GEOLOGY AND PETROLOGY OF USU VOLCANO, HOKKAIDO, JAPAN

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Contents

Abstract: Usu Volcano began to form in the early Holocene age, just on the southern wall of the Tōya caldera, due to repeated eruptions of lava flow (somma lava)and scoria of basalt or mafic andesite. After the completion of a

strato-cone its summit was broken by violent eruption, accompanied by pyroclastic flow, which led to the formation of a crater 1.5 km. in diameter.

At that time, composition of the magma suddenly changed to dacitic. The type of activity had also changed to the extrusion of the lava domes and explosive eruptions of pumice and ash. Moreover, several activities have been recording until the present; the activity of Shōwa-Shinzan (398.9 m, sea level) which was extruded at the eastern foot of the volcano in 1943–1945, is most newly and well-known.

The petrographic character of the somma lavas change gradually from augite-hypersthene-olivine basalt (SiO_2=49.36%) to pigeonite-hypersthene andesite (SiO_2=53.21%). Simultaneously the composition of the olivine and hypersthene phenocrysts become richer in FeO content during the later stage, and finally pigeonite crystallized out as phenocryst.

Contrary to the somma lavas, the dome lavas and essential pumice ejecta are salic hypersthene dacite (SiO_2=68.26–73.04%).

The chemical and petrographical study of the lavas and the pyroclastic ejectas of the volcano suggests that these materials have been derived from tholeiitic parental magme by the process of fractional crystallization without any assimilation of the wall rock of the magma reservoir.

The writer's conception is fairly supported by the result of hypothetical calculation, subtraction of suitable crystal phases from the original magma to obtain the required high salic derivatives such as the dome lavas, following the method of Osborn (1959).

1. INTRODUCTION

Mt. Usu is an active volcano, situated in the south western part of Hokkaido and belonging to the Nasu volcanic zone. The volcano has a composite structure just on the southern rim of the Tōya caldera. The somma, consisting of basalt or mafic andesite, forms a typical truncated cone crowned by a summit crater. Two central cones (lava domes) of dacite named Ō-Usu and Ko-Usu protrude from the summit crater, and a new lava dome known as Shōwa-Shinzan stands on the eastern foot of this volcano (Plate 16, Fig. 1, 2, 3, 4).

There are recorded six violent explosive activities, including the 1943–1945 activity of Shōwa-Shinzan. Because of those peculiar activies, Usu Volcano has been studied by many scientists.

Previously Kato (1910), Tanakadate (1930), Yagi (1949, 1953), Minakami et al (1951), Nemoto et al (1957) and Ōta (1956, 1958) had investigated the lava of the volcano, but their petrogenetic conceptions do not explain in a satisfactory manner to the relationship of the sudden change between the somma lavas and the dome lavas or pumice ejectas.

The present paper gives a more detailed petrographical descriptions of the lavas,

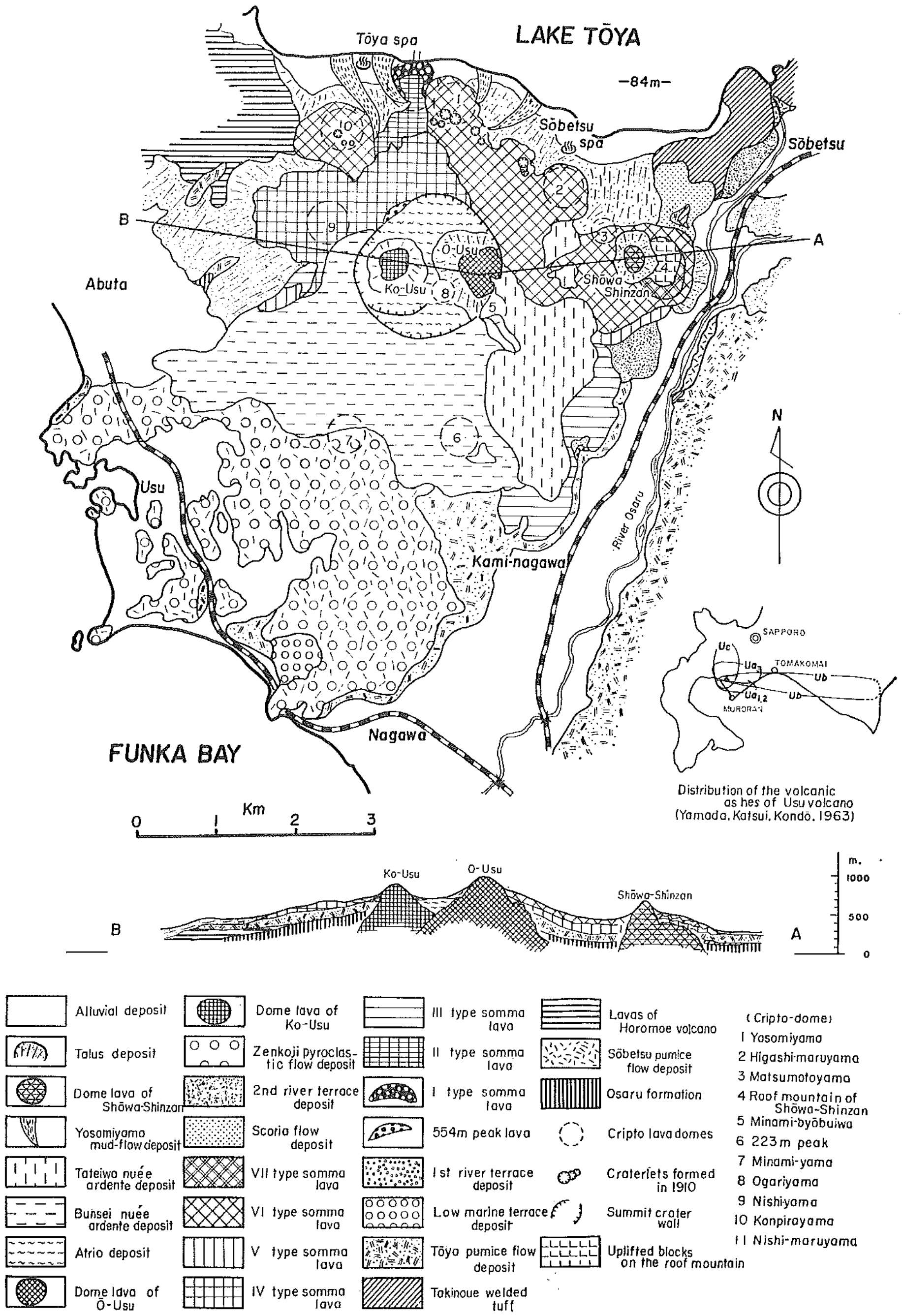

Fig. 1
Geological map of Usu Volcano.

by means of ten newly gained chemical data; it also discusses problems related to the crystallization of some rock-forming minerals.

2. THE GENERAL GEOLOGY AND VOLCANIC ACTIVITIES OF USU VOLCANO

The geological map and geological succession are shown in Fig. 1, and Table 1. In this chapter, the writer is mainly concerned about the growth history of the volcano.

2-1. Basement geology

The Tertiary formations constituting the basement of the volcano are altered volcanic rocks and pyroclastics of the Miocene age, and pumice flow deposit, the welded tuff or lavas of the Pleiocene age. These basement materials are considerably eroded and covered by new volcanic materials or the terrace deposits, so their exposure is limited to very small areas such as the cliff facing to the Osaru-river and the wall of the Tōya caldera.

The Pleistocene formations, consisting also of the basement of the volcano, are thick pumice flow deposit, volcanic ashes and terrace deposit. This voluminous pumice flow erupted intermitently during the later Pleistocene age, and this is thought to have caused the large scale caldera collapse, resulting in formation of the Tōya lake.

2-2. Somma

The formation of the somma was begun during the Holocene age by the pouring out of a small amount of olivine basalt lava (I type somma lava); the eruption then became more and more violent, and considerable amounts of basalt or mafic andesite lava (II~VI type somma lavas) and scoria erupted repeatedly. The strato-cone was completed by this time. Finally, a small quantity of pigeonite andesite lava (VII type somma lava) flowed on the eastern flank of the somma.

After a quiescence, the summit was broken by violent phreatic explosions, and a pyroclastics (the Zenkoji pyroclastic flow*) descended the southern flank, by that events, a summit crater was completed.

Thus, the somma consists of a truncated strato-cone, crowned with a crater 1.5 km. in diameter. The rim of the crater attains a height of 450–500 m. The base of the somma is about 10 km. in diameter. According to KONDO (1962, 1963) and YAMADA, KATSUI and KONDO (1963) the completion of the somma had been about 2,000–2,500 years before, from the archaeological evidences of the human remains just under the pyroclastic flow deposit.

The most typical outcrop, showing the relationship between the somma lava and the basement formation, is a cliff located at the eastern foot of the volcano facing the Osaru-river. Here the somma lava overlaps the reddish burned terrace

* The volume of this flow is roughly calculated as 0.3 km^3.

Table 1. Geological succession of the basement formations and the erupting materials of Usu Volcano.

Age		Stage	Erupting materials of Usu volcano		Other deposits	Remarks (volcanic activities)
			Lavas	Pyroclastics		
Quaternary	Holocene	Final stage (domes and pyroclastics)	Dome lava of Shōwa-Shinzan	Ash (Ua_0)	Fluvial deposit	Shōwa-shinzan Ua_0 (1943–1945)
				Yosomiyama mud flow deposit	Talus deposit	Yosomiyama (1910)
				Tateiwa nuée ardente deposit		Tateiwa nuée ardente (1853)
				Bunsei nuée ardente deposit		Bunsei nuée ardente (1822)
				Ash (Ua_1)		Ua_1 (1822 or 1768)
			Dome lava of Ō-Usu	Ash (Ua_2)		Ua_2 (1663)
				Ash and its secondary ash flow (Ua_3)		Ua_3 (about 350 y.B.P)
			Dome lava of Ko-Usu	„ Ub " pumice fall deposit	Atrio deposit	" Ub " pumice fall (350–500 y.B.P)
		Main stage (somma lavas and scoria)		Zenkoji pyroclastic flow deposit		Crater of the summit (2000–2400 y.B.P)
			VII type somma lava	Scoria flow deposit		
			VI "	(each lavas accompaning scoria.)		
			V "			
			IV "			
			III "			
			II "			
			I "			Formation of a strato-cone
	Pleistocene	Basement	1 st river terrace deposit			
			Lower marine terrace deposit			
			Pumice fall deposit of the Nakajima Volcano (Uc)			Nakajima Volcano in the Toya lake
			Tōya pumice flow deposit			Tōya caldera depression
Neogene Tertiary	Pliocene		Takinoue welded tuff. Lavas of the Horomoe volcano.			
			Sōbetsu welded tuff			
			(?) Basement volcanic rock of 554 m. peak			
	Miocene		Osaru formation			

deposits, and the lower part consists of very thick, more than 30 m, pumice flow deposit (Fig. 2).

The somma lavas also have relatively good exposures in other places ; at eroded

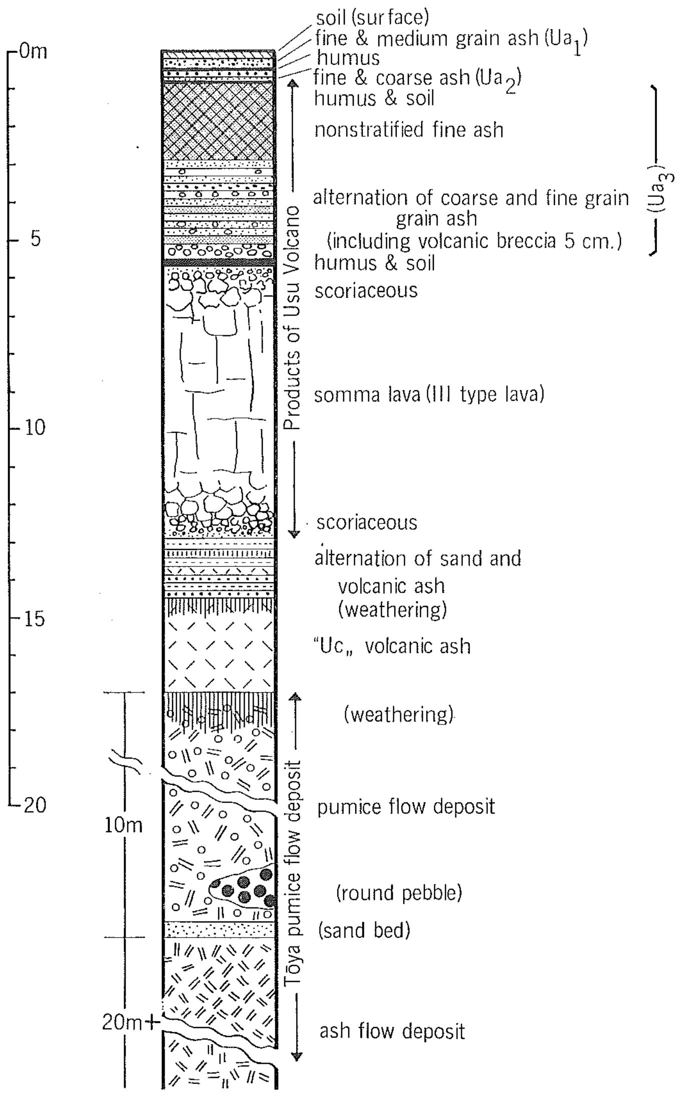

Fig. 2
Columnar section of a outcrop at the cliff facing the Osaru river, 1.2 Km. north of Kami-nagawa village.

valleys cutting the western and eastern slope around Konpirayama and Nishi-maru-yama, the inner side of the summit crater, and the wall of craterlets of 1910 activity. Especially the blocks of pigeonit andesite, destroyed by the uprifting movement of Shōwa-Shinzan, are able to collect at the quarry of the roof-mountain.

Commonly the somma lavas are constituted of the alternations of thin lava flows (up to 5 m in thick) and scoria, and there are no critical boundaries between them. At the above mentioned out-crop of Fig. 2, the lower most part of the somma lava has a scoriaceous and very vesicular appearance.

Hand specimens of the somma lavas have variable features in colour, density, grain size and hardness. Commonly the earlier mafic lavas (basalts) are black to dark-gray, dense and including coarse pyroxene and olivine phenocrysts; on the other hand the later salic lavas (basalts or andesites) are gray to pale gray, light and vesicular, and poor in mafic phenocrysts.

Besides, at the north-western rim of the summit crater (554 m. point), an abnormal volcanic rock which is essentially different from the common somma lavas is exposed. There is no clear evidence, the writer presumes probably that the basement volcanic rock has been upheaved this height within the volcano. This explanation is supported by the existence of similar basement rocks at about 250 m. sea level on the western foot of the volcano.

2–3. Lava domes and the final stage activities

After a quiescence from the completion of the somma, the final stage activities of Usu Volcano, characterized by upheaval of domes and ejection of volcanic ashes of dacitic composition, commenced.

As is illustrated by Table 1, the final stage activities are expressed as repeating eruptions of volcanic ashes, mud flows or nuées ardentes and lava domes. Historic records of the formation of Meiji-Shinzan (1910) and Shōwa-Shinzan (1943–1945), and the eruption of " Bunsei nuée ardente " (1822), and " Tateiwa nuée ardente " (1853) are present. However, the age of Ō-Usu is uncertain and that of Ko-Usu is unknown.

(A) Pumice fall deposit " Ub ".

Pumice fall, the first product of the final stage activities and named by NAGANUMA and YAMADA (1933) as "volcanic ash Ub", erupted violently and was distributed as far as the Tokachi Plain, 600 km. east of Usu Volcano (YAMADA, 1958). The projected crater of the pumice fall has been considered as being near Ko-Usu (KONDŌ, 163).

Recently, more detailed investigations of this pumice fall deposit, have been carried out by the writer, working with Mr. KONDŌ (Hokkaido Development Agency), and have been published (ŌBA and KONDŌ, 1964). So the writer wishes to express deepest appreciation to him for making the following descriptions. In this report, we used the name " pumice fall deposit Ub ", or " Ub " pumice, for this pumice fall deposit.

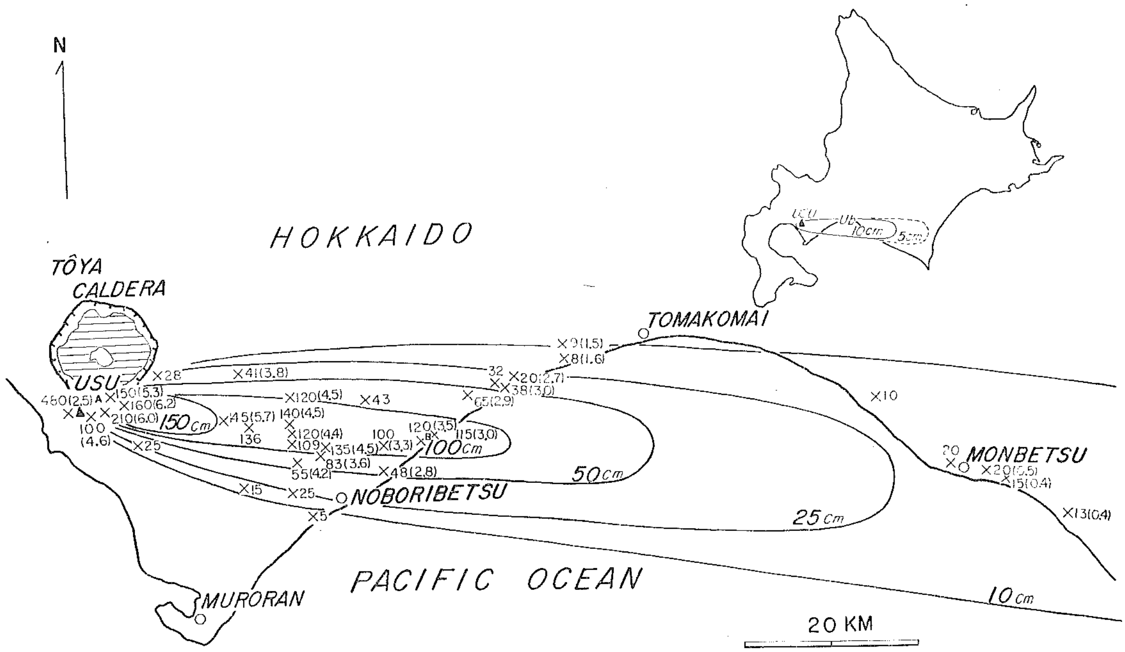

Fig. 3
Distribution of the " Ub " pumice fall deposit (after ŌBA and KONDŌ, 1964).

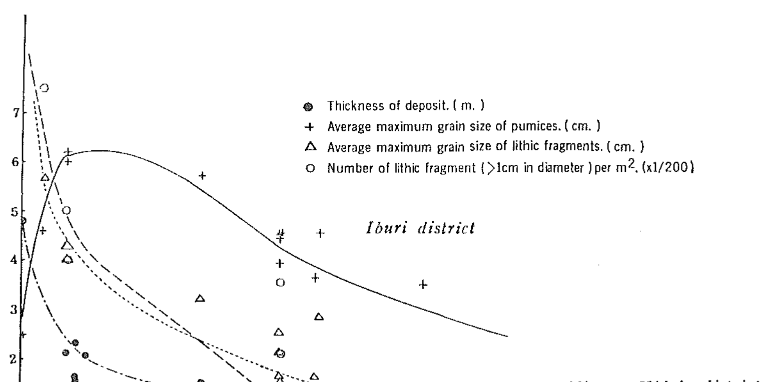

Fig. 4
Variation of thickness, number and grain size of pumice and lithic fragment of the " Ub " pumice fall deposit (after ŌBA and KONDŌ, 1964).

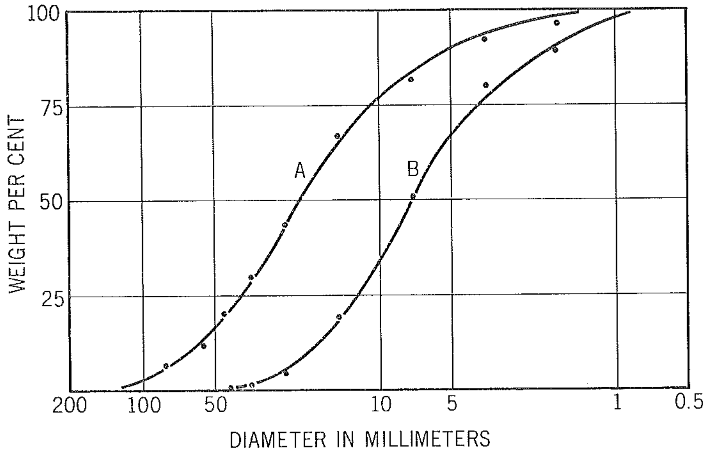

Fig. 5
Cumulative curves of the grain size distribution of the pumice fall deposit.
A: At near Shōwa-Shinzan, 4 km. far from the source (cf. Fig. 3)
So*=1.88
B: At Hagino, situated on the beach side of the Pacific Ocean, 40 km. far from the source (cf. Fig. 3).
*So: The coefficient of sortion= $\sqrt{Q_3/Q_1}$
(Q_1=Grain size (mm.) corresponds with 75 weight %)
(Q_3= ,, ,, ,, 25 ,,)

The " Ub " pumice is fresh, white in colour, and shows good vesiculation (Plate 18, Fig. 1, 2). Many points were chosen for the measurement of the thickness of the deposit, the grain size of the pumice, and for determining the number of lithic fragments included in the pumice deposit per square meter. In Fig. 3, the thickness (m) of the deposit, the average maximum grain size of the pumice (number in blackets), and the couter lines of each 150 cm, 100 cm, 50 cm, 25 cm, 10 cm and 5 cm thickness of the deposit are shown. Moreover, the number and the average maximum grain size of the lithic fragments are plotted against the distance from the volcano (Fig. 4). In Fig. 4, all values, excepting the average maximum grain size of the pumice itself, gradually decrease at nearer than 10 km to the volcano. Fig. 5 shows the cumulative curves of the grain size distribution of " Ub " pumice, and it indicates that the sorting is good (S_0=1.8) irrespective of the distance from the volcano.

The total volume of the pumice deposit is calculated at about 2.2 x 10^9 m^3 (6.5 x 10^8 ton in weight), which, therefore, would exceed the 1707 activity of Fuji Volcano (TSUYA, 1955) and the 1783 activity of Asama Volcano (MINAKAMI, 1942 b) in magnitude.

On the basis of the above information, the mechanism of this pumice fall is considered by the writer as follows. As a result of the vesication of the dacite magma in the reservoir, which was not so deep and being just under the crater, the pumice was thrown straight out to a height just beneath the stratosphere by violent explosion; and it was then conveyed by a strong westerly wind to the eastward.

The petrological and petrochemical discussions will be made in the following chapters.

From the next data, age of this pumice fall is presumed to be about 350–500 years old.

(1) In surrounding areas, the pumice deposit is covered by Ua_2 ash (350 years old), without any humus or soil between the two layers (YAMADA, 1958).

(2) At nearby Tomakomai, 55 km. NEE from Usu Volcano, the "Ub" pumice deposit is covered by the volcanic ash of the 1667 activity of Tarumai volcano with very thin humus between the two layers; and it overlaps the volcanic ash of about 1500 years old, with a thick humus interlayer (YAMADA, 1958).

(3) It has clarified by the recent archaeological survey, which performed by Prof. KOHAMA of Osaka University, that the "Ua_2" ash formation covers the human remains of the Aius* of 15–16 century at Zenkoji village, which situates on the southern foot of Usu Volcano.

It would be necessary to determine the age of the pumice fall by the C^{14} method about the peat or calcareous material just below the deposit.

(B) Ko-Usu

The lava dome of Ko-Usu (611.4 m) was extruded at the western corner of the summit crater in an almost solid condition, as is evidenced by the striations on the walls of the dome, and by the water-worn gravels or the basement rocks on the top of the dome. The similar features also are characteristics of Ō-Usu and Shōwa-Shinzan.

Ko-Usu was split into several blocks by differential movement during the process of upheaval (TANAKADATE, 1918).

(C) Ō-Usu

The lava dome of Ō-Usu (725.1 m) was extruded by a mechanism similar to that of Ko-Usu, but it is larger and exists at the eastern rim of the summit crater. Considering from the topography around Minami-byōbuiwa, Ō-Usu was pushed up at the south-eastern part of the somma at first, then it moved to the westward and protruded along the rim of the summit crater. We are able to observe the "Ub" pumice fall deposit, folded by the uplifting movement, at the south side of the dome.

The age of the upheaval of Ō-Usu is not known, but it is considered to have been done perhaps by the activity of 1663. Due to later activities, Ō-Usu was

* The natives of Hokkaido.

broken, whereby the pyroclastics resulted to the Bunsei nuée ardente* (1822) and the Tateiwa nuée ardente (1853) respectively.

(D) Meiji-Shinzan (alias Yosomiyama)

Meiji-Shinzan (258.4 m) and the 45 craterlets on the northern foot of the volcano were formed in 1910. After biolent earthquakes and eruptions of craterlets, uplifting of the ground commenced and this mountain was formed on the gentle slope of the lake side. There was no eruption of juvenile material, but the " Yosomiyama mud flow " ran down from several craterlets to the north. (ŌMORI, 1911, SATŌ, 1913)

On the surface of this mountain, mostly covered by plants, there are still fumaloric areas.

(E) Shōwa-Shinzan

Shōwa-Shinzan (406.9 m)** appeared on the arable land at the eastern foot of Usu Volcano during 1943 and 1945. It is composed of a nearly circular platform called " roof-mountain ", and a pinnacled projection called " dome ". Violent earthquakes and eruptions related to the formation of Shōwa-Shinzan, had started on December 28, 1943, and continued until September, 1945. Many researchs had been carried out upon these activities (MINAKAMI, 1944, 1947; FUKUTOMI and ISHIKAWA, 1944; ISHIKAWA, 1947, 1950; MIMATSU, 1962; MINAKAMI, ISHIKAWA and YAGI, 1951; YAGI, 1949, 1953). Today the mountain is still fumaloric and has a high temperature.

All three domes are composed of similar grayish compact dacite lavas, which are to be described in detail later.

(F) Volcanic ashes of Usu Volcano

According to YAMADA (1958); KONDŌ (1963); YAMADA, KATSUI and KONDŌ (1963), the volcanic ashes of Usu Volcano are able to be classified into four kinds (Ua_0, Ua_1, Ua_2, and Ua_3) by means of the existence of thin interbeded layers of humus or soil.

These ashes are distributed mainly on the east side of the volcano, but not so widely as the " Ub " pumice fall deposit (Fig. 1). They are correlated to the chronological records of the volcanic activities of Usu (YAMADA et al, 1963) as follows:

	(related phenomena)
Ua_0=1943–1945	Shōwa-Shinzan
Ua_1=1768 or 1822	Bunsei nuée ardente
Ua_2=1663	Ō-Usu
Ua_3 (ash fall) } Ua_3 (ash flow) } about 350 y. B.P. or more	Ko-Usu

* Nuée ardente in the strict sence (ARAMAKI, 1957).

** By KANEKO (1950). But in recent map made from air photography, the geographical survey of the Japan Air Survey Company (1964) determined the height to be 398.9 m.

Those volcanic ashes have much less importance petrologically, because they are not composed of essential (juvenile) materials.

(G) Cripto-domes.

There are several remarkable dome-shaped hills, Higashi-maruyama (312.8 m, Plate IV, Fig. 1), Matsumotoyama (247.6 m), nameless 223.3 m peak, Minami-yama (247.1 m), Nishiyama (549.2 m), Konpirayama (311.5 m) and Nishi-maruyama (177.4 m), arranged circularly around the foot of Usu Volcano. Moreover, there are similar projections, Ogariyama (486.7 m) and Minami-byobuiwa (580.4 m), on both sides of the Ō-Usu dome. It is clear that those projections are also cripto-domes; and it is probable that almost solidified magma, such as the dome-lava, intruded along the tectonic weak zones and pushed up the ground above it. Meiji-Shinzan (Yosomiyama) and the roof-mountain of Shōwa-Shinzan would be also criptodomes (Plate 19, Fig. 1.)

Last two examples are the rare volcanic activities of this type in Japan, actually eye-witnessed by the people.

3. PETROGRAPHY AND MINERALOGY

3–1. Somma lavas

Somma lavas have have already been described petrographically by several

Table 2. Mode of the rock forming minerals of the somma lavas.

		I	II	III	IV	V	VI	VII
Phenocrysts	Pl	27.9	31.8	17.3	23.3	35.8	32.3	36.3
	Au	0.1	1.1	1.2	1.9	+	0.1	0.2
	Hy	1.9	12.0	0.8	10.3	1.2	1.3	0.8
	Pi	—	—	—	—	—	—	0.4
	Ol	6.3	1.5	2.4	0.2	—	+	—
Micro pheno-crysts	Pl	0.1	1.0	4.8	2.8	0.5	1.1	1.3
	M	0.1	1.8	2.5	2.0	0.5	1.0	1.7
Groundmass	Pl	27.1	18.7	37.5	25.5	18.4	25.9	25.5
	Pi (Au)	22.4	25.1	24.9	16.1	16.3	24.2	23.5
	Mt	2.2	2.5	3.2	2.2	2.1	3.3	2.5
	Ap	+	+	—	—	0.1	0.8	0.1
	An	+	0.1	1.5	—	—	1.0	0.9
	Cr	+	0.3	—	0.6	—	0.9	0.9
	Gl*	12.0	3.6	3.9	15.1	25.1**	8.0	5.9

Pl=Plagioclase, Au=Augite, Hy=Hypersthene, Pi=Pigeonite, Ol=Olivine, M=Ol, Hy, Au, Pi, Mt=Magnetite, Ap=Apatite, An=Anorthoclase, Cr=Cristobalite, Gl=Glass.

* Gl includes cryptocrystalline part

** Because the groundmass beeing so altered that undistingushable materials are counted in this value.

workers, but no attempt has been made to do more detailed mineralogical and petrochemical researches on the whole of the somma lavas. YAGI (1949, 1951) has described a somma lava of the roof-mountain of Shōwa-Shinzan, particularly with relation to its chemical composition.

The writer divided the somma lavas into seven rock types, according to their mode of occurrence, microscopic mineralogy and texture. The somma lavas are not rocks completely different from each others, but they show considerable variations in volume and in the character of the rock-forming minerals.

Following are the petrographical descriptions of the somma lavas. The relative volumes of the rock-forming minerals are shown in Table 2, and the photomicrographs are shown in Plates 20～22.

I type lava (Augite-hypersthene-oliving basalt)

Mode of occurrence: There is an outcrop of I type lava at the lake side of Nishi-maruyama, but it occurs also at the southern saddle between somma and Nishi-maruyama, where a borig was done. The description is mainly from the core because the outcrop has been hydrothermally altered. According to the evidence of the boring, there are thick deposits of the gravel bed and "Tōya pumice flow deposit" just under the lava.

This lava is as thick as 20 m, and is directly covered by the II type lava.

Macroscopic observation: The lava is coarse grained, dark gray in colour, and rich in plagioclase and olivine phenocrysts. The sporadic presence of large crystals of plagioclase and olivine, rarely exceeding 2.5 cm in size, are worthy of notice (Plate 19, Fig. 2).

Microscopic observation: (Phenocrysts) Large crystals of plagioclase are distinguished from the normal phenocrysts, because they have quite different crystal habits.

The large plagioclase is euhedral, short prismatic, 1～2.5 cm in size, and shows regular twinning of the Carlsbad and the Pericline type though rarely of the Albite type. It is mostly uniform anorthite of $An_{95\sim90}$, as estimated optically ($n_1=1.577\sim 1.579$),* with a thin rim composed of labradorite, similar to the normal phenocrystic plagioclase compostion. Olivines are recognized near the surface of large anorthite.

The presence of large anorthite or bytownite crystals in this lava was reported by KATŌ (1910), SASAKI (1935), HARADA (1936), YAGI (1949) and ISHIKAWA (1950); and Yagi has interpreted this large crystal as xenocryst.

The normal plagioclase phenocryst is euhedral or subhedral, 1～3 mm in size, and frequently shows glomero-porphiritic aggregates of smaller plagioclase. The main part is $An_{95\sim78}$** in composition, and faint zoning is detected. The outer rim shows strong zoning, $An_{60\pm}$ in compostion.

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* After TSUBOI (1934). ** Infered from the data by KANŌ (1955).

Next to plagioclase, olivine is the most abundant crystals in this lava; moreover of all the somma lavas, the I type lava is richest in olivine. Olivine is a subhedral or rounded crystal, up to 1 cm in size. Usually it has a reaction rim of hypersthene, but the large crystals occuasionally have no reaction rim. The optical characteristics are as follows: $2V=(-)88°\sim(+)85°$; refractive indices, $\alpha=1.673\sim1.675$, $\beta=1.694$ (max.), $\gamma=1.712\sim1.714$; hence, the average compositin is $Fo_{71}Fa_{21}$.*

Hypersthene is a prismatic or tabular crystal, 0.5–1.5 mm in length, and glomero-porphiritic aggregates with augite and plagioclase are also detected. Usually it surrounded by a reaction rim of pigeonite. The optical characteristics are as follows: $2V=(-)56°\sim(-)54$; refractive indices, $\alpha=1.688\sim1.689$. $\beta=1.695$–1.697, $\gamma=1.699\sim1.702$; pleochroic colours, X=pale brown, Y=pale greenish brown, Z=pale green; absorption, X>Y>Z; hence, the average composition is $En_{73}Fs_{27}$.**

Augite is poor, a subhedral prismatic or rounded crystal, up to 0.5 mm in size. Usually it makes glomero-porphiritic aggregates with the hypersthene and plagioclase. Rarely there have been detected large augite crystal, some up to 1.0 cm in size. The optical characteristics are as follows: $2V=(+)54°$; refractive indices, $\alpha=1.694$–1.695, $\beta=1.699\sim1.701$. $\gamma=1.721\sim1.722$; hence, the average composition is $Wo_{44}En_{33}Fs_{23}$.***

(Microphenocrysts) Plagioclase is a lath-sphaped crystal, 0.1, 0.2 mm in size, and $An_{69\sim60}$ in composition. It shows simple twinning and normal zoning, and olivine rimmed by hypersthene, are prismatic or grain crystals, 0.1–0.2 mm in size. Grain augite, $2V=(+)52°\sim(+)42°$, is also detected.

(Groundmass) Groundmass shows a some what fine grain interstitial texture, compared to the other somma lavas. Its constitutents are mainly lath-shaped zonning plagioclase, $An_{65\sim55}$ in composition; and grain augite, $2V=(+)52°\sim(+)48°$ in optical characteristics. Accessary grained iron ore, cristobalite and anorthoclase are also present, and brown glass is found interstitially (Plate 20, Fig. 1).

II type lava (Augite-olivine-hypersthene basalt)

Mode of occurrence: There is a large outcrop in the southern valley of Nishi yama, which is covered by the III type lava. At Nishi-maruyama, as already mentioned, this lava laies over the I type lava. Thought to be not of the original occurrence, the explosive rock fragments distibuted around the rim of the craters of 1910 activity, and the blocks broken by the rising of Ō-Usu at Minami-byōbuiwa, are also able to be identified in this type lava.

Macroscopic observation: The lava is coarse grained, gray or dark-gray colour

* Infered from the diagrams by POLDERVAART (1950).
** In feral from the diagrams by POLDERVAART (1950).
*** Infered from the diagrams by HESS (1949).

in appearance, and rich in pyroxene, olivine and plagioclase phenocryst. The large anorthite such as the I type lava is sometimes detected.

Microscopic observation: (Phenocrysts) The plagioclase is up to 5 mm in size, and frequently shows glomero-perphyritic aggregates of smaller plagioclase. The main part is almost homogeneous, $An_{94\sim89}$, while the outer rim shows zoning, $An_{72\sim44}$, in composition. The large anorthite has characteristics similar to that of the I type lava.

Hypersthene is most abundant in the II type lava, being over 10% of the total volume. It is a prismatic or tabular crystal, 0.5~1.0 mm in size, and frequently shows glomero-porphyritic aggregates with plagioclase, augite and iron ore. A reaction rim of pigeonite around the hypersthene is very common, but at the same time the hypersthene itself has anhedral relic olivine crystal in its inner part. The optical characteristics are as follows: $2V=(-)76°\sim(-)62°$; refractive indices, $\alpha=1.689$–1.692, $\beta=1.696$–1.698, $\gamma=1.701$–1.706; hence, the average composition is $En_{73}Fs_{27}$.

Olivine is commonly subhedral or rounded crystal, up to 1.0 mm in size, and rarely large crystals of 4~5 mm in size are found. It is alwaysr immed by grained pigeonites or wraped by hypersthene. The optical characteristics are as follows: $2V=(-)85°\sim(-)78°$; refractive indices, $\alpha=1.685$–1.691, $\beta=1.706$ (max.), $\gamma=1.723$: hence, the average composition is $Fo_{72}Fa_{28}$.

Augite is poor in this type. It is subhedral or rounded crystal, up to 0.5 mm in size. It co-exists with the hypersthene, as was mentioned above. Its optical characteristics are as follows: $2V=(+)54°\sim(+)48°$; $C\wedge Z=43°$; hence, the average composition is $Wo_{41}En_{34}\ Fs_{25}$. Very rarely, this augite is covered by a thin pigeonite rim, which forms a parallel intergrowth. This pigeonite shows remarkable zonning, and the optical axial angel changes continuously from $(+)42°$ in inner zone to $(+)\ 0°$ in the outer zone.

(Microphenocrysts) Plagioclase is a lath-sphaped euhedral crystal, up to 0.3 mm in length. Pigeonite is prismatic crystal, about 0.3 mm in length, and occasionally hypersthene is included in its core. The optical characteristics of the pigeonite and associated hypersthene are as follows: pigeonite, $2V=(+)37°\sim(+)16°$; hypersthene, $2V=(-)66°\sim(-)60°$.

(Groundmass) The groundmass shows medium to fine grained intersertal texture. Its constituents are mainly lath-shaped zonning plagioclase, some up to 0.05 mm in length and $An_{65\sim50}$ in composition; grained pigeonite, 0.05~0.1 mm in size, $2V=(+)33°\sim(+)16°$ in optical character; and a small amount of augite, $2V=(+)48°$ in optical character. Accessory grained iron ore, interstitial anorthoclase, cristobalite, apatite and the brown glass are also present (Plate 20, Fig. 2).

III type lave (Hypersthene-augite olivine basalt)

Mode of occurrence: There is a typical outcrop at the cliff on the eastern foot of Usu, facing the Osaru river (north of Kami-nagawa). Other small outcrops can also be found in the southern valley of Nishiyama. At the former place, the III type lava covers the basement formation (Fig. 2). This lava is about 4～6 m in thickness, and shows a compact appearance, but the lower part of the lava, 1–1.5 m in width, is rather slaggish.

Macroscopic observation: The lava is compact, light gray colour in appearance, and pyroxene and olivine phenocrysts are scattered throughout it. Large phenocrysts of plagioclase are also rarely found.

Microscopic observation: (Phenocrysts) Plagioclase is rather small, up to 1.5 mm in size, and is a euhedral or aggregated crystal. It is almost homogeneous, $An_{95\sim91}$, but has a thin rim which shows zoning, $An_{65\sim54}$ in composition.

Olivine is subhedral or anhedral crystal, 1–2 mm insize, and it is rimmed by grained pigeonite. Sometimes olivine is included in the hypersthene phenocrysts as a relic crystal. The optical characteristics are as follows: $2V=(-)86°\sim(-)80°$; refractive indices, $\alpha=1.680$–1.682, $\beta=1.703$ (max), $\gamma=1.721$–1.722; hence the average composition is $Fo_{76}Fa_{24}$.

Augite is subhedral or anhedral, up to 1 mm in size, and frequently shows glomero-porphyritic aggregates with hypersthene and plagioclase. Faint zonning in the augite is some times detected. The optical characteristics are as follows: $2V=(+)54°\sim(+)46°$ and $(+)\ 20°$ in the outer most rim of crystal; refractive indices, $\alpha=1.694\sim1.695$, $\beta=1.699\sim1.701$, $\gamma=1.721\sim1.722$; hence, the average composition is $Wo_{36.5}En_{37}Fs_{26.5}$.

Hypersthen is prismatic and up to 1 mm in length. The reaction rim of pigeonite is present, similar to the other types, but it is not so noticable. The optical characteristics are as follows: $2V=(-)67°\sim(+)61°$; refractive indices, $\alpha=1.690\sim1.692$, $\beta=1.698\sim1.700$, $\gamma=1.703\sim1.705$; hence, the average composition is $En_{71}Fs_{29}$.

(Microphenocrysts) In this lava, microphenocrysts are remarkably coarse and abundant. Plagioclase is a lath-shaped crystal and is up to 0.5 mm in length. It shows weak zonning, An_{70} in composition. Pigeonite is a prismatic crystal, as large as the plagioclase. And occasionally hypersthene is included in the core of pigeonite as a relic crystal. The optical characteristics of the pigeonite are as follows: $2V=(+)20°\sim(+)0°$, and that of the hypersthene, $2V=(-)66°\sim(+)60°$

(Groundmass) The groundmass shows coarse grained interstitial texture. Its constituents are mainly lath-shaped zoning plagioclase, about 0.2 mm in length, and $An_{68\sim57}$ in composition; and grained pigeonite, as large as the plagioclase, $2V=(+)26°\sim(+)10°$ in optical character. Accessory grained iron ore, interstitial anorthoclase and a small amount of brown glass are also detected (Plate 20, Fig. 3).

IV type lava (Olivine bearing augite-hypersthene basalt)

Mode of occurrence: This type lava is more widely distributed, mainly on the western half of the somma. The lava outcrops in the southern valley of Nishiyama and at the wall of the summit crater. Moreover the lava-blocks of " Zenkoji pyroclastic flow " are almost all composed of this type lava. Commonly the lava is everywhere accompanied by alternative slaggish scoria.

Macroscopic observation: The lava has a gray or dark-gray colour and a porphyritic appearance. Some faint variations are found in the lava, with respect to colour, porosity and the quantity of olivine phenocrysts.

Microscopic observation: (Phenocrysts) Plagioclase is euhedral and up to 0.2 mm in size. It is almost homogeneous, $An_{95\sim80}$ in composition, but a thin outer rim is $An_{63\sim50}$ in composition.

Hypersthene is abundant, and it is prismatic or tabular crystal, $0.5\sim1.0$ mm insize. Commonly a reaction rim of the plagioclase is found. Rarely, relic olivine is included in the core of the hypersthene. The optical characteristics are as follows: $2V=(-)67°\sim(-)61°$; refractive indices, $\alpha=1.689\sim1.692$, $\beta=1.696\sim1.700$, $\gamma=1.702$–1.705; pleochroic colour, X=pale brown, Y=pale brownish green, Z=pale green; hence, the average composition is $En_{70}Fs_{30}$.

Augite is subhedral crystal, $1\sim2$ mm in size. Sometimes it shows a tendency to constructs glomero-porphyritic aggregate with plagioclase and hypesthene. The optical characteristics are as follows: $2V=(+)50°\sim(+)48°$; $C\wedge Z=43°$–$41°$; refractive indices, $\alpha=1.694\sim1.696$, $\beta=1.699\sim1.701$, $\gamma=1.721\sim1.722$: hence, the average composition is $Wo_{39}\ En_{36}Fs_{25}$.

(Microphenocrysts) In this lava, the microphenocrysts are not striking. Plagioclase is lath-shaped crystal, 0.1–0.3 mm insize, and $An_{72\sim68}$ in composition. Pigeonite is a grained or prismatic crystal, about 0.2 mm in size, and $2V=(+)0°$ in optical character. Relic hypersthene, included in the pigeonite, is found and its optical characteristics are $2V=(-)65°\sim(-)60°$.

(Groundmass) The groundmass is rather fine grain intersertal in texture. Its constituents are mainly lath-sphaped zoning plagioclase, up to 0.1–0.2 mm in length, and grained pigeonite, $2V=(+)14°\sim(+)0°$ in optical character. Accessory grained iron ore, cristobalite, and the interstitial brown glass are also detected (Plate 20, Fig. 4).

V type lava (Augite bearing hypersthene andesite)

Mode of occurrence: This lava is distributed only in the southern area of Shōwa-Shinzan. It can'be seen to be about $2\sim4$ m in thickness in the outcrop, and has rough columner joint. The sequence of this lava with the other somma lavas is not known directly, but from topographic observation of the lava flow, it probably covers the III type lava, as mentioned previously.

Macroscopic observation: The lava is dark-gray in colour and porphyritic in appearance. Its white plagioclase phenocrtsts are remarkable, but the pyroxenes or olivines are almost not visible. Differing from the other somma lavas, this lava is particularly porous. The porosity, measured by a point counter, is 7.4% of the volume.

Microscopic observation: (Phenocrysts) Plagioclase is euhedral, commonly up to 1.0 mm in size, however rarely aggregates of plagioclase as large as 5 mm are detected. It shows faint zoning, $An_{95\sim 85}$, and the thin outer rim is $An_{60\sim 54}$ in composition.

Hypersthene is a subhedral prismatic crystal, up to 0.5 mm in length, and it frequently constructs glomero-porphyritic aggregates with augite, plagioclase and iron ore. Commonly the hypersthene is rimmed by grained pigeonites. The optical characteristics are as follows: $2V=(-)65°\sim(-)62°$; refractive indices, $\alpha=1.694\sim 1.695$, $\beta=1.704$, $\gamma=1.707\sim 1.708$; hence, the average composition is $En_{67}Fs_{33}$.

Augite is very poor, and is a small subhedral crystal, up to 0.5 mm in size. Usually it consists in aggregates with hypersthene, such as just mentioned above. The optical characteristics are as follows: $2V=(+)50°$; $C\wedge Z=45°$; refractive indices, $\alpha=1.695$, $\beta=1.700$, $\gamma=1.722$; hence, the average composition is $Wo_{40}En_{35.5}Fs_{24.5}$.

(Microphenocrysts) In this lava microphenocrysts are not conspicuous. Plagioclase is a lath-shaped or a short prismatic crystal, $0.1\sim 0.2$ mm in size, and is zoning crystal, $An_{67\sim 50}$ in composition. Some grained pigeonite is also found.

(groundmass) The groundmass is fine grain, black in colour and shows intersertal texture. This lava suffers somewhat alteration, because of its very porous character. Consequently, detailed observations of the rock-forming minerals can no tbe made easily. Only lath-shaped plagioclase and grained pyroxene (pigeonite?) and interestitial crist-obalite can be detected (Plate 21, Fig. 1).

VI type lava (Augite-hypersthene andesite)

Mode of occurrence: This lava is the most widely distributed; typical outcrops can be found at the eastern side of the somma, within the crater (of 1910 activity) near Sōbetsu spa and Yosomiyama, and at the western foot of Konpirayama.

Everywhere this lava shows alternation of thin compact lava flows and scoria, usually about 2–3 m in thickness. Apart from this, however, on the surface of the roof-mountain of Shōwa-Shinzan, there are many blocks of VI type lava, but their original mode of occurrence is not known.

Macroscopic observation: The lava is gray or dark-gray in colour, and compact in appearance. The white plagioclase phenocrysts are striking, though the pyroxene phenocrysts are not so remarkable. Sometimes marginal parts of the lava flow are rather porous in appearance.

Microscopic observation: (Phenocrysts) Plagioclase is commonly seen in aggregates of smaller plagioclase of up to 1.0 mm in size. It has an almost homogeneous omposition, $An_{95\sim 75}$, but its thin rim which shows zoning is $An_{64\sim 50}$ in composition.

Hypersthene, which is rather poor, is a prismatic crystal, 1.0–5.0 mm in size, and always rimmed with grained pigeonite. Its optical characteristics are as follows: $2V=(-)64°\sim(-)60°$, rarely $(-)75°$; refractive indices, $\alpha=1.694$, $\beta=1.702$, $\gamma=1.707$; hence average composition is $En_{68}Fs_{32}$.

Augite is very poor, and is subhedral or anhedral, up to 1.0 mm in size. Rarely, euhedral crystals reaching 2.0 mm in size, are found. Sometimes the augite is surrounded by pigeonite, showing parallel intergrowth (Fig. 6). The optical characteristics are as follows: $2V=(+)54°-(+)48°$; $C\wedge Z=44°-41°$; refractive indices, $\alpha=1.695\sim1.697$, $\beta=1.701\sim1.703$, $\gamma=1.721\sim1.722$; hence, the average composition is $Wo_{41}En_{33}Fs_{26}$. The accompaning pigeonite, shows remarkable zonning, $2V=(+)20°\sim(+)0°$, in optical character.

Olivine occurs very rarely as the relic core of hypersthene, and its optical characteristics are $2V=(-)75°\pm$.

(Microphenocrysts) In this lava, microphenocrysts are obviously abundant. Palgioclase is lath-shaped, up to 0.5 mm in length, $An_{62\sim45}$ in composition. Pigeonite is a short prismatic crystal, up to 1.0 mm in length, and the grained pigeonite is some 0.5 mm in size. The crystal includes relic hypersthene in its core and the grains show reiterated twinning at (100) plane. The optical characteristics are as follows: $2V=(+)20°\sim15°$; $CZ=44°\sim42°$.

(Groundmass) The groundmass shows medium to coarse grained intersertal texture. Its constituents are mainly lath-shaped zoning plagioclase, up to 0.2 mm in length and $An_{59\sim47}$ in composition; and grained pigeonite, some 0.1 mm in size and $2V=25°\sim(+)0°$ in optical character. Accessory grained iron ore, anorthoclase, cristobalite, apatite and interstitial brown glass are detected (Plate 21, Fig. 2).

The VI type lava shows faint differences in accordance with its locality. Namely, the lava from the western foot of Konpirayama and the surface of the roof-mountain of Shōwa-Shinzan are somewhat poor in phenocrysts of pyroxene, and rich in microphenocrysts of prismatic pigeonite which include relic hypersthene. YAGI (1949) has also presented the petrographic description of this lava.

VII type lava (Pigeonite-hypersthene andesite)

Mode of occurrence: This lava has very limited distribution. It is observed near the Shōwa-Shinzan dome, where it occurs as the blocks, broken by the uplifting movement of the dome.

Macroscopic observation: This lava is light gray in colour, and its white plagioclase phenocrysts are remarkable. On the other hand, pyroxene phenocrysts are very rare. The lava is somewhat similar in appearance to the VI type lava.

Microscopic observation: Previously, the writer has reported the occurrence of the pigeonite phenocrysts in the VII type lava (ŌBA, 1961), because this is a rare phenomenon in volcanic rocks (KUNO, 1950, 1954).

(Phenocrysts) Of all the somma lavas, plagioclase is the most abundant in this lava, reaching 36% of the volume. It is up to 5.0 mm in size, and shows characteristically aggregated crystal of smaller plagioclase (Fig. 6). The crystal is almost homogeneous in composition, $An_{95\sim75}$, and dusty inclusion is almost undetectable. However, its outer rim (very thin, 0.05·mm±) shows distinct zonning and includes dusty zone.

Hypersthene is very poor, and is usually covered by a thick reaction rim of pigeonite. It is a short prismatic crystal, up to 1 mm in length, and rarely includes relic olivine in its core (Fig. 9). The optical characteristics are as follows: $2V=(-)65°\sim(-)59°$, average $(-)62°$; refractive indices, $\alpha=1.692\sim1.694$, $\beta=1.699\sim1.703$, $\gamma=1.705$–1.706; pleochroic colours, X=pale brown, Y=pale yellowish green; hence, average composition is $En_{69}Fs_{31}$. An example of the optical measurement of rimmed pigeonite shows $2V=(+)10°$.

Because augite does not occur as an individual crystal, pigeonite and the associated augite will be mentioned together.

Pigeonite is no so common in this lava. The pigeonite phenocrysts are observed in thin sections with the following features (Fig. 7).

(a) Single or aggregated crystals: In this case the pigeonite is an ill-define subhedral or rounded crystal, some 1.0∼1.5 mm in size. It often shows common twinning at (100) plane. Sometimes augite is included in the core.

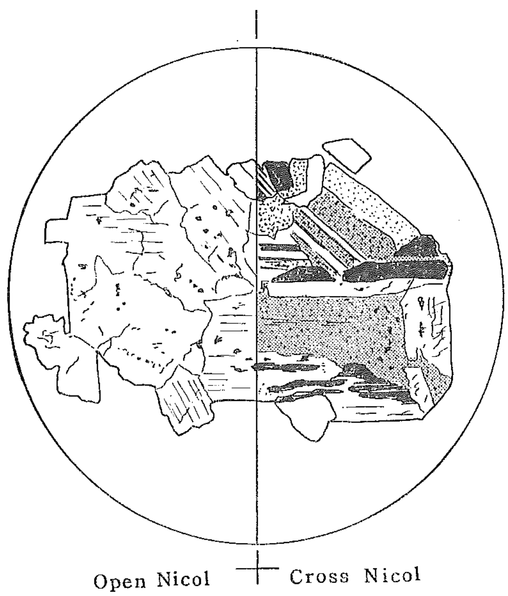

Fig. 6
An aggregate of plagioclase phenocrysts in the VII type somma lava.

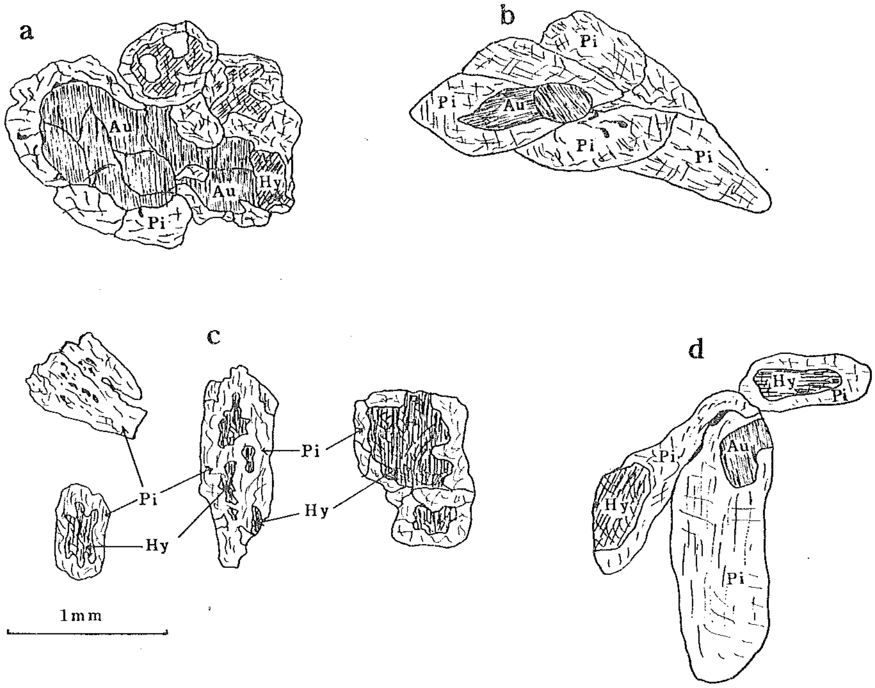

Fig. 7
Mode of occurrence of some pigeonite phenocrysts.
a, b: An aggregate of pigeonite and augite.
c: Pigeonite beeing inverted from hypersthene.
d: Pigeonite forming parallel intergrowth with augite.

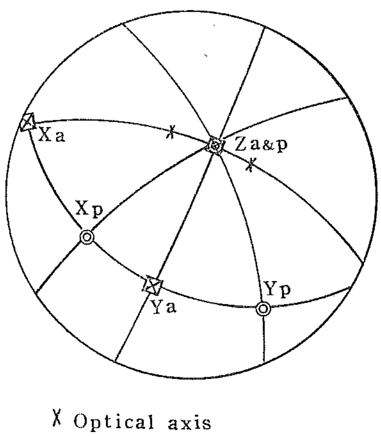

Fig. 8
The stereographic representation of the in ergrowth of pigeonite and augite. (For example, simbol " X_A " expresses the optical axis X of augite).

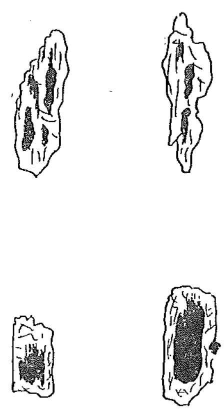

Fig. 9
Relic hypersthene in the pigeonite microphenocrysts.

(**b**) Pigeonite forming a parallel intergrowth with augite: In this case, the pigeonite always occurs as a thick mantle over the augite, and the both crystals are co-holding the optical axis of elasticity (Fig. 8). The boundary between the augite and the pigeonite is rather clear, and not show relationship of zonning.

(**c**) Somewhat tiny pigeonite crystals, having relic hypersthene inside: In this case, the pigeonite is 0.7~1.0 mm in size, and subhedral short prismatic crystal in habit. The relic hypersthene is an irregular shape crystal, and most likely the remnant from the replacement process of hypersthene to pigeonite (Fig. 9).

In the case of (a) and (b), the optical characteristics of pigeonite are as follows: $2V \fallingdotseq 0°$; $C \wedge Z = 40°$; refractive indices, $\alpha \fallingdotseq \beta = 1.697 \sim 1.699$, $\gamma = 1.724 \sim 1.725$; no pleochroism; hence, average composition is $Wo_{11}En_{51}Fs_{38}$. The optical characteristics of the associated augite are $2V = (+)52° \sim (+)47°$, refractive indices, $\alpha = 1.699 \sim 1.703$, hence, average composition is $Wo_{36}En_{37}Fs_{27}$. And those of hypersthene are $2V = (-)68° \sim (-)62°$.

In the case of (c), the optical characteristics of pigeonite is $2V \fallingdotseq 0$, and those of the included hypersthene are $2V = (-)66° \sim (-)61°$.

The genesis of the pigeonite phenocrysts are to be discussed later, in reference to other examples in the volcanic rocks of the world.

(Microphenocrysts) In this lava, microphenocrysts are obviously abundant in a manner similar to that of the VI type lava. Plagioclase is a lath-shaped and zoning crystal, up to 0.5 mm in length, and $An_{60\pm}$ in composition. Pigeonnte is either markedly prismatic, up to 0.7 mm in length, or else it occurs as grained crystal. The optical characteristics of this pigeonite are as follows: $2V = (+)10° \sim (+)0°$, and refractive indices, $\alpha = 1.699 \sim 1.701$, $\beta = \alpha$, $\gamma = 1.726$ (max.); hence, the average composition is $Wo_{12}En_{48}Fs_{40}$.

Table 3. Chemical composition of pigeonite in the groundmass (VII type lava).

	Wt %
SiO_2	50.58
TiO_2	0.82
Al_2O_3	3.84
Fe_2O_3	3.94
FeO	18.39
MnO	0.67
MgO	14.31
CaO	7.08
Na_2O	n.d
K_2O	n.d
$H_2O^{(+)}$	n.d
$H_2O^{(-)}$	0.12
Total	99.75

Analized by the writer

(Groundmass) The groundmass is coarse grained and typicaly intersertal in texture. Its consituents are mainly lath-shaped zoning plagioclase, up to 0.2 mm in length, and $An_{58\sim44}$ in composition; and grained zoning pigeonite, some 0.1~0.3 mm in size. Other accessory constituents are iron ore, anorthoclase, cristobalite, apatite and very small amounts of brown glass.

The optical characteristics of the pigeonite are as follows: $2V=(+)15^\circ\sim(+)0^\circ$; refractive indices, $\alpha=1.699\sim1.705$, $\beta=\alpha$, $\gamma=1.727$ (max.). The composition of the pigeonite, infered from the optical data, is $Wo_{11\sim17}En_{48\sim46}Fs_{41\sim37}$. This value is roughly concordant with the composition, calculated by chemical analysis ($Wo_{15.6}En_{44.1}Fs_{40.3}$, Table 3), (Plate 21, Fig. 3).

3–2. Scoria flow deposit

As was mentioned previously, the scoria deposit are interbeded with the somma lavas. Differing from them, however, considerable amounts of the scoria flow deposit are found at the north-eastern foot of Shōwa-Shinzan (Plate III, Fig. 1).

At the most typical outcrop, the thickness of this scoria flow deposit is up to 7~10 m. The lowest part of the deposit shows faint bedding with thin mud or sand formations, but for the most part the deposit shows no bedding and black slaggish appearance. A considerable number of compact angular lava blocks, up to 1 m in size, are included. The surface of the deposit is altered to reddish brown by weathering, and then covered by the newer " Ub " pumice fall deposit.

The petrographical character of the scoria and the included lava blocks is completely similar, except for the remarkable vesiculation in the former. They are both composed of plagioclase, hypersthene and olivine phenocrysts with the intersertal groundmass, simmilar to the somma lavas.

The time of the eruption of the scoria deposit was probably simultaneous with that of the IV or VI type somma lava, namely during the most active period in the formation of the somma stage of Usu Volcano.

3–3. Dome lavas

The dome lavas of Usu Volcano have been petrograhically described by several researcers (KATŌ, 1910; TANAKADATE, 1930; YAGI, 1949, 1953; YAGI in MINAKAMI, ISHIKAWA and YAGI, 1951; ŌTA, 1956; NEMOTO, et al., 1957). Among them, Yagi has presented the detailed microscopical description and the chemical compositions of the lavas. The writer will describe here outlines the petrographical character of the dome lavas, including some newly obtained data.

(A) Dome lava of Ko-Usu (Hypersthene dacite)

Macroscopic observation: This lava has a light-gray to pale blushgray colour, and a compact minutly appearance. Plagioclase and hypersthene phenocrysts, 1~2 mm in size, are found sporadically.

On the surface of the dome, the lava shows occasionally mottled features because of its dark coloured glassy texture.

Microscopic observation: (Phenocrysts) Plagioclase is a euhedral short prismatic crystal, up to 1.5 mm in length, and it shows remarkable zonal structure, $An_{65\sim45}$ in composition.

Hypersthene is a prismatic crystal, up to 1.0 mm in length, and frequently aggregated with plagioclase and iorn ore. Its optical characteristics are as follows: $2V=(-)60°\sim(-)54°$, pleochroism is remarkable (X=pale brown, Y=yellow, Z=green).

(Groundmass) The groundmass shows fine grain hyalopilitic texture. Its main constituents are lath-shaped or tabular plagioclase, up to 0.05 mm in length, needle-like green hypersthene which is as long as plagioclase, and a considerable amount of the aggregates of silica minerals (quartz and cristobalite), about 0.05 mm in diameter. Accessory grained iron ore and interstitial brown glass are also detected.

By the way, in the glassy part of this dome lava, quartz, hornblende and augite are found. These are all anhedral and up to 1.5 mm in size. The quartz is occasionally rimmed by grained cristobalite. The hornblende is green in colour and opacitized partially. The autie is composed of aggregates of minute augite accopaning a few plagioclase, magnetite and glass. These features are worthy of note, with relationship to the petrogenesis of the dome lava.

(B) Dome lava of Ō-Usu (Hypersthene dacite)

Macroscopic observation: This lava very much resembles the dome lava of Ko-Usu.

Microscopic observation: (phenocrysts) Plagioclase and hypersthene phenocrysts are similar to those of Ko-Usu. Corroded quartz is found rarely. Plagioclase phenocrysts often show notable zonal structure, $An_{93\sim45}$. Concerning this feature, the writer intends to discuss it in a later chapter in relation to the petrology of Shōwa-Shinzan.

(Groundmass) The groundmass shows fine grained pilotaxitic or hyalopilitic texture. Its main constituents are lath-shaped or skeletal plagioclase, some 0.05–0.1 mm in length, needle-like green hypersthene which is as long as the plagioclase, and cosiderable amounts of the tile-shaped aggregates of cristobalite. Accessory apatite, quartz, grained iron ore and the interstitial brown glass are also detected.

(C) Dome lava of Shōwa-Shinzan (Hypersthene dacite)

Macroscopic observation: This lava also has a similar appearance to the lavas of Ko-Usu and Ō-Usu. However, observing in detail, it shows that there are a considerable amount of black patches and xenoliths.

Microscopic observation: (phenocrysts) Plagioclase is a short prismatic crystal, up to 2.0 mm in length. Its zonal structure is remarkable, beeing about An_{60} at the core, An_{40} at the margin. Sometimes, abnormal composition is detected in the core, $An_{95\sim85}$ in which case included dust is also detected. The meaning of these features will be considered in a later chapter. Hypersthene is a prismatic crystal, up to 1.5 mm in length, and it often becomes aggregate crystal with plagioclases and iron ores. The optical characteristics of the hypersthene are as follows: 2V $=(-)61.5°\sim(-)55°$; refractive indices, $\alpha=1.705$, $\beta=1.714$, $\gamma=1.720$; hence, the average composition is $En_{57}Fs_{43}$, which agrees with the result of the chemical analysis of this hypersthene. Table 4 and 5 present the chemical and crystallographic data of the hypersthene. A small amount of magnetite (1.0%) is found as phenocryst.

Table 4. Chemical composition of the hypersthene phenocryst from the dome lava of Shōwa-Shinzan

wt %		Atomic rations (O=6.0000)		
SiO_2	51.04	Si	1.9328	Z=2.0000
Al_2O_3	3.12	Al	672	
			718	
TiO_2	0.23	Ti	66	
Fe_2O_3	1.89	Fe^{+++}	536	
FeO	21.12	Fe^{++}	6664	
MnO	1.11	Mn	354	WXY =1.9729
MgO	18.35	Mg	10424	
CaO	1.96	Ca	795	
Na_2O	0.22	Na	159	
K_2O	0.03	K	13	
$H_2O^{(-)}$	0.37			
Total	99.44			

Analized by the writer

(Groundmass) The groundmass shows hyalopilitic texture, and it has the highest crystallinity in comparison with the other two dome lavas. Its main constituents are small lath or skeletal plagioclase, some 0.1 mm in length and $An_{44\sim33}$ in composition, and the needle-like green hypersthene.

In addition, considerable amounts of quartz and cristobalite are detected. The quartz which always forms rounded crystal, $0.1\sim0.2$ mm in diameter, and it includes microlites of plagioclase and hypersthene. Cristobalite also is presents in interstitially with these minerals. Accesory anorthoclase and magnetite are also detected. The pale-brown glass which includs dusty inclusion, is found lying between the other minerals (Plate 21, Fig. 4).

The chemical composition of the lava, newly obtained, is shown in Table 8.

With regard to the hypersthene, although its optical characteristics were presented previously, more detailed chemical and mineralogical data will now be described.

Table 5. X-ray powder diffraction data.

h	k	l	Observed 2θ	Observed dÅ	Calculated dÅ	I/I_0
1	2	0	13.9	6.36	6.38	9
2	0	0	19.4	4.56	4.45	8
2	2	1	27.93	3.192	3.179	100
2	4	0			3.190	
3	0	0	30.14	2.963	2.963	16
1	6	0	30.93	2.889	2.889	51
1	5	1	31.40	2.846	2.846	9
2	4	1	32.86	2.723	2.725	12
3	1	1	35.11	2.554	2.554	20
0	2	2	35.63	2.519	2.519	9
1	1	2	36.10	2.486	2.489	13
2	5	1			2.489	
3	4	0			2.488	
3	2	1			2.483	
3	3	1	37.85	2.375	2.376	5
0	8	0	39.28	2.292	2.291	3
0	5	2	42.50	2.125	2.131	5
3	6	0			2.127	
3	5	1	42.84	2.109	2.109	13
4	1	1	44.63	2.039	2.033	3
2	8	0			2.036	
4	4	0	45.27	2.001	2.000	7
4	2	1			1.996	
3	6	1	46.05	1.969	1.970	14
2	9	1	52.43	1.744	1.746	10
1	8	2	54.19	1.691	1.693	6
4	1	2			1.688	
2	10	1	57.15	1.610	1.612	6
5	6	0	60.01	1.538	1.537	6
4	5	2			1.538	
0	12	0	60.61	1.527	1.527	7
6	0	0	62.62	1.482	1.482	14
5	4	2	66.79	1.399	1.400	8
3	11	1			1.400	
0	0	4	71.92	1.312	1.310	7

Condition: Rad. Cu (fil. Ni), 35 k.V, 13 mA,
Scan. sp. 0.5°/1 min., Time Const. 4., Scale. fac. 8,
Slit 1.0°-0.006″-1.0°, Multiplier 1.

Calculated unit cell dimensions of the hypersthene are as follows.

a=8.89Å b=18.33Å c=5.24Å (accuracy: ±0.005Å)

The analysis was carried out on pure material, which was obtained by using an isodynamic mineral separator in conjunction with Cleric solution, and finally, the purity of the sample was tested under the microscope.

Although the sample was not abundant, it was analyzed by the classical method, except for the alkalies which were analized by the flame photometer.

The components of this hypersthene, calculated from the analysis data (Table 4) are $Wo_{4.4}En_{58.3}Fs_{37.3}$.* Moreover, if the Wo component is not taken into consideration, the reduced component ($En_{61}Fs_{39}$) shows agreement with the component infered from the optical characteristics. The analysis was recalculated on the basis of six oxygen atoms, using the method outlined by HESS (1949), in which the electrical charges are always balanced between each of the (W X Y) and Z group. Ideally the number of cations to six oxygen atoms in the (W X Y) and Z group should be exactly 2.000. However the analyzed hypersthene does not meet this requirement, it has been necessory to include some Al^{+3} ions in the Z group to make Z into 2.000.

The hypersthene was studied using the X-ray diffractometer (*Norelco*), under the conditions presented in Table 5, through the courtesy of Dr. HARIYA of Hokkaido University; and the unit cell dimension have been calculated as Table 5. Silicon metal was used as the internal standard material, and the scaning speed was 1/2 per minute. The results are plotted against the variation curves of the unit cell dimensions of the orthopyroxene series, presented by HESS (1952), (Fig. 10).

It clearly can be seen from this data that the hypersthene is rather rich in CaO, in comparison to normal volcanic hypersthene. The capacity of the CaO in hyper-

Table 6. Infered 2V(−) values of the hypersthene phenocryst from refractive index (γ=1.7195), following the variation diagrams of some investigators.

	2V value corresponded to γ=1. 7195 and composition		
WALLS, 1935	2V=−55°	$MgSiO_3$	52 (wt %)
HENRY, 1953	2V=−53°	$MgSiO_3$ $FeSiO_3$	52 48 (wt %)
POIDERVAART, 1950	2V=−53°	$MgSiO_3$ $FeSiO_3$	57 43 (mol %)
WINCHELL, 1951	2V=−58°	$MgSiO_3$ $FeSiO_3$	57 43 (mol %)
HESS, 1952	2V=−53°	$Mg^{+2}:Fe^{+2}$=57 : 43 (atom %)	
KUNO, 1954	2V=−55°	$(Fe^{+2}+Fe^{+3}+Mn)SiO_3$	42 (mol %)

(Observed value 2V=−59° (average)

* $MgSiO_3$: $FeSiO_3$ Mol. %.

sthene is 0.61–2.67 wt %, followed by KUNO (1954). Moreover, the unit cell dimensions indicate abnormal values; the expansion of " a " dimension and the contraction of " b " dimension are remarkable.

The writer would drow his attention to the fact that the 2V(−) values of this hypersthene are slightly larger than those infered from the diagrams which given by the other investigators (Table 6).

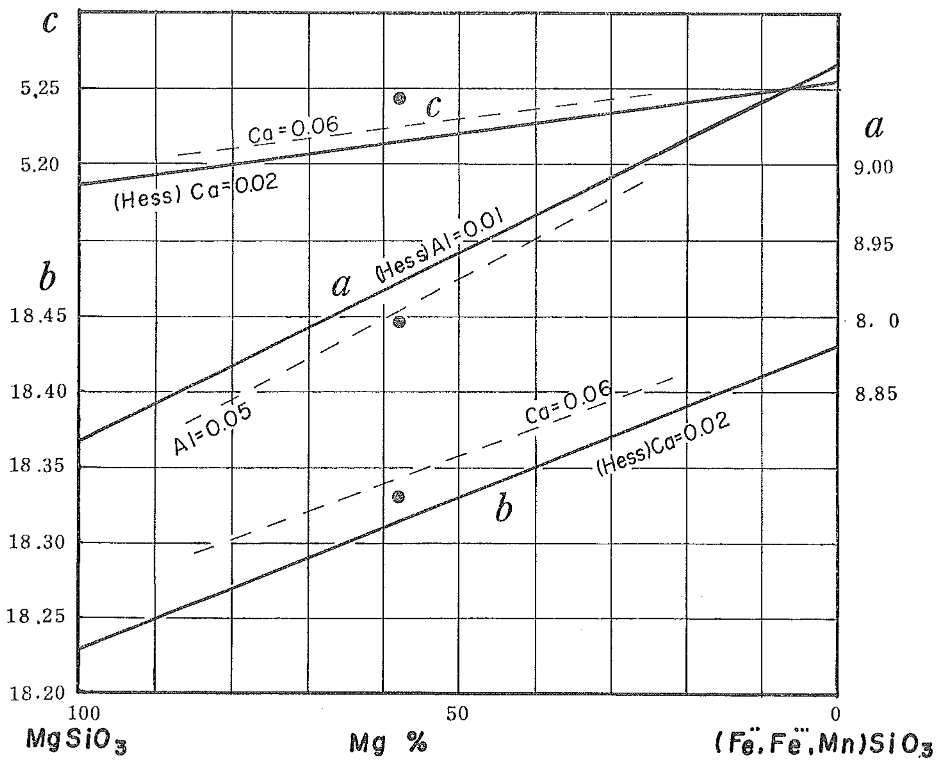

Fig. 10
The variation diagram of the unit cell dimensions of orthopyroxene series after KUNO (1945)
Solid circles are of hypresthene from the lava of Showa-Shinzan.

4. PETROCHEMISTRY

4–1. Somma lavas

Table 7 presents the chemical compositions of the somma lavas. The VANAtion diagrams of the main oxides, total iron—MgO—total alkali, Norm Or—Ab—An, and En—Wo—Fs relations are shown in Figures 11 to 14. The chemical compositions of the lavas of Usu Volcano, which have been previously published (TANA-

Table 7. Chemical compositions of the somma lavas.

	1	2	3	4	5	6	7
SiO_2	49.36	51.80	52.81	53.02	53.21	53.36	53.46
Tio_2	0.69	0.83	0.86	0.79	0.87	0.86	1.06
Al_2O_3	16.07	16.79	16.47	16.42	19.22	17.27	18.99
Fe_2O_3	3.79	4.14	3.54	3.22	2.34	3.81	2.75
FeO	7.68	6.74	6.91	7.09	6.33	7.47	6.74
MnO	0.21	0.17	0.17	0.17	0.13	0.09	0.22
MgO	8.92	6.01	6.23	4.95	4.21	3.63	3.82
CaO	10.75	10.20	9.95	10.24	10.43	9.41	9.79
Na_2O	2.03	1.93	2.46	2.80	2.76	2.67	2.47
K_2O	0.18	0.46	0.43	0.58	0.53	0.51	0.48
$H_2O^{(+)}$	0.37	0.26	0.20	0.17	0.13	0.28	0.33
$H_2O^{(-)}$	0.10	0.32	0.09	0.18	0.19	0.11	0.20
P_2O_5	0.12	0.33	0.23	0.16	0.11	0.31	0.32
Total	100.27	99.98	100.35	99.79	100.46	99.78	100.36
Colour* index	42.7	36.5	37.9	36.3	28.6	30.9	28.0

1-6, Analized by the writer. 7, YAGI, 1949.

1. I type lava (Augite-hypersthene-olivine basalt) Loc. Nishi-maruyama.
2. II type lava (Augite-olivine-hypersthene basalt) Loc. Southern valley of Nishi-yama.
3. IV type lava (Olivine-bearing augite-hypersthene basalt) Loc. Southern valley of Nishi-yama.
4. III type lava (Hypersthene-augite-olivine basalt) Loc. Eastern cliff, facing to the Osaru river.
5. VII type lava (Pigeonite-hypersthene andesite) Loc. Roof-mountain of Shōwa-shinzan.
6. VI type lava (Augite-hypersthene andesite) Loc. Konpirayama.
7. Somma lava of the Usu volcano. Loc. Eastern part of the roof-mountain of Shōwa-Shinzan (YAGI, 1949).

* Colour index=Total mafic minerals of the Norm.

KADATE, 1930; YAGI, 1949, 1953) are also plotted for the purpose of comparision with the other Quaternary volcano of south-western Hokkaido.

It is remarkable that the range of the SiO_2 contents fall into two different extents, 49.36~53.46% in the somma lavas and 68.26~71.25% in dome lavas. Peakock's alkali lime index, reading from Figure 11, is about 67.

Generally speaking, the somma lavas are poor in alkalies and small in Fe_2O_3/FeO and K_2O/Na_2O, and rich in CaO. This is characteristic of the tholeiite rock series, which includes rocks of the Chishima volcanic zone (KATSUI, 1962), the northern sub-zone of the Nasu volcanic zone (KAWANO et al., 1961) and the southern subzone of the Fuji volcanic zone (KUNO, 1950).

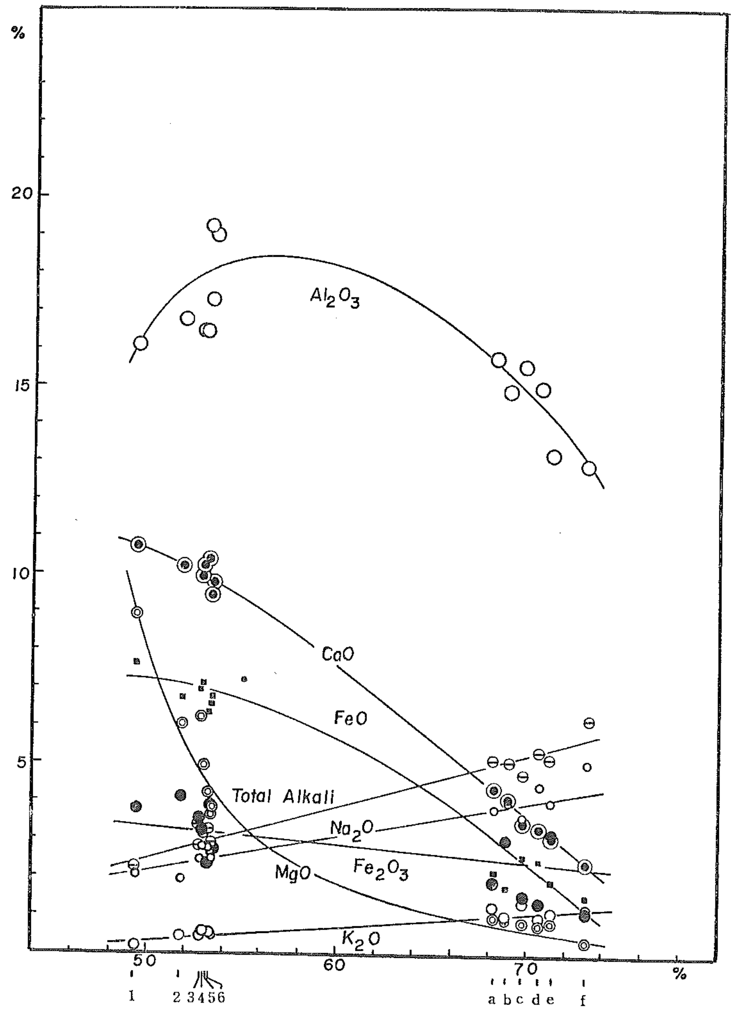

Fig. 11
Variation diagram of the main oxides of the erupting matrials.
Somma lavas: 1–7. Numbers are correlated to Table 7.

a; Dome lava of Ō-Usu. (TANAKADATE, 1930)
b; Dome lava of Shōwa-Shinzan. (present author)
c; Dome lava of Shōwa-Shinzan. (YAGI, 1947)
d; Glassy lava block from the Tateiwa nuees ardents. (YAGI, 1948)
e; Dome lava of Ko-Usu. (YAGI, 1948)
f; Pumice of Ub pumice flow deposit. (present author)

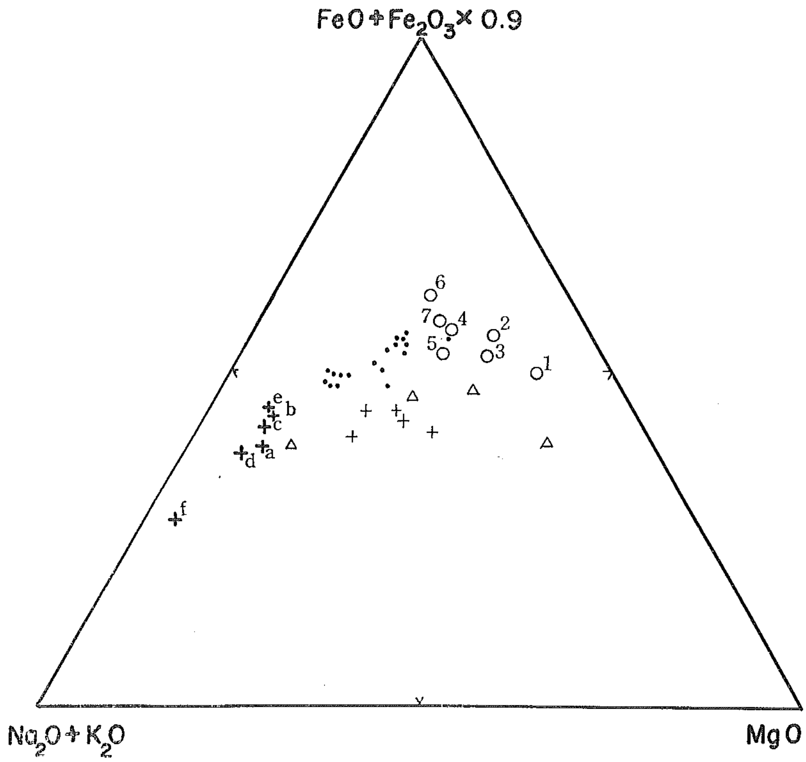

Fig. 12
Total FeO- MgO- total alkali diagram.
Large open circle: Somma lavas. Numbers are correlated to Table 7.
Large cross: Erupting materials of the final stage activity. Letters are same as Figure 11.
Ploted values of the other Quaternary volcanoes of south -western Hokkaido for comparision.
Small solid circle: Volcanoes of the Nasu volcanic zone. (Shikotsu, Tarumai, Komagatake and Yōtei Volcano) (KATSUI, 1962)
Open triangle: Oshima-ōshima. (KATSUI, 1962)
Small cross: Niseko Volcano. (ŌBA, 1960)

Other notable tendency is the markedly decreasing of MgO content. The writer considers that this feature is due to the remarkable decreasing of the olivine phenocryst from the early stage somma lavas to the later ones.

4–2. Dome lavas and the pumice fall deposit

The chemical compositions of the three dome laveas and the one dacite block of " Tateiwa nuée ardente " were published previously. However, one more datum of the lava of Shōwa-Shinzan which was made by the writer, given in Table 8.

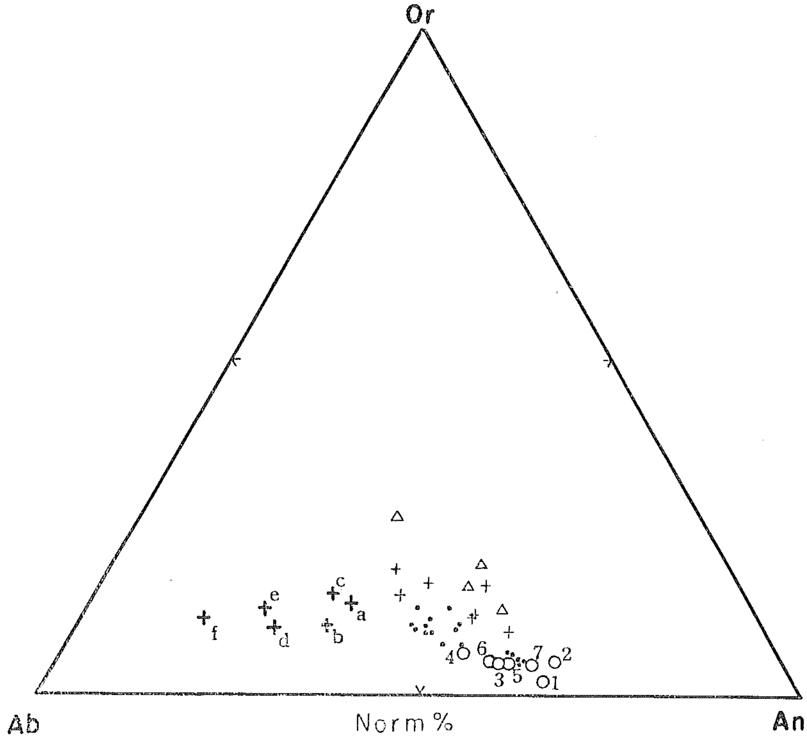

Fig. 13
Norm Or- Ab- An diagram.
The simboles are same as Figure 12.

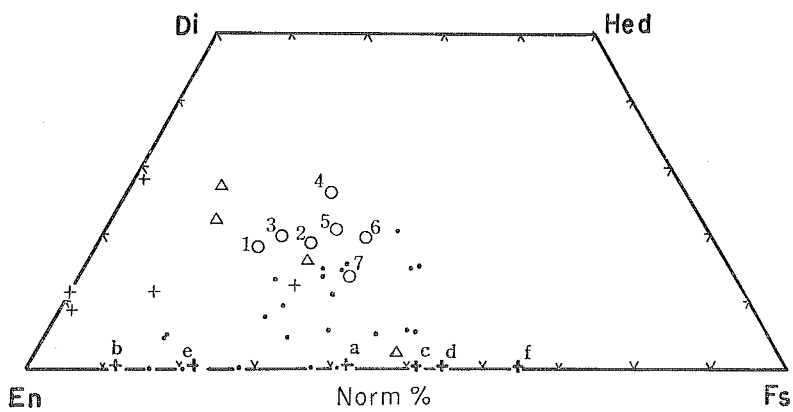

Fig. 14
Norm En- Wo- Fs diagram.
The simboles are same as Figure 9.

Table 8. Chemical compositions of the dome lavas.

	1	2	3	4	5
SiO_2	68.26	68.89	69.74	70.60	71.25
TiO_2	0.36	0.47	0.45	0.36	0.43
Al_2O_3	15.77	14.92	15.59	15.00	13.21
Fe_2O_3	1.91	3.01	1.52	1.37	3.19
FeO	2.15	1.78	2.59	2.49	1.96
MnO	0.31	0.16	0.08	0.09	0.27
MgO	0.99	0.90	0.85	0.77	0.84
CaO	4.37	4.10	3.63	3.30	3.10
Na_2O	3.83	4.00	3.43	4.42	4.02
K_2O	1.29	1.03	1.36	0.98	1.15
$H_2O^{(+)}$	0.51	0.12	0.67	0.69	0.50
$H_2O^{(-)}$		0.32	0.23	0.12	0.25
P_2O_5	0.18	0.24	0.22	0.21	0.46
Total	99.93	99.94	100.36	100.40	100.63
Colour index	8.69	8.32	8.59	8.09	9.36

1. Hypersthene dacite. Loc. Ō-Usu (YAGI, 1949).
2. Hypersthene dacite. Loc. Shōwa-Shinzan (Analized by present writer).
3. Hypersthene dacite. Loc. Shōwa-Shinzan (YAGI, 1949).
4. Hornblende-quartz bearing glassy dacite of Tateiwa nuée ardente (YAGI, 1949).
5. Hypersthene dacite. Loc. Ko-Usu (YAGI, 1949).

The dome lavas are also very similar in their chemical composition. And in comparison with other acidic volcanic rocks, those which are the same in SiO_2 content, the dome lavas of Usu Volcano are very poor in K_2O and rather rich in FeO, Fe_2O_3 and MgO.

The chemical composition of the " Ub " pumice is also presented, and compares with the calculated groundmass composition of the lava of Shōwa-Shinzan. (Table 9).

A diagramatic representation of those lavas and pumice has been plotted, together with that of the somma lava, in Figures 11 to 14.

5. XENOLITHS AND XENOCRYSTS

(A) Xenoliths from the lava of Shōwa-Shinzan

There have been no reports concerning the xenoliths of the dome lavas of Usu Volcano. However, the writer has found a small amounts of xenoliths from the lava of Shōwa-Shinzan.

Several different types of xenoliths are recognizable.

Granodioritic xenolith: To the naked eye, it is coarse grained aggregate of white

Table 9. Chemical composition of the pumice of the " Ub " pumice fall deposit (collected from northern foot of Shōwa-Shinzan), compares with the calculated composition of the groundmass of the dome lava of Shōwa-Shinzan.

	1	2
SiO_2	73.04	72.4
TiO_2	0.26	0.6
Al_2O_3	12.95	13.5
Fe_2O_3	1.11	2.7
FeO	1.54	1.2
MnO	0.06	0.2
MgO	0.36	0.6
CaO	2.41	3.4
Na_2O	5.07	3.8
K_2O	1.14	1.2
$H_2O^{(+)}$	1.02	0.4
$H_2O^{(-)}$	0.21	
P_2O_5	0.43	0.3
Total	99.60	100.3

1. Pumice of " Ub " pumice fall deposit.
2. Calculated composition of the groundmass of the dome lava of Shōwa-Shinzan.

(Analized by the writer)

and dark coloured minerals. Commonly, it occurs as rounded patch, 1.0–2.5 cm in diameter, and the boundary between it and the country rock is not sharp.

It has an equigranular holocrystalline texture, under the microscope, and consists mainly of plagioclase, pyroxene, subsidiary quartz and magnetite.

Plagioclase is distinguished between calcic variety and sodic one. The former is an unzoning crystal, showing Carlsbad and Pelicline twinning, some 5.0 mm in size; the later is a zoning crystal, and prismatic up to 1.0 mm in length. The composition of the former is very calcic, $An_{93\sim77}$, while that of the later is sodic, $An_{65\sim50}$ which resembles that of the common phenocrysts of the dome lavas. Sometimes, the former is covered by the later. Moreover, the felspar, having lower refractive indices (andesine or oligoclase), is found as interstitialy.

Pyroxenes are augite and hypersthene. They do not make a single crystal, but construct aggregates of similarly orientated tiny prismatic crystals, accompaning plagioclase and grained iron ore. They show the features of one crystal, on the whole, some 1.5 mm in size.

Such a occurrence of pyroxene is also often found in the glassy part of the dome lavas. The optical characteristics of the hypersthene are $2V=(-)58°\sim(-)52°$, and those of the augite are $2V=(+)53°\sim(+)51°$.

Quartz is anhedral, up to 1.0 mm in size, and is found interstitialy between the plagioclase and the pyroxene. The myrmekitic texture is found at the contact part with the felspar. At the margin of the xenolith, the quartz suffers corrosion and is rimmed by fine grained cristobalites (Plate 22, Fig. 1).

The xenoliths, to be mentioned following, all have clear boundary between the host lava, and merely seem to be captured wall rocks, in cluded in the lava by mechanical processes.

Dioritic xenolith: It is an angular, gray or dark-gray piebald xenolith, and 3–5 cm in size. The boundary between it and the host rock is rather sharp and often druses can be found by the naked eye. The black margin, some 0.5 cm in width, is remarkable. Although it shows a little turbidity, it has a typical equigranular holocrystalline texture. It is constructed of plagioclase (labradorite—bytownite), 0.5–1.5 mm in size; prismatic or fibrous aggregates of hypersthene; and opacitized hornblende (Plate 22, Fig. 2).

It is interesting that the plutonic rocks of the ejecta, which are sparsely distributed on the roof mountain of Shōwa-Shinzan, resemble this xenolith in their features. Diabasic fine grained holocrystalline xenolith : It is a gray coloured and subangular xenolith, some 2.0 cm in size. The boundary between the host rock is rather sharp. At the marginal part of this xenolith, a thin and more darkly coloured zone is found by the naked eye. It has a fine ophitic texture, and constructed of plagioclase and grained hypersthene, which shows remarkable turbidity due to including iron ore and dusty inclusion. The margin is made from the drifting hypersthene.

Xenolith, suggesting volcanic rock origin : It is a xenolith about 2.0 cm in size, and looks like a dark coloured patch. The boundary between it and the host rock is clear to the naked eye. It is constituted of plagioclase and hypersthene phenocrysts, and the groundmass composed of lath-shaped plagioclase and grained pyroxene. Although it shows a little turbidity, this xenolith resembles the somma lava of Usu Volcano.

Medium to fine grained holocrystalline xenolith : This is also a gray coloured angular xenolith, about 3.0 cm in size. The boundary between the host rock is clear. Some irregular black patchs in inner part and the marginal black zone are found. It has a medium to fine heterogeneous allotrimorphic granular texture, constituted of plagioclase and grained pyroexne (hypersthene>augite in volume), 0.05–0.3 mm in size. Phenocrystic plagioclase, up to 1.0 mm in size, are found sporadically. The marginal part of this xenolith is more fine grained and shows turbidity, and it often includes amoeba-shaped black material, which rarely holds relic pale green hornblende.

(B) Xenocrystic plagioclase of the dome lava

A more detailed study of the zonal structure of this plagioclase, clarifies the existence of a " calcic core* " in the phenocrysts of plagioclase (Fig. 15). The

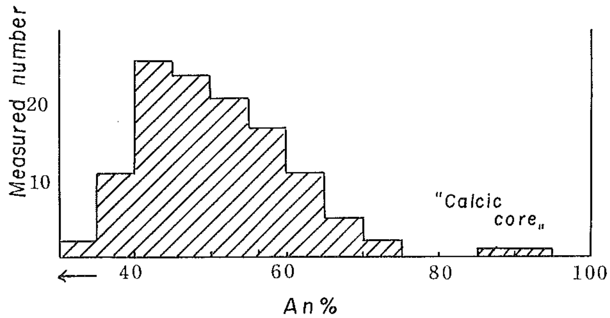

Fig. 15
The frequency diagram for An% of the plagioclase phenocrysts of the dome lava of Shōwa-Shinzan.

plagioclase shows commonly distinct zonal structure, each zone which has equal composition is very thin, the range of the composition is $An_{65\sim35}$.

The most usual zoning types are " osillatory ", and the next most sual types are " normal ". But of particular interest is the abnormal " calcic core ", which is $An_{93\sim80}$ in composition, and exists in the interior part of somewhat large plagioclase. This " calcic core " is characterized by its corroded form, twinning of a different orientation—compared with the marginal part—and by its turbid aspect (Plate 22, Fig. 3, 4).

High- magnified microscopic observation reveals that the " calcic core " is corroded in a manner which gives it a hornet's nest-like appearance, and that it is filled with more sodic plagioclase, some An_{55} in composition.

It seems probable that this " calcic core " was derived from the xenocryst. Reacting with the magma of the dome lava, it was covered with the more sodic plagioclase. This thinking is supported by more existence of " calcic cores " in the autolithic glomero-porphyritic plagioclase of the dome lava.

6. SOME CONSIDERATION OF THE PIGEONITE PHENOCRYSTS FROM THE SOMMA LAVA

The features of occurrence and the optical data have already been described in Chapter 3. Under this heading the writer will consider the relationship of the

* An % of the plagioclase changes from the calcic in the core and sodic in the margin.

pigeonite to the other pyroxenes and the crystallization of the pigeonite phenocryst.

Moreover, for the purpose of comparison, the characteristics of pigeonite phenocrysts of the volcanic rocks of Japan and other regions are quoted from the literatures. Before this investigation, pigeonite phenocrysts have not been recorded in the lava of Usu Volcano. Hence, a short note on this subject has already been published by the writer (1961, ŌBA).

The occurrence of the pigeonite phenocrysts (Fig. 7), indicates that the pigeonite might have been precipitated as hypersthene in the early stages of crystallization. But the residual magma becomes rich in iron, as much as $En_{70}Fs_{30}$, which is the critical point of Ca-poor pyroxene crystallizating as clinopyroxene in mafic

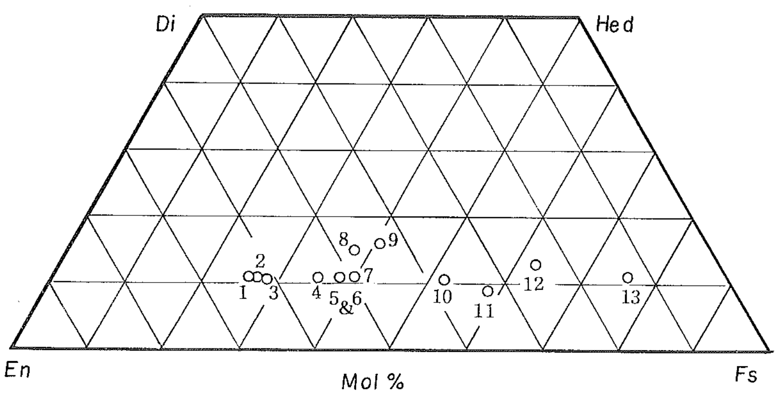

Fig. 16
Chemical components of the pigeonite phenocrysts, found in volcanic rocks of the world.

	Locality	Rock	Reference
1–3.	Funagata Volcano, northeastern Japan	Tholeiitic basalt	AOKI, 1961
4.	Moniwa, Sendai City, Japan	Andesite	OIDE, 1959
5.	Kayodake Volcano, northeastern Japan	Tholeiitic basalt	KAWANO & AOKI, 1969
6.	Usu Volcano	Tholeiitic andesite	ŌBA, 1961
7.	Senganmori, Fukushima Pref., Japan	Andesite	YASHIMA, 1961
8.	Mujina-goro, Nagano Pref., Japan	Andesite	TAKESHITA & YAGI, 1961
9.	Hakone Volcano, Japan	Andesite	KUNO, 1936, 1950
10.	Weiselberg, Germany	Weiselbergite	KUNO, 1947
11.	Mull, Scotland	Inninomorite	HALLIMOND 1914
12.	Minami-Aizu, Fukushima Pref., Japan	Andesite	KUNO, 1940
13.	Ashio, Tochigi Pref., Japan	Glassy dacite	KUNO, 1948

magma (HESS, 1941; KUNO and NAGASHIMA, 1952), then the precipitated hypersthene would be inverted to pigeonite from its surface.

In Fig. 16, the compositions of the other pigeonite phenocrysts plotted, to the best of the writer's knowledge, for the purpose of comparison.

Pigeonite phenocrysts found in tholeiitic basalt or basaltic andesite, for example, the lava of Funagata Volcano (AOKI, 1961), or the Tertiary volcanic rocks of northern Honshū (OIDE, 1959; YASHIMA, 1961), are rather rich in En content. On the other hand, those found in andesite or more felsic rocks, for example the somma lava of Hakone Volcano (KUNO, 1936, 1950), or the dike rock of Ashio (KUNO, 1947), are of a more Fs rich variety.

KUNO (1954) has stated that the groundmass pyroxenes of a lava which includes the pigeonite phenocrysts, are pigeonites or ferropigeonites. But later, AOKI (1961) maintained that Ca-rich clinopyroxenes (augite or ferroaugite) are crystallized in the groundmass, after the precipitation of the pigeonite phenocrysts, in Funagata Volcano. In the case of Usu, only pigeonite is crystallized in the groundmass.

In Japan, all pigeonite phenocrysts are found in tholeiitic volcanic rocks, but the crystallization process of these rocks is not always the same.

With regard to the somma lava of Usu Volcano, the writer has come to the conclusion that the factors, which may have some bearing on the development of the pigenonite phenocryst, are: (1) The lavas are derived from tholeiite magama, (2) Concentration of iron content in magma is remarkable. (3) Magma, reaching the end of intratelluric stage, is existent on the clinopyroxene area of the clinopyroxene-orthopyroxene inversion curve (HESS, 1941); in other words, it must have rather high temperature.

7. DISCUSSIONS

7-1. The relationship between the crystallization process and the variation in the chemical composition of the somma lavas.

The cystallization process in the somma lavas are able to summerized as Fig. 17. Although the Ca-rich ferromagnesian mineral (augite) shows little variance in composition, the Ca-poor ones (olivine-hypersthene-pigeonite) show notable fractional crystallization, throughout the somma lavas.

Olivine phenocryst, the most Mg-rich mineral, is abundant in the earliest stage somma lava (I type lava). However, olivine phenocryst rapidly decreases, being replaced by hypersthene, and the olivine phenocryst disappears after the middle stage of the somma lavas.

The succeeding hypersthene phenocryst is most abundant in the early and middle stages, with the exception of the III type lava. But it also decreases in the later stage and are replaced by pigeonite phenocryst.

The groundmass pyroxenes are augites or subcalcic-augites in the early stage of the somma lavas, but these monoclinic pyroxenes become pigeonite in the later

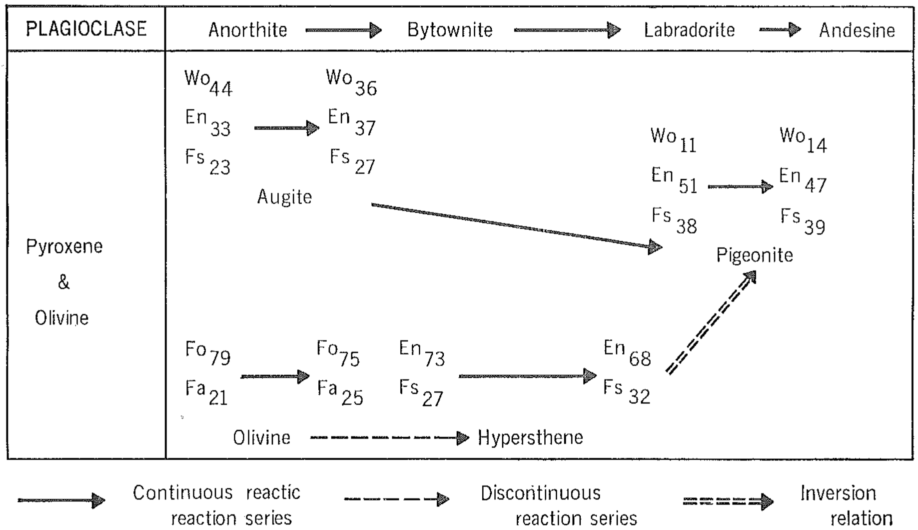

Fig. 17
Order of crystallization of rock-forming minerals on the somma lavas.

stages. And the latest stage of the somma lavas is characterized by the crystallization of pigeonite alone both in the phenocryst and in the groundmass.

Through the entire trend of crystallization, the iron content of olivine and pyroxene is becoming richer, according to the order of eruption of the somma lavas. That is to say, the distinct fractional crystallization in the magma can be expressed as the evolution of olivine, hypersthene and pigeonite.

Concordant with this fractional crystallization, the bulk compositions of the somma lavas vary successively. As is shown in Fig. 11, the MgO content decreases remarkably, corresponding to the decreasing of olivines. On the other hand, the iron content which would be one of the factors determining the character of pyroxene, clearly becomes greater in the later stages of the somma lavas.

7–2. Petrogenesis and the petrochemical character of the dome lavas and pumice

It has already mentioned that the dome lavas and " Ub " pumice are dacitic (or rhyolitic). And it is of interest that these are completely different from the somma lavas in character. The difficulties in the method of elucidating the processes of crystllization, arise chiefly from the fact that lava or pyroclastics having an intermediate composition between the two are entirely lacking.

KATŌ (1910) and TANAKADATE (1930) suggested in a few words that the dome lavas were derived from the mafic original magma by gravitational differentiation, due to the settling of the early formed minerals in the conduit.

Later, YAGI (1949, 1951) pointed out the impossibility of such a mechanism in the conduit, owing to the solid state of extremely high viscosity of the dome lavas (10^{11} poise, by MINAKAMI and others, 1951), and to the time and space of their formation. He stated conclusively that the salic magma of dacite was derived by some process from the original basaltic or andesitic magma. But he did not assert the process by which the salic magma was derived from the basic one.

NEMOTO and others (1957) advanced a theory concerning the remelting process of granite, for the genesis of the dome lavas. This idea was based on the resemblance between the dome lava and the average Japanese granite (SUZUKI and NEMOTO, 1935) in chemical composition. However, the writer considers that the content of K_2O and CaO of the dome lavas are rather unlike that of granite. Morever, the occassional existence of " calcic core " in the plagioclase is difficult to explain by this theory.

ŌTA (1958) put forward another opinion for the genesis of the dome lavas. According to him, the somma lavas originated from the basaltic magma, filling up the reservoir in a slatic basement formation. On the other hand, the dome lavas

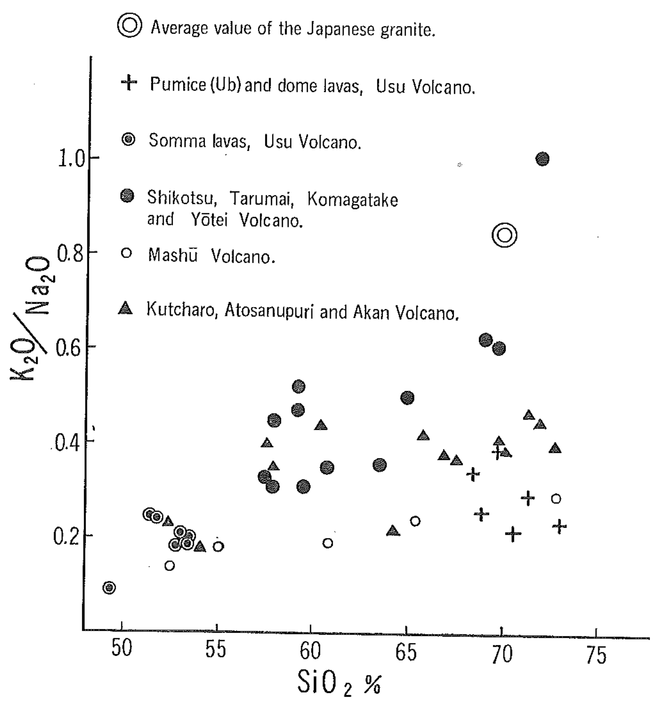

Fig. 18
SiO_2—K_2O/Na_2O diagram of the Quaternary volcanic rocks of Hokkaido, quoted only the rock derived from tholeiitic magma.

were derived by assimilation, from the more felsic magma of a deep granitic layer. But his opinion does not explain the relationship between the two magmas; it appears to be not very different from NEMOTO's idea.

It does not seem to the writer that the assimilation or remelting of granitic material is a justified explanation, because of the fact of the small K_2O/Na_2O ratio in the dome lavas and the pumice (Fig. 18).

YAMASAKI (1956) stated " when the tholeiitic magma contaminates with the granitic rocks, K_2O/Na_2O of the magma increases markedly. . ."

Although the evidence is not conclusive, the writer proposes the conception

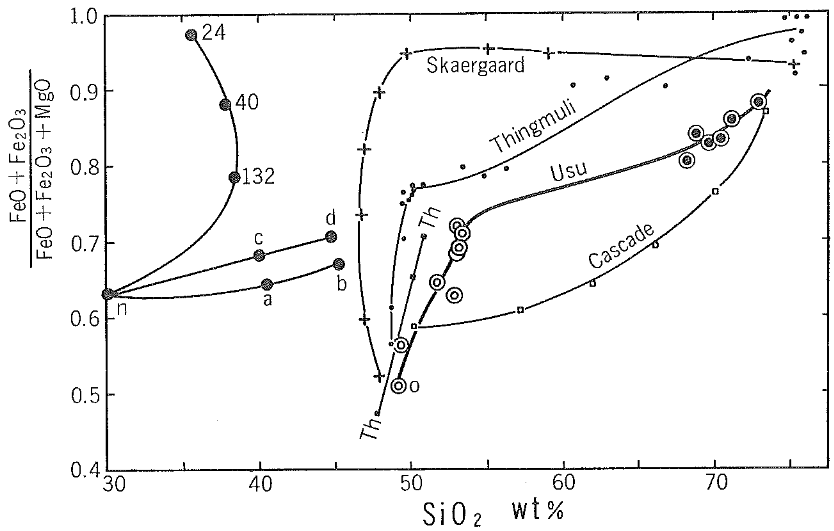

Fig. 19

The ratio $FeO+Fe_2O_3/FeO+Fe_2O+MgO$ plotted against silica. The writer makes some supplements to the original diagram of CARMICHAEL, 1964.

◎ : Somma lava
⊙ : Dome lavas and pumice } Usu Volcano
◎o: Infered original magma

n–a–b–: At increasing pO_2

n–c–d: At constant pO_2

n–132–40–24: At constant total composition

Above three are fractional crystallization trends of original liquid n, in the system MgO–FeO– Fe_2O_3–SiO_2 (OSBORN, 1959).

Skaergaard: Fractional crystallization trend of the Skaergaard intrusion. A representative example of the tholeiitic trend).

Thibgmuli: Fractional crystallization trend of the Thingmuli rocks, Iceland.

Cascade: Basalt—Andesite—Rhyolite association of the Cascade province, United State. A representative example of the Calc-alkali trend.

Th—Th: Average tholeiite. (NOCKOLDS, 1954) that the dacite was alone derived by fractional crystallization from the andesitic magma, which is represented by the groundmass composition of the latest somma lava. Of course, the somma lavas are derived from tholeiitic parental magma by fractional crystallization.

The rule of fractional crystallization in the quaternary system MgO-FeO-Fe_2O_3-SiO_2 (OSBORN, 1959), is very suggestive to the differentiation phenomena observed in igneous rocks (e.g. TAKESHITA and YAGI, 1961; CARMICHAEL, 1964). The principal idea is that there exist two types of crystallization trends which depend on the conditions of partial oxygen pressure (pO_2): (1) The Tholeiitic trend, at a constant total composition and decreasing pO_2, is represented by increasing iron while

Table 10. Compositions of L_1, L_2 and X_1 in Figure 20.

	1	2	3	4		
SiO_2	49.06	56.09	41.6	Plagioclase	Ab 12.3 An 87.7	54.8 Wt%
TiO_2	0.66	1.38	0.0			
Al_2O_3	15.34	11.83	18.8	Wollastonite	Wo	6.8
Fe_2O_3	3.66	3.67	4.6	Olivine	Fo 84.0 Fa 16.0	31.8
FeO	8.00	9.39	5.8	Magnetite		6.7
MnO	0.20	0.21	0.2	Added Oxygen		0.1
MgO	10.71	6.12	15.1	Solidify ratio		50%
CaO	10.24	7.37	13.0			
Na_2O	1.93	3.12	0.8			
K_2O	0.17	0.84	0.0			

1. Infered original magma of Usu Volcano. Calculated from the earlist somma lava (I type lava), and summations are 100%, because $H_2O^{(+)}$, $^{(-)}$ P_2O_5 ommited, following the same. Since S·I of the I type somma lava is 29.7, solidify ratio of the lava is infered about 40% of the original magma*. I type lava is already including 35% (Wt%) of olivine, hypersthene and augite phenocrysts, so 5% of olivine (Fo_{80}·Fa_{20}) must be added and recalculated in compensate for the removed crystal.
[$S \cdot I = MgO \times 100 / MgO + Fe_2O_3 + Na_2O + K_2O$, Soldification Index of KUNO (1954).]
2. Groundmass of the latest somma lava (VII type lava). Andesitic magma in the next Table 12 is the same one.
3. Possible crystal phases extract from the original magma (1) to give the andesitic magma (2).
4. Calculated mineral compositions of 3.

* The solidify ratio (percentage of the crystal fraction) is infered from S·I of (2) in imitation of a relation between S·I and solidify ratio of the liquid of the Skaergaard intrusion (WAGER and DEER, 1939).

remaining almost constant in SiO_2 (n-132–40–24 in Fig. 19); (2) The Calc-alkali trend, at constant pO_2 and changeable total composition, is represented by increasing SiO_2 and a constancy of iron (n-a-b and n-c-d in Fig. 19).

The writer prepares a plot of $FeO+Fe_2O_3/MgO+FeO+Fe_2O_3$ vs. SiO_2, first used by OSBORN, in order to illustrate the existence of two distinct trends in the lavas of Usu Volcano. This diagram casts some light on the problem of the crystallization mechanism (Fig. 19).

The fractional crystallization of the parental magma is figured as follows;

(1) **The gensis of the somma lava;** fractional crystllization on the tholeiitic trend. Calcultion is shown by the next equation.

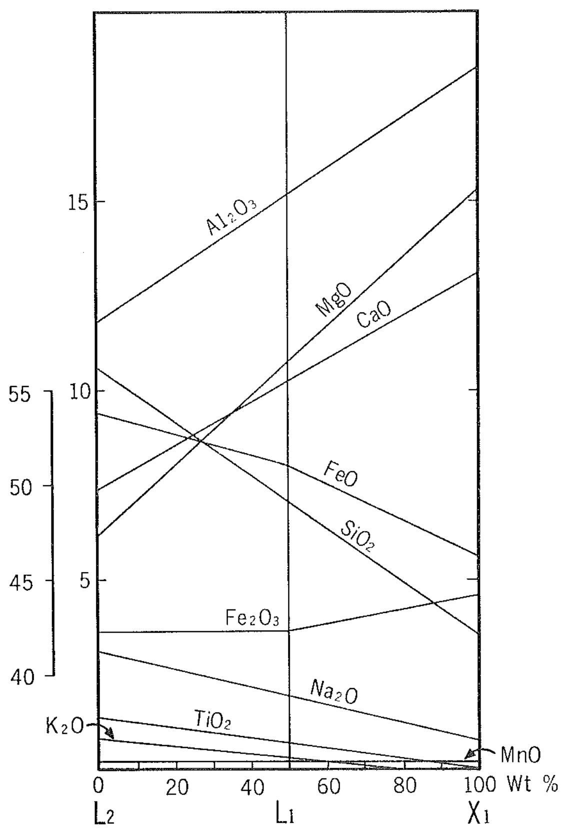

Fig. 20
Substraction diagram deriving by fractional crystallization of andesitic magma L_2 from original magma L_1, by subtracting 50% of crystal phases X_1. These magmas and crystals are respectively the composition 2, 1 and 3 of Table 10.

$$\left(\begin{array}{c}\text{Infered parental magma}\\ (L_1)\\ \text{(Table 10–1)}\\ 100\%\end{array}\right)-\left(\begin{array}{c}\text{Crystal phases to be}\\ \text{subtracted } (X_1)\\ \text{(Table 10–3, 4)}\\ 50\%\end{array}\right)=\left(\begin{array}{c}\text{Groundmass of the latest}\\ \text{stage somma lava } (L_2)\\ \text{(Table 10–2)}\\ 50\%\end{array}\right)$$

To illustrates this, a subtraction diagram is given in Fig. 20.

In this case the solidification index* (MgO 100/$MgO+FeO+Fe_2O_3+Na_2O+K_2O$) of the right hand lava is useful in presuming the solidify ratio of the magma, by applying the relationship between the solidify ratio and S•I value of the Skaergaard intrusion (cf. the explanations for Table 10).

The conditions of this crystallization are not so critically constant in total composition, and a small net of oxygen has been added to the magma.

(2) **The genesis of the dome lava;** fractional crystallization on the calc-alkali trend.

Table 11. Compositions of L_2, L_3 and X_2 in Figure 21.

	1	2	3	4			
SiO_2	56.09	72.63	48.9	Plagioclase	Or 8.2		Wt%
TiO_2	1.38	0.56	2.0		Ab 57.1	44.2	
Al_2O_3	11.82	13.58	11.1		An 34.7		
Fe_2O_3	3.67	2.74	7.8	Subcalcic Augite	Wo 29.3		
FeO	9.39	1.24	9.6		En 46.8	42.3	
MnO	0.21	0.19	0.2		Fs 23.9		
MgO	6.12	0.63	8.5	Magnetite		13.9	
CaO	7.37	3.39	9.0	Added Oxygen		0.4	
Na_2O	3.12	3.81	2.9	Solidify ratio		70%	
K_2O	0.84	1.23	9.6				

1. Andesitic magma (ibid. Table 10–2)
2. Groundmass of the dome lava of Shōwa-Shinzan for the representative of dacite.
3. Possible crystal phases extract from andesitic magma (1) to give dacitic magma (2).
   It is very uncertain to decide the solidify ratio of crystal phases (X_2) from S•I value (8.4) of L_2. But if the solidify ratio is larger than 90% of andesitic magma, it is not necessary to add oxygen for the oxidation of FeO and to accelerate the precipitation of magnetite for produceing dacitic magma. On the contrary, this value is smaller than 60%, it is so scarce in SiO_2 and Na_2O, while surplus in MgO and CaO, that a lots of magnetite and Mg-rich augite, which are not possible component, must be including in X_2. For these reasons, much more oxygen add to the condensed phases during change of liquid from andesitic magma to dacitic one.
4. Calculated mineral compositions of 3.

* For short S,•I,

Andesitic magma		Crystal phases to be subtracted		Groundmass of the dome lava of Showa-Shinzan
(L_2)	−	(X_2)	=	(L_3)
(Table 11–1)		(Table 11–3, 4)		(Table 11–2)
100%		70%		30%

The subtraction diagram is given in Fig. 21. Thus 13.9% of the magmetite crystallizes to produce dacitic magma. Because the solidify ratio infered by the S•I value is uncertain, the more crystal phases subtracted, the less magnetite is precipitated, and *vice versa*, in order to produce a change in the required high salic derivative. But in such extreme cases, another difficulty arises in doing calcu-

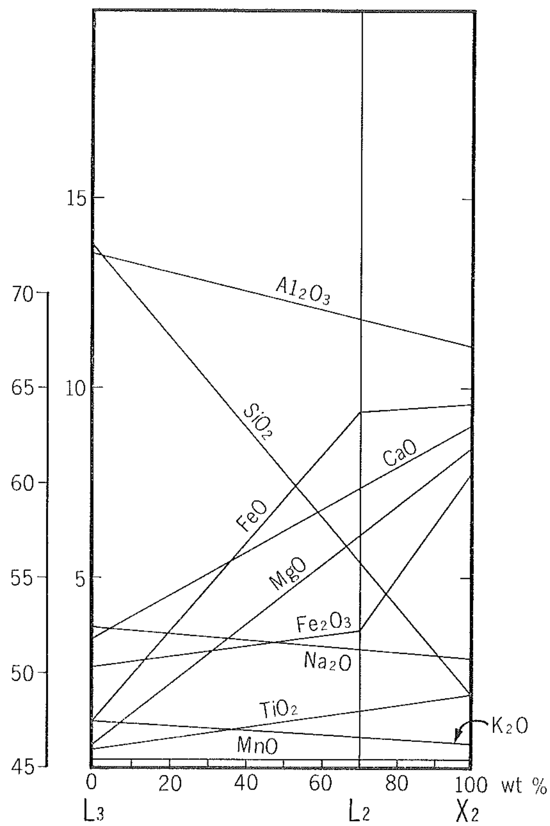

Fig. 21
Subtraction diagram deriving by fractional crystallization of dacitic magma L_3 from andesitic magma L_2, by subtracting 70% of crystal phases X_2. These magma and crystals are representively the composition 2, 1 and 3 of Table 11.

lation (see the explanation for Table 11). Some attention should be given to the trend of the FeO and Fe_2O_3 contents. These can not be shown as a straight line (see Fig. 21), because 0.4% of oxygen must have been added to the magma. Thus, the lines of the iron content have the turn of direction at the vertical line (L_2), representing the composition of the primary magma.

After all, the primary magma is solidified as 85% crystal aggregates and 15% residual dacitic magma, in the proportions shown in Fig. 22.

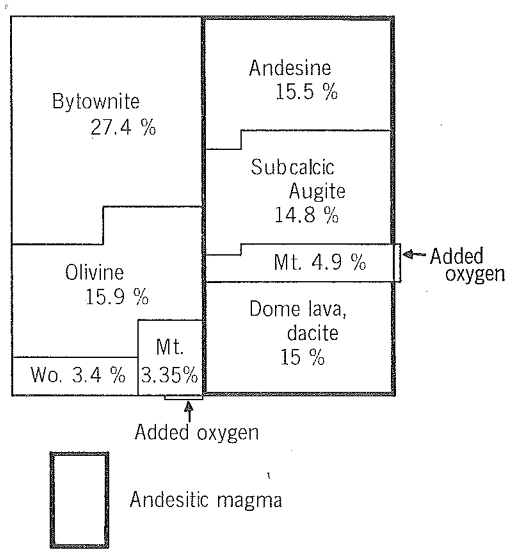

Fig. 22
Conclusively each crystal phase precipitating from 100% of original magma, is figured. Small amount of oxygen adds to the formation of magnetite crystal.
Wo=Wollastonite Mt=Magnetite

The writer's arguments are also convenient to explain some of the petrographic evidences. For instance, some xenolithes and xenocrysts in the dome lavas can be considered as kind of autolith, composing of crystals precipitated at an early stage. Moreover, each of the subtracted crystal phases, Table 10–4, and 11–4, are not significantly different from the modal minerals of the lavas.

But there is a question of the volumetric relationship of the actual products.

The roughly assumed volume and mass of the products of Usu Volcano are listed in Table 12. (Zenkoji pyroclastic flow deposit is not included in the somma lava, and the volcanic ashes are neglegible) It is clear from Table 12 that the salic products are too great quantity (60%) to balance with the mafic ones, if they have been derived by simple fractional crystallization from the mafic magma. For example, at the Thingmuli volcanic rocks of Iceland, the felsic differentiates (ryolites, obsidians and granophyres) exist as about only 20% of the whole products (CARMICHAEL, 1964).

Table 12. Dimensions of the products of Usu Volcano.

	Volume (km^3)	Mass (10^9 ton)
Dome lavas	0.3 +	0.8 +
Nuées ardents & Volcanic ashes	>0.01	>0.02
" Ub " pumice	2.1_8	0.6_5
Somma lavas	0.3_5	0.9_8

Concerning to the above questions, it should be pointed out in rebuttal that, there is no necessity to think that all the derivative materials from a tholeiitic magma should be effused by the volcanic activity of Usu Volcano; in other words, probably much more basaltic or andesitic materials, as same character as the somma lavas, would be remain under the volcano. Moreover there might be a underestimation about the volume of the somma lavas, by mean of these uncertain thickness.*

Finally, a word must be said about the genesis of " Ub " pumice fall. A comparision of the chemical compositions of the pumice of " Ub " and the groundmass of the dome lava of Shōwa-Shinzan is shown in Table 9. This table shows that the pumice is a somewhat rich in SiO_2 and alkali contents. The genesis of " Ub " pumice might be explained in the light of the work of KENNEDY (1955). According to him, the included water content is the same thoughout the magma reservoir, and the water with co-ordinative alkalies tends to be concentrated at the upper part of the magma body, at that place where the lowest pressure and temperature is possible.

In the case of the Ko-Usu lava dome, during the solidifcation process of the lava in the conduit, the silica and alkalis would have been concentrated just under the volcanic neck. Then, in the course of nature, the very violent explosion occurred due to the vesiculation of the dacitic magma.

The result of this explosion, " Ub " pumice shows a distinct vesiculation and is chemically rich in silica and alkalies. Such a inference is supported by the occurrence of hornblende phenocrysts, which are completely lacking in the dome lava.

7–3. The petroprovincial situation of Usu Volcano

In respect to the petroprovince of the Quaternary volcanoes, KATSUI (1962)

* The borings for hot spring have done at the the northern foot of Konpirayama and Higashi-Maruyama reveal recently that the thickness of the somma lavas at these places are 145 m, and 98 m respectively. Those values, perhaps might be due to the topographical condition (on the rim of Tōya caldera), are greatly in excess of the previous estimations infered from the field survey.

has pointed out that there are three main petroprovincial zones in Hokkaido: (1) the tholeiitie rock series in outer zone (Pacific side), such as Komagatake, Usu, Tarumai Volcano, Shiretoko-Akan Volcanic belt; (2) the weak alkali tholeiite rock series in the intermediate zone, such as Niseko Volcano, Daisetsu-Tokachi volcanic belt; (3) the alkali rock series in the inner zone (Japan Sea side), such as Oshima-Ōshima, Rishiri Volcano. And these three rock series each have derivative calc-alkali rock series. Series (2) is identifiable with the high-alumina basalt series of Kuno (1960).

The lavas of Usu Volcano is no doubt belonging to the tholeiitic rock series. The somma lavas resemble the tholeiitic basalt or andesite of the northern sub-zone of the Nasu volcanic zone in northern Honshū (KAWANO et al., 1961), and that of the Shiretoko-Akan volcanic belt of eastern Hokkaido (KATSUI, 1962). And these are only one example of tholeiitic rocks in south-western Hokkaido.

Figure 12 clearly shows that the somma lavas are the most iron concentrative rock series among the volcanic rocks in southwestern Hokkaido. Moreover, the I type somma lava, although porphyritic, might closely resemble the original tholeiite magma of this district.

But, some attention should be paid to the lavas of Usu Volcano, because of the rather low-grade concentration of iron content, in comparison to the other typical tholeiitic rock series of Hawaii (KUNO et al., 1957), Izu-Hakone (KUNO, 1950) and the Skeargaard intrusion (WAGER and DEER, 1939). The trend of the lavas of Usu Volcano is similar to that of the tholeiitic Nasu volcanic zone (YAMASAKI, 1954; KAWANO et al., 1961). Concerning this fact, AOKI (1961) has stated that the slight difference in the composition of the original magma might have caused the variety in the trends of fractional crystallization. The I type somma lava, which is perhpas representative of the original magma of Usu Volcano, shows itself to be poorer in iron and lime while recher in soda than typical tholeiitic magma.

8. CONCLUSIONS

By the way of conclusion, a characteristic growth history of Usu Volcano will be emphasized.

In the beginning, the somma lavas and the accompanying scoria of basalt or andesite, erupted rather quietly, and a strato cone was completed. After then, the summit of this volcano was broken by violent explosion, at which time the pyroclastic flow occurred. Due to the effect of this explosive activity, two volcano-stractual fissures—the ring-fissure on the foot of the volcano, and the straight-fissure on the summit running from east to west—were born and became the cause of uprifting of the dome lavas and the cripto-domes.

After a considerable quiescence, continuing about 1,500–2,000 years, the eruption of dacite materials, represented by " Ub " pumice and the dome lavas, had begun and the activity had entered into its final stage. Therefore, the character of the magma of Usu Volcano might had been changed from andesitic to dacitic, during this period.

The activity of " Ub " pumice fall would be resulted from the concentration of the volatile substances at the upper part of the conduit, suppressing by the solidified dacite lava.

After the eruption of " Ub " pumice, the intensity of activity had declined more and more, by releasing of the interior pressure of the volcano. This is proved by the upheaval of the following lava domes.

To the writer's way of thinking, the most suitable reason for the sudden change in composition of the magma, from mafic to salic, might be attributed to the process of fractional crystallization.

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Explanation of Plate 16

Explanation of Plate 16

Figure 1. A view of Usu Volcano, looking north-west from Date town.

Figure 2. Shōwa-Shinzan, viewed from the lake side of Toya. The roof-mountain of Shōwa-Shinzan is composed of the basement rocks and uplifted somma lavas.

Plate 16

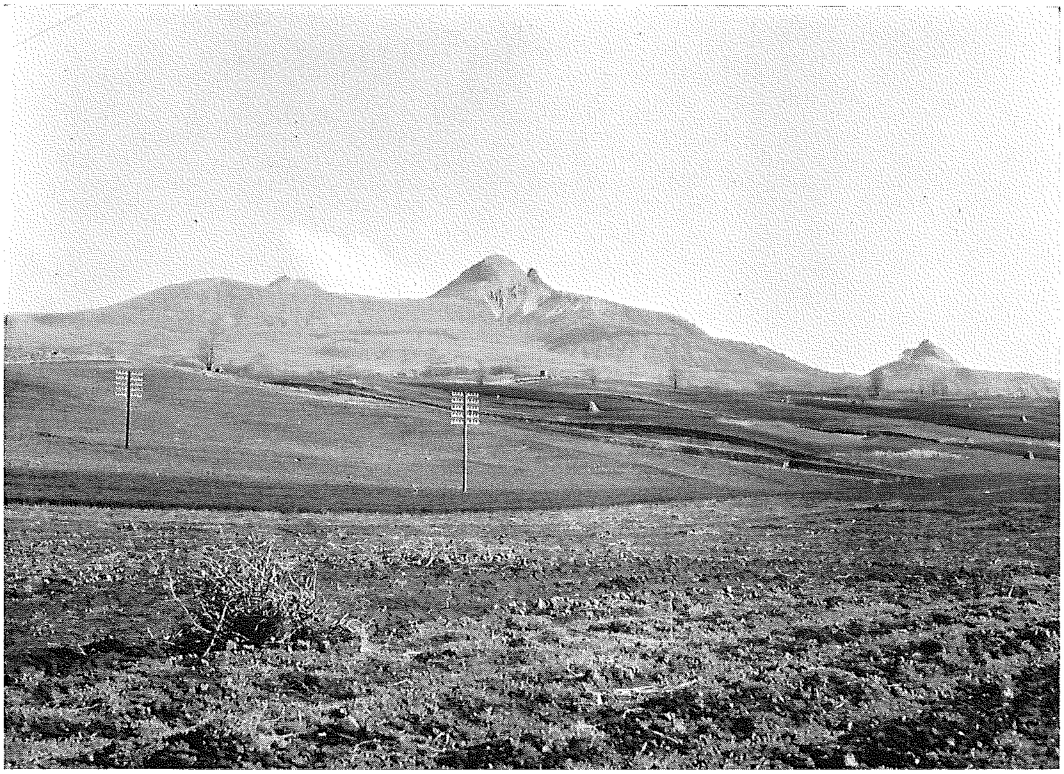

Figure 1

Figure 2

Explanation of Plate 17

Explanation of Plate 17

Figure 1. Ō-Usu lave dome, viewed from the roof–mountain of Shōwa-Shinzan.
Figure 2. Ko-Usu lava dome, viewed from the southern rim of the somma.

Plate 17

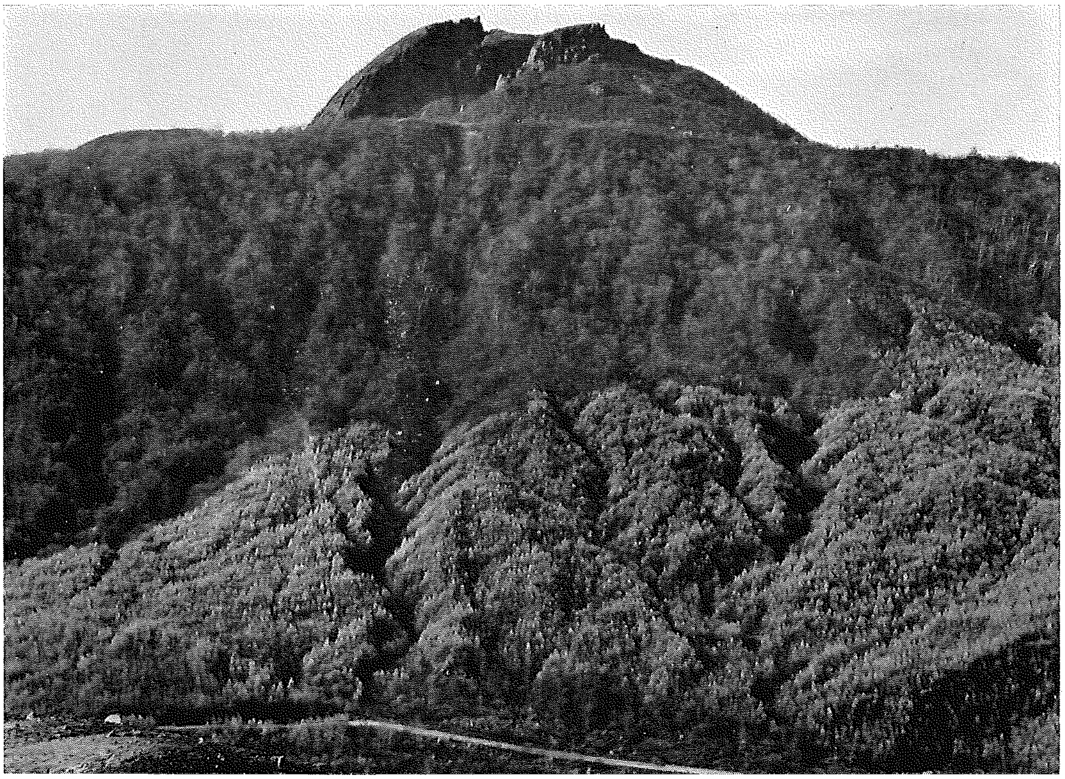

Figure 1

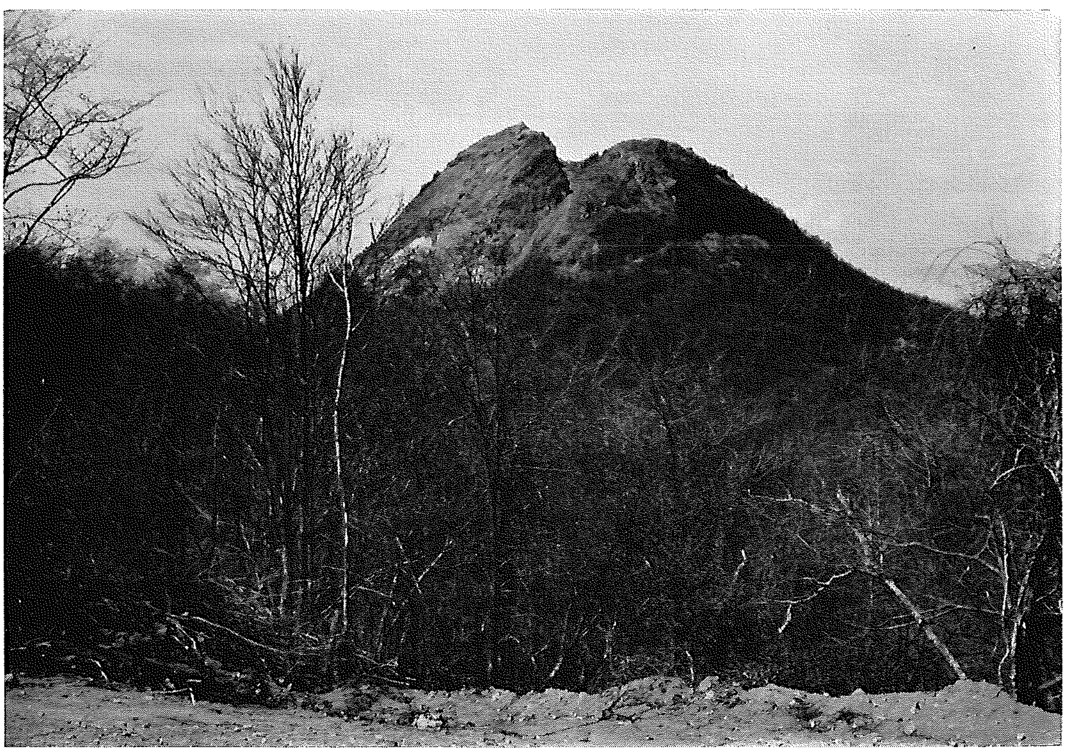

Figure 2

Explanation of Plate 18

Explanation of Plate 18

Figure 1. An outcrop of the scoria flow deposit and the "Ub" pumice fall deposit. (about 1 km. north of Shōwa-Shinzan).

Figure 2. A close-up of the "Ub" pumice fall deposit. (at the same place of Figure 1).

Plate 18

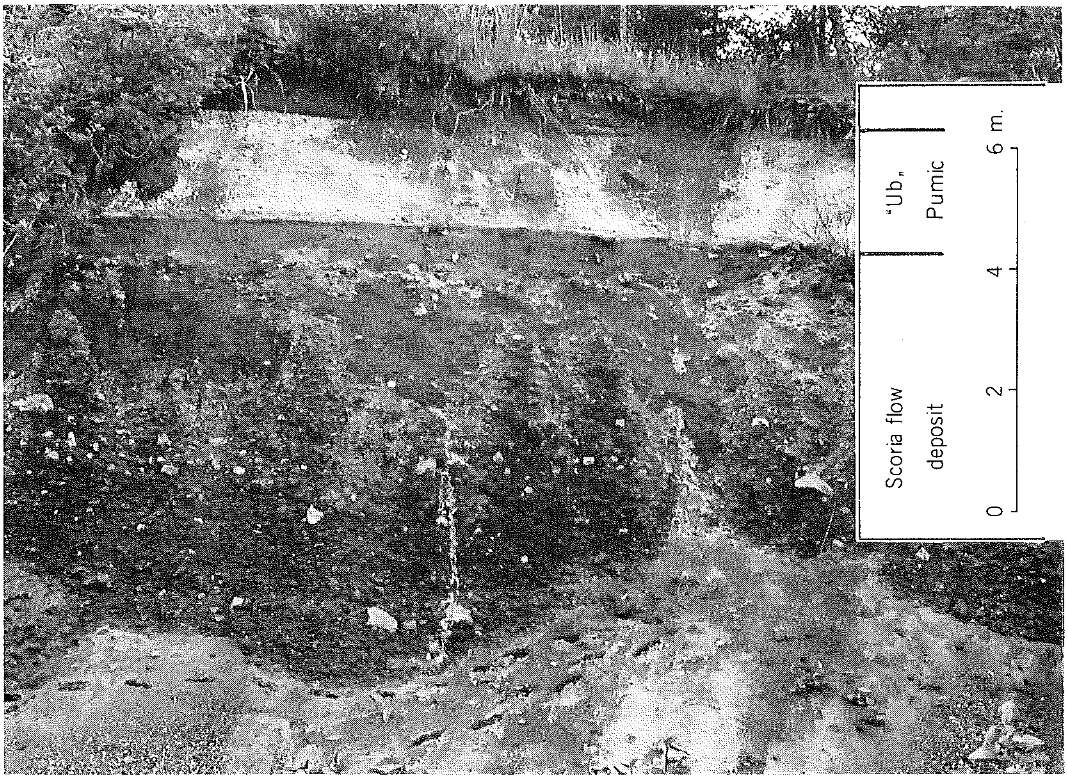

Figure 1

Figure 2

Explanation of Plate 19

Explanation of Plate 19

Figure 1. The cripto-dome "Higashi-maruyama", viewed from the lake side of island Ōshima.
Figure 2. Large anorthite phenocryst found in the I type somma lava, at the lake side of Nishi-maruyama.

Plate 19

Figure 1

Figure 2

Explanation of Plate 20

Explanation of Plate 20

Photomicrographs of the somma lavas.

Figure 1. Augite-hypersthene-olivine basalt (I type somma lava). Showing plagioclase (Pl), augite (Au), hypersthene (Hy) and olivine (01). A lave collected at Nishi-maruyama.

Figure 2. Augite-olivine-hypersthene basalt (II type somma lave). A lava of the southern valley of Nishi-yama.

Figure 3. Hypersthene-augite-olivine basalt (III type somma lava).
A lava collected at the western cliff of Kami-nagawa. The groundmass composed of mainly coarse-grain plagioclase and pigeonite.

Figure 4. Olivine bearing augite-hypersthene basalt (IV type somma lova).
A lava of the western rim of the summit crater.

Plate 20

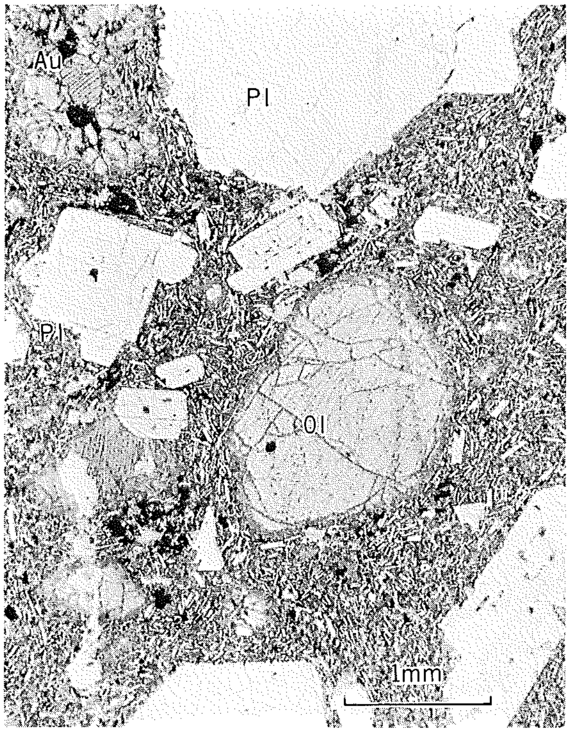

Figure 1

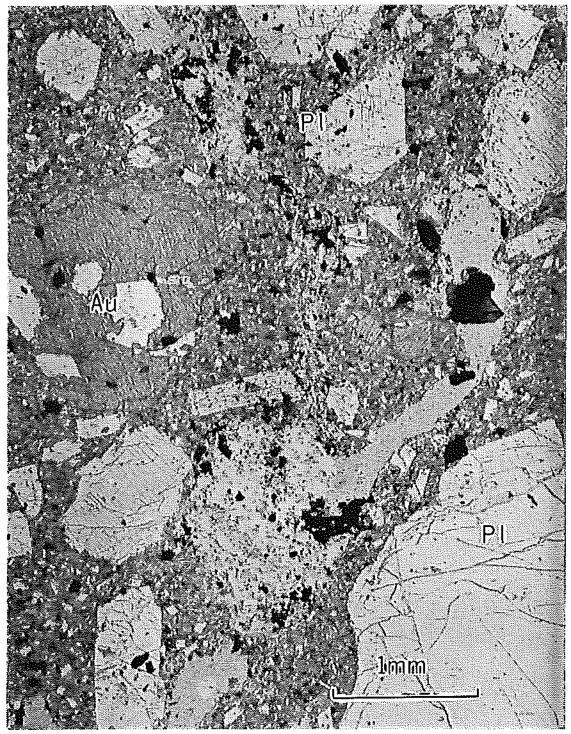

Figure 2

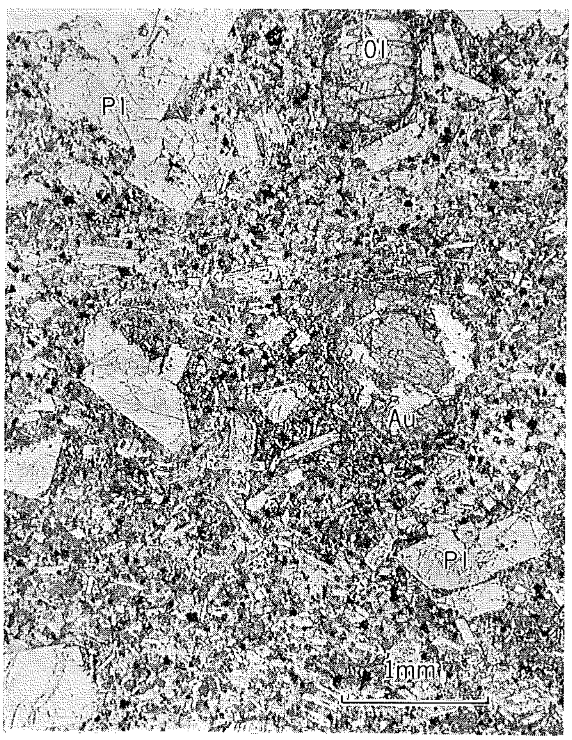

Figure 3

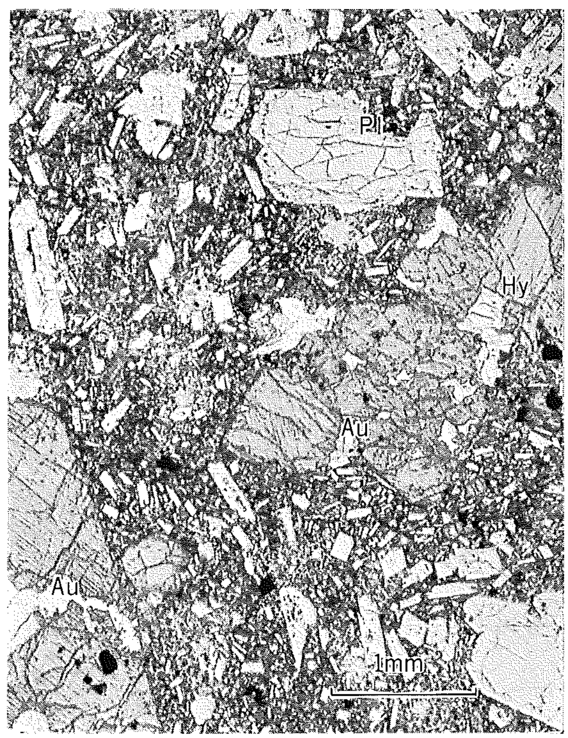

Figure 4

Explanation of Plate 21

Explanation of Plate 21

Photomicrographs of the somma lavas and the dome lavas.

Figure 1. Augite bearing hypersthene andesite (V type somma lava).
A lava collected at the south-eastern foot of Shōwa-Shinzan.

Figure 2. Augite-hypersthene andesite (VI type somma lava).
A lava collected at the western foot of Kompirayama.

Figure 3. Pigeonite-hypersthene andesite (VII type somma lava).
A lava collected at the south-western side of the roof-mountain of Shōwa-Shinzan.
Showing the typical phenocryst of pigeonite (Pi) at the center of this picture.

Figure 4. Hypersthene dacite (dome lava of Shōwa-Shinzan).
Showing the aggregate of quartz (Qz) and autolithic glomero-porphyritic part (G1).
A lava collected at the northern wall of the dome.

Plate 21

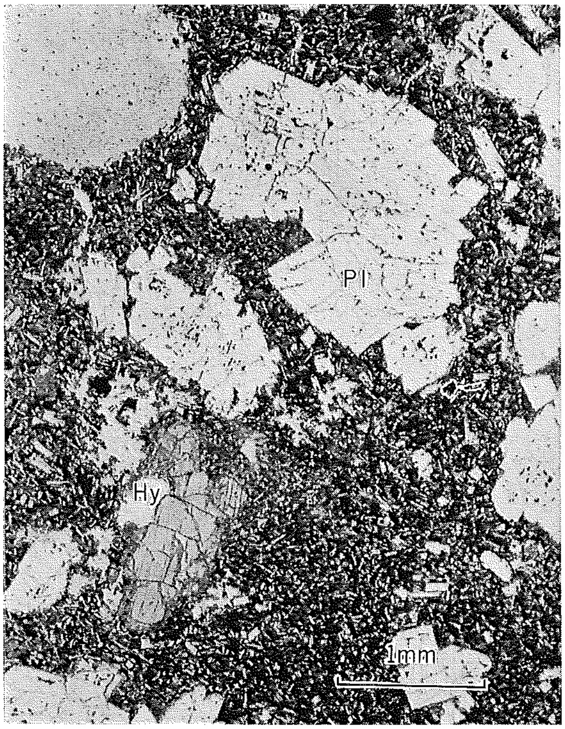

Figure 1

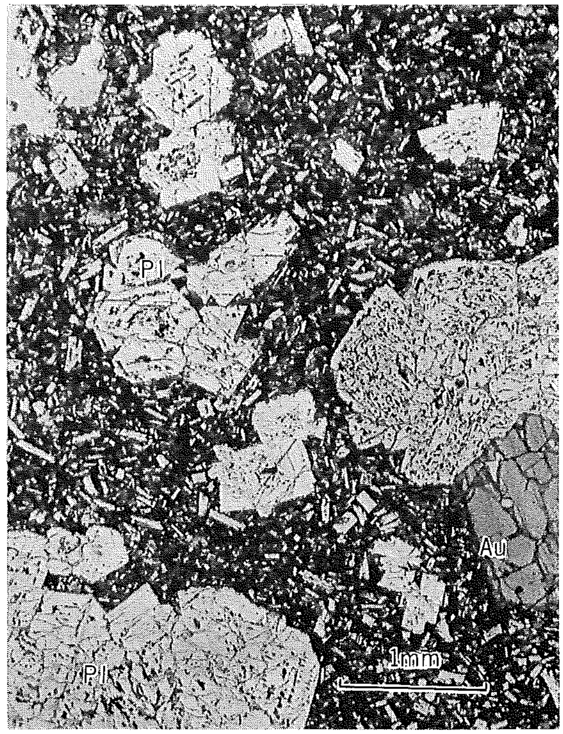

Figure 2

Figurc 3

Figure 4

Explanation of Plate 22

Explanation of Plate 22

Photomicrographs of xenoliths and the abnormal zoning plagioclases including in the dome lavas.

Figure 1. Grano-dioritic xenolith, including in the dome lava of Shōwa-Shinzan. It is composed of coarser crystals of plagioclase (Pl), quartz (Qz) and the aggregate of minute grained augite and hypersthene (Au and Hy). Quartz is remelted and covered with grain cristobalite.

Figure 2. Fine to medium grained holocrystalline xenolith, including in the dome lava of Shōwa-Shinzan. It is composed of heterogeneous fine to medium aggregate of plagioclase, hypersthene and augite.

Figure 3. A plagioclase phenocryst having so-called "calcic core" in the dome lava of Ō-Usu. The core shows peculiar textures due to inclusions.

Figure 4. As same as Figure 3. In this case, the boundary between "calcic core" and "sodic margin" is clearly distingushable by relief.

Plate 22

Figure 1

Figure 2

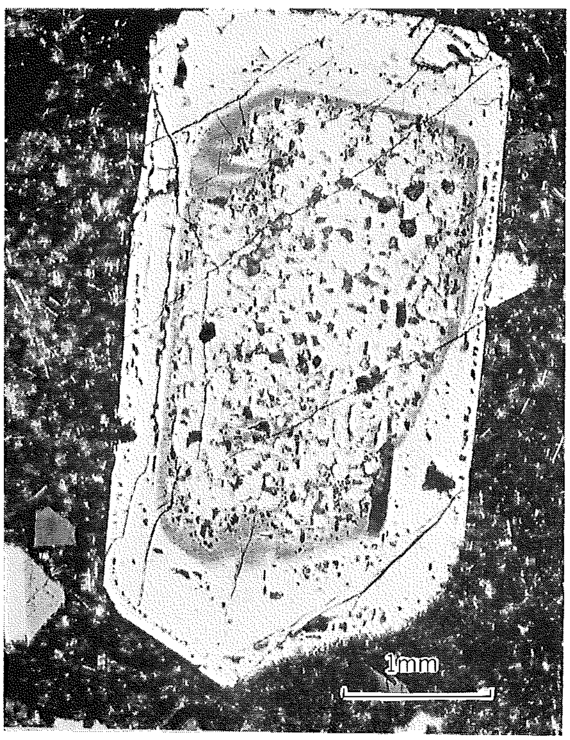

Figure 3

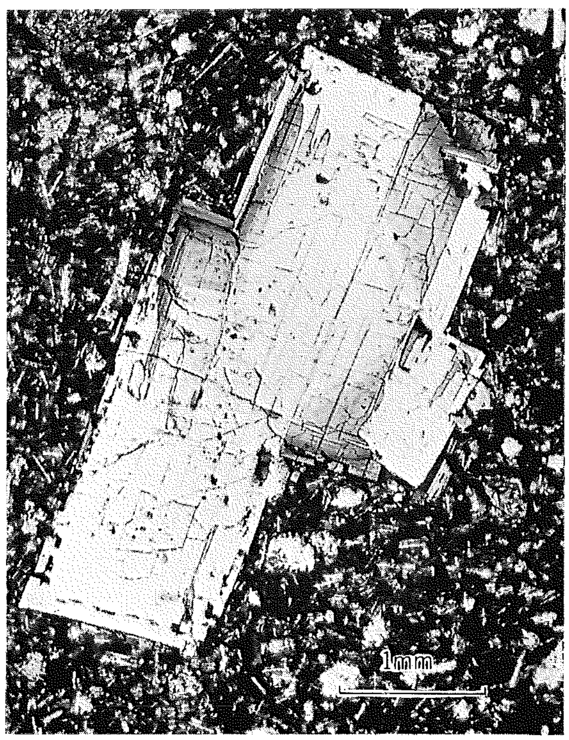

Figure 4