Petrological Studies of Naturally Heated Zircons. Part II. : Petrology of Some Granitic Xenoliths in Volcanic Rocks

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https://doi.org/10.5109/1543604

出版情報：九州大學理學部紀要 : Series D, Geology. 14 (1), pp.39-68, 1963-01-30. Faculty of Science, Kyushu University

Mem. Fac. Sci., Kyushu Univ., Ser. D, Geol., Vol. XIV, No. 1,
pp. 39-68, tables 1-6, figs. 1-4, pls. 7-10, January 25, 1963

Petrological Studies of Naturally Heated Zircons. Part II. Petrology of Some Granitic Xenoliths in Volcanic Rocks*

By

Yoshifumi KARAKIDA

Abstract

Besides many granitic xenoliths of volcanic rocks, their original granitic rocks and the host volcanic rocks ranging from basalt to andesite, all found in Southwest Japan, were petrographically examined before the detailed studies of zircons in them were made. The xenoliths can be divided into five groups according to the degree of rock alteration.

In the granitic xenoliths mafic minerals are most easily decomposed to produce mainly iron-ores and brown glass. The microperthitic texture of the original potash feldspar in the greater parts of the xenoliths disappeared and this mineral is readily resorbed after the mafic minerals. Plagioclase and quartz are more resistant to fusion: the former is commonly clouded to various extent with minute inclusions, and the latter is usually crackled, while vitrified plagioclase is apt to show fine mesh works of glass along its cleavages. Feldspar optics shows that potash feldspar and plagioclase in all the xenoliths are completely or incompletely converted to the high-temperature form.

The observations described above may support the conclusion that the temperature attained by the granitic xenoliths in question should be between 500° and 573° in one example and above 500° to 700° and probably below about 900° in the others.

Contents

Introduction

I am investigating zircons of granitic xenoliths naturally heated in some volcanic rocks of Southwest Japan as a part of the research program regarding geological significance of accessory zircon under the auspices of Professor Tôru

* Received October 15, 1962

TOMITA. The results of my investigation show that some of character changes in the zircons under consideration may be attributed to volcanic heating, an answer to these problems having been already discussed in paper I (TOMITA and KARAKIDA, 1958).

It is the purpose of this investigation to describe the modes of occurrence of granitic xenoliths collected from some volcanic fields in Southwest Japan; to examine the alteration of their main constituent minerals; to estimate the temperatures attained by the xenoliths on the basis of those observations. These description and discussion would serve as a fundamental knowledge for understanding the petrologic significance of the natural change in zircon characters which will be dealt with in a series of papers now in preparation.

Acknowledgements

I wish to express my gratitude to Professor Tôru TOMITA of our Department for his helpful suggestions and for the critical reading of the manuscript and correction of my English writing.

Grateful acknowledgements are also expressed to the following gentlemen for their aid in this work: Professor Kamaji YAMAGUCHI of Risshô University courteously placed at my disposal a specimen of granitic xenolith collected from the Sakurajima Volcano and permitted me to use a part of his unpublished field observations about it; Professor Hideyoshi TOYODA of Hiroshima University, Dr. Hirosato YAMAMOTO of the Fukuoka College of Education and Liberal Arts, and Dr. Michitoshi MIYAHISA of Ehimé University allowed me to examine their rock collection of the Kashima granite xenoliths, the Tamana granodiorite, and the Takakuma granite, respectively; Dr. Masaru YAMAGUCHI and Dr. Hitoshi MOMOI of our Department and Dr. Taro KASAMA of Ôsaka City University gave me helpful informations on the geology of Shôdo-shima Island, of the Matsuyama area, and of the Tsurumi and Yufu Volcanoes, respectively: discussions made by Dr. Sadakatu TANEDA of our Department contributed largely to this study.

Special thanks are expressed to Miss Shizué SUDÔ for her valuable help in the preparation of the manuscript and to Miss Chizuko OKAMURA for typewriting.

Parts of this work were financed by the Grant in Aid for Scientific Researches from the Ministry of Education, Japan.

Occurrence of granitic xenoliths

Though the localities of granitic xenoliths which contain naturally heated zircons examined and the modes of occurrence of the xenoliths are shown in the Part I of this series of papers (TOMITA and KARAKIDA, 1958), more detailed descriptions of the geology of the localities will be given here.

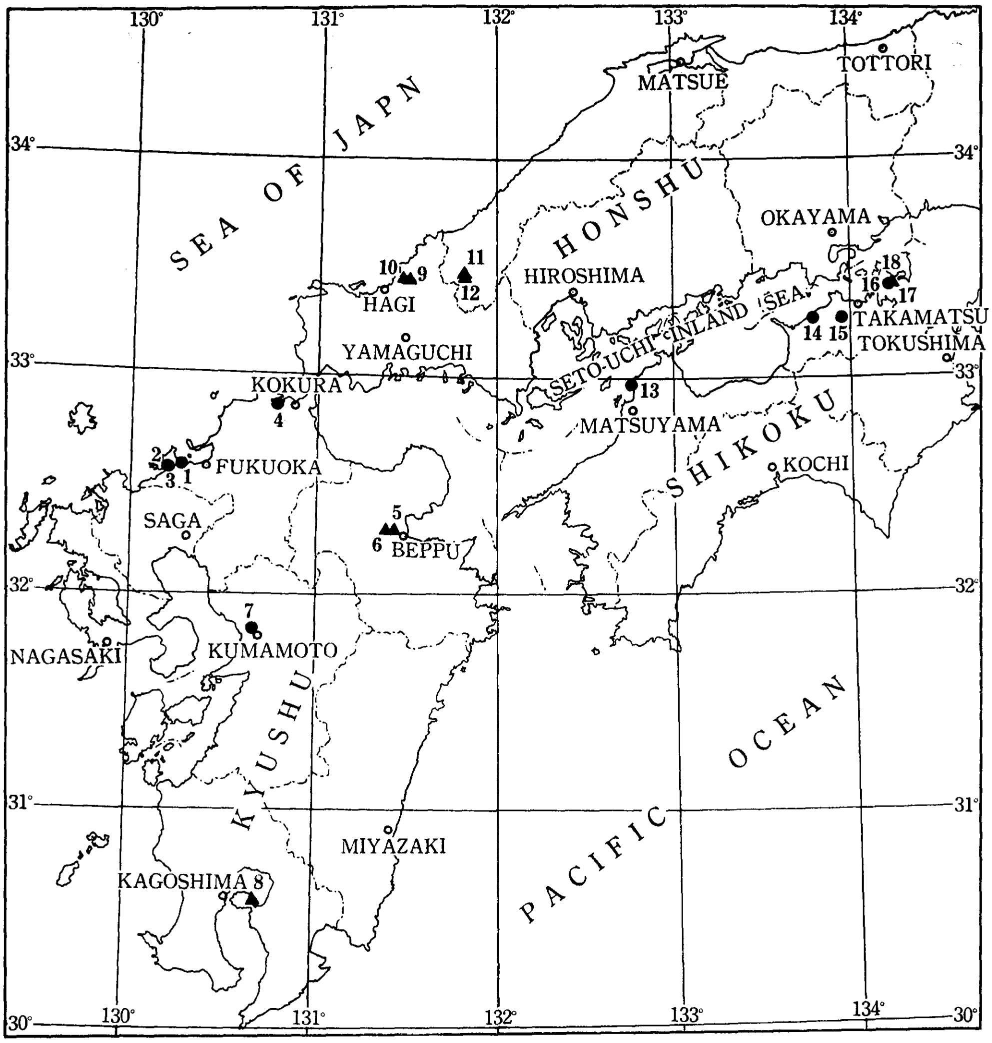

Fig. 1. Locality map of granitic xenoliths from Southwest Japan.
1. Imayama, 2. Mizukami, 3. Kubota, 4. Myôken-yama, 5. Tsurumi Volcano, 6. Yufu Volcano, 7. Ishigami-yama, 8. Sakura-jima Volcano, 9. Shibuki, 10. Nanae, 11. Aono-yama, 12. Machida-yama, 13. Kashima, 14. Marugamé, 15. Washino-yama, 16. Kô-no-ura, 17. Gongen-saki, 18. Yoshino.
Solid circle—plugs; solid triangles—lavas.

1. **Imayama** (Fig. 1, Loc. 1)

A small butte-like hill, about 80 m high and about 1.5 km large around the bottom, faces Hakata Bay on the northeast and the Itoshima Plain on the southwest. It is made up of granodiorite (the Kitazaki granodiorite) and tuff as well as volcanic breccia that fill a volcanic vent cross-cutting the granodiorite (see the geologic map of Fukuoka City, YAMAZAKI et al., 1958). The breccia is composed principally of irregularly rounded blocks of scoria and angular blocks of basalt, with a few fragments of granodioritic and metamorphic rocks. Sinuous and irregularly-shaped dikes with veins of basalt penetrate the volcanic breccia in places, but no outcrop is found where they directly cut the granodiorite.

Some of the basalts carry locally many xenoliths, which are generally granodioritic in composition and texture, being irregular in shape and ranging in diameter from 1 mm to 40 cm. The boundary between xenoliths and basaltic matrix is quite sharp but irregular. Megascopically the basalt just close to the xenolith occasionally shows so strong mechanical mixing of the basic and acid rocks that thus produced hybrid rocks show a porphyritic appearance with xenocrysts of quartz and feldspar scattered comparatively uniformly through the ground-mass of compact black basalt (Fig. 2). In such parts of the basalt, olivine phenocryst is smaller in amount the groundmass is finer in grain size than in the normal part.

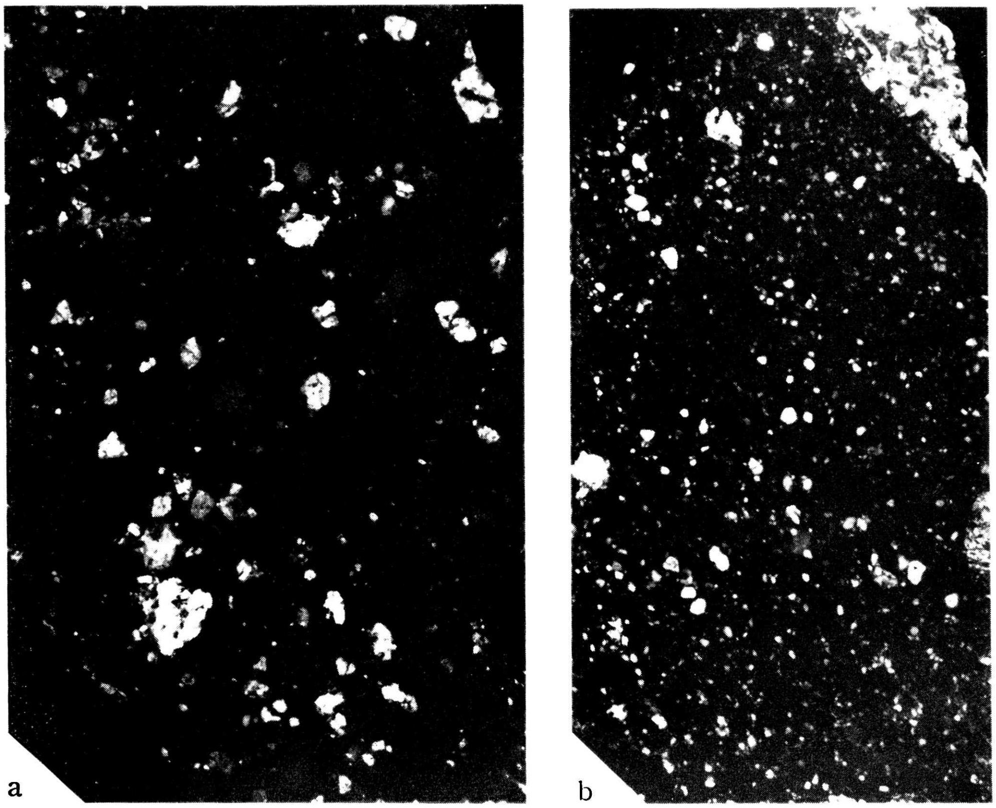

Fig. 2. Imayama basalt showing porphyritic appearance due to small fragmental xenoliths of granitic rocks and xenocrysts of quartz and feldspar scattered uniformly throughout the compact black groundmass (a—It 983t; b—It 983b) (in natural size).

2. Mizukami and Kubota (Fig. 1, Locs. 2 and 3)

There are two distinct plugs of basalt at the foot of Kaysa-an butte (365.1 m):

one is at Mizukami on the north side and the other at Kubota on the east side. This butte consists mainly of the remnants of basaltic lava, tuff, and tuff breccia, which are of probably the same origin as these plugs. These plugs, 50 to 100 m in diameter, penetrate the Itoshima granodiorite and contain many xenoliths of exclusively granodioritic origin, ranging from chips of xenocrystic dimensions to blocks about 50 cm across. The boundaries between xenoliths and basaltic matrix and between the plugs and the granodiorite are both distinct but sinuous. Intense weathering prevents the ordinary petrographical examinations on the xenoliths and the country rocks as well.

3. **Myôken-yama** (Fig. 1, Loc. 4)

A basalt plug, volcanic breccia, and the Hirao granodiorite compose a small hill, Myôken-yama (about 57 m), To the west of this hill across a small valley, there is a small mesa (about 66 m) of basaltic lava and volcanic breccia resting on the Hirao granodiorite. These volcanics are of the same age as those of the Myôken-yama hill.

The plug, nearly circular in outline and about 200 m in diameter, may be intruded into the granodiorite on the north while the volcanic breccia on the south. Granitic xenoliths were not found in the central part of the plug at the Myôken-yama quarry, but in an outcrop where veins from the plug cut the granodiorite were met with granitic and aplitic xenoliths, in either rock only one specimen being collected, and several xenocrysts of quartz and feldspar. The granitic xenolith, more or less rounded and about 8 cm in diameter, is rather porous, fragile, and surrounded by a zone, several centimeters wide, composed of basalt rich in vesicles, the boundary between xenoliths and the matrix being distinct.

4. **Tsurumi and Yufu** (Fig. 1, Locs. 5 and 6)

These two tholoides standing side by side are composed of the Tsurumi-dake volcanics (hornblende andesites), which represents the latest eruption (Upper Pleistocene) in this area (KASAMA, 1953, p. 170–171).

Most of the xenoliths are of granitic origin; others are of metamorphic. They range in size from 5 mm to 30 cm across but generally 2 to 4 cm. They are irregular in shape and angular. The boundary between xenoliths and andesite matrix is distinct, but it is irregular owing to an incipient mechanical breaking of the marginal parts of the xenoliths into small pieces. However, the products of chemical reaction between the andesitic magma and the xenoliths are scarcely recognizable, though the xenoliths have undergone intense alteration by the magma and commonly small vesicles are present near the boundary between xenoliths and the host andesite.

5. Ishigami-yama (Fig. 1, Loc. 7)

The Kimpô-zan volcano-group is composed of the Kimpô-zan tholoide (hornblende andesite) and the underlying pyroxene andesite and hornblende andesite; the former, according to MATSUMOTO (1943), corresponds to the Tsurumi and Yufu tholoides mentioned above.

The granitic xenoliths in question were collected from a quarry of augite-hornblende andesite, making up a small hill, which is probably composed of a member of the basement. However, no direct geological relationship of the andesite to the surrounding rocks has been observed. In the rock are well-developed columnar jointing accompanied in places by irregular cavities encrusted with small crystals of tridymite.

Granitic xenoliths, up to about 20 cm across, are fairly common in the andesite. They consist essentially of coarse- to medium-grained massive or weakly foliated granites or granodiorites, with subordinate amounts of fine-grained massive granites and pegmatites, all of which are of subangular to rounded form. Also are present angular to subangular xenoliths, as much as 30 cm across, of metamorphic rocks. They consist of slaty to phyllitic rocks, schists, banded schists, amphibolites, metabasites, and gneissic rocks, all of which are commonly of thick platy form parallel to their schistosity and gneissosity. The boundary between xenoliths and the andesite matrix is generally distinct. Andesites within a zone, 0.5 to 1 cm wide, around some metamorphic xenoliths are more compact than the normal andesite, whereas around most granitic xenoliths such a phenomenon is not illustrated.

6. Sakura-jima (Fig. 1, Loc. 8)

In the first lava, pyroxene andesite, of the Sakura-jima eruption in 1914, K. YAMAGUCHI discovered several xenoliths of highly vitrified granite and other rocks. According to him (personal communication) the granitic xenoliths, generally about 10 cm across, are rounded in form and very small in number.

7. Shibuki and Nanae (Fig. 1, Locs. 9 and 10)

This area is composed mainly of liparitic rocks and "quartz porphyries," which are invaded by several granitic intrusions. It has long been known that Pleistocene basaltic lavas occurring at several hills together with agglomerate and tuff frequently contain granitic xenoliths (SUGI, 1942, p. 79–84).

At Shibuki, olivine basalt lava, which is accompanied in places by an underlying thin bed of tuff breccia, is seen covering granite at the south end of the flow and liparitic rocks at other ends. It generally contains vesicles strongly or weakly elongated parallel to the flow plane, up to 2 cm long, variable in abundance from place to place. Besides, more or less milky quartz crystals or aggregates, up to 2 cm across, are frequently found in nearly spherical form.

The lava carries xenoliths in places. They are exclusively of granitic origin and rarely of aplitic, ranging in diameter from 0.5 to 10 cm. The boundary between xenoliths and the basalt matrix is distinct but irregular. Various stages in the fragmentation of xenoliths are observed; at an extremely advanced stage, clusters of small fragments of quartz or feldspar or both are produced, and in this case the surrounding basalt contains smaller and more abundant vesicles than the normal basalt.

At the Nanae quarry is met with a hornblende andesite carrying fragile and porous granitic xenoliths, some of which occur as thin plates or films, about 1 cm in thickness and 1 m^2 in area, stretched along the flow plane of the host andesite —— this may be the evidence of mobilization of the partially fused granitic fragments. Other xenoliths attain lengths of as much as 15 cm and, as usual xenoliths at other localities studied, they are rounded in form. The boundary between xenoliths and andesite matrix is generally distinct.

8. **Aono-yama and Machida-yama** (Fig. 1, Locs. 11 and 12)

The Aono volcano-group near Tsuwano, Shimanè Prefecture, is composed of about ten tholoides of hornblende andesite, including the volcanoes of Aono-yama (907.6 m) and Machida-yama (ca. 500 m). They are arranged along the contact between Paleozoic formations on the west and invading granite porphyry on the east, which regularly extends in the NE–SW direction. It is reported that granitic and quartz-dioritic xenoliths are often found in all of the Aono dome lavas (TANEDA and YAMAGUCHI, 1950, p. 67), but only those from the Aono-yama and Machida-yama domes are dealt with here.

In the Aono-yama andesite, xenoliths range in size from a few millimeters to 10 cm and irregular in form. The boundary between xenoliths and the enclosing andesite is generally distinct but sometimes irregular owing to fragmentation of xenoliths along their margin. Most of the xenoliths are granitic, in which glass and vesicle make up about half of the rock, and therefore they are very fragile; a few are dioritic.

In the Machida-yama andesite, most of xenoliths consist of coarse-grained granodioritic rock, some of which are weakly schistose; others of banded gneissic or diabasic rock. These granodiorite xenoliths, in general, are lower in vitrification than those of the Aono-yama andesite (Table 6) and larger in size, reaching about 30 cm in diameter. They are generally rounded to subrounded, but occasionally discus-shaped, the marginal portion being crushed and deformed into an aggregate of smaller fragments and cavities. The extremely crushed xenolith is deformed to a thin film consisting of small granite fragments and cavities, placed parallel to the flow plane in the andesite as seen in the Nanae xenoliths already described.

9. **Kashima** (Fig. 1, Loc. 13)

On Kashima islet, about 12 km north off Matsuyama City, according to TOYODA (1931), an andesite plug with granitic xenoliths is intruded into granitic rock, which is so intensely decomposed by weathering that the microscopic observations can not be made. The andesite near the contact with the granitic country rock is rich in granitic xenoliths, which gradually decrease in amount towards the center of the plug.

Two specimens of the andesite collected by TOYODA were examined. The andesite, compact, fine-grained, gray black with lustrous black glass, carries many small angular to rounded fragments of granite about 2 cm in diameter, together with xenocrysts of quartz and feldspar; these small xenoliths and xenocrysts make up as much as 70 per cent of the rock in one specimen and about 50 per cent in another. The boundary between enclosed fragments and the host rock is sharp but abrupt.

We could not succeed in ascertaining the source of these granitic xenoliths by means of our zircon-habit correlation method (TOMITA and KARAKIDA, 1958, p. 31).

10. **Marugamé** (Fig. 1, Loc. 14)

A small hill (67 m) where the ruins of the Marugamé Castle stand, consists mainly of coarse-grained biotite granite, fine-grained two-mica granite, fine-grained quartz-biotite diorite, and associated gneissose metamorphic rocks. Near the center of the hill there is a dike of augite-bearing sanukitic andesite, about 20 m thick, which trends nearly northeast-southwest and dips at high angles (SATO, 1936, p. 31). This andesite contains some granitic xenoliths about 1 to 30 cm across, which are too strongly weathered to be examined under the microscope.

11. **Washino-yama** (Fig. 1, Loc. 5)

Washino-yama hill (321 m) is composed of coarse-grained hornblende-biotite granodiorite and overlying hypersthene-hornblende andesite. In the andesite at a quarry on the eastern slope, columnar joints are developed well, and many xenoliths of granites, diorites, hornblende gabbro, etc. together with aggregates of biotite and of garnet are found.

Two granitic xenoliths differ from the basement granodiorite according to the zircon-habit correlation method (TOMITA and KARAKIDA, 1958, p. 31).

12. **Kó-no-ura, Gongen-saki, and Yoshino** (Fig. 1, Locs. 16, 17, and 18)

The Mito Peninsula on the south side of Shôdo-shima Island is mainly composed of some basalt plugs and lavas of Neogene age and the underlying Mito granodiorite with the enclosed blocks of schist at many places (SATO, 1932; YAMAGUCHI, 1958, Fig. 3, p. 220). The Mito granodiorite may be geologically different from the biotite granite composing main part of Shôdo-shima Island.

Some of the volcanic plugs and lavas contain several xenoliths derived from granodioritic and metamorphic rocks.

At Kô-no-ura (Kuzure-hana) a basalt plug intruded into the Mito granodiorite is seen intimately associated with volcanic breccia. This basalt is characterized by wavy columnar joints developed well at most portions and is vesicular at some portions. Some of the cavities contain magmatic (?) water. The plug carries granodioritic xenoliths mainly in the portion where jointing is not developed. The xenoliths are generally rounded and commonly attain lengths of as much as 1 m, larger than those from the other localities examined. The boundary between xenoliths and the basalt matrix is distinct.

The granodioritic xenoliths in the Gongen-saki plug about 1 km northeast of the Kô-no-ura plug are generally smaller in size and lower in the degree of vitrification than those in the Kô-no-ura plug. These two plugs, however, closely resemble each other in the other aspects.

In the southern part of Yoshino hamlet andesitic basalt lava covers the Mito granodiorite. At a quarry are found some xenoliths derived from coarse-grained granodiorite, medium-grained gabbroic to dioritic rocks, and schists with or without granitic lamellae, ranging in diameter from two or three to ten and odd centimeters rarely reaching up to 30 cm. Most xenoliths, commonly subangular to rounded, are characterized by the presence of irregularly elongated cavities of various size which intermittently lie between the xenolith and the vesicular host rock. On the other hand, a few xenoliths are roughly discus-shaped, placed along the flow plane, and in general their central portion is more or less compact, whereas their margin is porous in various degrees and also partly mixed with the host rock. This may be produced by the mobilization of the partially melted granitic fragments in the flowing lava.

Table 1. Petrographic characters of the host volcanic rocks enclosing granitic xenoliths

Imayama (1), **Mizukami** (2), **Kubota** (3), **Myôken-yama** (4)

Olivine basalt (plug).

Dark gray to black; slightly porphyritic with small olivine phenocrysts about 1 mm across scattered throughout the compact groundmass.

Phenocrysts: well-shaped or more or less round olivine; microphenocrysts of composite iron-ore octahedra and/or augite.

Groundmass: plagioclase microlites with some degree of parallel disposition showing flow structure, augite prisms and granules, iron-ore octahedra, and alkali feldspar.

Tsurumi (5), **Yufu** (6)

Hornblende andesite (lava).

Two varieties are known, brown and gray; porphyritic with conspicuous plagioclase and hornblende phenocrysts up to 1 cm across embedded in the dull reddish brown or dull purplish to light gray groundmass.

Phenocrysts: short-prismatic, strongly zoned plagioclase and long-prismatic, variably opacitized hornblende.

Groundmass: hyalopilitic; lath-shaped microlitic plagioclase, prismatic hornblende, octahedral iron-ores, and/or prismatic rhombic and monoclinic pyroxenes, with subordinate silica mineral, olivine, and biotite

Ishigami-yama (7)

Hornblende andesite (plug).

Porphyritic with many plagioclase and a few hornblende phenocrysts up to 2 mm across embedded in the bluish gray fine-grained groundmass.

Phenocrysts: tabular zoned plagioclase with dirty core and prismatic hornblende with opacitic rim, breadth of which is different from crystal to crystal.

Groundmass: hyalopilitic; microlitic tabular plagioclases, prismatic rhombic and monoclinic pyroxenes, octahedral and granular iron-ores, and interstitial glass with silica mineral.

Shibuki (9)

Olivine basalt (lava).

Dark gray; nearly aphanitic with sporadic olivine spots up to 2 mm across, containing milky quartz aggregates and vesicles.

Phenocrysts and microphenocrysts: clusters and skeletons of monoclinic pyroxene, laths of unzoned plagioclase, and subhedral crystals of olivine.

Groundmass: microlitic lath-shaped plagioclase, monoclinic pyroxene, olivine, iron-ores, and interstitial alkali feldspar.

Nanae (10)

Hornblende andesite (lava).

Gray; porphyritic appearance due to striking long-prismatic oxyhornblendes encrusted by iron-ore rims with varying breadths.

Groundmass: hyalopilitic; microlitic lath-shaped plagioclase, prismatic oxyhornblende, fringed by iron-ore grains or completely replaced by iron-ores, prismatic pyroxene, octahedral iron-ores, and glass.

Aono-yama (11), **Machida-yama** (12)

Hornblende andesite (lava).

Rocks of these two domes are very similar in every petrographic character except some difference in crystallinity: the Machida andesite is richer in brown glass. Gray or brownish; porphyritic due to hornblende rather than plagioclase.

Phenocrysts: long-prismatic brown hornblende in varying amounts, being commonly opacitized in the crystal margin.

Microphenocrysts: besides hornblende, lath-shaped or tabular plagioclase with a not conspicuous zonal structure.

Groundmass: lath-shaped or tubular plagioclase, monoclinic and rhombic pyroxene, biotite, iron-ores, cristobalite, and glass.

Kashima (13)

Olivine-bearing two-pyroxene andesite (plug).

Gray black; not strongly porphyritic.

Phenocrysts and microphenocrysts: monoclinic and rhombic pyroxenes, the former being surrounded by the latter in places, and subordinate olivine.

Groundmass: hyalopilitic; microlitic lath-shaped plagioclase, pyroxene, and black iron-ores embedded in brown glass.

Washino-yama (15)

Hypersthene-hornblende andesite (lava or plug).
Gray white; rich in phenocrysts and more or less porous.
Phenocrysts and microphenocrysts: tabular calcic plagioclase, long-prismatic brown hornblende opacitized in the margin, and hypersthene not so strongly pleochroic.
Groundmass: lath-shaped and tabular plagioclase, rhombic and monoclinic pyroxenes, iron-ores, and glass.

Kô-no-ura (16), **Gongen-saki** (17)

Olivine basalt (plug).
Dark gray or black with sporadic olivine phenocrysts scattered throughout the compact groundmass.
Phenocrysts: more or less rounded, fresh olivine.
Groundmass: microlitic lath-shaped plagioclase, subhedral olivine, prismatic to granular augite, minute granular iron-ores, and glass.

Yoshino (18)

Olivine-augite andesitic basalt (lava).
Dull purplish gray; porphyritic due to sporadic brownish yellow altered olivine phenocrysts embedded in the more or less porous matrix.
Groundmass: plagioclase microlites, pyroxene prisms and granules, minute iron-ore octahedra, cristobalite, and interstitial clear glass.

Note 1: The volcanic rocks from Sakura-jima (8) and Marugamé (14) could not examine under the microscope, because of the lack of specimen and of strong weathering of the rock respectively.
Note 2: The figure in parenthese after locality name is locality number referred to Table 1 and Fig. 1.

Thin Section Petrography of Original Rocks of Granitic Xenoliths

In this chapter are given the results of megascopical and microscopical observations of the granites that have been ascertained as the source of the granitic xenoliths by investigation of zircon habits (Tomita and Karakida, 1958). Of the eighteen localities in the last chapter, Aono-yama, Machida-yama, Kashima, Washino-yama, Mizukami, Kubota, Myôken-yama, Nanae, and Marugamé are not dealt with in this chapter, because the source rocks of the granitic xenoliths from the first four localities could not have been known and because strong weathering prevents microscopical examination of the granitic xenoliths from the rest five localities and therefore the petrography of their source rocks may be unnecessary.

The optic angles of potash feldspars determined with a four-axis universal stage are shown in Table 2; the state of microcline twinning and perthitic structure in potash feldspars in Table 3; modes for some of the granitic rocks in Table 4. Each mode is a mean of those which were determined by the point counter method from two thin sections with normal size cut from the same specimen.

Table 2. Optic axial angles (2Vα) of potash feldspars in xenoliths and their original rocks

Alteration type	Rock / Locality	Original granitic rock	Granitic xenolith, Optic plane ⊥(010)	Granitic xenolith, Optic plane // (010)
I	Imayama	74, 76, 79, 82, 83, 88	12, 30, 24, 36, 38	—
I	Gongen-saki	58, 61, 78, 80	—	45, 46, 57
II	Tsurumi	53, 56	n. d.	
II	Ishigami-yama	57, 61, 61, 61–70	23, 27, 33, 35	—
II	Shibuki	57, 64	—	8, 18, 36
II	Yoshino	58, 61, 78, 80	—	33, 37
III	Kô-no-ura	58, 61, 78, 80	None	
IV	Tsurumi and Yufu	53, 56	None	
V	Sakura-jima	45, 45, 47	—	25, 27

Table 3. Thermal effects on the microcline twinning and perthitic structure in potash feldspars

Alteration type	Potash-feldspar / Lacality	Microcline twinning: Original rock	Microcline twinning: Xenolith	Perthitic structure: Original rock	Perthitic structure: Xenolith
I	Imayama	Common; distinct or indistinct grid twinning in the whole or parts of crystal	None	Rather rare; elongated blebs closely arranged or rarely strings in parts of crystal	None
I	Gongen-saki	Very rare; very faint only in part of crystal; moirè extinction common	Very rare; heterogeneous and moirè extinction	Practically none	None
II	Tsurumi	Not so common; heterogeneous extinction in the whole or parts of crystal	None	None	None
II	Ishigami-yama	Very rare; indistinct grid twinning	None	Very rare; lenticular blebs in parts of crystal	None

	Shibuki	None	None	Common; elongated irregular patches or blebs with parallel close arrangement	None
	Yoshino	Refer to Gongen-saki	None	Refer to Gongen-saki	None
III	Kô-no-ura	Do	(Crystal disappeared)	Do	(Crystal disappeared)
VI	Tsurumi and Yufu	Refer to Tsurumi	(Crystal disappeared)	Refer to Tsurumi	(Crystal disappeared)
V	Sakura-jima	Very rare; faint grid twinning only in parts of crystal	Very rare; indistinct grid twinning	Common; irregular patches scattered irregularly in the whole of crystal or in parts of crystal thin string lamellae	Rare

Table 4. Modes of certain granitic xenoliths and their original rocks

Rock / Mineral	Granitic xenolith						Original rock			
	Type I		Type II		Type III	Type IV				
	Imayama (It 982c)	Gongen-saki (Sd 23g)	Ishigami-yama (Km 28b)	Yoshino (Sd 17a)	Kô-no-ura (Sd 26g)	Yufu (Bp 15)	For Imayama (It 1 Bc2)	For Gongen-saki, Yoshino, and Kô-no-ura (Sd 35)	For Ishigami-yama (R 6)	For Yufu (Bp 27)
Quartz	11.5	20.5	4.5	10.5	11	5.5	20.5	21.5	31	23
Potash feldspar	6	14	32.5	2	—	—	9.5	15.5	11.5	5
Plagioclase	42	47	46	65	48.5	62.5	49	56	49	55.5
Biotite	—	—	—	—	—	—	8.5	5	7.5	11
Hornblende	—	—	—	—	—	—	10.5	1	—	3.5
Iron-ores	32	12	8.5	15	2	6	—	—	—	—
Pyroxene, biotite, sillimanite, etc.	3.5	—	2.5	1	0.5	6	—	—	—	—
SiO_2-mineral	—	—	2.5	0.5	—	0.5	—	—	—	—
Glass: Brown	3	5.5	—	1	21	1	—	—	—	—
Glass: Colorless	1	1	3	5	17	18	—	—	—	—
Others	1	trace	0.5	trace	trace	0.5	2	1	1	2
Total	100	100	100	100	100	100	100	100	100	100

1. **Imayama** (Loc. 1)

The Kitazaki grandiorite: It is coarse-grained, moderately foliated, and purplish.
Microscopic character: It consists mainly of plagioclase, quartz, potash feldspar,

biotite, and hornblende, and is characterized by scattered crystals of conspicuous sphene.

Plagioclase is generally subhedral and zoned, and twinning lamellae of some

Table 5. Modifications and composition of plagioclases in the granodiorite xenolith from Imayama and its original Itoshima granodiorite

Rock	Twin law	Köhler's angle αα	ββ	γγ	Low-temp. opt. An %			High-temp. opt. An %			Modification
Granodioritic xenolith (It 982C)	Albite	174	125	56	35	62	52	41	41	42	High-temp. form
	〃	174	124	55	35	65	51	41	42	41	〃
	〃	177	130	50	32	51	47	38	37	37.5	〃
Kitazaki granodiorite (It 613B)	Albite-Carlsbad	67	115.5	165	37	37	34	40	42.5	21.5	Low-temp. form
	〃	60.5	119.5	168.5	34.5	35.5	31	36	40	15.5	〃
	〃	76.5	116	164.5	41.5	37.5	34.5	44.5	42	22.5	〃

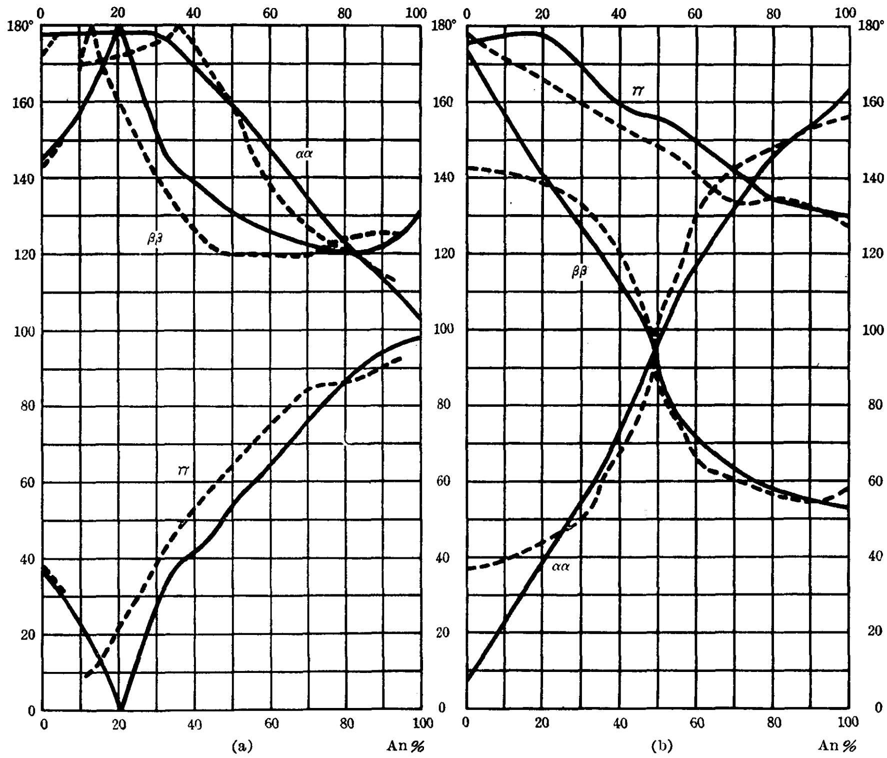

Fig. 3. KÖHLER's angle curves, constructed from values in v.D. KAADEN's tables 2 and 3 (standard plagioclases) and columns IA and IIA (natural plagioclases) (1951) and in KANO's tables 1 and 3 (natural plagioclases) (1955).

(a)—plagioclases twinned after albite-law; (b)—plagioclases twinned after albite—Carlsbad-law.

Full line—low-temperature plagioclases; broken line—high-temperature plagioclases.

crystals are bent and broken. The most distinctive feature of this mineral is cloudiness due to the presence of abundant minute dusty inclusions, which faintly give it a tint of purple in hand specimen. Determination of the KÖHLER's angle for some crystals of plagioclase without zonal structure (VAN DER KAADEN, 1951, p. 18–23) reveals that plagioclase here may be of the low-temperature form (Table 5 and Fig. 3). Potash feldspar and quartz occur interstitially, but the latter, which commonly exhibits undulatory extinction, tends to show crystal faces against the former, and it is one of characteristics of this granodiorite that quartz encloses rutile hairs. Strongly pleochroic brown biotite usually occurs as bent flakes. Green common hornblende has a tendency to show imperfect poikilitic texture with inclusions of plagioclase and quartz grains. It is usually associated with sphene, epidote, and magnetite.

2. **Tsurumi and Yufu** (Locs. 5 and 6)

The Maruta granodiorite: Narrow exposure is met with along the Tsubusa River about 8 km north of the Yufu Volcano. It is medium-grained and weakly schistose rock commonly with discus-shaped basic inclusions placed along schistosity planes.

Microscopic character: It consists mainly of plagioclase, quartz, biotite, and common hornblende.

Plagioclase and quartz make up the greater part of the rock, the former being in excess of the latter (Table 4). Plagioclase generally occurs as subhedral crystals with conspicuous zoning. Quartz shows very commonly undulatory extinction and sometimes enclosed rutile hairs as in the case of the Kitazaki granodiorite. Potash feldspar only in small amounts occurs interstitially. Myrmekite is common. Brown biotite of comparatively thick flake occurs commonly in association with green common hornblende, being accompanied by epidote and sphene.

3. **Ishigami-yama** (Loc. 7)

The Tamana granodiorite: It is developed along with small roof pendants of metamorphic rocks to the north~northwest of the Kimpô Volcanoes.

It is coarse-grained as a whole; massive and porphyritic at some places, where weakly schistose at other places, the former facies being generally more acid than the latter.

Microscopic character: It consists mainly of plagioclase, quartz, potash feldspar, biotite and/or hornblende.

Plagioclase is more perfectly idiomorphic and more strongly zoned in the schistose facies than in the non-schistose. Potash feldspar usually occurs as large poikilitic as well as interstitial crystals, especially in the non-schistose facies. Myrmekite is common. Biotite tends to occur as clots rather than as single crystals.

4. Sakura-jima (Loc. 8)

The Takakuma granite: It is exposed about 15 km southeast of the eastern foot of the Sakura-jima volcano. A rock facies within this granite mass, corresponding to the original granite of the Sakura-jima xenolith is coarse- to medium-grained, massive, and adamellitic, being more melanocratic than the other facies (ÔBA, 1958).

Microscopic character: It consists mainly of plagioclase, quartz, potash feldsper, and biotite, with varying amounts of subordinate tourmaline, garnet, and muscovite.

Plagioclase, generally subhedral to euhedral, 0.1 to 0.2 mm across, commonly shows conspicuous zoning, consisting of the oscillatorily zoned core and the more sodic unzoned periphery. Along the boundaries between plagioclase and potash feldspar albitic plagioclase bands are frequently grown instead of myrmekite. Potash feldspar occupies interstices between the other minerals. Biotite, brown and strongly pleochroic, occurs as large single hexagonal plates and as clots composed of small crystals.

5. Shibuki (Loc. 9)

Biotite granite: It is coarse-grained and massive, and sporadically carries porphyritic potash feldspar about 1 cm across and biotite clots about 0.5 cm across. Rounded basic inclusions are found in places.

Microscopic character: It consists mainly of plagioclase, potash feldspar, quartz, and biotite.

Plagioclase is generally subhedral and not so conspicuous in zoning. Instead of typical myrmekite narrow zones of more sodic plagioclase up to 0.05 mm wide are common between oligoclase and potash feldspar. Potash feldspar is generally interstitial. Quartz sometimes shows a micrographic intergrowth with perthite and faint undulatory extinction. Deep brown biotite generally occurs as thick flakes and tends to make clots.

6. Kô-no-ura, Gongen-saki, and Yoshino (Locs. 16, 17, and 18)

The Mito granodiorite: Being coarse-grained and usually white gray, it shows a rude parallelism of dark minerals and plagioclase.

Microscopic character: It consists mainly of plagioclase, potash feldspar, quartz, biotite, and hornblende.

Plagioclase, subhedral to anhedral, shows a slight zoning. Myrmekite is present in places. Potash feldspar is interstitial, frequently showing an incipient stage of replacing plagioclase. Quartz, interstitial but euhedral towards potash feldspar, generally shows a wave extinction. Strongly pleochroic brown biotite is present as thick flakes commonly associated with green common hornblende.

Thin Section Petrography of Granitic Xenoliths

Based upon the degree of alteration and recrystallization in constituent minerals and also upon amounts of glass and vesicle, granitic xenoliths in question are divided

Table 6. Alteration type of the granitic xenoliths

Alteration type	Locality	Host volcanic rock	General characters	Iro-ores replacing original mafic minerals
I	Imayama Machida-yama Kashima Gongen-saki	Olivine basalt (plug) Hornblende andesite (lava) Olivine-bearing two-pyroxene andesite (plug) Olivine basalt (plug)	Hardened. Vitrification is recognized only under the microscope in the margin of feldspar. Vesicles is present in little.	Compact large crystals after original mafic minerals reaching several centimeters (Pl. 9, Figs. 1–3).
II	Tsurumi Ishigami-yama Shibuki Washino-yama Yoshino	Hornblende andesite (lava) Hornblende andesite (plug) Olivine basalt (Lava) Hypersthene-hornblende andesite (lava or plug) Olivine-augite andesitic basalt (lava)	Fragile. Vitrification is seen for some distance from the margin of feldspar and quartz. Small vesicles as much as 2 mm in diameter are scattered throughout the rock.	The tendency is observed that iron-ore is divided into angular fine grains about 0.01 mm across (Pl. 9, Figs. 4 and 5).
III	Kô-no-ura	Olivine basalt (plug)	Rather hard. Black material (glass and iron-ores) makes up 30 to 60 per cent of the rock. Vesicles, reaching 5 mm in size, are not so much abundant as in the type II.	Dense aggregate of grains ranging in diameter mainly from 0.01 to 0.03 mm (Pl. 9, Fig. 6).
IV	Tsurumi Yufu Aono-yama	Hornblende andesite (lava)	Not so much fragile. Glass is less than in the type III. Irregular vesicles are abundant; many of them are associated with black glass. In many specimens, vesicles and glass comprise belts about 0.5 mm wide around quartz (Pl. 8, Fig. 2). Plagioclase is partly recrystallized.	Dense aggregate of grains ranging in diameter commonly from 0.02 to 0.06 mm (Pl. 9, Figs. 7 and 8).
V	Sakura-jima	Pyroxene andesite (lava)	Fragile. Glass and vesicles are so abundant that the rock shows trong resemblance in appearance to a pumice with phenocrysts of plagioclase. Recrystallization of plagioclase is more conspicuous than in the type IV (Pl. 10, Figs. 7 and 8).	Dense aggregate of grains ranging in diameter from 0.02 to 0.1 mm (Pl. 10, Figs. 1 and 2).

into five types: Types I—V (Plates 7 and 10). Although they are not always sharply distinguished from one another, some diagnostic characters for distinguishing them, together with the kinds and modes of occurrence of the enclosing volcanic rocks are given in Table 6.

Marked effects of natural heating on potash feldspars of the xenoliths are seen in that optic axial angles of all crystals observed have become decidedly smaller (Table 2) and that microcline twinning and/or perthitic structure in almost all of the crystals have disappeared (Table 3).

Modal proportions measured with a point-counter on the samples representative of Types I—V already referred to are given in Table 4.

A. Type I (Pl. 7, Fig. 1)

1. *Imayama* (Loc. 1)

Megascopic character: In appearance, original mafic minerals are replaced by dull black material, and plagioclase become dark gray (Plate 7, Fig. 1). The rock is hardened, presenting a strong contrast with the fragile granitic xenoliths enclosed in the andesitic rocks to be described later. Such features of alteration appear throughout the xenolith irrespective of its size. The black material exhibits a parallelism to the same extent as that of the mafic minerals in the original Kitazaki granodiorite.

Microscopic character: It consists mainly of plagioclase, quartz, iron-ore, and potash feldspar.

Plagioclase is generally clouded with black minute inclusions, which are arranged parallel to the crystallographic axes in some crystals. It is also crackled along cleavages or irregularly and cut by irregular veinlets of greenish brown glass in places, especially near the iron-ores. The distinct vitrification of this mineral, however, is seen only in the margin of a few crystals. The measurement of the Köhler's angles reveals that this mineral is a high plagioclase transformed from a low-temperature form (Table 5 and Fig. 3). The small 2V values in potash feldspar (Table 2) seem to be due to "sanidinization." Microcline twinning and perthitic structure have disappeared nearly entirely (Table 4), but myrmekite is preserved. Quartz is more considerably crackled than the associated plagioclase. It shows an undulatory extinction and a little fusion. It contains rutile hairs as that in the original rock.

The mafic minerals of the original granodiorite are nearly perfectly replaced by compact large iron-ore crystals, being accompanied by greenish brown glass and minute pyroxene (?) grains that are concentrated in a zone around the iron-ores and along the original cleavages or cracks (Plate 9, Fig. 1). Sphene is highly crackled, though there is no trace of corrosion.

Glass occurs in minor amounts between mineral grains as well as within the minerals themselves, and it contains needle-like crystals of pyroxene at some places.

2. *Machida-yama* (Loc. 12)

Megascopic character: Coarse-grained granitic, some appear weakly schistose. The rock is rich in cracks and fragile but not vesicular.

Microscopic character: It consists mainly of plagioclase, quartz, potash feldspar, and iron-ores, with small amounts of biotite and glass.

Plagioclase sometimes shows a distinct zonal structure with small but highly calcic core. The core tends to be clouded with minute inclusion more intensely than the acid periphery. Potash feldspar with negative small optic angle shows indistinct microcline structure at some places but no perthitic structures. Quartz shows undulatory extinction in contrast to that of the Aono-yama xenoliths. Each of mafic minerals is commonly replaced by a large crystal of iron-ore associated with biotite. The biotite is dark in color, pleochroic from black to dark reddish brown, and irregular in form and separated to isolated parts maintaining the same orientation as if the biotite was replaced by the black iron-ores.

3. *Kashima* (Loc. 13)

Megascopic character: Small granitic xenoliths are gray and have little vesicles. They are conspicuous by quartz and feldspar grains with fine intersertal glass.

Microscopic character: It consists mainly of plagioclase, quartz, potash feldspar, iron-ores, and glass.

Plagioclase, potash feldspar, and quartz are generally not so rich in cracks as those in the Imayama xenoliths and little vitrified except those in the Imayama xenoliths and little vitrified except those in the contact with the host andesite where they are sometimes irregularly fused in margin. Plagioclase has a comparatively weak zonal structure and it is accompanied by myrmekite at the contact with potash feldspar, which is not perthitic, shows rarely indistinct cross-hatch twinning, and is poorer in amount than the plagioclase. No quartz shows a strong undulatory extinction. Original mafic minerals are usually replaced by compact large iron-ores—this appears to characterize the xenoliths which is in the category of the alteration type I.

4. *Gongen-saki* (Loc. 17)

Megascopic character: The granitic xenoliths here have almost the same appearance as those at Imayama except for the difference in the proportion of constituent minerals.

Microscopic character: The characters of constituent minerals are very similar to those of the Imayama granodiorite xenoliths, but the following differences are observed: the optic plane of the potash feldspar may be parallel to (010) (Table 2) and iron-ores, pseudomorph after the original mafic minerals, are accompanied by glass only without pyroxene grains (Plate 9, Figs. 2 and 3).

B. Type II (Pl. 7, Figs. 2–4)

1. *Tsurumi* (Loc. 5)

A few of the granitic xenoliths in the light gray variety of andesite from this volcano belong to this type.

Megascopic character: Vesicles up to 1 mm across are present throughout the light gray xenolith, but they are not so highly confined to between plagioclase and quartz crystals as those in the type IV xenolith from the same area described later.

Microscopic character: The xenolith consists mainly of plagioclase, quartz, iron-ores, and glass, with very small amounts of potash feldspar.

Plagioclase is clouded with minute inclusions throughout the crystal, some of which show a tendency to be arranged along the cleavages. Most of this mineral show little effect of alteration, but a few contain sporadical bubbles or irregular patches of glass. Moreover, in many of the crystals near the contact between the xenolith and the host andesite, the peripheral zone is vitrified along two cleavage directions, giving a mesh-like appearance, whereas the core contains only irregular patches of glass. Quartz is very similar in appearance to that in the Ishigami-yama xenoliths mentioned above. Potash feldspar generally shows a little clouding with minute inclusions are in the coexisting plagioclase.

A crystal of biotite or hornblende is replaced by an aggregate of iron-ore grains, most commonly accompanied by randomly oriented flakes of biotite that is strongly pleochroic from greenish brown to pale yellowish green, and rarely by rhombic pyroxene and tridymite (?) in the place of the biotite. Each grain of iron-ores tends to be of larger size in the former than in the latter.

At some places pale greenish brown to colorless glass associated with cristobalite and monoclinic pyroxene fills the interstices between the quartz and plagioclase.

2. *Ishigami-yama* (Loc. 7)

Megascopic character: The coarse- to medium-grained granitic xenoliths with porphyritic appearance are deeper gray than the original granodiorite. Irregular vesicles about 1 mm across commonly occur between mineral grains and within minerals themselves (Plate 7, Fig. 3). The rock is fragile.

Microscopic character: It consists mainly of plagioclase, quartz, potash feldspar, and iron-ore, with small quantities of newly born biotite, pyroxene, silica minerals, and glass.

Plagioclase crystals are generally vitrified for varying distances from their margin, where they show an alligator skin-like appearance due to fine mesh works of glass along the cleavage lines in some sections (as seen in Fig. 3 on Plate 10). On the other hand, the core escaped such an alteration is only clouded conspicuously with a multitude of minute inclusions. Potash feldspar is usually not so much clouded as the plagioclase, but it sparsely contains trains and irregular aggregates of the minute grains and is turbid with dusty inclusions throughout the crystal. In some crystals slight vitrification is seen along cleavages. Quartz is more strongly crackled than the coexisting plagioclase and contains two sets of minute inclusion trains intersected at some angles. It shows no trace of vitrification in general.

Mafic minerals are replaced by aggregates of small iron-ore grains about 0.01 mm across and small flakes of biotite as much as 0.02 mm across (Plate 9, Figs. 4 and 5). This newly born biotite is pleochroic from deep brown-green to pale yellowish green. In some of these aggregates is seen a rough banded structure due to alternating layers rich in biotite and iron-ores respectively.

Some of feldspar and quartz crystals are cut by veinlets consisting of glass, rhombic pyroxene, tridymite, cristobalite, and calcite.

3. *Shibuki* (Loc. 9)

Megascopic character: The xenolith from this locality contains more abundant vesicles than those from the two localities mentioned above, but the amount of glass is about equally balanced (Plate 7, Fig. 4).

Microscopic character: It consists mainly of plagioclase, quartz, potash feldspar, and iron-ores.

Plagioclase and quartz are crackled and clouded with minute inclusions. They are commonly cut by irregular veinlets of, and surrounded by belts of, glass. Embayment of the crystals by the glass and selective progression of the glass along the cleavage cracks of the plagioclase, however, are not common except near iron-ore aggregates. Mode of occurrence of the iron-ores is very similar to that in the Yoshino xenoliths described later.

4. *Washino-yama* (Loc. 15)

Megascopic character: Two granitic xenoliths, zircons of which were examined, are dull gray and generally not so porous. They are medium-grained and weakly schistose due to rough parallel arrangement of black minerals.

Microscopic character: It consists mainly of plagioclase, quartz, biotite, and iron-ores.

Plagioclase is marked by cracks, frequently vitrified, and clouded along margin and cracks. Quartz is commonly crackled and shows undulatory extinction. Original mafic crystals probably of biotite are altered into aggregates of darker colored biotite, pleochroic from black to dark reddish brown, and a great amount of black iron-ores together with stout rhombic and monoclinic pyroxene grains. A few of the aggregates are composed of iron-ores, pyroxenes, and quartz.

5. *Yoshino* (Loc. 18)

Megascopic character: The xenolith from this locality is more dull gray than the original granodiorite and contains small vesicles. Generally, between quartz and feldepar, there are irregular fine zones, colored partly brownish red, as much as 1 mm wide, which are mainly composed of glass and elongated vesicles (Plate 7, Fig. 2).

Microscopic character: It consists mainly of plagioclase, quartz, potash feldspar, and iron-ores.

Plagioclase and quartz are crackled and clouded with minute inclusions. Glass belts and veinlets are seen along the margins of the plagioclase and quartz and along the cleavages and other fractures within them respectively. Crystals embayed by the glass are found commonly. These glass channels contain vesicles, cristobalite crystals, and long needle-like microlites of pyroxene (?). Some plagioclases, especially those near iron-ore aggregates, are selectively vitrified along cleavages to show the appearance of alligator-skin. A large crystal of iron-ore is partly replaced by fine grains of the same mineral. Some large iron-ore crystals have a corona of iron-ore grains, followed by the second corona of pyroxene grains, which are accompanied by glass and range in width from 0.03 to 0.1 mm.

C. **Type III** (Pl. 8, Fig. 1)

1. Kô-no-ura (Loc. 16)

Megascopic character: Abundant black materials associated with black glass give this rock the appearance of a foliated gabbro or diorite (Plate 8, Fig. 1). Even within larger xenoliths about 1 m in diameter the alteration has been uniformly developed.

Microscopic character: It consists mainly of plagioclase, quartz, iron-ore, and glass.

Plagioclase is conspicuously cut by abundant irregular veinlets of glass and is commonly vitrified in varying degrees: the first stage of the vitrification is represented by fine mesh works of glass along the surface of the crystals and the fractures within it. This phenomenon extends to the whole crystal of the plagioclase, though rounded rectangular grains of the mineral with the same orientation are left in a set of the fine lattice-like channels of glass (Plate 10, Figs. 3 and 4); so vitrified crystals with the lattice-like appearance are divided into angular pieces of various sizes, which are scattered in a large glass channel (Plate 10, Figs. 5 and 6). The clouding of this mineral by minute inclusions seems to be intense in little vitrified crystal while very slight in much vitrified one. Quartz commonly contains many minute inclusion trains and is cut by irregular glass channels.

Glass near iron-ore aggregates which are pseudomorphs after mafic minerals is larger in amount and dark brown in color; whereas glass far from the aggregates is smaller in amount and colorless. The glass in places contains needle-like microlites of plagioclase (?) and long prisms of pyroxene (?).

D. Type IV (Pl. 8, Fig. 2)

1. Tsurumi and Yufu (Locs. 5 and 6)

The great majority of granitic xenoliths from the Tsurumi and Yufu Volcanoes belong to this type; the rest to the type II as already mentioned.

Megascopic character: It is dull gray and contains more abundant vesicles than the xenoliths of the type III mentioned above. These vesicles occur as crusts, a few-tenths of a millimeter in width, associated with glass around the crystals of aggregates of quartz and as irregular aggregates with glass scattered throughout the rock (Plate 8, Fig. 2).

Microscopic character: It consists mainly of plagioclase, quartz, iron-ores, and glass.

Plagioclase free from vitrification is enormously richer in minute inclusions than intensely vitrified crystals. The minute inclusions forming trains or aggregate bands along cleavages are seen in some sections. For some distance from crystal margin

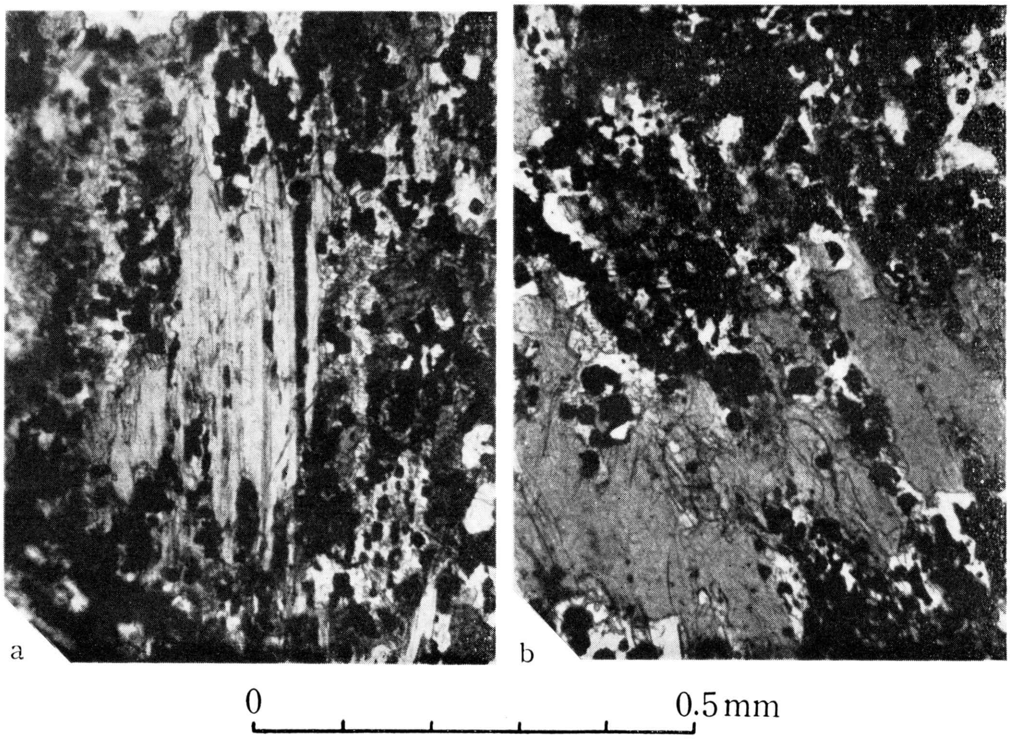

Fig. 4. Comparatively large biotite crystals (dark gray parts), which are irregular in form and separated into isolated parts with the same orientation accompanied by the associated iron-ores and plagioclase grains, in the Tsurumi xenolith (a–Bp 9c; b–Bp 15b).

it is partly vitrified, containing dotts and fine lattices of glass. Within and between some crystals, especially near the contact with the host andesite, there are isolated patches or veinlets consisting of composite lath-shaped or granoblastic plagioclase grains, up to about 0.4 mm in length, which are clear with sharp cleavage lines and twinning lamellae in strong contrast with the relict plagioclases. Quartz is crackled and clouded with minute inclusion trains.

The mafic minerals are replaced by aggregates of iron-ores, biotite, and plagioclase (Plate 9, Figs. 7 and 8), which are encrusted and enchased by composite pyroxene grains in places. Iron-ore grains, as a rule, are larger in size than those in the xenolith of the type II caught by the same lava (Table 6). The newly born biotite associated with the iron-ore grains is generally irregular flake, commonly ranging in size from 0.05 to 0.2 mm. It is of a brown variety in the xenoliths enclosed by the brown andesite while greenish brown by the gray andesite (Table 1). Some large crystals enclose numerous iron-ore grains, showing a poikilitic texture, and as the iron-ore grains increase in size the biotite crystals become separated into isolated parts with the same orientation (Fig. 4). Glass channels contain short or long prisms and fine needles of microlitic pyroxene as well as vesicles.

2. *Aono-yama* (Loc. 11)

Megascopic character: Granitic or mineral fragments as much as about 5 mm long are embedded in the glass matrix. Many vesicles, several millimeters in diameter, are present making up about 30 to 40 per cent of the rock, but they decay readily by the weathering.

Microscopic character: The xenolith consists mainly of plagioclase, quartz, glass, and iron-ores.

Plagioclase commonly shows clouding with dust inclusions, and is vitrified along the crystal margin and glass veins, where fine lattice-like channels of glass are observed along two cleavage directions. Potash feldspar is little found. Quartz is strongly crackled but shows homogeneous extinction. Probable mafic minerals are replaced by the aggregates of iron-ore and strongly pleochroic biotite.

Colorless glass enters into the boundary between mineral grains and their cracks, containing many vesicles and a little amount of small plagioclase laths.

E. Type V (Pl. 8, Fig. 3)

1. *Sakura-jima* (Loc. 8)

Megascopic character: The xenolith is gray and contains so abundant gray glass and vesicles as to show the appearance of a pumice with phenocrysts of plagioclase and quartz (Plate 8, Fig. 3).

Microscopic character: It consists mainly of plagioclase, quartz, glass, and iron-ores. Because of abundant glass and vesicles, thin sections good enough to obtain accurate volume per cent of each constituent could not be made.

Plagioclase is deeply embayed by glass channels rather than is progressed by glass along the fine lattice-like channels in the marginal parts of the crystal as mentioned above. It is one of the most important phenomena that this mineral is partly recrystallized (Plate 10, Figs. 7 and 8). The crystallized grains are clear, short lath-shaped or equidimensional crystals about 0.05 mm across, and show distinct cleavages and twin lamellae. They aggregate to make irregular bands along the margins, cleavages, cracks, or boundaries between zones in the larger relict plagioclase and potash feldspar in places. Potash feldspar is less clouded than the plagioclase. Myrmekite is preserved unchanged. Quartz, though smaller in amount than the plagioclase, is deeply embayed by glass. It is, however, not so crackled and clouded as those in the above-mentioned xenoliths, but is as clear as quartz in the original granite.

There are aggregates of iron-ore grains with subordinate newly generated pyroxene and plagioclase crystals here and there (Plate 10, Figs. 1 and 2). In places the composite pyroxene grains make the rim around each aggregate. Colorless glass commonly occurs in abundance, containing scattered pyroxene grains generally ranging in size from 0.1 to 0.2 mm at many places and dust material locally.

Temperatures Attained by the Granitic Xenoliths

The temperatures that the granitic xenoliths under consideration reached may be estimated from the changes that have taken place in the constituent minerals.

(1) In all the xenoliths examined here the mafic constituents of the original granitic rocks are completely decomposed to produce aggregates of iron-ores accompanied by some of such materials as glass, biotite, hornblende, and pyroxene. The iron-ores tend to progressively increase in grain size with progress of alteration in the xenoliths, though they know compact large crystal in the type I (Table 6 and Plates 9 and 10). Thus, mafic minerals, as HARKER (1932, p. 113) pointed out, are most easily affected in a granitic xenolith in a volcanic rock.

As an experimental value of the temperature at which biotite is completely decomposed with the formation of magnetite during heating, WATSON and MATHEWS (1948, p. 611) cited from DAY and ALLEN's work (1925) above 900° at atmospheric pressure and from WILLIAMS' one (1929) 810° in a neutral atmosphere of steam and carbon-dioxide. On the other hand, GORANSON (1932, p. 230) found that by heating of granite for 400 hours under a wet condition its biotite is completely altered to magnetite and chlorite at temperature as low as 600° at 385 bars. As a natural example, KNOPF (1938, p. 374-376) found that, although granodioritic xenoliths in an olivine basalt intrusive are so slightly altered that no orthoclase is sanidinized, they contain mixtures of magnetite, spinal (?), and red biotite changed from the original biotite. Thus, in nature mafic minerals may be affected by heating at temperature much lower than that obtained from the experiment.

(2) Quartz crystals in all the xenoliths examined except those from the Sakura-jima lava are conspicuously crackled. Some authors interpretted this fact as due to the high-low inversion at about 573° (LARSEN and SWITZER, 1939, p. 567; WATSON and MATHEWS, 1948, p. 609).

(3) Plagioclase crystals in the xenoliths have the optical properties of the high temperature form (Table 5).

According to BOWEN and TUTTLE (1950, p. 493–498), the inversion of albite from low-temperature form to high-temperature one takes place at about 700° under hydrothermal condition.

(4) As shown Table 3, the microperthitic texture has disappeared in the granitic xenoliths except that from Sakura-jima.

SPENCER (1937, p. 463–473, p. 491) points out that plagioclase lamellae in orthoclase-microperthite being to disappear by heating at a temperature between 350° and 450° and completely disappear when heated for a long time at 650° to 850° and that the more the composition of perthite is sodic the more the temperatures of the beginning and end of the solution are high. He also observed that the microperthitic texture, which vanishes on heating, can be partly restored by very slow cooling. GOLDSMITH and LAVES (1954, p. 7 and 12) found that albite-lamellae of five microcline perthites were completely dissolved by heating for 144 to 168 hours up to 800°, except coarse particles of albite in one specimen, and that when heated for 24 hours under hydrothermal condition at a pressure of more than 30,000 lb/in^2 and a temperature of 550° the same perthitic microclines became homogeneous.

(5) All the potash feldspar crystals in the original granitic rocks have large optic axial angles (Table 2). They may belong to the microcline-cryptoperthite series (TUTTLE, 1952, p. 558) or to the orthoclase-cryptoperthite series (MACKENZIE and SMITH, 1955, p. 730). On the other hand, the optic angles of the potash feldspars in the xenoliths are small with some range, the optic axial planes being either parallel or perpendicular to (010) — this may indicate that some of these feldspar belong to the sanidine-anorthoclase cryptoperthite series in the TUTTLE's classification or the high sanidine-high albite series (MACKENZIE and SMITH, 1956, p. 408) and others are intermediate between the two series.

These observations show that the potash feldspars of the xenoliths have been transformed by heating due to the host volcanic rocks from the low-temperature form into the high-temperature one. In this connection it should be noted that the presence of the potash feldspar that have small to nearly zero optic axial angles in granitic xenoliths of volcanic rocks was reported by RICHARZ (1924, p. 686) and, according to KNOPF (1938), by LACROIX, but KNOPF himself (1938, p. 376) did not find "sanidinized" feldspar in his granitic xenoliths, whilst WILLIAMS (1936, p. 159–160) observed in alaskite xenoliths both orthoclases partly transformed into water clear sanidine and orthoclases untransformed.

As the stable modifications of $KAlSi_3O_8$, LAVES (1952, p. 570–571) establishes two distinct forms, triclinic microcline and monoclinic sanidine, and infers on petrological evidences that the transformation temperature is about 700°. Again, GOLDSMITH and LAVES (1954) find that by hydrothermal treatment microcline has begun to transform into sanidine at a temperature below 500°, though under dry condition this transformation has been achieved only by heating for a long time at a temperature above 1000°. By dry heating has already been obtained by SPENCER (1937, p. 492) the similar result: by heating orthoclase and microcline for a long time the transformation into sanidine has taken place at 1075°. Thus, it is natural to infer that under hydrothermal condition such a transformation should take place at a lower temperature than under dry one.

In the Sakura-jima xenolith, quartz remains uncrackled and moreover some microperthites are preserved, whilst low-temperature potash feldspars have been transformed into high-temperature forms or the intermediate variety. If cracks in quartz crystals can be used as evidence of the high-low inversion at about 573° as has long been believed, the temperatures attained by the Sakura-jima xenolith may have been below 573° but above about 500°. For the same reason, it is inferred that all of the xenoliths examined except the Sakura-jima xenolith may have been heated at temperatures above 573°. Even if the quartz cracks cannot be regarded as a satisfactory basis for estimating the temperature attained by the xenoliths, it may safely be said that all the xenoliths examined should reach temperatures above about 500°, inversion temperature of potash feldspar. It may be well to note here that the Imayama xenoliths might reach the temperature above about 700°, for the original low-plagioclases have been inverted into the high-temperature form in the xenoliths.

The upper limit of the temperatures attained by the xenoliths, however, cannot be, in general, estimated on conclusive evidence.

Summary and Conclusions

Many granitic xenoliths in volcanic rocks have been collected for zircon studies from eighteen localities in Southwest Japan. Of these xenoliths, those from nine localities suitable for the microscopic studies as well as their original granitic rocks and host volcanic rocks were petrographically examined. The results are summarized as follows:

(1) The leading features in the alteration of mafic minerals, in the crackling

of quartz, and in changes in the optical properties of plagioclase and potash feldspar in the xenoliths are summarized in the preceding chapter.

(2) The granitic xenoliths are divided into five classes on the basis of the degree of vitrification and recrystallization of constituent minerals and the amount of vesicles. Highly altered xenoliths show some tendency to be developed in andesitic host rocks rather than in basaltic ones (Table 6). This may indicate that in the melting or fusion of the xenoliths mineralizers rather than heat of the surrounding host volcanics have played a more important role.

(3) Practically, the Sakura-jima xenolith that is the most highly altered illustration among the xenoliths examined was heated up to a temperature lower than that attained by the other less altered xenoliths.

The changes in feldspar optics, the presence of cracks in quartz, and the alteration of original mafic minerals lead to the conclusions that the temperature attained by the Sakura-jima xenolith may be above 500° and possibly below 573°C and that those attained by the xenoliths from other localities may be above 500° to 700°C.

(4) It has been pointed out by RICHARZ (1924, p. 678), HARKER (1932, p. 113), SUGI (1938, p. 26), and WATSON and MATHEWS (1948, p. 611) that brown glass may represent fusion product of biotite and other mafic minerals in granite. In the granitic xenoliths examined, especially those from the Kô-no-ura, brown glass is usually found closely associated with the composite iron-ore grains altered from mafic minerals, whereas near feldspar and quartz far from the iron-ore grains glass is white. This fact may support the above-mentioned suggestion as to the origin of the brown glass. It is very interesting to note here that the brown glass and the mafic minerals in the original granitic rocks are in approximately equal proportion (Table 4).

(5) The Tsurumi and Yufu andesites may be divided into at least two kinds according to their color: brown and gray andesites. The variety of the newly formed biotite in the xenolith has direct bearing upon the kind of the host andesite: brown variety occurs in the brown andesite and brownish gray in the gray in spite of that the two groups of the xenolith are of the same origin. This may clearly prove that the magmatic alteration or pyrometamorphism of the xenoliths is strongly controled by the nature of their host volcanics.

On the other hand, SUGI (1938, p. 26) finds that in the same granitic xenolith enclosed in an olivine-bearing sanukitic andesite lava the alteration products differ with original mafic minerals: that of hornblende is augite and rhombic pyroxene with black materials, while that of biotite is only rhombic pyroxene with black materials. However, the xenoliths dealt with in this paper do not clearly show such phenomena.

(6) The majority of plagioclase crystals in the xenoliths examined in this paper are clouded with minute inclusions composed mainly of iron-ores, which are dis-

tributed throughout the crystal or arranged in numerous trains along cleavages and cracks. MacGregor (1931, p. 536–537) and other authors believed that the clouding of plagioclase is the result of exsolution of iron originally contained in the crystal lattice by later heating, whereas Poldervaart and Gilkey (1954, p. 83–86) interpret that intense clouding is produced by diffusion of extraneous materials into the crystal after its formation. In short, in either case just referred to, there is very little doubt that the clouding of plagioclase in the xenoliths is due solely, or at any rate mainly, to volcanic heating.

According to further observation, no minute inclusion occurs in the small plagioclase grains remaining among the fine lattices or mesh works of glass and in the peripheral zones of some crystals, especially those surrounded by glass channels. These facts suggest that the already-formed minute particles in the plagioclase crystals may have been migrated to the outside of the crystals to be resorbed by glass produced around them.

(7) It has frequently been reported that in the partly for very highly vitrified granitic xenoliths potash feldspar is very strongly or completely resolved, though some crystals of plagioclase and quartz are remained (Sugi, 1938, p. 25; Larsen and Switzer, 1939, p. 566: Kuno, 1954, p. 261). In the xenoliths dealt with in this paper such a selective vitrification of feldspar is also observed in the highly vitrified xenoliths (types III and IV), but not definitely in the most highly vitrified one (type V).

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Yoshifumi KARAKIDA

Petrological Studies of Naturally Heated Zircons. P't II

Petrology of Some Granite Xenoliths in Volcanic Rocks

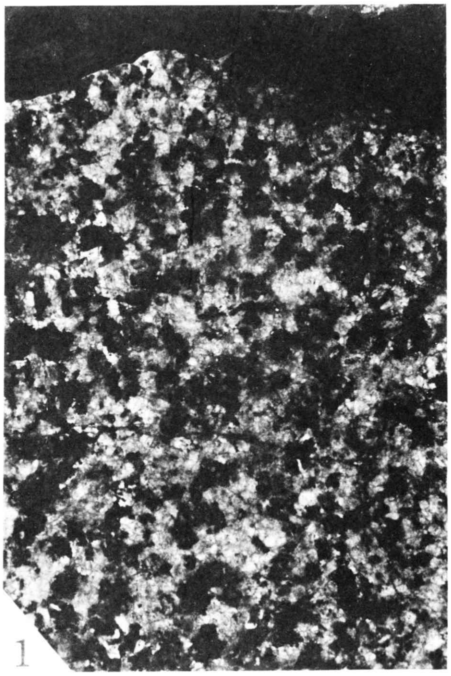
Plates 4-7

Plate 4

Explanation of plate 4

Fig. 1. Graodioritic xenolith of the alteration type I in the Imayama basalt (It 982c) (in natural size).

Figs. 2–4. Granitic xenoliths of the alteration type II: Fig. 2—in the Yoshino andesite (Sd 17c); Fig. 3—in the Ishigami-yama andesite (Km 28b); Fig. 4—in the Shibuki basalt (Ab 8) (in natural size).



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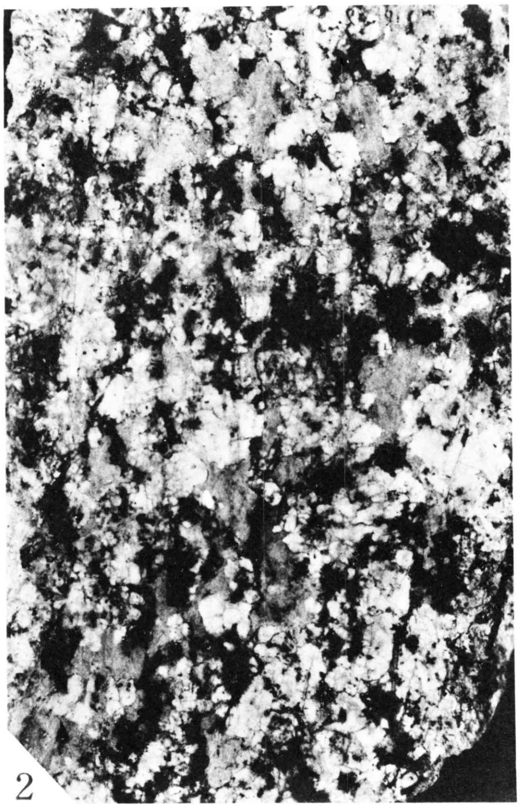

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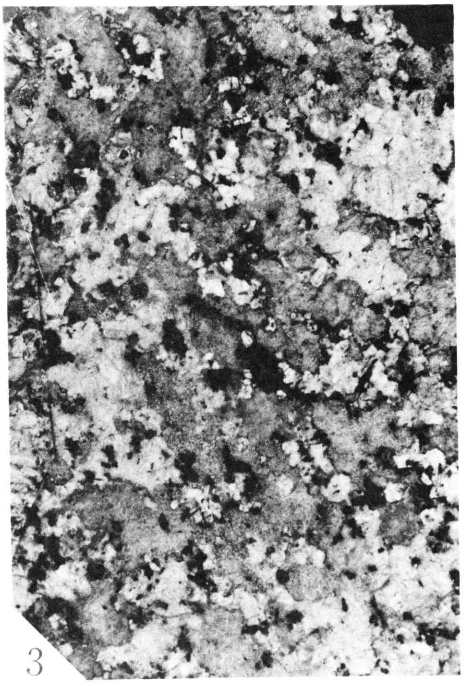

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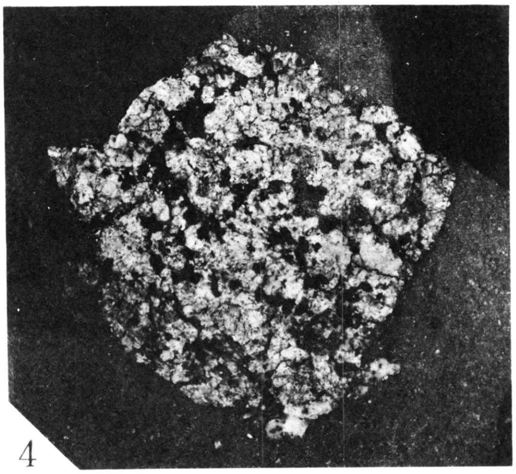

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Y. Karakida: Petrology of Some Granite Xenoliths in Volcanic Rocks

Plate 5

Explanation of Plate 5

Fig. 1. Partially fused granodioritic xenolith of the alteration type III in the Kô-no-ura basalt (Sd 26g) (in natural size).

Fig. 2. Partially fused granitic xenolith of the alteration type IV in the Yufu andesite (Bp 15) (in natural size).

Fig. 3. Partially fused granitic xenolith of the alteration type V in the first lava (andesite) of the Sakura-jima Volcano (collected by K. YAMAGUCHI) (in natural size).

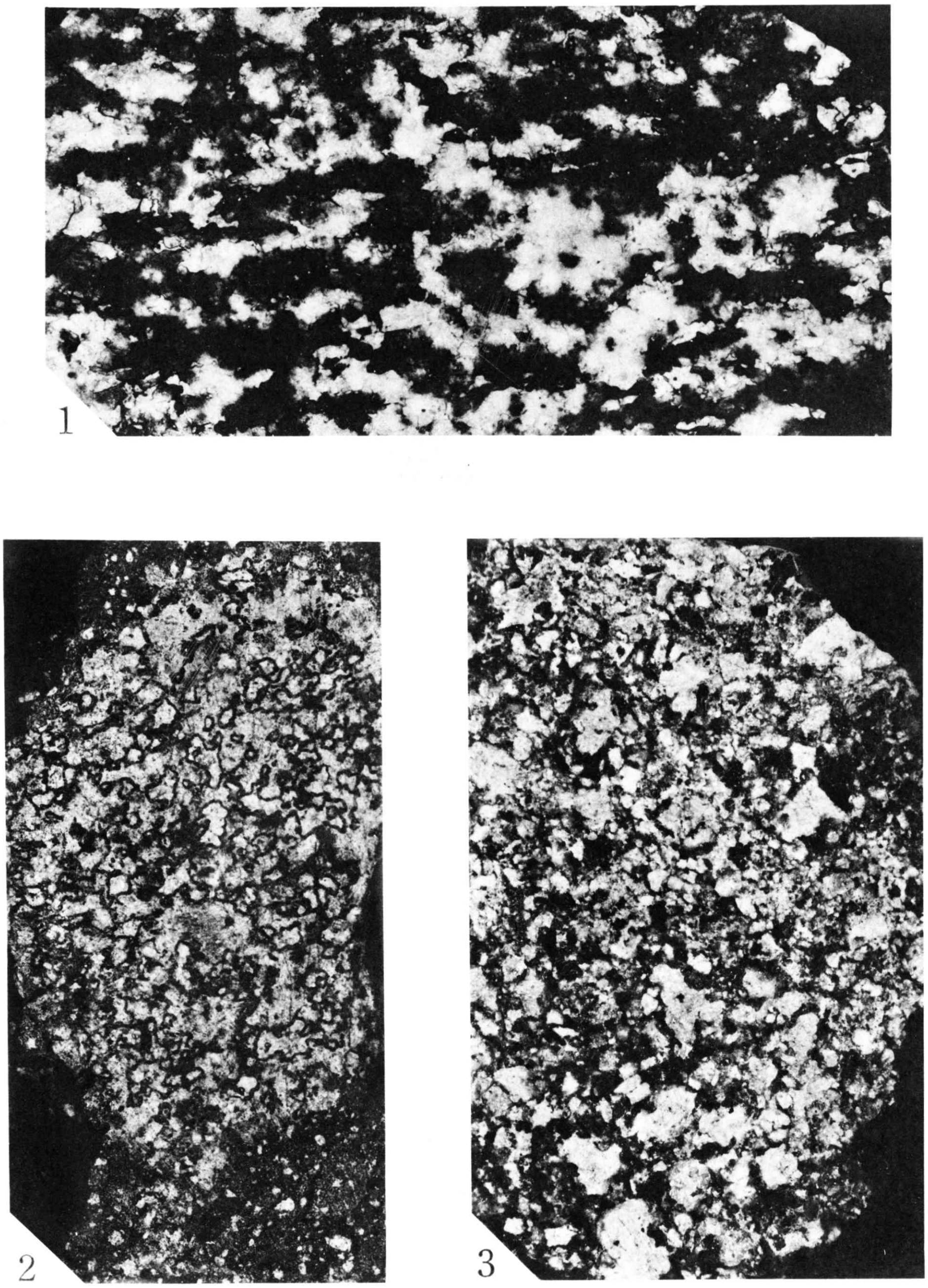

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Plate 6

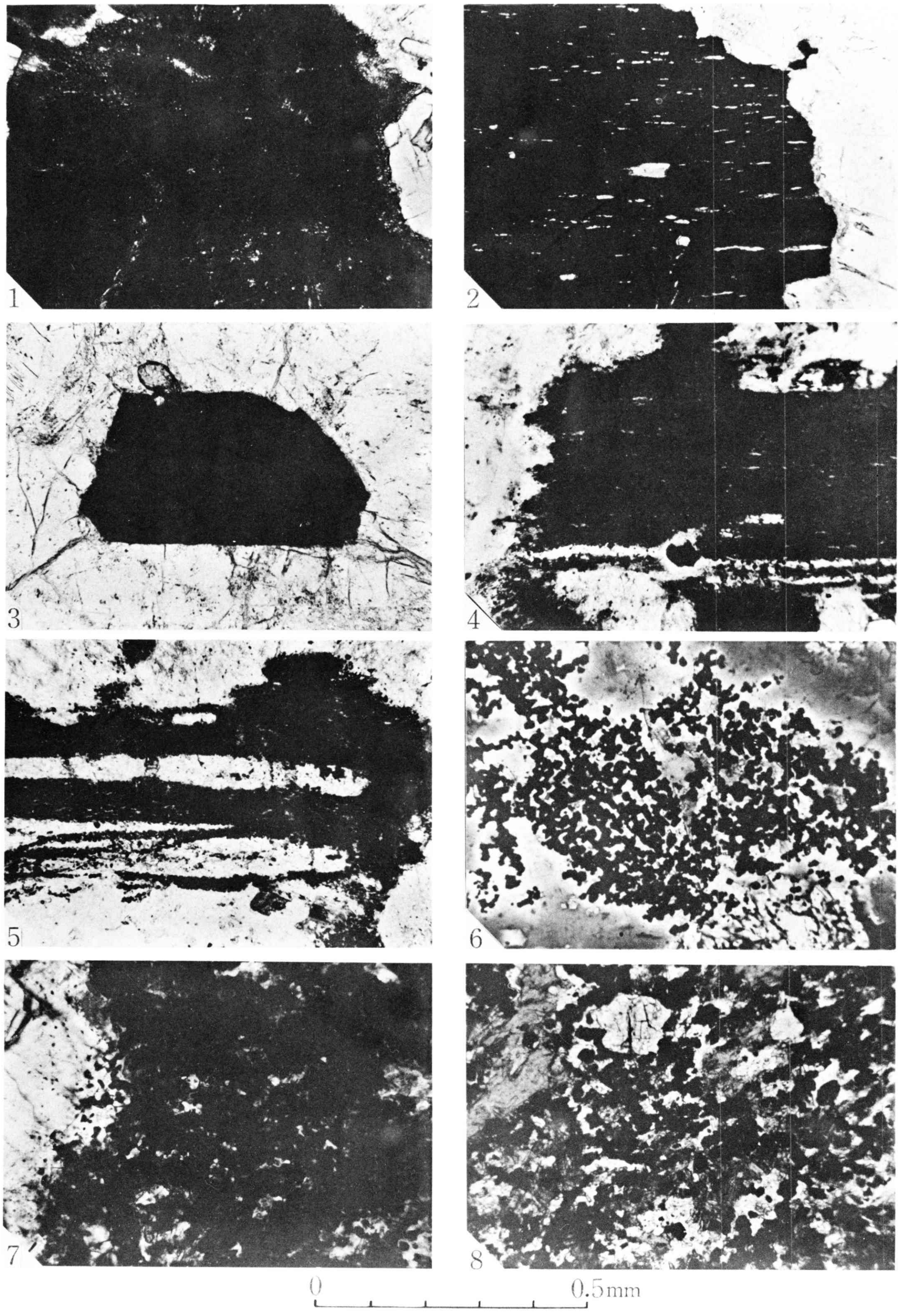
Explanation of Plate 6

Figs. 1–3. Large iron-ore crystals after mafic minerals in granodioritic xenoliths of the alteration type I: Fig. 1 shows the crystal accompanied by minute pyroxene (?) grains in the Imayama xenolith (It 982c); Figs. 2 and 3 in the Gongensaki xenolith (Sd 23g).

Figs. 4 and 5. Aggregates of small iron-ore grains and small biotite flakes after mafic minerals in granitic xenoliths of the alteration type II from Ishigami-yama (Km 28b).

Fig. 6. Dense Aggregates of iron-ore grains embedded in glass in the Kô-no-ura granodioritic xenoliths of the alteration type III (Sd 26g).

Figs. 7 and 8. Aggregates of iron-ore grains (black parts) and biotite crystals (dark gray parts) with plagioclase (pale gray parts) and scarce pyroxene grains after original mafic minerals in the Yufu (Bp 15b) (Fig. 7) and Tsurumi (Bp 9c) (Fig. 8) xenoliths of the alteration type IV.



Y. Karakida: Petrology of Some Granite Xenoliths in Volcanic Rocks

Plate 7

Explanation of Plate 7

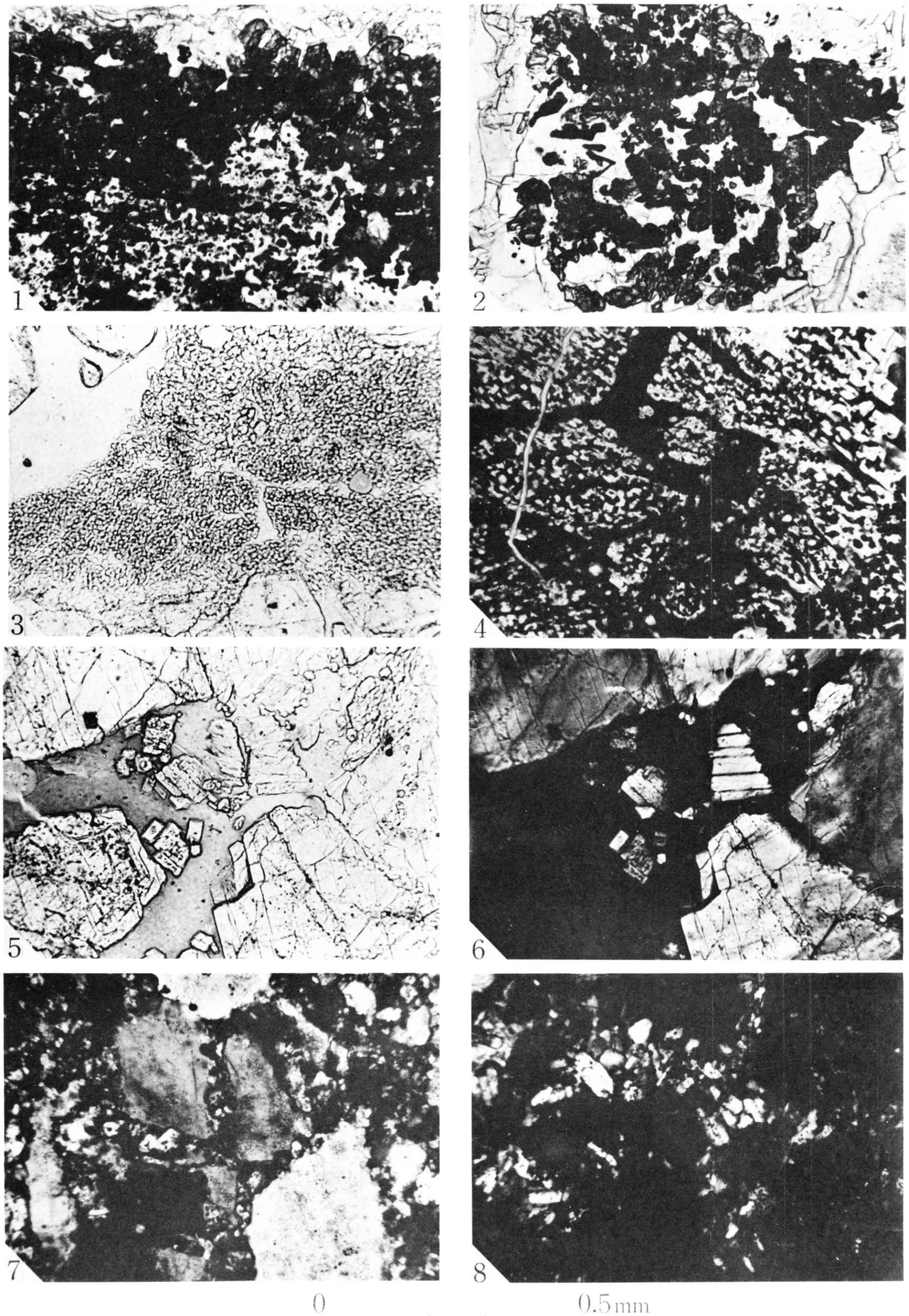
Figs. 1 and 2. Aggregates of iron-ores, pyroxene, and plagioclase grains after original mafic minerals in the Sakura-jima xenolith of the alteration type V.

Fig. 3. Fine mesh works of colorless glass in plagioclase crystals of the Kô-no-ura xenolith (Sd 26a).

Fig. 4. More or less irregular fine lattice-channels of brown glass in plagioclase crystals near the aggregates of iron-ore grains in the Kô-no-ura xenolith (Sd 26a).

Figs. 5 and 6. Irregular glass channels invading plagioclase crystals in the Kô-no-ura xenolith (Sd 26a) (Fig. 5—open nicols; Fig. 6—crossed nicols.)

Figs. 7 and 8. Newly formed plagioclases within or between larger relict plagioclases in the Sakura-jima xenolith.



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