XENOLITHS INCLUDED IN THE LAVAS FROM VOLCANO TARUMAI, HOKKAIDÔ, JAPAN

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(With 3 Tables and 2 Plates)

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Introduction

Among volcanoes in Japan, Sakurajima,[1] Yufutsurumi[2] and Komagatake[3] have from many years ago been known to be rich in the sorts of xenoliths included in the lavas and accidental ejectas derived from the basement rocks of volcanoes. Thereafter MORIMOTO found many interesting xenoliths in the lavas from Volcano Nijô, some of which were reported by him.[4] Not a few xenoliths and accidental ejectas were described by the author[5] also from Volcano Tarumai, Hokkaido, in 1939. By his further study, the genesis and petrological significance of some of the xenoliths and ejectas were clarified. Two sorts of aegirine augite bearing xenolith were newly added by the author[6] in 1949. Petrographical properties of xenoliths and accidental ejectas from this volcano will be briefly described and genesis of some of them discussed in the present paper.

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Occurrence of xenoliths

Volcano Tarumai is noted for the typical dome formed in the crater of the central cone in 1909.(7) Xenoliths are included the most abundantly in the dome lava, and subordinately in the black compact lava blocks, most of which are considered to have been ejected in 1909. Other xenoliths were collected in Nishiyama upper lava (scoriaceous lava), Shishamonai lava and Kuchawakkanai lava. All these including lavas are petrographically augite hypersthene andesite.

Except the xenoliths included in the lavas, ejectas derived from the basement rocks of this volcano are frequently found scattered in the neighbourhood of its top part. Some of them are covered with or attached to the lava crusts, some retain traces of lava on their face, and others are quite free of being enveloped in them. These may be called accidental ejecta. Some of the above ejectas seem to have erupted in 1909, from the character of the lava crusts attached to them.

The fact that abundant xenoliths and accidental ejectas were related to the activity in 1909 may suggest that the magma in question had some favourable conditions for keeping xenoliths in respect to temperature and viscosity or mechaism of eruption. Generally xenoliths are more abundantly found in volcanoes of andesitic lavas than in those of basaltic lavas. Consequently the chemical composition of the lava are considered to be related closely with the formation of xenoliths.

Sorts of xenoliths

Xenoliths are commonly classified as the cognate xenoliths solidified earlier than the including lava from the same magma and the accidental xenoliths derived from the basement rocks of the volcano. Igneous textured xenoliths such as micronorite, microgabbro etc. have been generally considered to be cognate xenoliths. But some of them may be not purely of cognate origin. Therefore xenoliths from this volcano will be roughly classified into metamorphic and igneous textured rocks as follows.

A. Metamorphic textured rocks
  1. Wollastonite-anorthite-monoclinic pyroxene hornfels
  2. Wollastonite-aegirine augite-quartz-plagioclase rock
  3. Wollastonite-grossularite-anorthite-aegirine augite rock
  4. Plagioclase-monoclinic pyroxene-quartz hornfels
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B. Igneous textured rocks
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  3. Micro-norite
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    c) Augite hypersthene andesite with vitrophyric groundmass
  8. Hornblende-hypersthene-plagioclase rock

TABLE I. Chief mineral components of xenoliths and accidental ejectas from Volcano Tarumai.

Minerals \ Sort No.	A1	A2	A3	A4	A5	A6	A7	B1	B2	B3	B4	B5	B6	B7	B8
Quartz	+	+	+	+				+	+						
Plagioclase		+	+	+	+	+	+	+	+	+	+	+	+	+	+
Anorthite	+		+				+								
Biotite					+										
Hornblende						+									+
Diopside or Augite	+		+	+			+				+	+	+	+	+
Soda-diopside		+													
Aegirine-augite		+	+												
Hypersthene					+			+	+	+	+	+	+	+	+
Cordierite								+							
Wollastonite	+	+	+												
Grossularite			+												
Glass								+	+					±	

The chief mineral constituents of the above rocks are shown in Table I, excluding accessory minor minerals such as magnetite, hematite, apatite, zircon and others.

Descriptions of xenoliths

(A) Metamorphic textured rocks

(1) Wollastonite-anorthite-monoclinic pyroxene hornfels

The specimens occur as xenoliths in the dome lava or lava blocks ejected in 1909 and as accidental ejectas. They are yellowish green, hard and compact. Microscopically they show hornfels texture and contain wollastonite, anorthite (An_{91}), monoclinic pyroxene, magnetite, quartz and sometimes orthoclase. (Plate 16, Figure 1) Quartz decreases generally with the increase of wollastonite. Anorthite is generally not great in quantity, though it is contained abundantly in delicate association with wollastonite in some specimens. Monoclinic pyroxene is abundant except in wollastonite and anorthite rich specimens.

Wollastonite has the following optical properties; $C^\wedge X=30°$; $(-)2V=39°$; $N_{1D}=1.619$, $N_{2D}=1.634$ on (100) cleavage flake.

Monoclinic pyroxene is pale green or pale yellowish green and rarely pleochroic. Its optical properties are as follows; $C^\wedge Z=52°$; $N_{1D}=1.700$, $N_{2D}=1.727$ on (110) cleavage flake; Its double refraction is stronger than that of augite. It is considered to be diopside rich in hedenbergite molecule, from its high refractive indices and greenish colour. Pyroxenes in similar xenoliths in volcanic lavas in Europe are green coloured and described as augite by Lacroix.[8] Diopside in wollastonite-andesine-diopside hornfels from Fukuhara in Hitachi district is $\beta=1.712$ in refractive index and contains hedenbergite molecule of 55%.[9] Hedenbergite molecule in diopside is attributed to the absorption of some oxidized iron, when limonite contained in the original rock is changed into magnetite by thermal metamorphism. The formation of the deeper green monoclinic pyroxene may be perhaps due to soda addition.

Hornfels of this type from Volcano Tarumai is considered to be originally calcareous clay rock. Though it was not completely analyzed, a certain specimen contains 55.91 percent of silica, 14.35 percent of alumina and 19.32 percent of lime. Thermal metamorphic rock derived from lime-alumina-rock, or shale-limestone-hornfels has commonly the following mineral assemblages;

Anorthite (or Plagioclase)-diopside,

Anorthite (or Plagioclase)-diopside-grossularite,
Diopside-grossularite,
Diopside-grossularite-wollastonite-(vesuvianite).

But the combination of wollastonite and anorthite or even plagioclase is very rare in common type of hornfels. HARKER[10] stated that this combination is formed only under such a special condition as that at the contact of minor intrusion where cooling is rapid. Generally mineral combination shown on the left side is stable above a certain temperature, while that on the right side is stable below it, in the following equation;

$$\text{Anorthite} + 2\ \text{Wollastonite} = \text{Grossularite} + \text{Quartz}.$$

Consequently the combination of wollastonite and anorthite molecules leads to the formation of grossularite in common type of hornfels.

The assemblage of wollastonite and andesine or bytownite in common hornfels has been reported from Carlingford, Deeside,[10] from Cambus O'May, Aberdenshire[10] and from Fukuhara in Hitachi district, Japan.[9] The formation of andesine in wollastonite-andesine-diopside-ortholcase rock from Carlingford is due to the combination of anorthite molecule with albite molecule originally contained, instead of the combination with wollastonite molecule to form grossularite, according to Osborn.[10] In such case as stated above, wollastonite-plagioclase hornfels may be formed even at such low temperature that grossularite might have been formed.

But wollastonite-anorthite assemblage can be formed only under such special condition that chemical equilibrium is not completely attained. Xenoliths in volcanic lava are often controlled by the just-stated condition. ESKOLA[11] regarded this mineral assemblage as one of sanidinite facies in pyrometamorphism. LACROIX[8] reported xenoliths belonging to this type from Santorin, Somma, Champs Phlegreens, Iles de Procida et de Vivara, Lac de Bracciano and Latium, though their detailed descriptions have not been published. In Japan, TSUYA[12] described wollastonite-anorthite (An_{90}) -augite-quartz-magnetite hornfels which was found as accidental xenolith from Volcano Komagatake, Hokkaidô.

From the above statement, wollastonite-anorthite-monoclinic pyroxene hornfels from Volcano Tarumai is concluded to have been formed by pyrometamorphism from calcareous clay rock. Hornfels of this type may be sometimes found among xenoliths or accidental ejectas from volcanoes.

(2) Wollastonite-aegirine augite-quartz-plagioclase rock.

The specimen at hand was found as an accidental ejecta at Shishamonai valley. It is an angular compact block, 5 cm in the longest diameter, and shows green colour scattered with small white spots. Under the microscope, it shows fine grained holocrystalline texture resembling that of hornfels, and contains basic plagioclase, green monoclinic pyroxene and quartz in the green part, and wollastonite, basic plagioclase and quartz in the white part. (Plate 16, Figure 2)

Green monoclinic pyroxenes are mostly granular and show sometimes hypidiomorphic prism with distinct cleavages. Their pleochroism is from remarkably strong to very weak as if non-pleochroic, and colour at the marginal part is usually deeper than at the central in the case of the larger crystals. Optical properties of green pyroxenes are shown in Table II.

TABLE II. Optical properties of green monoclinic pyroxenes in A2 rock.

$c \wedge Z$	(+) 2V	pleochroism		
		X	Y	Z
32				
33	43	green	green	green
36	44			
45	44			
49	58			
56	80	green	yellowish green	pale yellow
58		grass green	green	pale yellow
59				
86	82			
86	91	bluish green		pale brown

From the above optical properties, they are considered to be soda pyroxenes variable in soda content, from soda diopside or soda augite to aegirine augite.

The genesis of this rock is presumed to be as follows. It was originally calcareous sediment or lime-alumina-silicate rock, and might have been thermally metamorphosed into diopside-plagioclase-quartz hornfels, if in the common metamorphic course. There might have been originally lime concentration in some places where megascopical white spots are seen in the hand specimen. It may be calcite filling cavities in the original rock. Replacement of materials, or introduction of alumina and silica from the surrounding green part into the white part and diffusion of some lime from the latter into the former took place in thermal metamorphism at high temperature. Wollastonite, basic plagioclase and quartz were formed as the result of metasomatism in the white part. At the same time increase of lime in the surrounding green part accelerated formation of basic plagioclase, and soda was added to diopsidic pyroxenes, instead of being allotted for albite ($Na_2O \cdot Al_2O_3 \cdot 6SiO_2$). Thus soda pyroxenes variable in soda content were formed, and the deeper green colour at the margin of the larger crystal seems to show that soda addition advanced from the margin of diopsidic pyroxene.

(3) Wollastonite-grossularite-anorthite-aegirine augite rock.

The specimen occurs as a xenolith in the dome lava, and shows an irregular platy form, 8 cm in length and 4 cm in thickness. It is a green-coloured, hard and compact rock, penetrated by a white vein of 1 cm in maximum breadth. Under the microscope, it shows holocrystalline hypabyssal texture and contains phenocrysts of basic plagioclase scattered in the groundmass consisting of monoclinic pyroxene, wollastonite, anorthite and small amount of quartz and magnetite. The groundmass shows hornfels texture, or aggregation of small prism, grain and irregular form of those minerals. The margin of phenocrystic crystals is often irregular and associates delicately with groundmass crystals.

Monoclinic pyroxenes are diopsidic and colourless to very pale green, while they are bright green along contact part with a white vein. Green monoclinic pyroxene has the following optical properties; $C^\wedge Z = 55°$; $(+)2V = 80°$; strong pleochroic with X = green, Y = green, Z = pale yellow; Absorption $X = Y > Z$. From the above data, it is regarded to be aegirine-augite.

Grossularite, wollastonite and anorthite associate with aegirine augite in the contact zone with a white vein. (Plate 16, Figure 3) The white vein in question consists of wollastonite alone.

The genesis of this rock is considered to be as follows. The original rock may be pyroxene porphyrite penetrated by a calcite vein. Its groundmass part was first thermally metamorphosed and recrystallized. At the same time, exchange of materials, or introduction of silica from porphyrite into calcite vein and diffusion of lime from the latter into the former, took place. Calcite vein was changed into wollastonite

($CaO \cdot SiO_2$) by thermal metasomatism with addition of silica, while addition of lime to porphyrite gave rise to grossularite ($3CaO \cdot Al_2O_3 \cdot 3SiO_2$) and anorthite ($CaO \cdot Al_2O_3 \cdot 2SiO_2$) in the neighbourhood of the vein. Scantiness of alumina resulted in the very zone by formation of grossularite and anorthite prevented the formation of albite molecule ($Na_2O \cdot Al_2O_3 \cdot 6SiO_2$). Consequently soda that might have entered into albite molecule in normal case was added to diopsidic pyroxene to form aegirine augite.

(4) Plagioclase-monoclinic pyroxene-quartz hornfels

The specimens of this type xenolith were found as accidental ejectas in Opoppu and Shishamonai valleys. The former is an angular block of 10 cm in the longer diameter, grayish green, compact and hard. The latter is greenish, hard and rich in small pores, which are filled mostly with quartz and feldspar.

Under the microscope, they show hornfels texture, and they consist of quartz, plagioclase, monoclinic pyroxene and accessory minerals such as magnetite and zircon. (Plate 16, Figure 4)

Quartz shows comparatively large hypidiomorphic shape of 0.5 mm in the longer diameter. Plagioclase (An67) shows hypidiomorphic or granular shape of 0.1 mm in the average diameter and no zonal structure. Monoclinic pyroxene is hypidiomorphic or granular and less than 0.2 mm in size. It is pale green, and its extinction angle $C^\wedge Z$ is equal to 50°.

This type resembles Al type in appearance and texture, though it lacks wollastonite. Consequently the former may be considered to have been derived from less calcareous sediments than the original rock of the latter.

(5) Biotite-hypersthene-plagioclase hornfels

The specimen is an angular platy rock included in the dome lava, 6 cm in the longer diameter. It is gray or pale greenish gray and compact. Microscopically it shows a sort of hornfels texture with more or less parallel arrangement of minerals, and consists of hypersthene, plagioclase, biotite and magnetite. (Plate 16, Figure 5)

Hypersthenes are abundant and arrange their c-axes subparallel. Their crystals are mostly broken along cleavage and transverse crack, showing hypidiomorphic, granular or fork shapes. Their optical properties are as follows; $N_{1D}=1.698$ on (110) cleavage flake; $(-)\,2V=57°$; Pleochroism, X=pale pink, Y=pale yellow, Z=pale green. They sometimes include feldspar, biotite, magnetite and glass. Plagioclase (An78) shows mostly hypidiomorphic or granular forms smaller than 0.5 mm and often fills interstices among hypersthenes. It represents commonly polysynthetic twin after Albite law, but has no zonal structure, and it is not so fresh. Its included minerals are hypersthene, magnetite and brown glass. Biotite occurs grouping in some zone parallel to the arrangement of hypersthene. Its optical properties are as follows: $\gamma=1.634$; Pleochroism, X=yellow to pale yellow, Y=Z=deep brown.

From the above stated texture and mineral assemblage, this specimen may be considered to have been recrystallized from argillaceous sediment by thermal metamorphism. A similar xenolith has been reported from Volcano Eniwa.[(5)]

There is also a compact shaly rock found as an accidental ejecta, which is so fine grained that there are some undetermined minerals but it seems to have the same mineral composition as this type. The parallel arrangement of some minerals may be related to the texture of the original rock.

(6) Plagioclase-hornblende hornfels.

This rock is found as a microscopical inclusion in Kuchawakkanai lava. It consists of plagioclase and hornblende, both 0.1 mm in average size. Plagioclase being lath-shaped and hornblende granular, the specimen shows a sort of hornfels texture. Hornblende is pleochroic, or X'=pale greenish yellow and Z'=dark green, and its extinction angle $C^\wedge Z$ is equal to 7°. It is considered to have been thermally metamorphosed from some basement rock.

(7) Plagioclase-monoclinic pyroxene porphyroblastic rock.

The specimen is an angular xenolith in the dome lava; it is brownish, compact and hard. Microscopically it shows porphyroblastic texture, consisting of plagioclase, monoclinic pyroxene, quartz, magnetite and hematite in small crystals and grains below 0.05 mm in diameter, and rather large plagioclase.

Larger plagioclase (An88–An94) is 1.2 mm in the maximum diameter and shows hypidiomorphic or idiomorphic shapes. It commonly represents twinning, and rarely zonal structure. Smaller crystals of plagioclase (bytownite) show twinning after Albite law. Monoclinic pyroxene is granular, fork-shaped and often broken. Its optical properties are as follows; $N_{1D}=1.690$ on (110) cleavage flake; $C^\wedge Z'=47°$; Pale green and sometime pleochroic, X=Y=pale yellow, Z=pale green.

Most part of groundmass shows hornfels texture formed by recrystallization, though plagioclase porphyroblast and a part of groundmass are considered to have remained unmetamorphosed from the original rock. It is uncertain from what sort of rock this type was derived.

(B) Igneous textured rocks

(1) Cordierite-hypersthene-plagioclase glassy rock

The specimens of this type occur rather often as xenoliths in the dome lava and black lava blocks or rarely as accidental ejecta. They show irregular forms and are bounded sharply with including lava. Megascopically they are generally pale bluish gray and vesicular, resembling cordierite-bearing xenoliths from Sakurajima,[1] Komagatake[3] and Asama[13] volcanoes.

Under the microscope, they contain cordierite, hypersthene, plagioclase (An60), quartz and magnetite scattered in the glass rich in pores, (Plate 16, Figure 6) resembling "Lava scum" (cordierite-bearing xenolith) from Sakurajima[1] and cordierite bearing ejecta from Komagatake.[3] Cordierite is abundant and often shows distinct pseudohexagonal twinning. (Plate 16, Figure 7) It has refractive indices of $\alpha=1.534$ and $\gamma=1.543$, nearly the same as cordierite from Komagatake.[14] Hypersthene shows often imperfect crystal form, and its refractive index $N_{1D}=1.699$ on (110) cleavage flake. Glass is colourless and has refractive index $N_D=1.488$, while glass of the including lava is brown with a refractive index of 1.497.

Some specimens show porphyritic sturcture and contain the same large crystals of plagioclase, hypersthene and augite as phenocrysts in the lava, which scatter in the above mentioned cordierite rock. (Plate 16, Figure 8) These phenocrystic minerals have respectively the same optical properties as those of phenocrysts in the lava, and some of them are surrounded by the same brown glass as that of lava. This proves clearly that those phenocrystic minerals crystallized early in the including lava and migrated into the neighbouring xenolith before solidification. So-called "hybrid rock" from Sakurajima[15] is considered to be a similar rock to this in various points.

Chemical composition of a xenolith of this type (Table III) suggests that its original rock is siliceous clay rock or clayey sandstone, though it is rather rich in iron and poor in potash. Ceramicite (cordierite bearing xenolith) from Sakurajima[16] which resembles it in mineral composition and microscopical texture, (Table III), is richer in SiO_2, Al_2O_3, Na_2O and K_2O, but poorer in Fe_2O_3, FeO, MgO and CaO than it, seeming to be sedimentary in origin, though "ceramicite" is considered by KOTO[16] to be igneous in origin. Glassy rock included in basaltic andesite lava from Kollnitz is called "slaggy lava" by SCHOKLITSCH,[17] but contains cordierite and sillimanite characteristic to the thermal metamorphic rock. Gray spots contained abundantly in the above glassy rock are fine grained and very rich in Al_2O_3. The gray spot and glassy rock were both chemically analyzed separately (Table III), and plotted in the clayey sedimentary field of NIGGLI's tetrahedron.[17] The gray spot is clearly clayey sedimentary rock, and the glassy rock is considered to have been originally sedimentary rock which was melted by the magma and cooled rapidly. The latter is poorer in Al_2O_3, Na_2O and K_2O, and richer in Fe_2O_3, MgO and CaO than the former, suggesting that it was supplied some materials from the magma while melting. From the above, the latter may be derived from the former. The analyzed specimen from Tarumai and "ceramicite" from Sakurajima are both plotted on the boundary line between igneous and clayey

TABLE III. Chemical compositions of cordierite bearing xenoliths and allied rock.

	1	2	3	4
SiO_2	72.08	77.35	44.56	45.11
TiO_2	0.42	0.20	1.59	1.24
Al_2O_3	11.11	12.16	27.94	37.55
Fe_2O_3	3.95	0.81	12.73	2.20
FeO	3.09	1.09	—	—
MnO	0.19	0.05	0.04	—
MgO	2.29	1.26	6.07	1.36
CaO	2.26	0.90	1.20	0.97
Na_2O	1.14	2.43	—	2.52
K_2O	0.50	2.67	1.20	3.30
P_2O_5	0.32	0.08	—	—
$H_2O(+)$	0.71	0.52	3.78	3.78
$H_2O(-)$	0.12		1.37	2.64
Total	98.18	99.82*	100.48	100.67

* Contains S 0.30

(1) Cordierite hypersthene plagiocalse glassy rock (Bl) from Tarumai. Analyst, T. ISHIKAWA.

(2) Ceramicite 3rd type from Sakurajima. Analyst, ÔHASHI.[1]

(3) Slaggy lava (Glassy inclusion) from Kollnitz. Analyst, K. SCHOKLITSCH.[17]

(4) Gray spot included in the above rock. Analyst. K. SCHOKLITSCH.[17]

sedimentary fields of NIGGLI's tetrahedron. Cordierite-bearing xenoliths from Volcano Tarumai might have also acquired some materials from the magma while melting, though such xenoliths are clearly of sedimentary origin.

As shale formation of Tertiary age and alternation of clay and sandstone of Pleistocene form the basement of this volcano,[18] xenoliths of this type may be considered to have been derived from those formations. The original rock was captured by the magma, heated so far as to be melted, and cooled rapidly in the air before the whole mass was crystallized out.

Consequently abundant glass is contained accompanied by cordierite, hypersthene, plagioclase and quartz. This mineral assemblage belongs to class 4 of hornfels classified by Goldschmidt, but is due to pyrometamorphism according to ESKOLA,[11] as the existence of abundant glass suggests an instability in chemical equilibrium. Cordierite is experimentally crystallized from melt under 900°C.[19] Porous textured glass is formed by the explosive expansion at the neighbourhood of 900°C.[20] The facts that xenolith derived from alumina silicate rock contains abundant glass, while that from lime silicate rock contains no glass, suggest that the former can be kept longer in melting condition without crystallizing out on account of higher viscosity.

Consequently migration of phenocrystic minerals from the including lava into the xenolith while melting may take place. Glass in the lava has different composition from that in the xenolith, and may perhaps solidify earlier than the latter and migrate into the xonolith.

Cordierite-bearing xenoliths or accidental ejectas have been reported from Asama,[13] Gôrosan,[21] Iwatesan,[22] Akita-Komagatake,[23] Komagatake in Hokkaido,[3] Nijôsan,[24] Sakurajima,[1] Yufusan,[2] Daiton,[25] Hiyakejima[26] and other volcanoes or volcanic rocks.[27] The genesis of those xenoliths is mostly considered to be exogenetic, although some are reported to be igneous in origin on account of the presence of abundant glass.

(2) Hypersthene-plagioclase-quartz-glass rock.

The specimens occur as xenoliths included in the dome lava and block ejecta, and are angular or thick platy, 10 cm in the maximum length. They show bluish gray colour and rather vesicular texture.

Under the microscope, they consist of 0.03 to 0.04 mm grains of quartz and feldspar, rather larger hypersthene and quartz, irregular mass of magnetite and hematite, and interstitial glass. (Plate 17, Figure 1) Larger crystals of quartz are 0.5 mm in diameter and often corroded, including sometime glass and feldspar. Granular quartz is rounded and often aggregates. Feldspars are classified into plagioclase and granular feldspar undetermined exactly. Plagioclase (An50) is idiomorphic or hypidiomorphic, showing polysynthetic twins after Albite and Carlsbad laws as well as zonal structure. Hypersthene shows hypidiomorphic shape, 0.4 to 0.5 mm in length, and is often corroded or invaded with glass. Sometimes it is broken into small flakes or grains. Magnetite often groups around hypersthene, suggesting that the former was formed by remelting of the latter. Glass is colourless or pale brown and more or less porous. It may be formed by remelting of a part of the original rock and rapid cooling.

This type has some resemblance to Bl type in occurrence, appearance, texture and mineral compositions, though cordierite is absent and glass and air cavities are less than in the latter (Bl). It is considered that this type rock was derived from siliceous clay sediments, but not so strongly metamorphosed in comparison with Bl type. This may be due to the lower temperature of the lava at the moment of capturing than in the case of Bl type. Some microscopical inclusion in the dome lava consists of quartz, feldspar, hypersthene, magnetite, hematite and a very little glass. It is considered to have been formed from the same original rock as that of B2 type by the lower grade of thermal metamorphism. In appearance, the higher grade metamorphosed rock is more vesicular.

(3) Micronorite

The specimens occur as microscopical inclusions in a bomb found in ash formation at Opoppu valley and in a black compact lava block. The former shows irregular shape of 2 mm in diameter, bounded irregularly with the lava. The latter is 3 mm in diameter and migrates into cordierite-hypersthene-plagioclase-glassy rock (Bl) included in the same lava block.

Both specimens consist of plagioclase, hypersthene and magnetite, 0.2 to 0.8 mm in size, and show holocrystalline hypidiomorphic texture. (Plate 17, Figure 2) Plagioclase (labradorite) shows twinnings after Albite and Pericline laws and faint zonal structure. Magnetite is sometimes in aggregation of irregular mass, suggesting that this xenolith was refused by the including lava after solidification and pyroxene was secondarily changed into magnetite.

From occurrence and texture, it is considered that this type had solidified earlier from the same magma from which the mother lava crystallized out. Similar xenoliths have been already reported from Komagatake(3), Sakurajima(1), Norikura-dake(28), Ontake(29), Yufutsurumi(2), Iwôtorishima(30) and other volcanoes. Those from the above volcanoes consist mostly of plagioclase and hypersthene, but some of them contain olivine(31), cordierite(31) or biotite (32) in addition.

(4) Microgabbro

Rocks belonging to this type are found as microscopical inclusions in a black lava block and scoriaceous lava of Nishiyama upper lava group. Some are included in augite hypersthene andesitic xenolith (B7) in the lava block. They show nearly circular or elliptical shape of 6 mm in maximum diameter, and some are surrounded with basaltic textured part, transiting gradually to their mother lava.

They show granitic structure, and consist of plagioclase (acid bytownite), augite, less abundant hypersthene and magnetite, attaining to 1.2 mm in the maximum size and less than 0.6 mm in average. (Plate 17, Figure 3)

This type must have the same genesis as B3. Similar xenoliths have been known from Niijima(33), Sakurajima(1), Nantaisan(34), Yufutsurumi(2), Ôshima(35), Hachijôjima(36), Yugawara(37) and other volcanoes. Those from Niijima and Yufutsurumi have been named "gabbro-diabase" and "microgabbro-diabase" respectively from their texture. "Diopside gabbro" (Sakurajima), "eucrite" (Sakurajima),(38) "augite-microdiorite" (Ôshima) and "two pyroxene microdiorite" (Hachijôjima) were named from their mineral compositions and An content of plagioclase.

(5) Norite porphyrite

The specimen was captured by the dome lava, and shows platy form, 3 cm in thickness and 10 cm in the longer diameter, bounding sharply with the lava. It is dark gray coloured and compact.

Microscopically it shows porphyritic structure, consisting of phenocrystic plagioclase and groundmass minerals of plagioclase, hypersthene and magnetite. The groundmass shows hypidiomorphic equigranular to ophitic texture. (Plate 17, Figure 4)

Phenocrystic plagioclase (An56–An59) is 4 mm long in maximum, sometimes bent and not fresh. Inclusions such as pyroxene, magnetite, apatite and brown glass arrange parallel often along the cleavage plane. Hypersthene is hypidiomorphic, granular or forkshaped and shows the following optical properties; $N_{1D}=1.698$ on (110) cleavage flake; $(-)2V=62°–65°$.

A similar xenolith in mineral compositions and texture is "norite porphyrite" from Komagatake.[3] Its genesis is interpreted as "cognate origin" by KATO,[3] while this xenolith may be considered to have been more or less metamorphosed from the preexisting igneous rock, from its occurrence and some characters of minerals.

(6) Basaltic textured rock.

This rock is found as a microscopical inclusion in the scoriaceous lava belonging to Nishiyama upper lava group, and shows rounded shape of 1.5 mm in the longer diameter. It shows holocrystalline intersertal texture, consisting of plagioclase lath, augite, hypersthene and magnetite. Plagioclase (acid bytownite) is contained the most abundantly; it attains to 0.4 mm in the maximum length. Pyroxene shows granular or hypidiomorphic shapes, less than 0.2 mm in size. (Plate 17, Figure 5)

This specimen has irregular boundary with the lava, and some microgabbro (B4) shows the same texture as this type at its margin. Consequently it is considered that plutonic and basaltic textures are continuous and may be related with the rate of cooling.

(7) Augite-hypersthene andesite

Specimens of this type are found abundantly; they are paler in colour than including lavas. Similar xenoliths have been reported from Komagatake[39], Shiretoko-Iwosan,[40] Eniwadake[41] and other volcanoes. From texture of groundmass, this type is divided into three classes.

(a) Augite-hypersthene andesite with microcrystalline groundmass.

Two specimens occur as xenolith in the dome lava and as lava-crusted ejecta. They are both angular hard block of 10 cm in maximum diameter, showing distinct boundary with the lava. They are remarkably porphyritic and bluish, greenish gray or brownish.

Microscopically, they show porphyritic structure with microcrystalline groundmass, (Plate 17, Figure 6) and there is also an intermediate type between andesite and porphyrite. Phenocrystic minerals are plagioclase, augite and hypersthene of 2 mm in maximum diameter. Plagioclase shows strong zonal structure, and its composition changes from An90 at the core zone to An84, An72 and An63 at the outer zones successively. Augite shows the following optical properties; $N_{1D}=1.692$ on (110) cleavage flake; $C^{\wedge}Z=42°$. Hypersthene is not so fresh and its refractive index $N_{1D}=1.700$ on (110) cleavage flake. Both pyroxenes are often granulated at the margin or irregularly broken. Groundmass consists of plagioclase (labradorite), augite, hypersthene, magnetite, hematite and apatite. Some rocks of this type include microgabbro (B4) and basaltic textured rock (B6).

(b) Augite-hypersthene andesite with cryptocrystalline groundmass.

The specimens are found as xenoliths in the dome lava and Shishamonai lava, or as lava-crusted ejectas. They are angular hard blocks, 12 cm long in the largest one, and show pale bluish gray to dark blue.

They are remarkably porphyritic with cryptocrystalline to partly microcrystalline groundmass. (Plate 17, Figure 7) Phenocrystic minerals are plagioclase, augite and hypersthene. Some plagioclase exhibiting strong zonal structure is An77 in composition at the inner zone, An69 at the intermediate and An57 at the outer zone. Refractive indices of pyroxenes are as follows; Augite, N_{1D} on (110)=1.693; Hypersthene, N_{1D} on (110)=1.701. Tridymite and magnetite are contained in the groundmass. Some specimens belonging to this type include microgabbro (B4).

(c) Augite-hypersthene-andesite with vitrophyric groundmass.

The specimens were captured by the dome lava and lava blocks; they are angular blocks of 7 cm length in the largest one. They show dark blue and bluish gray, rarely banding of black and gray. Pheno crystic minerals of plagioclase (An90–An69), augite (N_{1D} on cleavage flake=1.694) and hypersthene (N_{1D} on cleavage flake=1.700) scatter in the vitrophyric groundmass consisting of abundant dark brown glass.

Origin of augite-hypersthene-andesite xenoliths included in augite-hypersthene andesite lavas may be variously considered to have been as follows;

(1) Augite-hypersthene andesite forming basement of volcano, or older lava of the volcano.

(2) Earlier solidified rock before eruption from the same magma, from which lava crystallized out.

(3) Earlier solidified rock after eruption from the same magma.

From the gradual change from 7a to 7c type in texture and colour, inclusion of microgabbro or basaltic textured rock in 7a and 7b type xenoliths, and absence of similar augite-hypersthene andesite at the base of this volcano, it may be considered that B7 type xenoliths were mostly derived from the magma, from which the lavas crystallized out, and partly from the older lavas of this volcano.

(8) Hornblende-hypersthene-plagioclase rock.

This rock is found as a microscopical inclusion in a lava block, and shows an irregular shape of 8 mm in the maximum diameter, having an irregular boundary with the lava. It consists chiefly of plagioclase, hornblende and hypersthene, and contains a small amount of augite and magnetite. It shows texture resembling that of hypabyssal rock, containing phenocrystic crystals of plagioclase and hypersthene.

Phenocrystic plagioclase (labradorite) shows idiomorphic or hypidiomorphic shape of 0.5 mm in the longer diameter. It is not fresh and includes hornblende and magnetite. Hornblende occurs partly in group, and shows short prism or rounded grain, below 0.1 mm in diameter. Its optical properties are as follows; Pleochroism, X=pale yellow or pale greenish yellow, Y=Z=deep greenish brown; $C^{\wedge}Z'=13°$. Hypersthene occurs as phenocrystic mineral of 3.5 mm in the maximum diameter, being hypidiomorphic or xenomorphic. Along its margin and cleavage plane, it changes gradually into hornblende. (Plate 17, Figure 8)

Generally thermal metamorphism advances from groundmass part to phenocrystic minerals. Hornblende was newly formed in the groundmass by recrystallization, and at the same time began to replace pyroxene from the margin of the phenocrystic crystal. Consequently the original rock may be pyroxene porphyrite.

Summary

Though there are some xenoliths not yet clarified in respect to their genesis, most xenoliths seem possible of classification into accidental and cognate ones.

Accidental xenoliths or ejectas are derived from siliceous clay sediments, calcareous clay sediments and igneous rocks forming the basement of this volcano. Each group includes transitional types formed by different grades of thermal metamorphism, though some difference of composition among original rocks must be taken in consideration.

Xenoliths of siliceous clay sediment origin embrace non-metamorphosed shale, partly recrystallized shaly rock, hypersthene-plagioclassquartz-glass rock (B2) and cordierite-hypersthene-plagioclase-glassy rock (B1). The last is a pyrometamorphic rock representing sanidinite facies, which can be found only as xenolith in volcanic lava. Further it is interesting that phenocrystic minerals or even micronorite crystallized out earlier from the magma often migrate into cordierite-bearing glassy rock while melting. (Plate 16, Figure 8 and Plate 17, Figure 2)

Xenoliths derived from calcareous clay sediments are described as wollastonite-anorthite-monoclinic pyroxene hornfels (A1) and plagioclase-monoclinic pyroxene-hornfels (A4); both seem to be transitional in texture and mineral compositions. Wollastonite-anorthite assemblage belongs to sanidinite facies and can be formed only as xenolith in volcanic lava by pyrometamorphism. It can be compared to cordierite-hypersthene-plagioclase-glassy rock metamorphosed from siliceous clay sediments.

Formation of glass in the latter is related to chemical composition rather than to cooling rate. Chemical composition of original rocks controls fusibility, viscosity and miscibility with lava or magma. Siliceous clay sediments are considered to be able to be placed longer in melting condition without so easy mixing with magma on account of their higher viscosity, though some degree of mixing may take place between them. Rapid cooling of the above melted part on the occasion of eruption leads to the formation of glass.

Aegirine-augite is supposed to be formed at some soda rich part newly introduced by metasomatism or movement of materials at very high temperature. Rapid cooling is also an important factor for the formation of aegirine augite at some part of xenolith, before a state of chemical equilibrium was attained throughout the whole mass.

Accordingly aegirine-augite or aegirine bearing xenoliths can be expected from volcanoes, although their lavas are calc-alkalic. In Japan, aegirine augite or aegirine bearing xenoliths have been reported from Yufutsurumi,[(2)] Mutsurejima,[(42)] Ishigamiyama,[(43)] Kanpûsan[(44)] and Misumidake.[(45)]

Xenoliths considered to be of cognate origin are micronorite (B3), microgabbro (B4), basaltic textured rock (B6) and augite-hypersthene andesite (B7), although chance of earlier segregation from magma is not always purely igneous.

There are certain transitional types in texture from micronorite or microgabbro to augite-hypersthene andesite with vitrophyric groundmass. Their mineral compositions are the same as those of lavas from this volcano. Augite-hypersthene andesite xenoliths (B7a and b) include sometimes microgabbro or basaltic textured rock. Difference in texture of cognate xenoliths may be due to temperature and cooling rate of magma when cognate xenoliths begin to segregate, that is, the difference is related to the depth where cognate xenoliths are solidified. The fact that micronorite, microgabbro and basaltic textured rock are found only as microscopical inclusions and transit to lava without any sharp boundary, seems to give some suggestion in this respect.

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Explanation of Plate

16

Plate 16

Figure 1. Wollastonite-anorthite-monoclinic pyroxene hornfels. (Crossed nicols, ×80)
W–wollastonite, P–monoclinic pyroxene, A–anorthite, Q–quartz

Figure 2. Wollastonite-aegirine augite-quartz-plagioclase rock. (One nicol, ×70)
W–wollastonite, A–aegirine augite

Figure 3. Wollastonite-grossularite-anorthite-aegirine augite rock. (One nicol. ×70)
W–wollastonite, G–grosssularite, A–aegirine augite

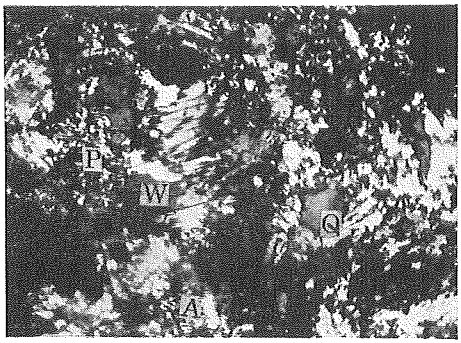
Figure 4. Plagioclase-monoclinic pyroxene-quartz hornfels. (Crossed nicols, ×80)
Q–quartz, P–monoclinic pyroxene, M–magnetite

Figure 5. Biotite-hypersthene-plagioclase hornfels. (One nicol, ×55)
B–biotite, H–hypersthene, P–plagioclase

Figure 6. Cordierite-hypersthene-plagioclase glassy rock. (One nicol, ×80)
C–cordierite, G-glass M–magnetite, A–pore (air cavity)

Figure 7. The same as Figure 6. (Crossed nicols, ×80)
C–cordierite, G–glass, magnetite and pore (air cavity)

Figure 8. Porphyritic part of cordierite-hypersthene-plagioclase glassy rock. (Crossed nicols, ×35)
H–hypersthene phenocryst, A–augite phenocryst, P–plagioclase phenocryst, C–cordierite, G–glass, magnetite and pore (air cavity)



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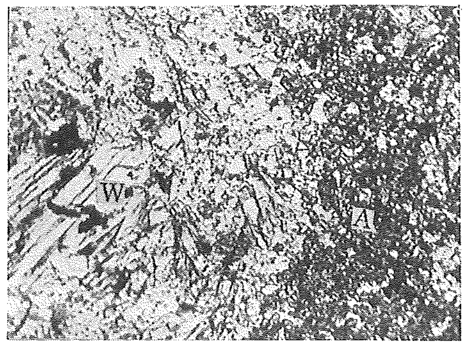

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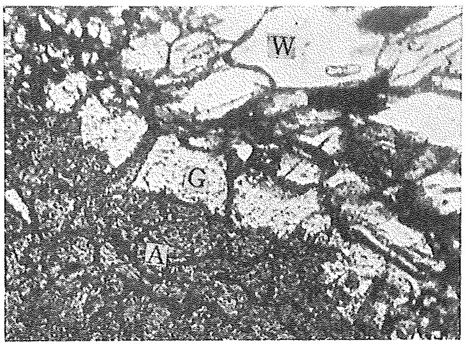

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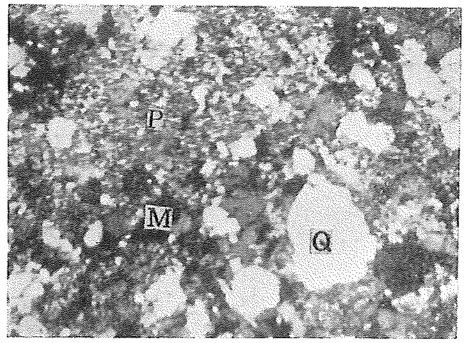

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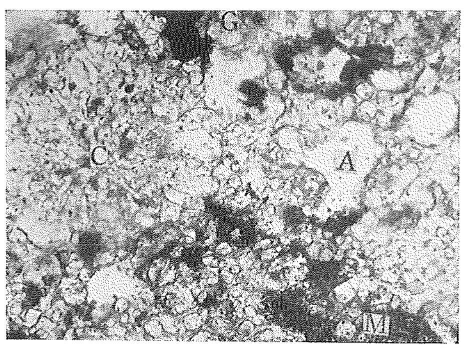

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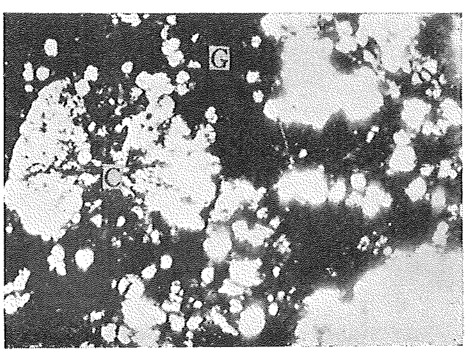

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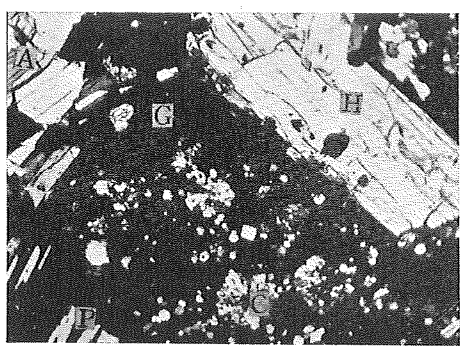

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T. Ishikawa: Xenoliths included in the lavas from Volcano Tarumai.

Explanation of Plate

17

Plate 17

Figure 1. Hypersthene-plagioclase-quartz glass rock. (Crossed nicols, ×80)
Q-quartz, F-feldspar, G-glass

Figure 2. Micronorite (left) and cordierite-hypersthene-plagioclase-glassy rock (right). (Crossed nicols, ×35)
P-plagioclase, H-hypersthene, C-cordierite, G-glass

Figure 3. Microgabbro (Crossed nicols, ×55)
P-plagioclase, A-augite, H-hypersthene, M-magnetite

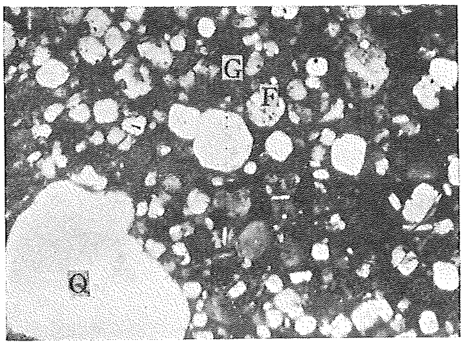
Figure 4. Norite porphyrite. (Crossed nicols, ×55)
P-plagioclase, H-hypersthene, M-magnetite

Figure 5. Basaltic textured rock. (Crossed nicols, ×55)
P-plagioclase, A-pyroxene, M-magnetite

Figure 6. Augite-hypersthene-andesite with microcrystalline groundmass. (Crossed nicols, ×55)
P-plagioclase, A-augite, M-magnetite

Figure 7. Augite-hypersthene-andesite with cryptocrystalline groundmass. (Crossed nicols, ×55)
P-plagioclase, A-augite, H-hypersthene

Figure 8. Hornblende-hypersthene-plagioclase rock. (Crossed nicols, ×55)
P-plagioclase, H-hornblende, h-hornblende changed from pyroxene, M-magnetite



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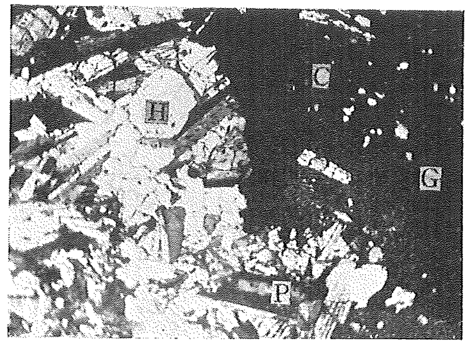

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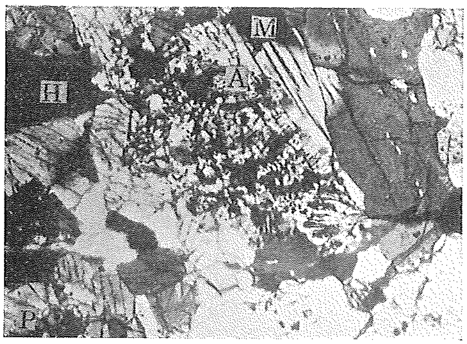

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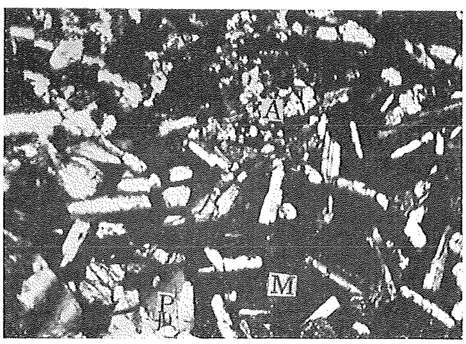

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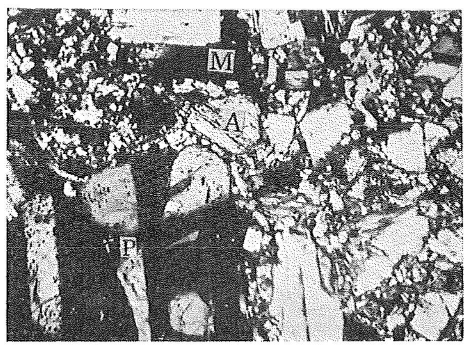

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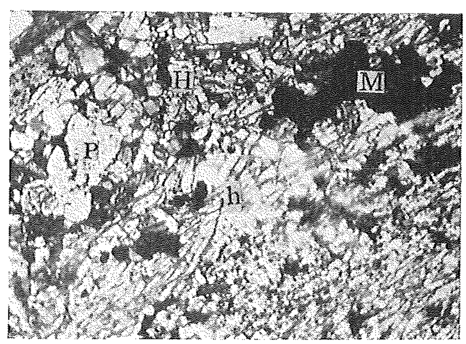

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T. Ishikawa: Xenoliths included in the lavas from Volcano Tarumai.