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Unzen Volcano : the 1900-1992 eruption

Ohta, Kazuya
Shimabara Earthquake and Volcano Observatory, Kyushu University

Nakada, Setsuya
Department of Earth and Planetary Sciences, Kyushu University

Okada, Hakuyu
Department of Earth and Planetary Sciences, Kyushu University

Matsuo, Norimichi
Shimabara Earthquake and Volcano Observatory, Kyushu University

他

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14. Temporal Variation in Chemical Composition of the Lava Extruded from the Jigokuato Crater, Unzen Volcano

Takeru YANAGI, Setsuya NAKADA and Shun'ichi MAEDA[1]

Introduction

The volcanic eruptive activity at Unzen volcano began with a phreatic eruption from the Kujukushima and Jigokuato craters open at the top of the Fugendake cone on 17 October 1990. The eruptive activity rapidly declined with time and almost stopped within a week. Much water erupted and ponded in two craters. Another new Byobuiwa crater opened on 12 February 1991. Then intermittent eruptions of ash clouds continued until the beginning of May 1991. On 20 May 1991, a lava dome emerged in the Jigokuato crater. The extrusion of lava continued and then filled the crater by 23 May. On 23 May the lava started overflowing from the crater towards a valley on the eastern slope of the Fugendake cone. The intermittent collapses of the lava dome resulted in the formation of successive pyroclastic flows, one of which ran more than 3.5 km along the Mizunashi river, burning houses and killing 43 persons including three missing. The extrusion of lava has continued at a rate of about 300,000 m^3 per day and the total volume exceeded more than 9×10^7 m^3 by the beginning of April 1992. Since the volcanic eruption was progressing very slowly, however, and showed varied aspects, it presented a unique chance to see its origin from the variation in lava composition along with the systematic geophysical observation.

The volcanic activity is originally due to magma lying beneath the volcano. Therefore chemical data on the lava, assembled with the geophysical observation of the volcano, presents information important for understanding the volcanic activity. Since we assume that the lava directly brings information as to chemical and physical conditions in the chamber to the surface, we at first present characteristics and a temporal variation in its chemistry from 20 May 1991, until the end of April 1992. Then we try to elucidate an eruption mechanism on the basis of the chamber model proposed by Yanagi et al. (this book).

Mineralogical characteristics of the lava extruded from the Jigokuato Crater.

The lava has a marked porphyritic texture with abundant phenocrysts such as plagioclase (11-12 vol%), hornblende (1.8 - 3.4 vol%), biotite (1.2 - 1.7 vol%), quartz (1.3 - 2.0 vol%), orthopyroxene (<0.04 vol%), clinopyroxene (0.03 - 0.2 vol%), and magnetite (0.5 - 1.1 vol%). Table 14-1 is a list of the modal abundance of phenocryst minerals in lava samples.

Plagioclase pnenocrysts comprise three types different in texture. They are clear tabular crystals, crystals having a sieve texture with many glass inclusions, and crystals having a dusty marginal zone with abundant minute glass inclusions. Hornblende phenocrysts in lava

Table 14-1. Modal abundances of phenocryst minerals

Date of sampling	May 24,1991	May 27,1991	June 1,1991
Quartz	1.6%	1.3%	2.0%
Plagioclase	10.9	11.8	12.2
Hornblende	1.8	2.3	3.4
Biotite	1.3	1.2	1.7
Orthopyroxene	0	0	0.04
Clinopyroxene	0.18	0.05	0.03
Magnetite	1.1	1.0	0.5
Total Phenocrysts	16.9	17.6	19.8
Groundmass	83.1	82.4	80.2
ToTal	100.0	100.0	100.0

1 Department of Earth and Planetary Sciences, Kyushu University

samples comprise two types different in color. One is pale brownish green and the other is light reddish brown. The latter seems to be formed by oxidation from green hornblende. The change in color from green to reddish brown is often observed within a single phenocryst. Brown biotite phenocrysts often have a thick opacite rim composed of dry assemblages of minerals such as magnetite, pyroxenes and plagioclase. Though they still remain in high form of crystal, all quartz phenocrysts have rounded and corroded forms. Often they show marked hollow structures.

All the samples have the same mineral assemblage of phenocrysts, and the variation in modal composition is small. The lava is hornblende bearing biotite dacite. The total amount of phenocrysts is the same as in the Sin'yake lava extruded in 1792, and is the lowest among the volcanic rocks of Unzen volcano.

The sieve texture and the dusty marginal zone observed in plagioclase phenocrysts, the opacite rim around biotite phenocrysts, the oxidation of some hornblende phenocrysts, and the marked corroded forms of quartz phenocrysts indicate

Table 14-2. Chemical composition of ash samples

Date of sampling	24/11/'90	18/3/'91	24/3/'91	31/3/'91	9/4/'91	30/4/'91
SiO_2	64.4	63.7	63.7	63.8	63.1	63.0
TiO_2	0.75	0.74	0.74	0.74	0.76	0.77
Al_2O_3	16.7	16.6	16.6	16.7	16.9	17.2
Fe_2O_3	6.08	5.32	5.31	5.32	5.42	5.53
MnO	0.05	0.08	0.08	0.07	0.07	0.08
MgO	1.94	2.33	2.36	2.30	2.36	2.30
CaO	4.75	5.19	5.20	5.06	5.32	5.34
Na_2O	3.28	3.84	3.73	3.76	3.85	3.57
K_2O	1.98	2.12	2.07	2.08	2.10	2.13
P_2O_5	0.12	0.13	0.13	0.13	0.14	0.18

Analyzed bt X-ray fluorecence method on dried samples (volitile free). Fe2O3 represents the total iron content

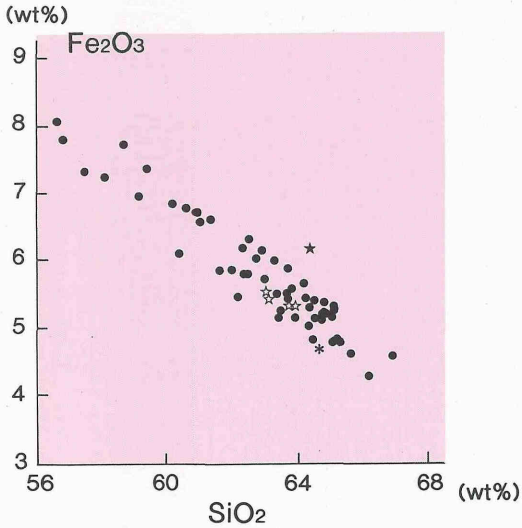

Fig. 14-1. Comparison between ash samples and Unzen volcanic rocks in chemical composition. Solid star, 24 November 1990; Open star, 18, 24, 31 March and 9, 30 April 1991; Asterisk, 1991-1992 lava; Solid circle, Unzen volcanic rocks.

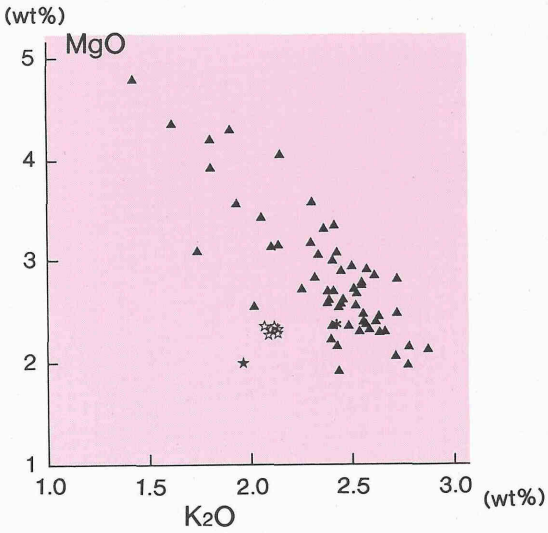

Fig. 14-2. Comparison between ash samples and Unzen volcanic rocks in chemical composition. Solid star, 24 November 1990; Open star, 18, 24, 31 March and 9, 30 April 1991; Asterisk, 1991-1992 lava; Solid triangle,Unzen volcanic rocks.

disintegration and/or melting, suggesting the heating of the magma before the eruption. This is very important for understanding the eruption.

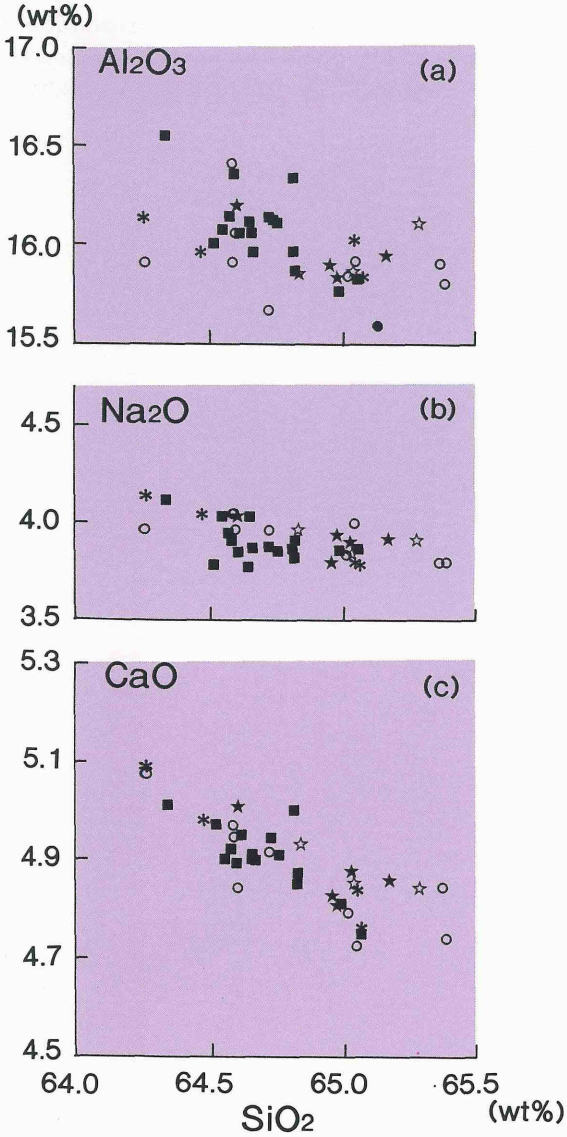

Fig. 14-3. SiO_2 versus oxides variation diagrams for 1991-1992 lava samples.
Solid square, 24 May to 12 June 1991; Solid star, 16 September 1991; Asterisk, 8 January 1992; Open star, 11 March 1992; Open circle, 3 and 26 April.

Chemical characteristics of ash compositions

Table 14-2 shows analytical results of ash samples collected on 24 October 1990, 18, 24, 31 March and 9, 30 April 1991. Fig. 14-1 and 14-2 show the chemical composition of an ash sample collected from the Kujukushima crater on 24 October 1990. Having lower K_2O and higher SiO_2 conterts (or higher Fe_2O_3 content), the ash sample is quite different in chemistry from the Unzen volcanic rocks. It contains much clay including such minerals as smectite and kaolin that formed at low temperatures, suggesting its origin in hydrothermally altered beds lying beneath the volcano. The phreatic eruption seems to have resulted from the contact of the leading top of the magma with the altered beds that contain much water.

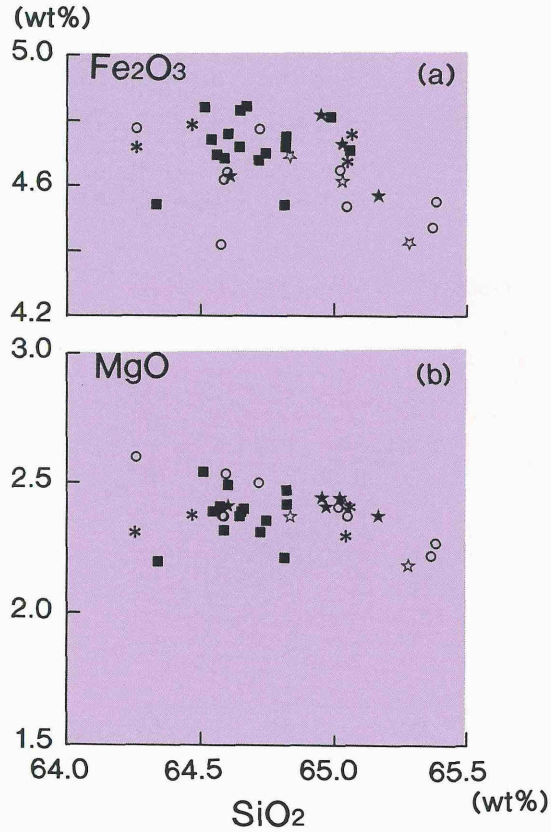

Fig. 14-4. SiO_2 versus oxides variation diagrams for 1991-1992 lava samples.
The marks are all the same as in Fig. 14-3.

Table 14-3. Average chemical compositions of 1991-1992 lavas

	5-24	5-27	6-1	6-9	6-12	9-16	92-1-8	92-3-11	92-4-3	92-4-26
SiO_2	64.67	64.63	64.72	64.71	64.74	64.96	64.72	65.05	65.03	64.71
TiO_2	0.67	0.67	0.66	0.66	0.66	0.66	0.66	0.64	0.65	0.65
Al_2O_3	16.04	16.09	15.97	16.17	16.21	15.91	16.00	15.94	15.82	16.02
Fe_2O_3	4.74	4.80	4.78	4.72	4.62	4.69	4.74	4.58	4.61	4.60
MnO	0.07	0.07	0.07	0.07	0.07	0.07	0.08	0.08	0.09	0.09
MgO	2.45	2.44	2.39	2.37	2.28	2.39	2.35	2.32	2.34	2.46
CaO	4.92	4.93	4.88	4.87	4.93	4.86	4.92	4.87	4.86	4.88
Na_2O	3.87	3.82	3.95	3.87	3.93	3.88	3.94	3.89	3.90	3.96
K_2O	2.42	2.41	2.42	2.42	2.40	2.42	2.45	2.47	2.55	2.47
P_2O_5	0.17	0.16	0.17	0.16	0.16	0.16	0,16	0.17	0.16	0.16
Total	100.02	100.02	100.01	100.02	100.00	100.01	100.02	100.01	100.01	100.00
Rb(ppm)	82.7	82.0	81.5	81.2	80.7	83.7	83.0	82.0	84.4	83.9
Sr(ppm)	320	321	318	322	326	319	319	320	313	322
Rb/Sr	0.259	0.255	0.257	0.252	0.248	0.262	0.260	0.256	0.270	0.260

Analysed by X-ray fluorecence ;major oxides reported as weight per cent(volatile free) and rubidium and strontium reported as part per million. Fe_2O_3 represents the total iron content.

Ash samples collected from 18 March to 30 April 1991, lie much closer to the variation trend of the Unzen volcanic rocks, but differ in chemistry from the lava extruded from the Jigokuato crater. These ash sample may probably have originated from shallower levels with much contribution from older volcanic rocks that constitute the Fugendake cone.

Chemical characteristics of lava compositions

Table 14-3 shows analytical results of lava samples collected during a period from 24 May 1991 to 26 April 1992. The lava extruded from the Jigokuato crater has MgO of 2.37 wt% and Fe_2O_3 (as total iron) of 4.69 wt% on the average. The lava is one of the lowest in Fe_2O_3 and MgO contents among the Unzen volcanic rocks. It SiO_2 content is 64.8 wt%. The lava is one of the most evolved rocks among the Unzen volcanic rocks. A Rb/Sr ratio is a parameter well reflecting the magmatic differentiation at low pressures. Having an average Rb/Sr ratio of 0.257, the lava is one of the highests in Rb/Sr ratio among the Unzen volcanic rocks. Similarly evolved lavas repetitively extruded in such older stages as Takadake, Kusenbudake and Fugendake (Yanagi, et al., this book), indicating that the differentiation has been in a steady state for, at least, 500Ka (Yanagi et al., this book). The average Rb/Sr ratio of the lava (0.257) is very close to Rb/Sr ratios (0.23-0.24) in evolved Myoko volcanic rocks formed under the steady state through batch fractionation (Yanagi and Ishizaka, 1978).

Lava samples show a very small variation in chemistry as illustrated in Figs. 14-3 and 14-4. So far as the available data are concerned, SiO_2 contents are limited beteew 64.2 and 65.4 wt%. Though a little scattered, Al_2O_3, CaO and Na_2O decrease with the increase of SiO_2 (Fig. 14-3). The decrease in Na_2O is whorthwhile to be noted because its behaivior is opposite to what is expected from crystallization differentiation at low pressures. Although much scattered, Fe_2O_3 and MgO also tend to decrease with the increase of SiO_2. Both Fe_2O_3/MgO and Rb/Sr ratios are good parameters which similarly reflect an extent of crystallization differentiation. Figure 14-5 (a) shows a relationship between these parameters. The Fe_2O_3/MgO ratio in samples of early stages of lava extrusion tends to decrease with the increase of Rb/Sr ratio, indicating again that the chemical variation is not due to crystallization differentiation. Rb/Sr ratios and Sr contents have a well defined negative correlation (Fig. 14-6b).

The Rb/Sr ratios and the Al_2O_3 contents similarly show a negative correlation (Fig. 14-6a). Though data are scattered, Fe_2O_3 contents tend to increase with the Rb/Sr ratios (Fig. 14-5c). Both CaO and Na_2O contents decrease with the increase of Rb/Sr ratio (Fig. 14-7). These relations indicate that these concomitant variations are mainly due to a variation in abundance of plagioclase phenocrysts in samples. Figure 14-8 is a Peace's plot (Peace, 1968) indicating more explicitly that a coherent relation between Al/Rb and (Na + 2Ca)/Rb ratios is due to the variation of plagioclase phenocryst abundance in the lava samples. The positive correlation between Fe_2O_3 contents and Rb/Sr ratios (Fig. 14-5c) indicates that Fe_2O_3 is less in samples more rich in plagioclase phenocrysts.

The rough positive correlations of Fe_2O_3 and MgO contents with Rb/Sr ratios (Fig. 14-5b and

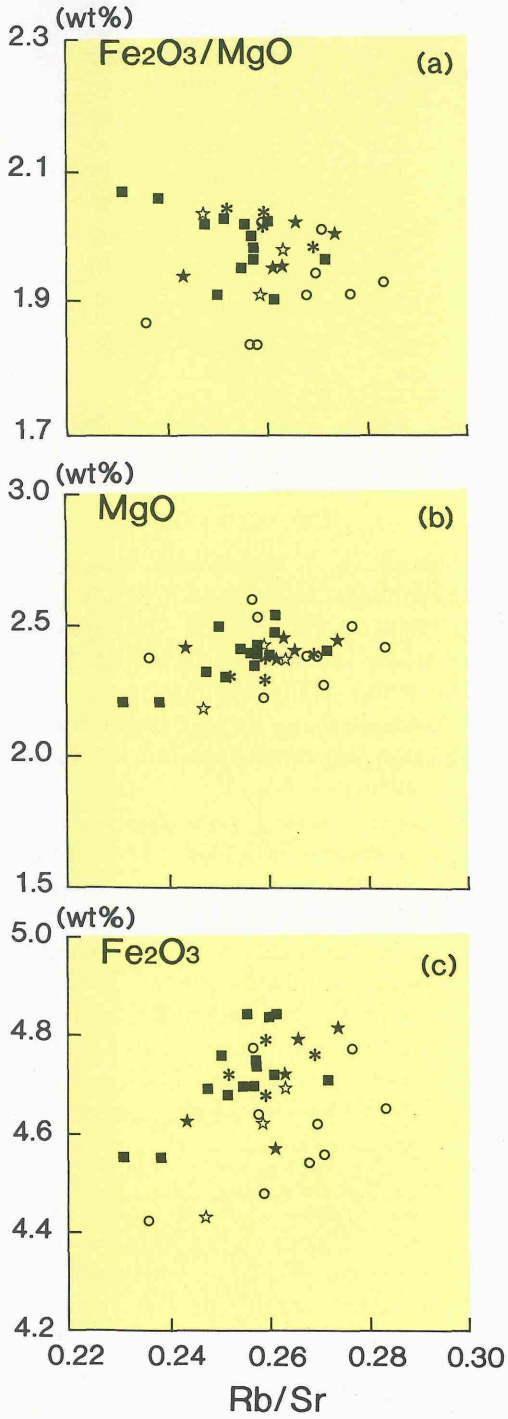

Fig. 14-5. Rb/Sr versus oxides variation diagrams. The marks are all the same as in Fig. 14-3.

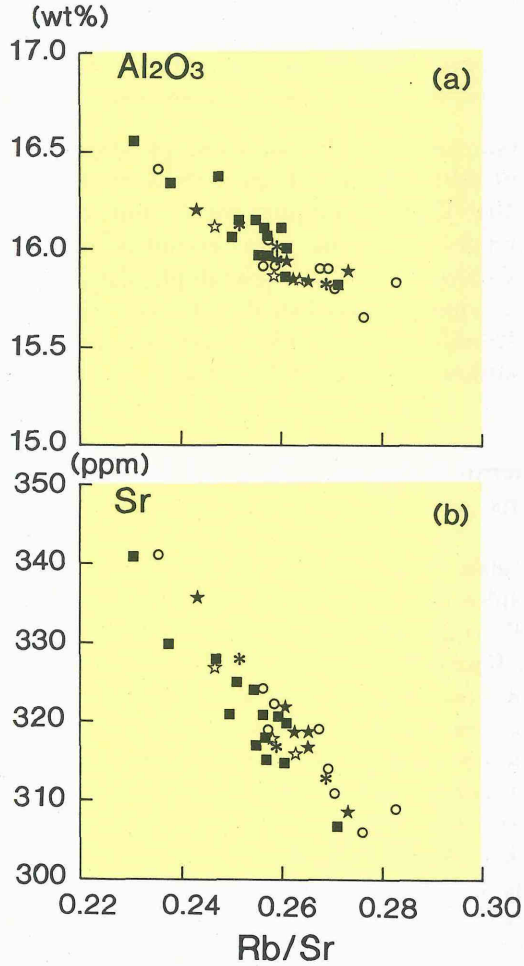

Fig. 14-6. Rb/Sr versus Al_2O_3 and Sr variation diagrams for 1991-1992 lava samples. The marks are all the same as in Fig. 14-3.

c) suggest that lava samples with more plagioclase phenocrysts contain less mafic components. Although Fe_2O_3 contents does not show a well defined correlation with the Fe_2O_3/MgO ratio (Fig. 14-9), as for those collected in early stages of extrusion, samples with lower Fe_2O_3/MgO ratios tend to have higher Fe_2O_3 contents. TiO_2 contents increase with Fe_2O_3 contents (Fig. 14-10). The negative correlation between Fe_2O_3/MgO and Rb/Sr ratios suggests that Fe_2O_3 is more enriched than MgO in samples rich in plagioclase phenocrysts. When the positive correlation between Fe_2O_3 and TiO_2 is taken into account, the enrichment of Fe_2O_3 indicates the concomitant accumulation of magnetite with plagioclase phenocrysts.

Therefore the ananlytical results so far presented indicate that the abundance of plagioclase phenocrysts has major control on the chemical variation in lava samples, and the accumulation of plagioclase phenocrysts accompanies the concomitant enrichment of magnetite.

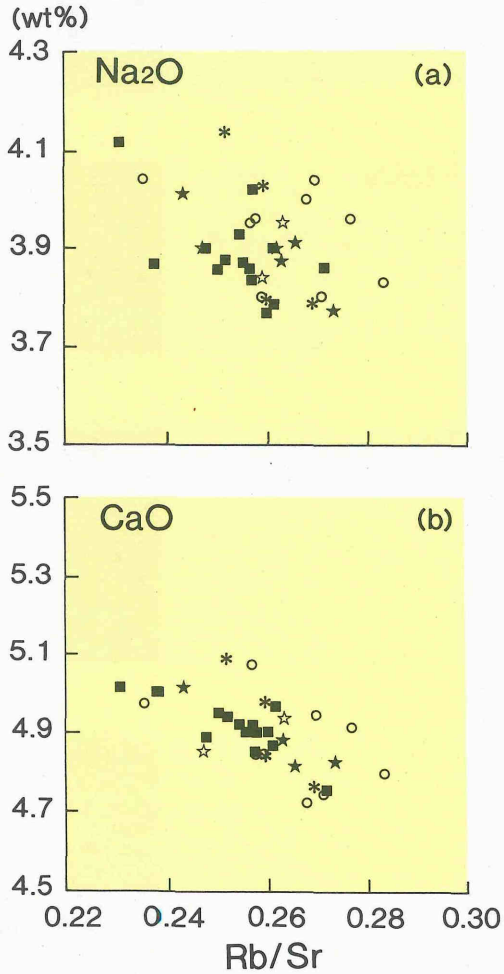

Fig. 14-7. Rb/Sr versus oxides variation diagrams for 1991-1992 lava samples.
The marks are all the same as in Fig. 14-3.

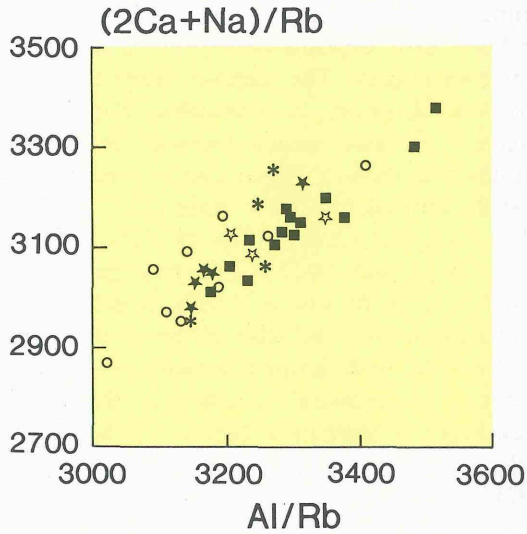

Fig. 14-8. Al/Rb versus (2Ca + Na)/Rb Peace's plot for 1991-1992 lava samples.
The marks are all the same as in Fig. 14-3.

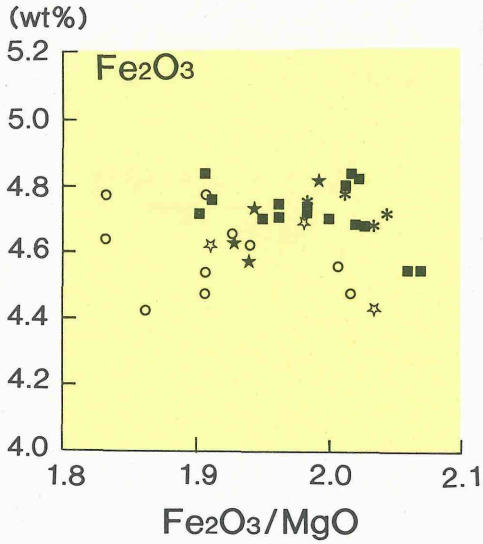

Fig. 14-9. Fe_2O_3/MgO versus Fe_2O_3 variation deiagram for 1991-1992 lava samples.
The marks are all the same as in Fig. 14-3.

Figures 14-11, 14-12 and 14-13 show temporal variations in SiO_2, TiO_2, Fe_2O_3, MgO contents and Rb/Sr and Fe_2O_3/MgO ratios of the lava extruding from the Jigokuato crater. Numbers on the abscissa in these diagrams indicate the time elapsed from 20 May 1991. Compositions of samples collected on the same day are averaged and shown on the date of collection. Most samples were collected from the flow front of proclastic flow deposits and some were directly from lava domes. The samples were hot when collected. However, it is possible that samples collected in later stages include lava blocks originated from lava domes and pyroclastic flow deposits formed in earlier stages.

The temporal variation has two phases (Figs. 14-11, 14-12 and 14-13). The first phase continued, at least, for about 23 days from beginning of lava extrusion. The start of the second phase could not be well defined because of a lack of sample. The temporal variation of the second phase started sometime before 16 September 1991, and continues until today (late in April 1992). In the first phase, Fe_2O_3, and MgO contents and Rb/Sr ratios quickly dropped, and Fe_2O_3/MgO and Al/Rb ratios sharply increased with time (Fig. 14-11 and 14-13). The time-dependent change in the second phase is very little. SiO_2, K_2O and Rb contents tend to increase a little with time, while MgO, TiO_2 and Fe_2O_3 tend to decrease a little (Fig. 14-11 and 14-12). Figure 14-12 shows that both K_2O and Rb are more enriched in samples collected later. Lava samples collected on 3 April 1992 are most enriched in SiO_2, K_2O and Rb contents. The Rb/Sr ratios are also the highest in samples collected on 3 and 26 April 1992 (Fig. 14-5 c). In Fig. 14-5 (c) the positive correlative trend between Fe_2O_3 contents and Rb/Sr ratios shifts

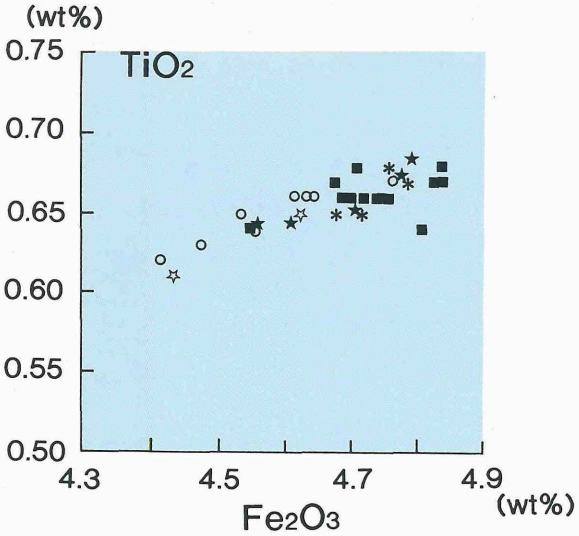

Fig. 14-10. Fe_2O_3 versus TiO_2 variation diagram for 1991-1992 lava samples.
The marks are all the same as in Fig. 14-3.

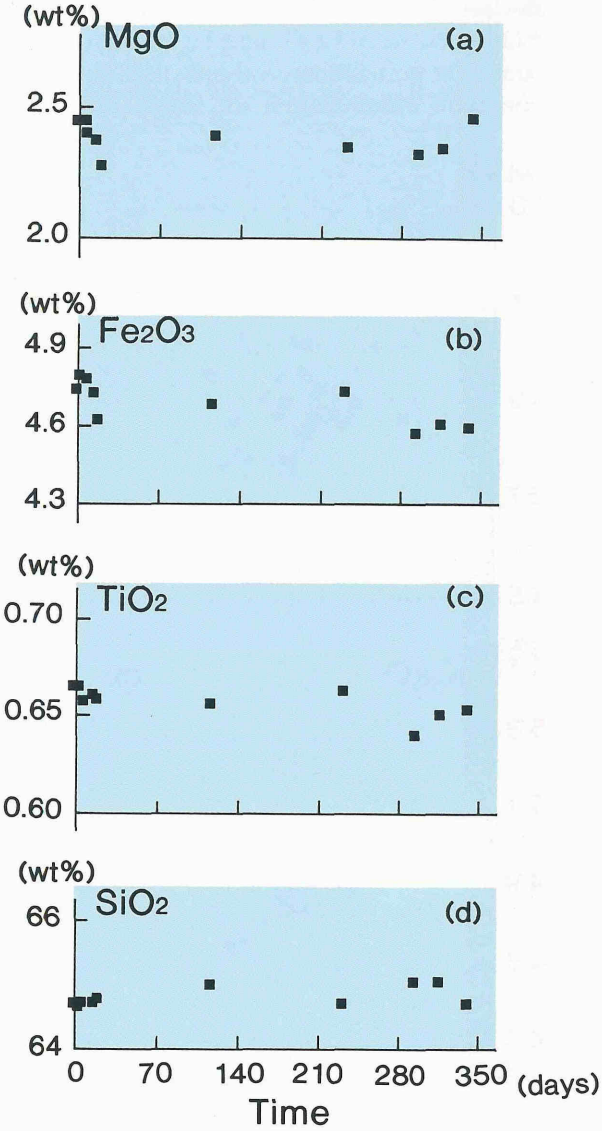

Fig. 14-11. Temporal variations in MgO, Fe_2O_3, TiO_2 and SiO_2 contents of the lava extruded from Jigokuato Crater.

toward the right hand side with time.

Rb, in general, is much concentrated in biotite phenocrysts and their host glass in the dacite magma. The samples contain biotite phenocrysts. But its modal abundance is very low (ca. 1.5 vol%) and there is no signifcant varation in its abundance. Therefore the variation in Rb content seems to depend mostly on the abundance of glass (groundmass) in the samples, and as a result, the rapid change in Rb/Sr and Fe_2O_3/MgO ratio in the first phase represents a quick change from a glass-rich lava to a lava relatively concentrated in plagioclase and magnetite phenocrysts. The slow increase in Rb, K_2O and SiO_2 contents in the second phase indicates the gradual increase in glass content with time in the extruding lava.

The chemical variation so far presented is again mostly due to phenocryst abundances. Plagioclase is the most abundant among phenocryst minerals. Though a little, the phenocryst abundance in the lava increased sharply in the first phase with time. It returned to the same as the start of extrusion, at most, about 100 days later, and then, with flactuation, gradually decreased with time. The accumulation of plagioclase phenocrysts may probably be due to gravitational settling in the chamber before the eruption.

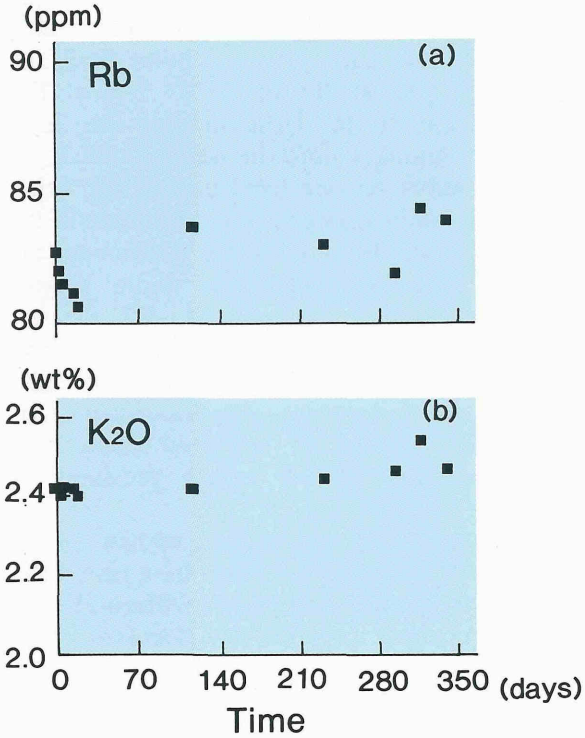

Fig. 14-12. Temporal variations in Rb and K_2O contents of the lava extruded from Jigokuato Crater.

Petrologic model for the 1990-1992 eruption

The corrosion of quartz phenocrysts, opacitization of biotite phenocrysts, the dusty marginal zone and the sieve texture in plagioclase phenocrysts, and the partial oxidation of hornblende phenocrysts in lava extruded from the Jigokuato crater suggest the heating of magma before the

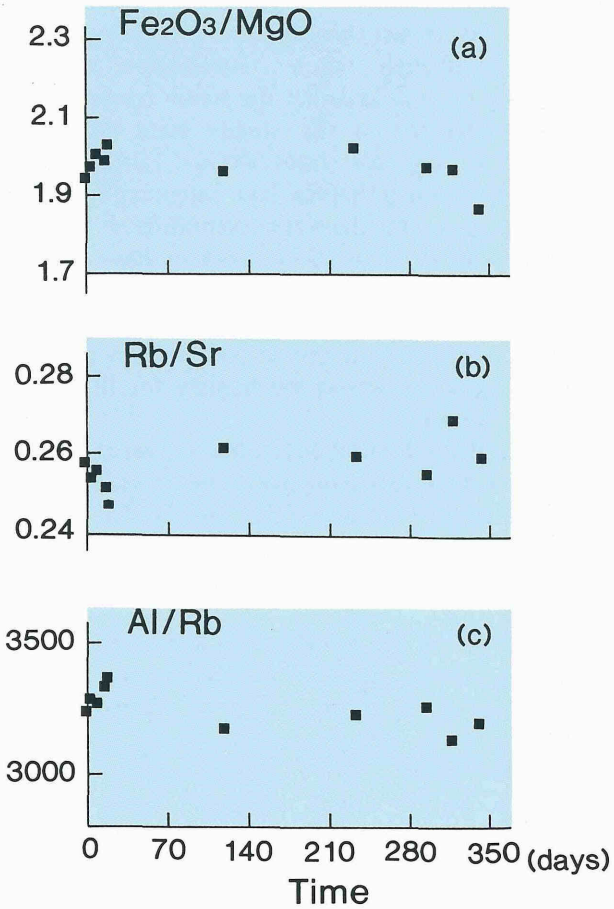

Fig. 14-13. Temporal variations in Fe_2O_3/MgO, Rb/Sr and Al/Rb ratios of the lava extruded from Jigokuato crater.

eruption. All the lava samples so far collected show the same mineralogical characteristics and they show no temporal variation. Furthermore, all the samples contain abundant vesicles. The vesiculation seems to have occurred in the chamber (Yanagi and Maeda, 1991), since they contain gas at excess pressures (Sato, et al., 1991), and the vesicles are not spherical but deformed and irregular in shape. The gas at excess pressures caused pyroclastic flows when the lava fell down along the eastern slope of Mt. Fugen. The quick changes in Rb/Sr and Fe_2O_3/MgO ratios with time in the first phase imply that the lava came from successively lower levels in the magma chamber. After then the level, from which the lava came, was probably raised and recovered in about 100 days and continued to be raised slowly until today.

Based on chemical analyses, Yanagi et al. (this book) has shown that the Unzen volcanic rocks formed through batch fractionation from a primary magma and that the batch fractionation have remained in the steady state from the Takadake stage for about 500 Ka. Furthermore, they have shown that the lava extruding from the Jigokuato crater has the composition formed under a steady state. Since, as they have shown, the batch fractionation gives a good explanation for chemical characteristics of the Unzen volcanic rocks, we follow the model proposed by them to elucidate an eruption mechanism for the 1990-1992 eruption.

Yanagi et al. (this book) has shown model of periodically refilled magma chamber where batch fractionation continues (Fig. 14-14). The model (Fig. 14-14) consists of upper and lower chambers and a set of cylinder and movable cumulate plug between the chambers. Associated with the subsidence of the cumulate plug into the lower chamber, the basaltic magma in the lower chamber moves through a space opened on the western side between the cylinder and the cumulate plug. There is originally a dacite magma in the upper chamber, which is the residual magma of the previous chemical step (Yanagi, et al., this book). The basaltic magma moved into the upper chamber may heat the lower part of the dacite magma and vesicate it at its contact. The dacite magma may increase in volume by vesiculation. The vesiculation may

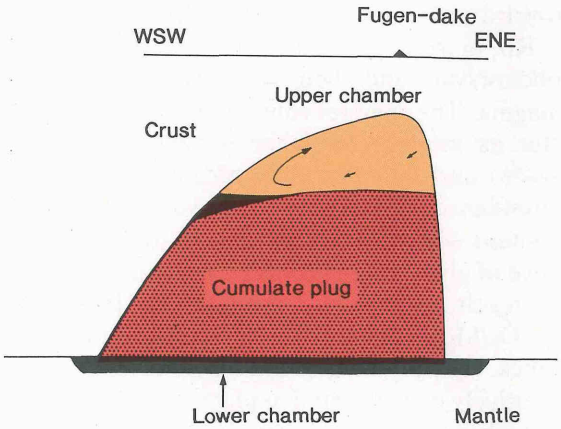

Fig. 14-14. SWS - ENE cross section of coupled magma chamber beneath Unzen Volcano to show a process which led to the extrusion of dacite magma in the upper chamber. Solid area in the lower chamber represents the basaltic magma which moved into the upper chamber in association with the cumulate-plug subsidence. See the text for detail.

reduce the magma density and force the vesicated dacite magma to rise along the western roof of the upper chamber toward the top of the chamber beneath the Mt. Fugen. This finally may resulted in the dacite lava eruption from the Jigokuato crater at the top of Mt. Fugen. The forced ascent of the dacite magma may have caused earthquakes along the western roof of the upper chamber on one hand and on the other caused the whole dacite magma to convect in the upper chamber. Because of this convection, the non-vesicated low-temperature dacite magma successively comes into contact with the hot basaltic magma, resulting in the successive heating and vesiculation of the dacite magma. This process of successive vesiculation causes the continuous eruption of vesicated dacite lava which contains gas at excess pressures in abundant vesicles.

The heating and vesiculation, at first, of the lower levels in the chamber may have resulted in the eruption of the dacite lava in which plagioclase phenocrysts progressively increased with time. In connection with this quick change, it is worthwhile to note that explosive activities occurred a few times when the lava rich in phenocrysts was extruding. The chamber volume may have increased during a migration period

from the start of vesiculation to the beginning of lava eruption. The chamber volume may then contract, due to the extrusion of lava from the Jigokuato crater. Kamo, et al. (1991) observed the subsidence of the land surface over the chamber, indicating the pressure drop in the chamber. This model for eruption mechanism gives good explanations to the observed facts. Therefore the successive eruptions may probably continue until the whole dacite magma successively meets with the basaltic magma and vesicates.