MINERAL PARAGENESES OF ARGILLACEOUS XENOLITHS IN ANDESITIC ROCKS FROM THE NIJO-SAN AND AMATAKI-YAMA DISTRICTS, SOUTHWEST JAPAN

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The argillaceous xenoliths within the andesitic lavas of the Nijo-san and Amataki-yama districts were recrystallized successively by the thermal effects of the magma. The mineral assemblages of these xenoliths can be classified into the large-grained and fine-grained groups. The former is subdivided into the staurolite-bearing and staurolite-free assemblages. The staurolite-bearing parageneses of the minerals can be regarded as the amphibolite or pyroxene hornfels facies and the staurolite-free ones composed of minerals with large grain-size belong to the pyroxene hornfels facies. Such fine-grained parageneses as the corona texture and the breakdown products of garnet were formed under the conditions of the pyroxene hornfels or sanidinite facies. From the progressive change of mineral facies and the distinct discrepancy of grain-size between the large mineral assemblages and fine mineral ones, it is possible to consider, roughly estimating, that the former indicates the stage of contact metamorphism and the latter the stage of pyrometamorphism.

INTRODUCTION

Since the early part of this century, the xenolithic inclusions in the andesitic rocks of the Nijo-san and Amataki-yama districts have been well known for the occurrences of staurolite, garnet, sillimanite, andalusite and corundum. Petrological studies on the volcanic rocks of these districts that are situated in the Setouchi (Inland Sea) Petrographic Province were made by Koza and Yagi (1941), Takeuchi (1941), Morimoto *et al.* (1953), Morimoto, Fuzita and Kasama (1957), Yamazaki and Onuki (1969), Kato *et al.* (1971), Ujike (1972) and Yamazaki *et*

al. (1973). The andesitic rocks erupted during the age from Late Miocene to Early Pliocene. The granitic rocks and metamorphic rocks as the basements of these districts belong to the Ryoke metamorphic terrane that was subjected to the low pressure series of metamorphism. The metamorphic rocks are characterized by pelitic schists and gneisses.

Up to this time, staurolite-bearing rocks in Japan, except the districts mentioned above, occur in the Unazuki district of the Hida metamorphic belt (Ishioka and Suwa, 1956), the Furudono, Takabo-yama and

Fig. 1. Index map of the Nijo-san and Amataki-yama districts.

Am: Amataki-yama, Ko: Kobe, Ky: Kyoto, Na: Nara, Nj: Nijo-san, Ok: Okayama, Os: Osaka, Ta: Takamatsu, To: Tokushima, Wa: Wakayama, M.T. Line: Median tectonic line.

Nishidohira districts of the Abukuma metamorphic belt (Urano and Kanisawa, 1965; Research Group of the Abukuma Plateau, 1969; Tagiri, 1971), and the Hazu district of the Ryoke metamorphic belt (Asami, 1971). The staurolites of the Unazuki and Nishidohira districts coexist with kyanite, andalusite, sillimanite and garnet. The others associate with andalusite, sillimanite, spinel and corundum. From their geological environment these staurolite-bearing rocks are contradistinguished from those of the Nijo-san and Amataki-yama districts.

The xenoliths from the two districts have been interpreted as the fragments of the older metamorphic rocks prior to the Ryoke metamorphism or of the deeper part of the Ryoke metamorphic rocks (Miyashiro,

1965). These xenoliths are described with reference to the mineral parageneses and discussions are presented on the metamorphic conditions of these xenoliths.

BRIEF DESCRIPTION ON THE ANDESITIC ROCKS

The xenolith-bearing andesitic rocks of the two districts mentioned above are of the calc-alkali rock series (Morimoto, Fuzita and Kasama, 1957).

The xenolith-bearing garnet biotite andesite lava in the Nijo-san district consists of phenocrystic plagioclase (An = 64-45), biotite, garnet and quartz, and its groundmass minerals are plagioclase, orthopyroxene, clinopyroxene, iron ores, apatite, cristobalite and glass. This andesite contains garnet, biotite, plagioclase, quartz

Table 1. Chemical compositions of the xenolith-bearing andesitic rocks.

	1	2
SiO ₂	61.67	57.57
TiO ₂	0.60	0.97
Al ₂ O ₃	17.92	17.78
Fe ₂ O ₃	0.41	1.58
FeO	3.91	3.96
MnO	0.11	0.13
MgO	1.52	2.79
CaO	4.77	5.77
Na ₂ O	3.00	3.35
K ₂ O	2.42	1.82
H ₂ O ⁺	0.87	3.64
H ₂ O ⁻	0.53	0.42
P ₂ O ₅	0.18	0.25
CO ₂	1.66	-
Total	99.57	100.01

- 1: Garnet biotite andesite from the Nijo-san district (after Morimoto, Fuzita and Kasama, 1957).
- 2: Hornblende hypersthene andesite from the Amataki-yama district (after Kozu and Yagi, 1941).

and corundum as the xenocryst. There are two types of phenocrystic garnets. One is fibrolite-bearing garnet and the other is a euhedral clear one.

The xenolith-bearing hornblende hypersthene andesite lava of the Amataki-yama district is composed of phenocrystic plagioclase ($An = 30-50$), biotite, hornblende, hypersthene, garnet and augite, and its groundmass minerals are hypersthene, plagioclase, alkali feldspar, iron ores, apatite, crisotbalite and glass. The andesite includes garnet, staurolite, biotite, spinel, plagioclase and quartz as the xenocryst.

The chemical compositions of the garnet biotite andesite from Nijo-san district (Morimoto, Fuzita and Kasama, 1957) and of the hornblende hypersthene andesite from the Amataki-yama district (Kozu and Yagi, 1941) are shown in Table 1. The garnet biotite andesite is richer in SiO_2 and poorer in (total $FeO + MgO$) than the hornblende hypersthene andesite.

DETERMINATION OF MINERAL PARAGENESES IN XENOLITHS

It is supposed that the xenoliths in the volcanic rocks were intensely affected by magmatic heat and that they had very high thermal gradient for a relatively short period of time. Some mass transfer is also expected to occur between the xenolith and magma. Under these conditions, the metamorphic reaction does not reach equilibrium completely, metastable minerals usually appear and metasomatic zonation is sometimes produced in the xenoliths. Therefore, much caution is necessary to decide the mineral parageneses of the xenoliths.

The mineral parageneses were determined by the coexistence of each mineral

with a crystallographically concordant form in addition to their concomitance within the radius of about 1 mm. Fibrous crystals were judged to associate stably with needle and symplectitic crystals, not columnar and granular ones. When both of columnar and/or granular crystals were euhedral or anhedral together, they were regarded as to be of paragenetic relation.

Furthermore, supposing that each part of the xenolith consists of constant inert components and perfectly mobile components through all stages of metamorphism, the mineral assemblages can be correlated with the mineral facies.

DESCRIPTION OF THE NIJO-SAN XENOLITHS

The argillaceous xenoliths of the Nijo-san district are about 15 cm long, 10 cm broad and 5 cm thick in maximum, and their arrangement is concordant with the flow structure of the andesite lava. As the xenoliths sometimes show banding and gneissose structures, their original rocks are probably sedimentary rocks or pelitic schists. Most of the xenoliths, however, show no schistosity. The metasomatic zonation appears rarely in the xenoliths. The grain-size of the xenoliths is usually medium and very rarely coarse. Porphyroblasts of andalusite, sillimanite, cordierite and garnet in them are commonly grains about 1 mm in diameter. All argillaceous xenoliths contain much calcic plagioclase, graphite and iron ores. Calcic plagioclase fairly euhedral, showing remarkable zonal structure and contains glass.

A coarse-grained quartzite is also found in the Nijo-san district.

There are three types of argillaceous xenoliths from this district. The type A

Fig. 3. Photomicrographs of the paragenetic relations (II).

- A: The Corona texture of spinel-corundum-glass around sillimanite porphyroblast, the Nijo-san xenolith (plane polarized light).
 B: The breakdown products of garnet, namely orthopyroxene-fibrolite-spinel, the Amatakiyama xenolith (plane polarized light)

Abbreviations as in Fig. 2.

lacks quartz, type B is quartz- and biotite-free, and type C contains quartz. The type A is most abundant among these xenoliths. Coarse-grained equigranular aggregates of quartz very rarely surrounds the quartz-free xenoliths. In the collection there is only one specimen, exceptionally a

large lump (about $5 \times 5 \times 5$ cm), of type B xenolith.

Mineral Assemblages of Type A Xenolith

This type consists of eight mineral assemblages as follow. For convenience such common minerals as plagioclase,

Fig. 2. Photomicrographs of the paragenetic relations (I).

- A: The mineral assemblages of andalusite-staurolite-corundum and andalusite-staurolite-cordierite (plane polarized light).
 B: Staurolite crosses the twin boundary of cordierite (crossed polars).
 C: The mineral assemblages of sillimanite-spinel-garnet and the corona texture of spinel-corundum-glass (plane polarized light).
 D: The mineral assemblage of orthopyroxene-reddish spinel (plane polarized light).

All are the Nijo-san xenoliths.

Abbreviations are as follows: And : andalusite, Bi : biotite, Cd : cordierite, Co : Corundum, Fibr: fibrolite, Ga: garnet, Opx: orthopyroxene, Pl: plagioclase, Sill: sillimanite, Sp: Spinel.

graphite, biotite and iron ores are omitted from the description of the assemblages.

- 1) Andalusite-staurolite-cordierite (Fig. 2A)
- 2) Andalusite-staurolite-garnet
- 3) Andalusite-staurolite-corundum (Fig. 2A)
- 4) Andalusite-staurolite-spinel
- 5) Sillimanite-spinel-corundum (+ metastable andalusite)
- 6) Sillimanite-garnet-cordierite
- 7) Sillimanite-garnet-spinel (Fig. 2C)
- 8) Fibrolite-corona spinel-corona corundum-glass (Fig. 2C)

Andalusite is subhedral porphyroblast, and has a zonal structure as shown by the shades of reddish pleochroism. Staurolite is subhedral, shows a golden yellow pleochroism and does not associate with sillimanite. Sometimes the staurolite crystals cross the twin boundary of cordierite (Fig. 2B). Cordierite is porphyroblast and shows pale bluish pleochroism. The distortion index and the optic axial angle of a cordierite ($\gamma=1.544$ and $\alpha=1.534$) is 0.28 and $45^\circ \pm 5^\circ$, respectively. Garnet is subhedral to euhedral and rich in almandine molecules. Spinel occurs as subhedral to euhedral crystals with green color. Corundum is subhedral to anhedral and blue in color. Sillimanite occurs as porphyroblast, and frequently coexists with metastable andalusite. Fibrolite grows in the crystals of plagioclase, cordierite, garnet and staurolite. The X-ray powder patterns of the fibrolite are those of sillimanite. Therefore, fibrolite is the fine needles of sillimanite and easily distinguished from sillimanite described here by the differences of grain-size and crystal habit in the Nijo-san xenoliths.

The mineral assemblages 1)–4) do not coexist stably with those of 5)–7) in a

xenolith. The mineral assemblage 8) showing corona texture occurs around andalusite, sillimanite and staurolite (Fig. 3A).

Mineral Assemblage of Type B Xenolith

The mineral assemblage of this type is as follow.

- 1) orthopyroxene-spinel-plagioclase-olivine-cordierite (Fig. 2D)

Because this massive xenolith is very coarse-grained equigranular in texture, the criteria for determination of the mineral paragenesis mentioned above does not apply to it. The zonal structure of plagioclase is not remarkable. The xenolith contains much graphite. Most of the iron ores are ilmenite. Orthopyroxene shows weak pleochroism and its optic axial angle is $(-)$ $56^\circ \pm 5^\circ$. Spinel is purplish red in color ($a=8.13$). Cordierite and olivine are rare.

Mineral Assemblage of Type C Xenoliths

All specimens of this type have the following single mineral assemblage.

- 1) Biotite - plagioclase - garnet - quartz-iron ores-graphite $\pm$ aluminosilicate.

DESCRIPTION OF THE AMATAKI-YAMA XENOLITHS

The xenoliths of the Amataki-yama district are much smaller than those of the Nijo-san district. These xenoliths also show a banding structure, and their grain-size are usually medium and rarely coarse. Porphyroblasts are not sillimanite and cordierite, but garnet and staurolite. Sillimanite crystals are fibrous or fine needles. All xenoliths contain calcic plagioclase, graphite, biotite and iron ores, and lack quartz as in the case of type A of the Nijo-san xenoliths. Biotite, staurolite, garnet

and spinel frequently have a opacite margin. These xenoliths consist of five mineral assemblages as follow. The common minerals of all assemblages, that is, plagioclase, biotite, graphite and iron ores, are omitted from the descriptions.

- 1) Staurolite-spinel-cordierite
- 2) Staurolite-spinel-garnet
- 3) Fibrous sillimanite-spinel-garnet
- 4) Orthopyroxene-fibrolite-spinel (Fig. 3B)
- 5) Fibrolite-corona spinel-corona corundum.

In the Amataki-yama xenoliths, all staurolites associate with spinel in contrast with the staurolite-bearing mineral assemblages of the Nijo-san xenoliths. The modal content of staurolite in the Amataki-yama xenoliths are more than those of the Nijo-san ones. Garnet including both staurolite and spinel occurs occasionally (Takeuchi, 1941). The mineral assemblage

4) is the breakdown product of garnet, and the grain-size of each mineral is very fine. Orthopyroxene shows pale greenish pleochroism and has a small optic axial angle ($-51^\circ \pm 5^\circ$). The corona texture of the mineral assemblage 5) appears around staurolite and garnet, and consists mostly of spinel. Corundum in this assemblage is very rare.

MINERAL PARAGENETIC RELATIONS OF THE QUARTZ-FREE XENOLITHS

Since staurolite forms over a wide range of rock-pressure, it is able to occur not only in regional metamorphic terranes but also in contact aureoles. From the textural relations the staurolite crystals in the xenoliths in question do not appear to be the relic of the product by older regional metamorphism. All of the observed minerals and textures of the xenoliths were

Fig. 4. The $Al_2O_3-(FeO+MgO)-SiO_2$ diagram.
A: Al_2O_3 , S: SiO_2 , F: $(FeO+MgO)$. Other abbreviations as in Fig. 2.

probably the result of the younger thermal metamorphism alone, if these xenoliths had formerly suffered regional metamorphism.

The paragenetic relations of the minerals of the quartz-free xenoliths can be represented in the triangular diagram of Al_2O_3 -(FeO + MgO)- SiO_2 system. All minerals except those of the excess and indifferent components in these xenoliths appear in this system. Orthopyroxene, red spinel, olivine and cordierite are probably so rich in MgO that system Al_2O_3 -(FeO + MgO)- SiO_2 admits tie-line showing tetragon. The corona texture of spinel-corundum-glass surrounding sillimanite is evidence that the SiO_2 component becomes a perfectly mobile one at the last stage of metamorphism, still this triangular diagram is applicable on these parageneses. The Al_2O_3 -(FeO + MgO)- SiO_2 diagrams, though they are not complete, are shown in Fig. 4.

The mineral assemblages of these xenoliths are divided into the following two groups in terms of grain-size which is clearly different between the two: one group is of the large-grained minerals and the other those of the fine-grained minerals. Furthermore, the former is subdivided into the staurolite-bearing parageneses and the staurolite-free ones. In the Nijo-san district, the type B xenolith is probably so rich in MgO that its paragenetic plane does not join any planes of the staurolite-free parageneses of type A. The staurolite-bearing, aluminous xenoliths are lacking in the Amataki-yama district.

As mentioned above, staurolite may not be a relic of older regional metamorphism, and practically it associates with some minerals according to the mineralogical phase rule. Therefore, it can be emphasized that those xenoliths recrystallized succe-

ssively with increasing temperature of the thermal metamorphism caused by the andesitic magma.

The staurolite-bearing parageneses can be regarded as the amphibolite facies or the pyroxene hornfels facies. The staurolite-free parageneses including the orthopyroxene-spinel-olivine-cordierite assemblage belong to the pyroxene hornfels facies (Chinner, 1962). The corona texture of spinel-corundum-glass and the breakdown products of garnet, namely, orthopyroxene-fibrolite-spinel indicate that the parageneses of the fine-grained minerals were formed under the conditions of the pyroxene hornfels or the sanidinite facies (Smith, 1969). From the experiments by Richardson (1968) and Ganguly (1972), the staurolite-bearing

Fig. 5. P-T projections of equilibria defining the limits of thermal stability of staurolite + quartz, at oxygen fugacities around the middle of the magmatic field of Ganguly (1972). The aluminosilicate equilibria stands for Richardson, Bell and Gilbert (1969), (R) for Richardson (1968) and (G) for Ganguly (1972). The arrow shows the approximate conditions of this thermal metamorphism. Alm: almandine, Qz: quartz. Other abbreviations as in Fig. 2.

quartz-free xenoliths recrystallized at a temperature below 750° C and at about 2 Kb (Fig. 5).

With increasing temperature, staurolite disappears and andalusite transforms into sillimanite. The association of sillimanite and the incompatibility of staurolite and sillimanite indicate a nearly constant pressure through the metamorphism. With further increasing of temperature, garnet decomposes to orthopyroxene, spinel and fibrolite. At the same time, sillimanite, metastable andalusite and staurolite react to the andesitic magma to form the corona texture of spinel-corundum-glass. In the metasomatic parts, which are 5–10 mm wide from the contact with the andesite, sillimanite prophyroblast is completely replaced with corundum mantled by spinel, and plagioclase becomes extremely euhedral. At the highest grade, the xenoliths in the magma become desilicified and partially melted. Consequently, the original mineral assemblages of the xenoliths become completely reconstructed during the thermal metamorphism by the andesitic magma, if they had suffered older regional metamorphism.

The difference of the staurolite-bearing assemblages between the Nijo-san and Amataki-yama xenoliths is probably caused by the difference of the original rocks and/or by the different degrees of the metasomatic reaction, especially desilicification, between the xenolith and the magma.

It is supposed that the xenoliths of the two districts first suffered contact metamorphism at the wall rocks of the magma chamber or of conduit for the rising andesitic magma, and then were intensely affected by magmatic heat as inclusions in the magma. From the progressive change of mineral facies and the distinct descrep-

ancy of grain-size between the large mineral assemblages and fine grained ones, it is possible to consider, roughly estimating, that the former indicates the stage of contact metamorphism and the latter shows that of pyrometamorphism in the andesitic magma.

The mineralogy and petrochemistry of these xenoliths will be reported at another opportunity.

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二上山および雨滝山産安山岩質岩石中の粘土質捕獲岩類の鉱物共生

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安山岩質岩漿の熱影響によって再結晶した捕獲岩類は比較的大きな粒度をもつ 鉱物組合せと細粒のそれらとを含んでいる。前者は十字石を含むものと含まぬものに分類できる。十字石を含む 鉱物共生は角閃岩相あるいは輝石ホルンフェルス相とみなされ、十字石を含まぬ 鉱物共生は輝石ホルンフェルス相に属する。細粒の 鉱物共生であるコロナ組織やざくろ石の 分解生成物は輝石ホルンフェルス相あるいはサニディナイト相の条件下で形成された。鉱物相の増進的变化や2種の粒度の差のはっきりした 鉱物共生の存在から、比較的大きな 鉱物共生関係は接触変成作用にて、細粒の 鉱物共生関係はパイロ変成作用の結果であると考えることが可能である。

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