional variation is markedly reduced with time as noted by Okumura et al. (1980). Orthopyroxene phenocrysts from the Ko-Usu dome lava, however, have a composition rather exceptional to this trend. It is also noticed that En-rich orthopyroxene (bronzite~hypersthene) occurs as a core in some phenocrysts. Clinopyroxene phenocrysts rarely found in the Us-b and the Us-IVa pumice are augite and subcalcic augite, respectively.

The above calcic plagioclase, magnesian orthopyroxene, and clinopyroxene included in the rhyolite and dacite are similar in composition to those of the basalt and mafic andesite of the somma (Ōba, 1966). Furthermore, the mode of occurrence of these minerals does not indicate that they are the crystallization products of the historic felsic magma. Hence, they are possibly xenocrysts derived from a mafic magma.

Amphibole phenocrysts from the Us-b pumice and Us-Va essential fragment have



Text-fig. 2 Composition of pyroxene phenocrysts in the rhyolite and dacite from Usu Volcano (after Ōba and Katsui, 1983). a-f: same as in Text-fig. 1, and solid circles: phenocrysts, and crosses: specimens in crystal clots.

pargasitic composition, being poor in silica and rich in Al^{IV} and $Na + K$ (Table 2). Pargasitic hornblende is common in andesitic rocks (Gill, 1981). It is unlikely that they are crystallization products of the felsic magma (Ōba and Katsui, 1983).

Crystal clots, 3 to 7 mm in size, consisting of calcic plagioclase (56–82%), hypersthene (8–20%), Fe-Ti oxide (2–10%), glass (0–14%) and cristobalite (0–8%), are often found in the dome lavas. An average value of calculated bulk chemical compositions of the clots is given in Table 3. This composition resembles that

Table 2 Average chemical composition of amphibole phenocrysts in the historic rhyolite and dacite from Usu Volcano

host rock	Us-b pumice		Us-Va essential fragment	
number of analysis	wt %	range	wt %	range
		9		5
SiO_2	43.03	41.52 — 44.34	44.63	43.70 — 46.73
TiO_2	2.26	2.16 — 2.37	2.02	1.89 — 2.10
Al_2O_3	11.78	10.53 — 12.49	10.21	9.52 — 11.10
FeO^*	13.34	12.31 — 15.19	16.65	14.22 — 18.30
MnO	0.30	0.19 — 0.48	0.44	0.36 — 0.49
MgO	13.74	12.41 — 14.67	11.94	11.35 — 13.09
CaO	10.96	10.56 — 11.40	10.46	9.83 — 10.91
Na_2O	2.38	1.80 — 2.80	1.77	1.52 — 1.90
K_2O	0.20	0.16 — 0.22	0.18	0.15 — 0.20
TOTAL	97.99		98.30	
Si	6.3296	} 8.000	6.6018	} 8.000
Al^{IV}	1.6704		1.3982	
Al^{VI}	0.3723	} 7.7571	0.3822	} 7.5539
Ti	0.2501		0.2249	
Fe	1.6414		2.0596	
Mn	0.0371		0.0551	
Mg	3.0132		2.6329	
Ca	1.7271		1.6578	
Na	0.6788		0.5076	
K	0.0371		0.0338	
O	23		23	

FeO*: total iron as FeO.

Table 3 Bulk chemical composition of crystal clots and a somma lava from Usu Volcano

	(1) crystal clots	(2) somma lava
SiO_2	51.37	54.33
TiO_2	1.09	0.62
Al_2O_3	20.75	19.91
FeO^*	11.12	8.18
MnO	0.32	0.17
MgO	3.51	3.22
CaO	8.45	9.16
Na_2O	3.16	2.84
K_2O	0.30	0.57
Total	100.07	99.00

FeO*: total iron as FeO.

1: Average composition of crystal clots in the dome lavas of Ko-Usu, Ogari-yama and Showa-Shinzan. The composition computed from mineral analyses and modal compositions.

2: Mafic andesite of the later stage of Usu somma lava. Loc. Kita-Byobu-yama, NW part of the Usu somma.

Analyses by Y. Ōba.

of the Usu somma lava, indicating that the crystal clots may not be breakdown products of amphibole.

Chemistry

Major elements

Fifteen bulk chemical analyses of the historic felsic rocks including previously published data, have been reported in Katsui et al. (1978b, Table 3). Thirty four new

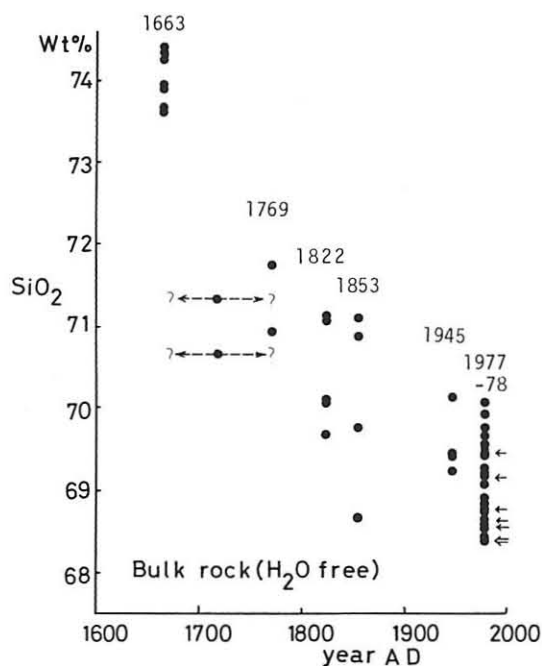
Table 4 Chemical analyses of the historic rhyolite and dacite from Usu Volcano (wt %)

No.	1	2	3	4	5	6	7	8	9	10	11	12
SiO ₂	73.10	72.40	72.73	72.16	73.25	72.35	73.29	70.19	69.30	70.96	69.95	69.60
TiO ₂	0.22	0.21	0.22	0.23	0.20	0.23	0.16	0.32	0.26	0.32	0.31	0.39
Al ₂ O ₃	13.79	14.48	14.49	14.22	14.03	14.34	14.33	14.94	14.91	14.74	15.43	15.39
Fe ₂ O ₃	0.84	0.64	0.48	0.89	0.60	0.48	0.64	1.96	1.15	1.21	1.25	1.12
FeO	1.55	1.50	1.57	1.56	1.55	1.96	2.04	1.73	2.37	2.10	1.92	1.85
MnO	0.17	0.16	0.16	0.18	0.16	0.09	0.14	0.12	0.12	0.16	0.16	0.14
MgO	0.29	0.25	0.23	0.34	0.24	0.43	0.36	0.76	0.74	0.64	0.69	0.87
CaO	1.98	2.21	2.16	2.33	2.32	2.03	2.11	3.49	3.21	2.94	3.08	3.34
Na ₂ O	4.69	4.83	4.88	4.72	4.90	4.94	4.43	4.61	4.27	4.48	4.45	4.57
K ₂ O	1.16	1.21	1.30	1.24	1.18	1.29	0.96	1.06	1.08	1.21	1.06	1.08
P ₂ O ₅	0.21	0.10	0.09	0.11	0.08	0.09	0.21	0.33	0.23	0.17	0.16	0.08
H ₂ O (+)	1.69	1.28	1.43	1.31	0.95	1.08	0.73	0.00	1.48	0.62	0.89	1.02
H ₂ O (-)	0.28	0.27	0.54	0.25	0.17	0.22	0.10	0.16	0.32	0.08	0.15	0.27
Total	99.97	99.54	100.28	99.54	99.63	99.53	99.50	99.67	99.44	99.63	99.50	99.72
No.	13	14	15	16	17	18	19	20	21	22	23	24
SiO ₂	69.58	69.40	70.03	69.23	69.07	69.22	69.09	68.63	68.87	68.98	68.34	68.85
TiO ₂	0.32	0.44	0.31	0.36	0.46	0.45	0.44	0.44	0.45	0.44	0.45	0.45
Al ₂ O ₃	15.88	14.98	14.53	15.40	15.48	15.20	14.95	14.76	14.69	15.20	15.20	15.19
Fe ₂ O ₃	1.16	1.49	1.94	1.82	2.13	1.55	1.53	1.63	1.56	1.32	1.51	1.32
FeO	2.48	2.69	2.13	2.09	2.26	2.42	2.46	2.26	2.38	2.57	2.56	2.74
MnO	0.14	0.16	0.11	0.15	0.16	0.16	0.15	0.14	0.15	0.15	0.15	0.15
MgO	0.78	0.90	0.71	0.91	0.92	0.92	0.89	0.88	0.87	0.81	0.90	0.91
CaO	3.59	3.99	3.34	3.83	3.84	4.12	3.90	3.91	3.95	4.00	4.05	3.99
Na ₂ O	4.19	4.43	4.12	4.15	4.07	4.48	4.68	4.60	4.63	4.59	4.55	4.48
K ₂ O	0.79	0.91	0.99	1.08	0.99	1.02	0.93	0.93	1.00	0.92	0.92	0.92
P ₂ O ₅	0.19	0.16	0.17	0.21	0.15	0.16	0.16	0.21	0.16	0.16	0.16	0.18
H ₂ O (+)	0.33	0.48	0.89	0.19	0.20	0.83	1.05	0.76	0.74	0.48	0.31	0.43
H ₂ O (-)	0.06	0.28	0.26	0.14	0.06	0.23	0.31	0.57	0.18	0.31	0.20	0.28
Total	99.49	100.31	99.53	99.56	99.79	100.76	100.54	99.72	99.63	99.93	99.30	99.89
No.	25	26	27	28	29	30	31	32	33	34		
SiO ₂	69.03	68.01	67.89	68.19	68.51	69.37	68.47	69.11	68.07	67.70		
TiO ₂	0.44	0.44	0.37	0.33	0.42	0.44	0.42	0.45	0.46	0.38		
Al ₂ O ₃	14.66	15.22	15.53	15.93	15.95	15.19	15.46	15.31	15.55	15.75		
Fe ₂ O ₃	1.33	1.44	1.24	1.43	1.43	1.66	2.00	1.79	1.93	1.84		
FeO	2.66	2.86	2.76	2.51	2.40	2.39	2.01	2.39	1.85	2.31		
MnO	0.16	0.16	0.15	0.14	0.15	0.14	0.15	0.14	0.21	0.19		
MgO	0.89	0.89	0.96	0.88	0.96	0.92	0.96	0.90	1.00	0.94		
CaO	3.90	4.03	3.97	4.21	3.94	4.07	4.30	4.11	3.94	3.77		
Na ₂ O	4.59	4.63	4.57	4.44	4.53	4.59	4.56	4.52	4.68	4.72		
K ₂ O	0.90	0.95	1.12	1.31	1.01	0.97	1.10	1.00	1.26	1.17		
P ₂ O ₅	0.17	0.16	0.22	0.26	0.33	0.15	0.33	0.15	0.33	0.21		
H ₂ O (+)	0.57	1.22	0.43	0.50	0.28	0.59	0.51	0.49	0.20	0.73		
H ₂ O (-)	0.38	0.44	0.23	0.04	0.08	0.06	0.02	0.04	0.04	0.21		
Total	99.68	100.45	99.44	100.17	99.99	100.54	100.29	100.40	99.52	99.92		

- 1: Essential lithic fragment from the basal part of the Us-b pumice-fall deposit (1663). Loc. Tateka, Sōbetsu town, 2.2 km ESE of Showa-Shinzan.
 - 2: Pumice from the same deposit, about 2 m from the top. Loc. same as 1.
 - 3: Ditto, 105 cm from the top. Loc. same as 1.
 - 4: Ditto 90 cm from the top. Loc. same as 1.
 - 5: Ditto, 30 cm from the top. Loc. same as 1.
 - 6: Pumice from the upper part of the same deposit. Loc. Sōbetsu town, 1.8 km ENE of Showa-Shinzan.
 - 7: Essential lithic fragment from the upper part of the same deposit. Loc. same as 6.
 - 8: Dome lava of Ko-Usu (1663 or 1769).
 - 9: Dense pumice from the lower part of the Us-Va pumice & ash fall deposit (1769). Loc. Sōbetsu town, 1.5 km ENE of Showa-Shinzan.
 - 10: Dense pumice from the same deposit. Loc. eastern slope of the Usu somma.
 - 11: Pumice from the Usu-IVa pumice & ash-fall deposit (1822) Loc. Karataki-zawa, southern foot of Showa-Shinzan.
 - 12: Ditto. Loc. eastern foot of the Usu somma.
 - 13: Cryptodome lava of Ogari-yama (1822) appeared by subsequent faulting. Loc. southern scarp of the 1977-1978 major fault.
 - 14: Ditto. Loc. same as 13.
 - 15: Pumice from the lower part of the Us-IIIa pumice & ash-fall deposit (1853). Loc. same as 9.
 - 16: Dome lava of O-Usu. Loc. southern foot of O-Usu.
 - 17: Dome lava of Showa-Shinzan. Loc. northern wall of the dome.
 - 18: Pumice from the Us-1977-I pumice-fall deposit.
 - 19: Pumice from the Us-1977-II pumice-fall deposit.
 - 20: Grey pumice from the same deposit.
 - 21: Ditto.
 - 22: White pumice from the Us-1977-III pumice-fall deposit.
 - 23: Grey pumice from the same deposit.
 - 24: White pumice from the Us-1977-IV pumice-fall deposit.
 - 25: Grey pumice from the same deposit.
 - 26: Grey pumice from the Us-1977-SB pumice & ash-fall deposit.
 - 27: Glassy surface of a bread-crust bomb from the same deposit.
 - 28: Grey pumice from the same deposit.
 - 29: Grey pumice ejected from L-crater on July 16, 1978.
 - 30: Grey pumice ejected from K-crater on Aug. 24, 1978.
 - 31: Dense grey pumice ejected from K-crater on Aug. 24, 1978.
 - 32: Dense grey pumice ejected from M-crater on Sept. 8, 1978.
 - 33: Essential fragment (bomb) ejected from K-crater on Oct. 5, 1978.
 - 34: A block of possible new lava appeared on the northern wall of I-crater in 1978. Loc. foot of the northern wall of I-crater.
- Analyses 14, 18, 19-26, 30, & 32 by Y. Ikeda and T. Uda (XRF method except for FeO, P₂O₅ and H₂O), and the rest by Y. Ōba (wet method).

analyses are given in Table 4, most of which were analyzed by conventional wet method and partly by XRF.

Silica contents of the historic products decrease from 73.29 to 67.70% with time (Text-fig. 3), but those of each eruption cycle vary within a limited range of about 2% SiO₂. The 1977-1978 products range in silica contents from 69.37 to 67.70%, and it appears that less silicic products tend to have erupted in the later stage of this eruption cycle (Table 4, Nos. 18 to 34). However, the pumice and essential fragments of the Us-b pumice-fall deposit which comprises a substantial part of the whole historic products, show neither considerable nor systematic variation in composition from the bottom to top of the deposit (Table 4, Nos. 1 to 7).

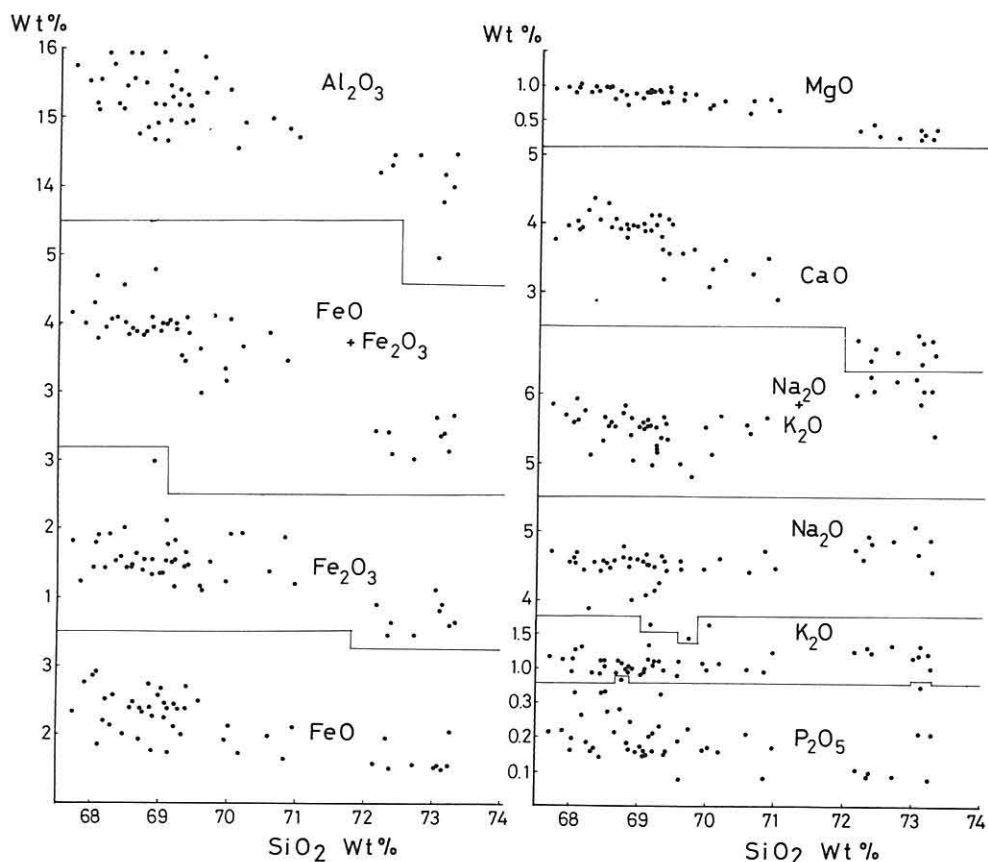


Text-fig. 3 SiO₂ content (H₂O free) of the historic products of Usu Volcano versus their age (AD). The date of Ko-Usu lava dome is 1663 or 1769. The 1978 products are distinguished from those of 1977 by arrows (single arrow: pumice and essential fragments, and double arrow: a block of possible new lava). (Ōba and Katsui, 1983)

Oxides versus silica diagrams for the rhyolite and dacite are illustrated in Text-fig. 4. It is evident that the K₂O content is very low for such silicic rocks and remains almost constant. Accordingly, the historic products of Usu are typical of the low-K dacite and rhyolite (Ewart, 1979) and all comprized in “dacite” of Irvine and Barager (1971). Such low-K and high silica volcanic rocks occur characteristically in early stage of island arc volcanism or intra-oceanic island arcs, e.g. Fiji (Gill, 1970), Tonga-Kermadec Islands (Bryan, 1970, 1979; Ewart et al. 1973), and South Sandwich Islands (Gass et al., 1963). CaO content of the rhyolite and dacite apparently decreases with increasing silica. The Peacock’s alkali-lime index for the Usu rocks is as high as 67. Such an extremely high index is also the characteristic feature of the low-K and high silica rocks. (e.g. Bryan, 1968, 1970, 1979). The iron oxides and MgO contents also decrease with increasing silica and the normative Fs/En + Fs ratios increase with silica, being consistent with the compositional change of the orthopyroxene phenocrysts as noticed earlier (Text-fig. 2)

Trace elements

Trace element abundances of some of the rocks from Usu Volcano have been reported (Ando, 1971; Masuda et al., 1975; Fujimaki, 1977; Katsui et al., 1978a; Tsunakawa and Kaneoka, 1978). In the present study, 13 representative rocks from the Usu somma lavas and historic products were selected, and their Ba, Rb, and Sr contents were determined by mass spectrometry (analyst, H.K.), and Co, Cr, Cu, Ni and V contents by atomic absorption spectrometry (analyst, Y.Ō.). Rb content of some



Text-fig. 4 Oxides versus silica diagrams for the historic products of Usu Volcano.

samples was also measured by mass spectrometry (analyst, Y.I.). The analytical results are listed in Table 5.

The felsic rocks of Usu Volcano show a notable variation in major element and mineral compositions, however their trace element abundances do not exhibit notable change, except for the earlier rhyolites which are generally depleted in Co, Cr, Cu and Ni compared with the later dacites.

The trace element abundances of the Usu rocks, as a whole, are similar to those of the low-K tholeiitic series from island arcs (Jakeš and Gill, 1979; Jakeš and White, 1971, 1972), except for Ba and Ni. The felsic rocks from Usu are characterized by low concentrations of large-ion-lithophile elements, but they are high in Ba (430–480 ppm) and Ni (5–14 ppm) contents as compared with the typical dacite of island arc tholeiitic suites (Jakeš and White, 1971). The high K/Rb ratios (561–700) and low La/Yb ratios (3.78–3.84; Fujimaki, 1977) of the Usu felsic rocks indicate a transitional feature between the typical felsic rocks of the island arc tholeiitic suites (870 and 1.9, respectively) and those of the calc-alkaline rock series (380 and 10) (Jakeš and

Table 5 Trace element abundances (ppm) and Sr isotope ratios of the rocks from Usu Volcano.

No.	1	2	3	4	5	6	7	8	9	10	11	12	13	JB-1	JG-1
SiO ₂	49.36	51.80	52.81	53.02	53.21	53.36	72.35	70.19	69.23	69.07	68.74	69.34	67.07		
K	1513	3866	3614	4874	4454	4286	10707	8798	8964	8798	9130	8466	10458		
Ba	123	146	168	202	124	180	466	444	457	470	442	457	463	490	462
Rb	2.4 ^{b)}	4.7	5.8	7.2	6.8	6.5	17.3 ^{b)}	13.6	12.8	14.7	14.2 ^{c)}	15.1 ^{d)}	15.9	41.2	181
Sr	220	262	232	240	333	314	306	283	311	346	248 ^{e)}	254 ^{f)}	322	435	184
Co	67	69	46	43	91	51	4	28	35	22	19	20	29	56	13
Cr	45	58	36	15	18	15	1	1	4	3	4	1	1	426	60
Cu	57	53	72	93	78	80	1	1	5	1	1	2	2	57	3
Ni	86	50	36	24	31	29	5	14	11	10	11	11	13	154	9
V	279	240	271	316	262	261	18	27	17	27	19	17	24	206	18
K/Rb	629	823	622	676	654	660	622	647	700	599	643	561	660	290	181
⁸⁷ Sr/ ⁸⁶ Sr #	0.70410	0.70398	0.70397	0.70399	0.70397	0.70396	0.70399	0.70402	0.70402	0.70404	0.70402	0.70401	0.70407	0.70417	0.71083

1-6: Somma lavas (Ōba, 1966, Table 7, Nos. 1-6)

7: Us-b pumice (Table 4, No. 6)

8: Dome lava of Ko-Uzu (Table 4, No. 8)

9: Dome lava of O-Uzu (Table 4, No. 16)

10: Dome lava of Showa-Shinzan (Table 4, No. 17)

11: 1977-I pumice (Katsui et al., 1978a, Table 3, No. 11)

12: 1977-II pumice (Katsui et al., 1978a, Table 3, No. 12)

13: 1978-Oct. 5 essential fragment (Table 4, No. 33)

a) 4.2 ± 0.1 and b) 19 ± 1 ppm by isotope dilution method, analyses by Y. Ikeda.

c) 12, d) 15, e) 219, and f) 251 ppm by XRF method on different samples (Tsunakawa and Kaneoka, 1978).

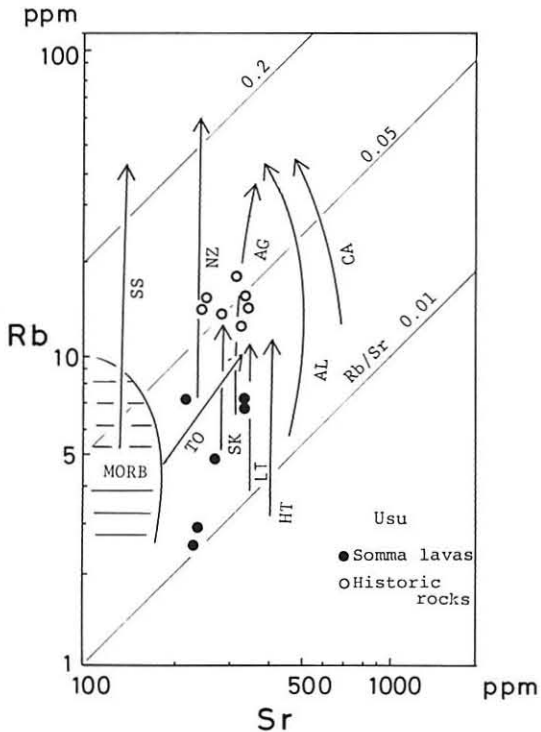
: E & A SrCO₃ standard 0.708054 ± 8 (1 σ) and NBS 987 SrCO₃ standard 0.710278 ± 9 (1 σ).

SiO₂, K, Co, Cr, Cu, Ni and V analysed by Y. Ōba.

Ba, Rb, Sr and Sr isotope ratios determined by H. Kurasawa.

White, 1970, 1971; Ewart, 1979).

The Rb-Sr relation of the Usu rocks is shown in Text-fig. 5. The trend of the Usu rocks resembles the low-K tholeiitic rock series from Japan (Kurasawa and Fujimaki, 1977; Kurasawa, 1980), Tonga (Ewart et al., 1973), and St. Kitts, Lesser Antilles (Brown et al., 1977).



Text-fig. 5 Rb vs. Sr contents in the rocks from Usu Volcano in comparison with those from island arcs and continental margins (Kurasawa and Fujimaki, 1977; Gill, 1981). Arrows indicate fractionation trends.

SS: South Sandwich Islands (Gledhill and Baker, 1973), TO: Tonga (Ewart et al., 1973; Bryan, 1979), NZ: New Zealand (Ewart and Stipp, 1968; Cole, 1978), SK: St. Kitts, Lesser Antilles (Brown et al., 1977; Tomblin, 1979), AG: Agrigan, north Mariana (Stern, 1979), HT: High-alkali tholeiite, Japan (Kurasawa and Fujimaki, 1977; Kurasawa, 1980), LT: Low-alkali tholeiite, Japan (ditto), AL: Aleutian Islands (DeLong, 1974), CA: Cascades (Church and Tilton, 1973), MORB: Mid-oceanic ridge basalts.

Sr isotope ratios

The Sr isotope ratios ($^{87}\text{Sr}/^{86}\text{Sr}$) of the Usu rocks are generally low (Katsui et al., 1978a). In the present study, the Sr isotope ratios of the 13 selected samples, most of which have been used for the previous measurements, were newly determined by H.K. using VG Isomass 54E (with double collector) and the results are shown in Table 5.

The new data of the Sr isotope ratios of the Usu rocks vary within a very limited range (0.70396—0.70410). It is noticed that the early lava (Table 5, No. 1) of the Usu Volcano is slightly higher in Sr isotope ratio than other somma lavas. On the other hand, the initial product of the historic activity (No. 7) is slightly lower in this ratio than other historic rocks. Except for both earlier products, the Sr isotope ratios are surprisingly uniform in the somma lavas (0.70396—0.70399) and the historic felsic rocks (0.70401—0.70407), respectively.

Discussion

Compositionally zoned magma chamber

As described in the earlier chapters, during historic times the essential products of Usu Volcano varied from rhyolite to dacite, decreasing in silica contents from 73.29 to 67.70% and increasing in Al_2O_3 , CaO, MgO and $\text{FeO} + \text{Fe}_2\text{O}$ contents. A slight variation in the trace-element abundances is also recognized, but the Sr isotope ratios remain almost constant. This chemical variation with time is consistent with mineralogical change in phenocrysts, i.e. most of plagioclase phenocrysts become more calcic and orthopyroxene more magnesian, although they have a wide range of composition. This evidence can be interpreted in terms of a compositionally zoned felsic magma chamber with silica increasing upwards, which formed prior to the first historic Plinian eruption in 1663, as previously pointed by Katsui et al. (1978b) and Ōba et al. (1979).

Thus, the sequence of historic eruptions of Usu can be interpreted as follows. The first historic eruption of Plinian type occurred in 1663, ejecting a large amount of highly vesiculated rhyolite pumice (Us-b pumice) which originated from the apex of the magma column where silica and volatile substances were concentrated. Due to discharging of a large volume of magma, eruptions were interrupted by a quiescence for about 100 years. Then, dacite eruptions occurred at intervals of 30 — 50 years, being accompanied by formation of lava domes or cryptodomes. The composition of the products has been gradually changing during last 200 years, indicating that each successive eruption tapped a deeper level in the compositionally zoned magma chamber.

Genesis of the historic felsic magma

The Usu somma lavas vary from augite-bronzite-olivine basalt ($\text{SiO}_2 = 49.36\%$) to augite-hypersthene andesite ($\text{SiO}_2 = 54.33\%$) toward the later stage, showing a typical trend of fractional crystallization of a low-K tholeiitic magma (Ōba, 1966). This fractional crystallization process is also supported by the new data of Sr isotope ratios as well as the behavior of REE (Fujimaki, 1977; Fujimaki and Kurasawa, 1981).

An important problem, however, arises here as for the genesis of the historic felsic magma. A model calculation showed that a rhyolitic magma can be produced by fractionation of 85% of crystal from the tholeiitic magma (Ōba, 1966). The absence of intermediate rocks in Usu Volcano may indicate that the fractional crystallization has completely proceeded to yield the felsic magma during a long period of quiescence for several thousand years before the historic activity. However, the behavior of REE in the felsic rocks, that is limited REE enrichment, especially rather depleted in HREE, and small negative Eu anomalies compared with the somma lavas, is hardly explained in terms of the simple fractional crystallization process alone (Fujimaki, 1977). The difference in Sr isotope ratios between the somma lavas and the felsic rocks is small, but may not be neglected in consideration of the genesis of the felsic magma. It is suggested that if the felsic magma was derived from the tholeiitic magma mainly by fractional crystallization, other processes, e.g. wall-rock contamination, mixing of magma,

and others, were taking place simultaneously, though their effects on REE abundances and Sr isotope ratios are not ascertained as yet.

It appears that there are no marked evidences for wall-rock contamination in the felsic rocks at least as far as they are inspected under the microscope. However, the presence of disequilibrated crystals in the felsic rocks indicates a process of magma mixing as discussed by Okumura et al. (1980). On the basis of detailed analyses of zoning pattern of the plagioclase and orthopyroxene phenocrysts, Okumura et al. (1981) considered that a hornblende andesite magma injected into the bottom of the rhyolitic magma. However, the existence of the hornblende andesite magma comes into question, because such andesitic magma has never erupted in Usu Volcano. The hornblende phenocrysts included in the earlier historic products are pargasitic in composition. Pargasitic hornblende occurs commonly in andesitic rocks (Ewart, 1979; Gill, 1981). There is a positive correlation in K content between amphiboles and their host rocks (Ujike and Onuki, 1976; Yamamoto et al., 1977). As shown in Table 2, the pargasitic hornblende from Usu Volcano may represent the lowest K variety, indicating that it precipitated from low-K andesitic magma. Accordingly, the pargasitic hornblende was possibly derived from the low-K magma of Usu Volcano. It is probable that the pargasitic hornblende was formed through reaction of magnesian olivine with mafic to intermediate magma at high P_{H_2O} , as discussed by Anderson (1980).

Mixing of the hornblende andesite magma and the rhyolite magma may have resulted in the formation of the compositionally zoned magma chamber because of different mixing ratios of the two magmas at different levels, as suggested by Okumura et al. (1981). The first historic Plinian eruption in 1663 would have been triggered by the injection of the andesite magma into the rhyolite magma through the mechanism proposed by Sparks et al. (1977). This mixing hypothesis, however, encounters difficulties because neither pargasitic hornblende phenocrysts nor their breakdown products are recognized in the dacite of recent years, though their abundant occurrence is expected from the higher mixing ratio of the hornblende andesite magma. Alternatively, other processes, e.g. convective stirring and mixing of crystals and liquid within a chamber, may have played in the formation of the zoned magma chamber.

Concluding Remarks

The historic essential products of Usu Volcano vary from rhyolite to dacite with time. They are typical low-potassic felsic rocks poor in Rb and Sr contents. There is a slight difference in Sr isotope ratios as well as in REE concentrations between the prehistoric somma lavas and the historic felsic rocks, which suggests that if the latter were derived mainly through fractional crystallization from the low-K tholeiitic magma that fed the somma lavas, other processes were possibly taking place simultaneously.

The mineralogical and chemical variations with time of the felsic rocks can be interpreted in terms of a compositionally zoned magma chamber with silica increasing upwards, which has formed before the historic eruptions. It seems that the zoned magma chamber was not produced by mixing of two different magmas alone, but by convec-

tive stirring within the chamber.

Acknowledgements

We are indebted to Prof. T. Konda and Dr. H. Tanaka of Yamagata University for their helpful discussion and advice. Sincere thanks are due to Prof. K. Aoki and Drs. T. Yoshida and H. Fujimaki of Tohoku University for use of EDX probe analyser, Dr. S. Yamasaki of Hokkaido National Agricultural Experiment Station for use of XRF analyser, Dr. T. Watanabe of Shimane University for analysis of an amphibole phenocryst, Dr. K. Niida of Hokkaido University for supply of samples to this study, and Mrs. S. Yokoyama of the same university for typing manuscript. We are also grateful to Dr. N. Stevens of University of Queensland and Prof. T. Bamba of Hokkaido University for a critical reading of the manuscript. This study was supported financially in part by the Grant for Scientific Research from the Ministry of Education, Science and Culture of Japan.

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(Manuscript received on August 23, 1983)